NBS SPECIAL PUBLICATION 540

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Fire Research and Safety

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[2]Some divisions within the center are located at Boulder, CO 80303.

Fire Research and Safety

Proceedings of the Third Joint Panel Conference of the U.S.-Japan Cooperative Program in Natural Resources held March 13-17, 1978 at the National Bureau of Standards, Gaithersburg, MD

Edited by:

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ABSTRACT

The Third Joint Panel Meeting of the United States - Japan Panel on Natural Resources (UJNR), Fire Research and Safety, was held at the National Bureau of Standards in Gaithersburg, Maryland, from March 13-17, 1978. The meeting consisted of in-depth technical sessions on detection and smoke properties, modeling of fire, and toxicity of fire gas. Progress reports briefly covered human behavior, building systems, and smoke control. The proceedings include the technical papers presented at the meeting along with the ensuing discussion and the summary reports prepared by each session chairman.

The first meeting of UJNR Panel on Fire Research and Safety was held in Washington, D.C. from April 7-8, 1976, where the current activities in the United States and Japan on fire research and safety were introduced. After this exchange, the following six topics were selected for initial cooperation: toxicity, building systems, human behavior, smoke control, detection and smoke properties, and modeling of fire.

The participants at the third meeting resolved that the next meeting, to be held in Tokyo in February of 1979, will cover the following topics in-depth: (1) human behavior in fires, (2) building systems and smoke control, (3) fire and smoke retardants and (4) fire investigation techniques. Progress reports will be submitted in the areas of toxicity, detection and smoke properties and fire modeling.

Key words: Building fires, conferences, fire detection, fire investigations, fire models, fire research, fire retardants, flame retardants, human behavior, smoke, toxic gases, toxicity.

AGENDA
THE THIRD JOINT PANEL MEETING
UJNR Panel on Fire Research

March 13-17, 1978

Date/Time	Program	Location
Monday, March 13	Session Chairman - Dr. J. W. Lyons	
9:00 a.m.	Opening Session Welcoming Addresses	Lecture Room B
10:30 a.m.	Coffee and Tea Break	
10:45 a.m.	Election of Officers Approval of Agenda	
12:30 p.m.	Lunch	Dining Room C
2:00 p.m.	Tour of NBS Fire Research Facilities	
Tuesday, March 14	Session Chairman - Prof. J. Miyama	
9:00 a.m.	Technical Session "Detection and Smoke Properties"	Lecture Room B
10:30 a.m.	Coffee and Tea Break	
10:45 a.m.	Continue "Detection"	
12:30 p.m.	Lunch	Dining Room C Senior Lunch Club Buffet
1:30 p.m.	Continue "Detection"	
2:30 p.m.	Coffee and Tea Break	
2:45 p.m.	Session Chairman - Mr. G. Bates Progress Reports on: Human Behavior Building Systems Smoke Control	
4:30 p.m.	Adjournment	
Wednesday, March 15	Session Chairman - Prof. H. Emmons	
9:00 a.m.	Technical Session "Modeling of Fire"	Lecture Room B
10:30 a.m.	Coffee and Tea Break	
10:45 a.m.	Continue "Modeling"	
12:30 p.m.	Lunch	Dining Room C Senior Lunch Club Buffet
1:30 p.m.	Continue "Modeling"	
3:15 p.m.	Coffee and Tea Break	

Wednesday, March 15	Session Chairman - Dr. A. Watanabe	
3:30 p.m.	Technical Session "Toxicity of Fire Gas"	Lecture Room B
4:30 p.m.	Adjournment	

Thursday, March 16

The Panel Meeting will be held at the Applied Physics Laboratory (APL) in Laurel, Maryland. A bus will leave for APL at 7:40 a.m. from the lobby of Building 225 on the Bureau's campus. The bus will also stop at 7:45 a.m. at the Holiday Inn in Gaithersburg, Maryland, to pick up the Japanese visitors and anyone else staying there.

9:00 a.m.	Presentation on APL Fire Programs	Applied Physics Lab. Laurel, Maryland
9:45 a.m.	Session Chairman - Dr. A. Watanabe Technical Session "Toxicity of Fire Gas"	
1:00 p.m.	Lunch	
2:00 p.m.	"Toxicity" Continued	
5:30 p.m.	Reception	
6:30 p.m.	Dinner	
8:30 p.m.	Bus departs from the Applied Physics Laboratory for the Holiday Inn, Gaithersburg, Maryland, and Building 225, National Bureau of Standards.	

Friday, March 17	Session Chairman - Dr. J. W. Lyons	
9:00 a.m.	Open Technical Session	Lecture Room B
10:30 a.m.	Coffee and Tea Break	
10:45 a.m.	Resume Technical Session	
12:30 p.m.	Lunch	Dining Room C
2:00 p.m.	Session Chairman - Dr. K. Nakano Closing Joint Session Reports of Technical Sessions Resolutions	Lecture Room B
4:30 p.m.	Adjournment	

LIST OF PARTICIPANTS

The Third Joint Panel Meeting
UJNR Panel on Fire Research

March 13-17, 1978

PANEL MEMBERS - Japan

Dr. Kiyoshi Nakano
Ministry of Construction

Mr. Fumiharu Saito
Ministry of Construction

Mr. Tekeyoshi Tanaka
Ministry of Construction

Dr. Ken-ichi Nakamura
Ministry of Construction

Dr. Akio Watanabe
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Dr. Tadahisa Jin
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Professor Kei-ichi Yamamoto
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Mr. Kakuji Ohkawa
Formerly with Tokyo Fire Dept.

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Mr. Irwin Benjamin
Center for Fire Research

Mr. Robert Levine
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Professor Howard Emmons
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Dr. Raymond Friedman
Factory Mutual Research Corporation

Dr. Walter Berl
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Professor Irving Einhorn
University of Utah

Professor John Bryan
University of Maryland

Mr. George Bates
Federal Aviation Administration

Dr. Takashi Kashiwagi - Secretary
Center for Fire Research

Invited Participants

Dr. George Mulholland
Center for Fire Research

Mr. Richard Bukowski
Center for Fire Research

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Dr. Robert Chaiken
Bureau of Mines

Dr. Constantine Sarkos
Federal Aviation Administration

Dr. M. Levine
Applied Physics Laboratory

Dr. B. Halpin
Applied Physics Laboratory

Third UJNR Meeting

Minutes of the Opening Session:

Dr. John W. Lyons, chairman of the United States delegation, opened the joint session by welcoming the delegation to the National Bureau of Standards (NBS). He then reviewed the United States' and Japanese experience with unwanted fire, referred to the successes of the UJNR Wind and Seismic Panel, and discussed the formation of the Fire Research and Safety Panel. The six topics agreed upon at the first Joint Panel Meeting at NBS in April 1976 were discussed at the second Joint Panel Meeting in Tokyo in October 1976. The Tokyo meeting was called very useful and productive by Dr. Lyons. He noted that the Joint Panel had agreed to a third meeting in about 18 months at NBS and to review three of the topics in detail - toxicity of fire gases, detection and smoke properties, and modeling - and the other three only in brief progress reports. The present meeting is being held in response to those decisions. Dr. Lyons pointed out that in the time between the second and third panel meetings, one exchange of a professional had occurred, namely, Prof. Terai of Kyoto University visited for a considerable time in the United States in the summer of 1977 under auspices of the panel and had spent a portion of that time at NBS.

Dr. Lyons noted that Dr. Shirayama, the first chairman of the Japanese delegation, had retired from the Building Research Institute (BRI) in Tokyo and is now teaching at Tsukuba University. Dr. Lyons welcomed the new chairman of the Japanese delegation, Dr. K. Nakano, the present Director of BRI, and observed that Dr. Nakano is no stranger to NBS, having been here earlier as a member of the UJNR Wind and Seismic Panel.

Mr. Nagara, Scientific Attaché of the Japanese Embassy in Washington, D.C. responded first for the Japanese delegation. He reviewed events leading to the formation of this panel, discussed the Wind and Seismic Panel, and reported that a new UJNR panel on predicting earthquakes was established last fall. Dr. Nakano stated his pleasure at the arrangements and said that the Japanese delegation was looking forward to a very useful meeting. The delegations were introduced by their chairman. (See list of attendees in preceding section.)

Elections were then conducted with the following results: Dr. J.W. Lyons to be chairman of the opening session, Dr. K. Nakano to be chairman of the closing session, Dr. W. Berl and Mr. A. Watanabe to serve as the resolutions committee.

The minutes of the second Joint Panel Meeting in Tokyo were approved as printed in the Proceedings, Vol. 2. Dr. Lyons indicated his pleasure with the appearance of the two volume proceedings of the second Joint Panel Meeting. He stated that the United States will undertake to publish the proceedings of the third Joint Panel Meeting.

The agenda for the week was then reviewed in detail and approved with minor modifications. Procedural details for the sessions were discussed fully.

The opening session adjourned after the foregoing discussions were completed.

SMOKE DETECTOR DESIGN AND SMOKE PROPERTIES[1]

Richard W. Bukowski and George W. Mulholland

The importance of a reference photometer and reference ionization detector in improving the reliability of smoke detectors is discussed. Recent developments in smoke detector technology are highlighted and theoretical as well as practical experience in regard to detector performance is summarized. Comparison of the theoretically predicted response of smoke detectors as a function of particle size with measured values is given. A monodisperse aerosol generator, an electrical aerosol analyzer with a size sensitivity from 0.01 to 1 μm, and an optical particle counter are described. The size distribution, mass and number concentration, optical density, and coagulation frequency for smoke from burning heptane and smoldering cotton lamp wick are presented. It is shown that a Junge type size distribution provides a good fit to the measured size distribution for both fresh and aged smoke.

Key words: Aerosol generators; detector testers; fire detectors; ionization detectors; light-scattering detectors; particle size distribution; smoke; smoke detectors.

1. INTRODUCTION

This paper consists of two parts. The first part concentrates on smoke detector design (sections 1-8) and the second part consists of recent research on smoke aerosol properties pertinent to smoke detection (sections 9-14).

Smoke detectors, particularly the residential variety, have undergone an extremely rapid growth in sales to where they are currently being compared with digital watches, pocket calculators, and citizens band radios in popularity. In the last five years, residential smoke detectors have grown from annual sales in the U.S. of less than a few hundred thousand to a market level of twelve to fourteen million in the calendar year 1977. You will note in figure 1 (which gives actual sales estimates prior to 1977 and our projections for 1977 and beyond) that the 1977 sales were two million units ahead of our projection made in May of 1977.

Because NFPA records indicate that approximately 75% of the U.S. fire deaths occur in residences and because studies [1][2] have indicated that almost half of these residential fire deaths could be prevented by the widespread use of residential smoke detectors, it is obvious that the impact of these sales on the reduction of U.S. fire losses can be great.

The vastly increased sales volume as well as technical developments in electronics have resulted in greatly decreased prices in the marketplace. For example, in 1971 residential smoke detectors cost an average of $125 per unit. Currently, a number of detectors are available for under $20 per unit retail

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[1] This paper was presented at the Third Joint Panel Meeting of the United States and Japan Natural Resources (U.J.N.R.) Panel on Fire Research and Safety, March 1978.

[2] Numbers in brackets refer to the literature references listed at the end of this paper.

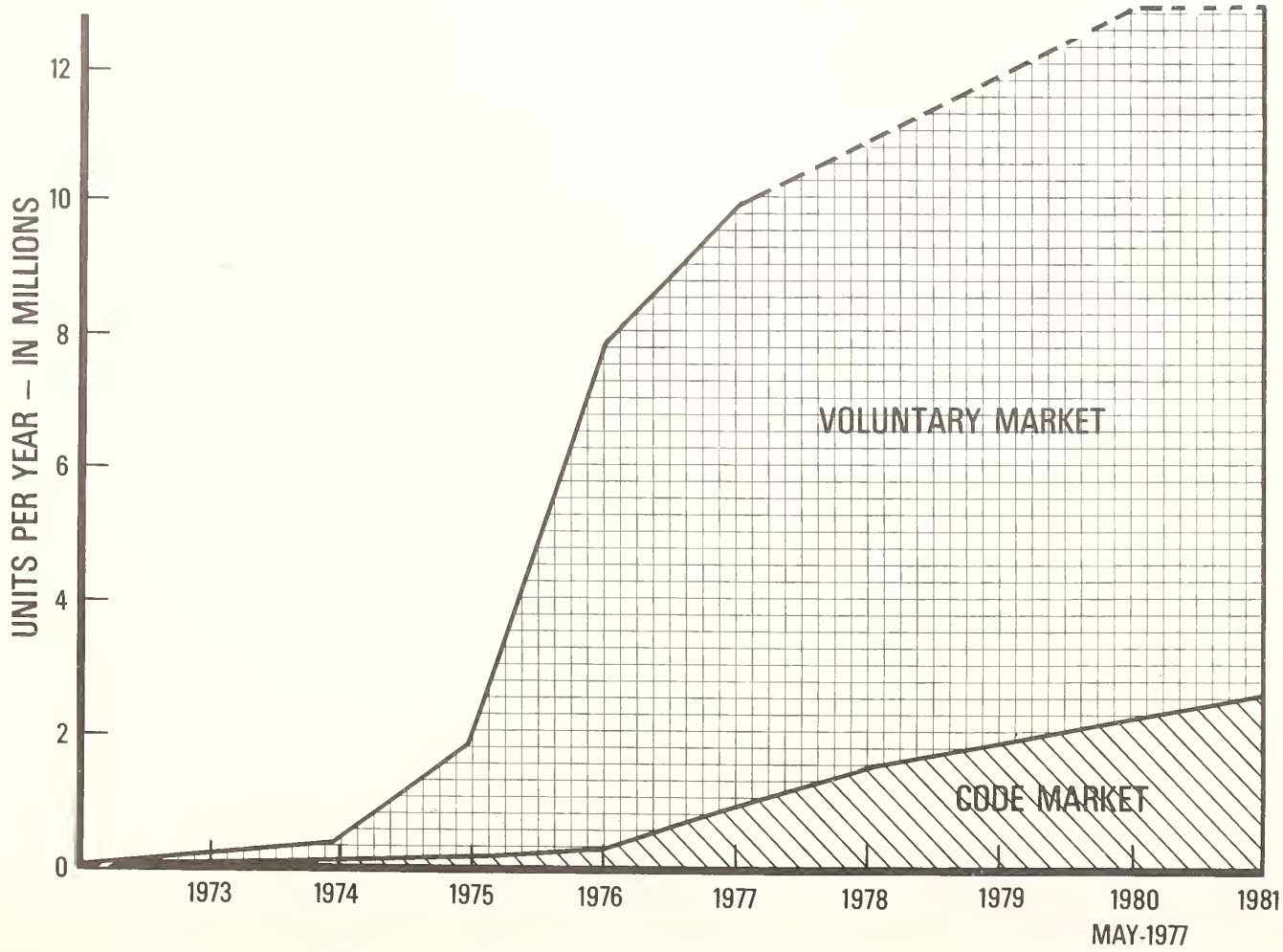

Figure 1. Smoke alarm market predictions.

($25 average - figure 2). While decreased cost, extensive consumer interest, and large-scale national advertising have all contributed to this increased sales volume it can also be readily understood that the performance and quality of the devices is critical in achieving the projected impact on fire losses. For this reason, the National Bureau of Standards, Center for Fire Research is deeply involved and committed to work which will provide a better understanding of the design, performance, and proper use of smoke detectors.

	1971	1977
NO.UNITS SOLD	50,000	12-14 MILLION
UNIT PRICE	$ 125	$ 25

Figure 2. Comparison of smoke detector sales and average retail cost -- 1971 and 1977.

2. POTENTIAL PROBLEM AREAS

Identified problem areas with residential smoke detectors can be divided into three broad categories. These are false alarms, performance and design, and reliability.

The primary cause of false alarms in residential applications is cooking. Technically, this is a difficult problem to overcome since the cooking process produces particulates of similar size ranges and concentrations to those seen in hostile fires. Our feeling is that, for most applications, optimum choice of type of detector and placement within the dwelling can preclude most false alarm problems from cooking. Also, a recent survey [2] has indicated that the false alarm problem with residential detectors may not be as large as was originally thought. Survey data indicate that, of the people contacted who own residential detectors, 96% rarely or never experienced a false alarm. Also, 97% of those people contacted indicated that they were completely satisfied with the device purchased.

With regard to design and performance, the problems are more complex. As the market has grown, many companies have begun manufacturing residential detectors. Some of these companies have invested little in research and have designed detectors strictly by trial and error. This has led to marginal designs and marginal performance. More recently, a number of semi-conductor manufacturers [3] have begun marketing smoke detector integrated circuits containing all necessary electronics except for the sensing chamber, power source, and sounding device (figure 3). Two manufacturers are producing ionization chambers which can be connected to these smoke detector integrated circuits, which essentially eliminates the need for any research and development on the part of the final manufacturer. Thus, more and more dependence

manufacturer [a]	model	ION	PHOTO
SILICONIX	SM 110	X	X
GENERAL INSTRUMENT	MEM 4962	X	
	MEM 4963	X	X
MOTOROLA	MC14461P/14462P	X	
SUPERTEX	SDIA	X	
	SD2A	X	X
NATIONAL SEMICONDUCTOR	LM1801	X	

a) RCA has also introduced an integrated circuit for smoke detectors (model CA3097).

Figure 3. Current smoke detector integrated circuits [3].

is being placed on the role of the approving laboratory for assurance that marginal or poorly performing units are not marketed. Thus, the need for strict approval standards which assure a fairly high minimum level of performance has become increasingly important.

Another complicating factor in the poor design and performance area has been the cost competition in the marketplace. Price erosion has resulted in a great deal of "value engineering" being used in smoke detector designs. Minimizing production cost and very large production volumes have increased the impact of performance problems which do not show up until the detector is in the field. This situation has led to three major smoke detector recalls in this country in the last two years and the possibility that additional recalls may involve millions of units instead of the hundred thousand or less involved in the first three product recalls.

The third problem area of reliability is again a complex factor. Based on current failure rate predictions, the average residential smoke detector is expected to last on the order of 15 to 20 years before it has to be replaced. It would be desirable to design a detector such that any failure which would prevent its detection of a fire would be indicated to the homeowner by some type of trouble signal. Taken to the extreme, this would result in an extremely expensive unit. Thus, the approach taken has been to try to maximize the reliability of the device without significantly impacting its retail cost. Attempts are being made to devise a realistic method by which the failure rate of a given smoke detector design can be predicted mathematically. While this project is still in its initial stages, we hope to have some answers to this question by the end of 1978. Figure 4 shows a general curve of the variation of failure rate with time, valid for most electronic products [4]. Our goal is to have point A when the unit leaves the factory and point B at 25 to 30 years after sale.

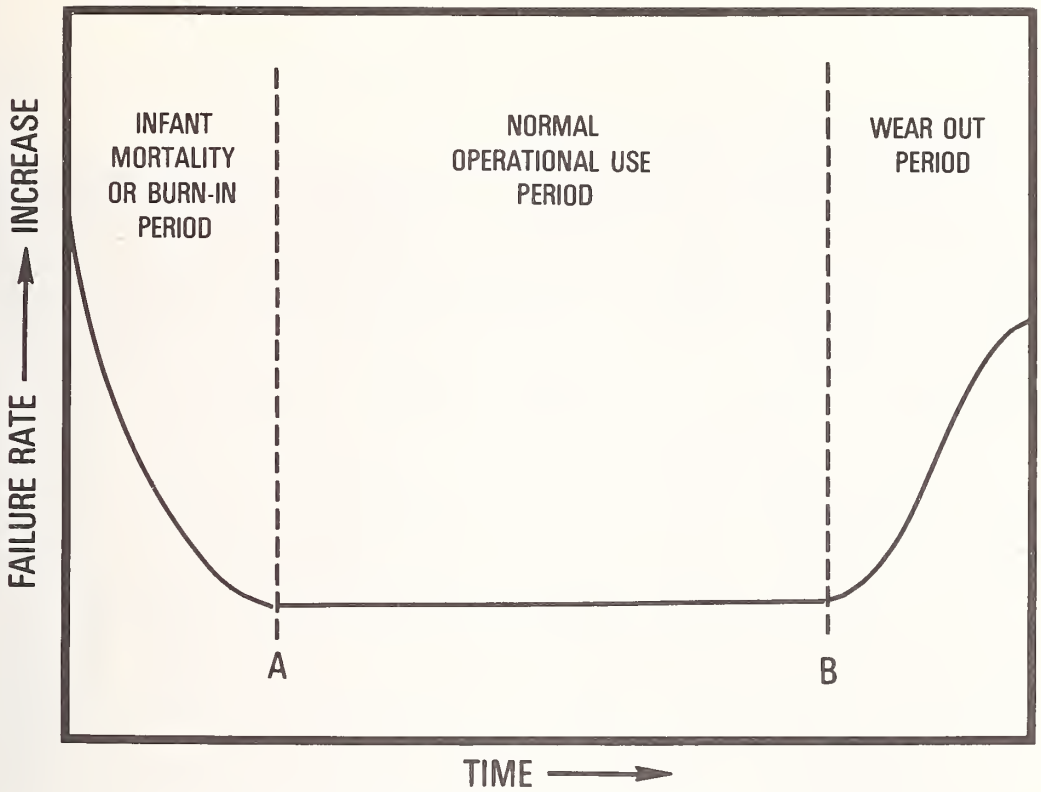

Figure 4. Typical variation of failure rate with time [4].

3. PHILOSOPHY OF APPROVAL STANDARDS

As was mentioned earlier, the product approval standards for residential smoke detectors are becoming increasingly important due to the large numbers of units and designs available. In the past, the philosophy of the U.S. approval standards has been essentially to try to duplicate the conditions of a few specific fires to which the detector might be exposed. While this philosophy has worked fairly well in the past, we feel that the philosophy used by the European approval standards would be better. This philosophy is not to duplicate a few specific fires at random but to design tests which exaggerate the differences between the units tested and which expose the detector to a bracketing range of conditions that might be expected but not necessarily any specific "real life" fire type. With regard to the detection performance testing of smoke detectors, for example, one would design a set of full-scale tests which expose the detector to a range of particle sizes, number concentrations, and refractive indices so that the reaction of the device to any particular combination of these variables within the extremes tested could be estimated.

4. REFERENCE INSTRUMENTATION

Both the increasing popularity of the use of smoke detectors and the increasing desire for additional knowledge about their performance has resulted in a large amount of testing being conducted by various organizations. More and more data are being generated which can be highly useful in expanding our knowledge of the subject. But, the increase in the numbers of people conducting tests has demonstrated the problems in comparability of the data obtained from different sources.

Basically, the comparability problems arise from the large variety of instrumentation being used to take smoke measurements in the tests. For example, the lamp color temperature and receiver spectral sensitivity of most photometers is not consistent or even specified. Therefore, we have developed a specification for a reference photometer (figure 5) which we are proposing as one such instrument. This photometer consists of a tungsten filament light source (figure 6) of a specified color temperature transmitting a collimated beam of light through a one-meter path length to a receiving element (figure 7) with a spectral response matching that of the human eye. By using the human eye response we hope not only to have a reference instrument by which to relate smoke detector response but also to be able to take measurements which relate to human visibility through smoke. While these measurements would not take into account the irritability of the smoke, we feel that the measurements will be meaningful in estimating the amount of time available to people in a fire area for escape or rescue.

In addition to the reference photometer, we are evaluating a reference measuring ionization chamber developed by a Swiss firm (figure 8). Since the photometer is not responsive to particles smaller than about 0.3 micrometers in diameter, the photometer will not correlate well with the output signal from an ionization chamber. Thus, where such correlations are necessary, some type of reference ionization chamber is necessary. This Swiss design is being evaluated by us and others in this country and in Europe and it appears to be the best design thus far proposed.

Another instrumentation problem that we are working on is that of reference test aerosols. Many people in fire research agree that the combustion generated aerosols now used for small-scale test purposes are too variable. Such parameters as material, density, moisture content, thermal history, ambient conditions, and others, have a great effect on the characteristics of the aerosol generated. Thus we feel that a mechanically generated aerosol is the only practical solution to eliminating or minimizing these variables. To this end, we are developing two types of aerosol generators. One will be a highly precise generator for laboratory use in small-scale test compartments; the other will be a less precise, but easy to use, portable unit for testing installed smoke detectors in the field. The field unit could be used to determine the sensitivity of an installed detector instead of just determining whether or not it is operating as is now done. A description of these aerosol generators is given in sections 11 and 14 of this paper.

5. TECHNICAL DEVELOPMENTS

Many technical developments have been made over the last few years in smoke detector design. Battery operated residential detectors which initially used special batteries which were expensive and hard to obtain are being replaced by designs using common batteries which are more available and inexpensive. Also, new concepts in the circuitry that monitor the battery condition have been made. Several detectors now on the market monitor the battery for both terminal voltage and internal resistance build-up which could prevent the operation of the sounding device in a fire situation.

Detector enclosure and chamber designs are making more use of basic theoretical parameters with great improvements in detection performance being seen. New types of sounding devices are being investigated which have better frequency characteristics for audibility, higher reliability, and lower power consumption.

Ionization detectors are being produced with less radioactive material and a new detector using a beta source is now being marketed for commercial applications. Designs of some newer ionization detectors exhibit increased sensitivity to larger particles. The lack of this capability has been a performance drawback in the past.

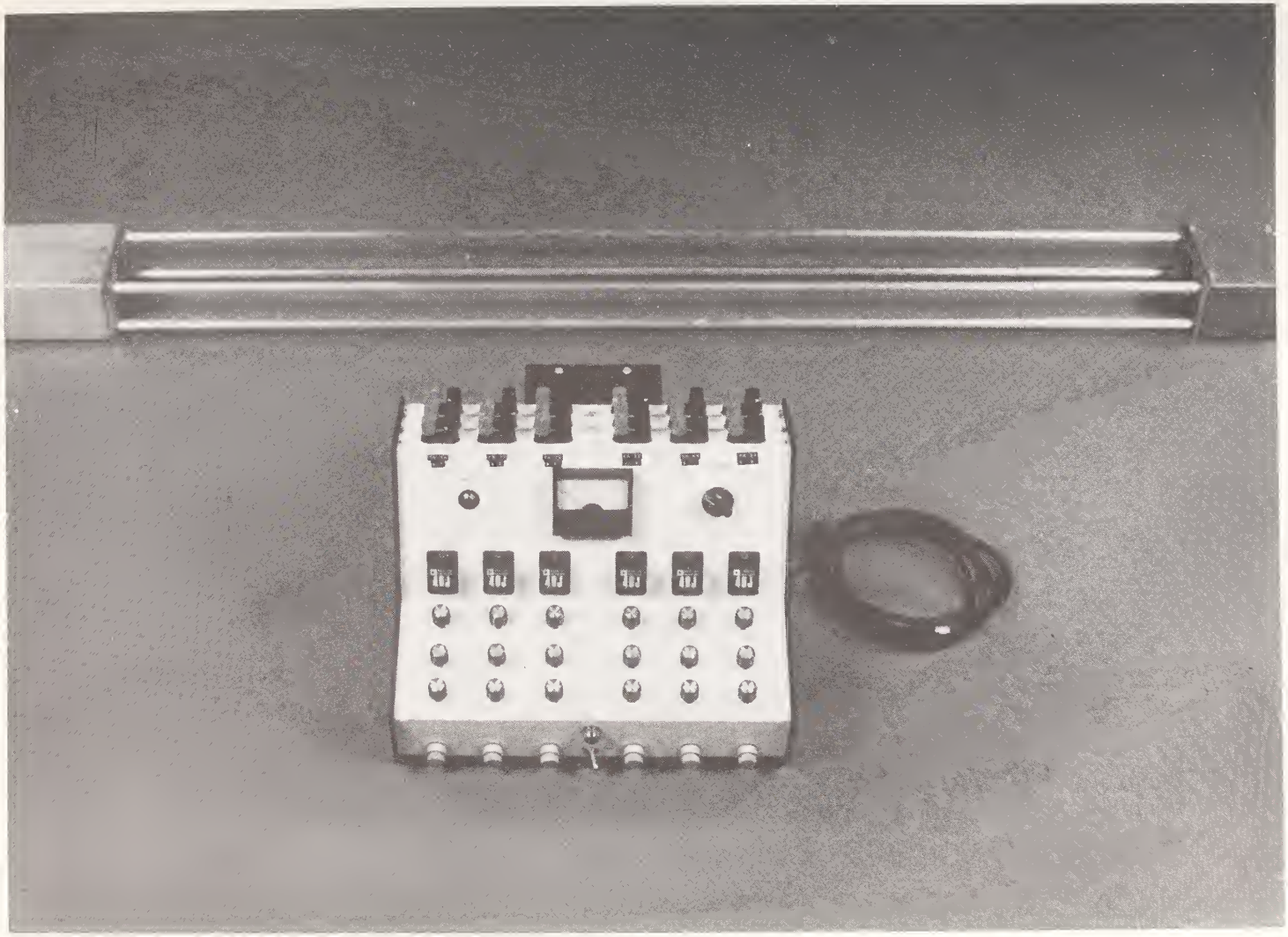

Figure 5. NBS reference photometer.

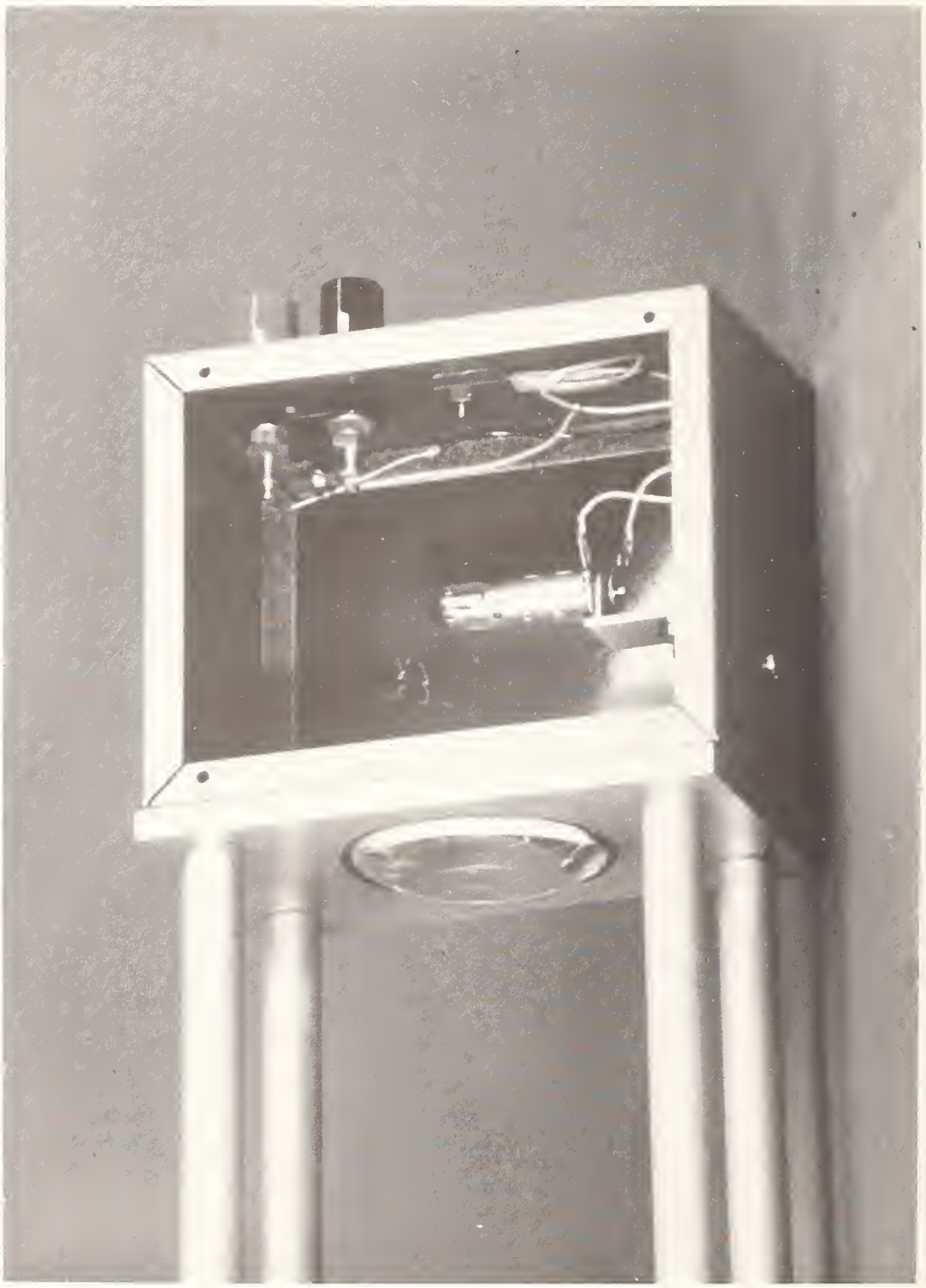

Figure 6. Photometer light source.

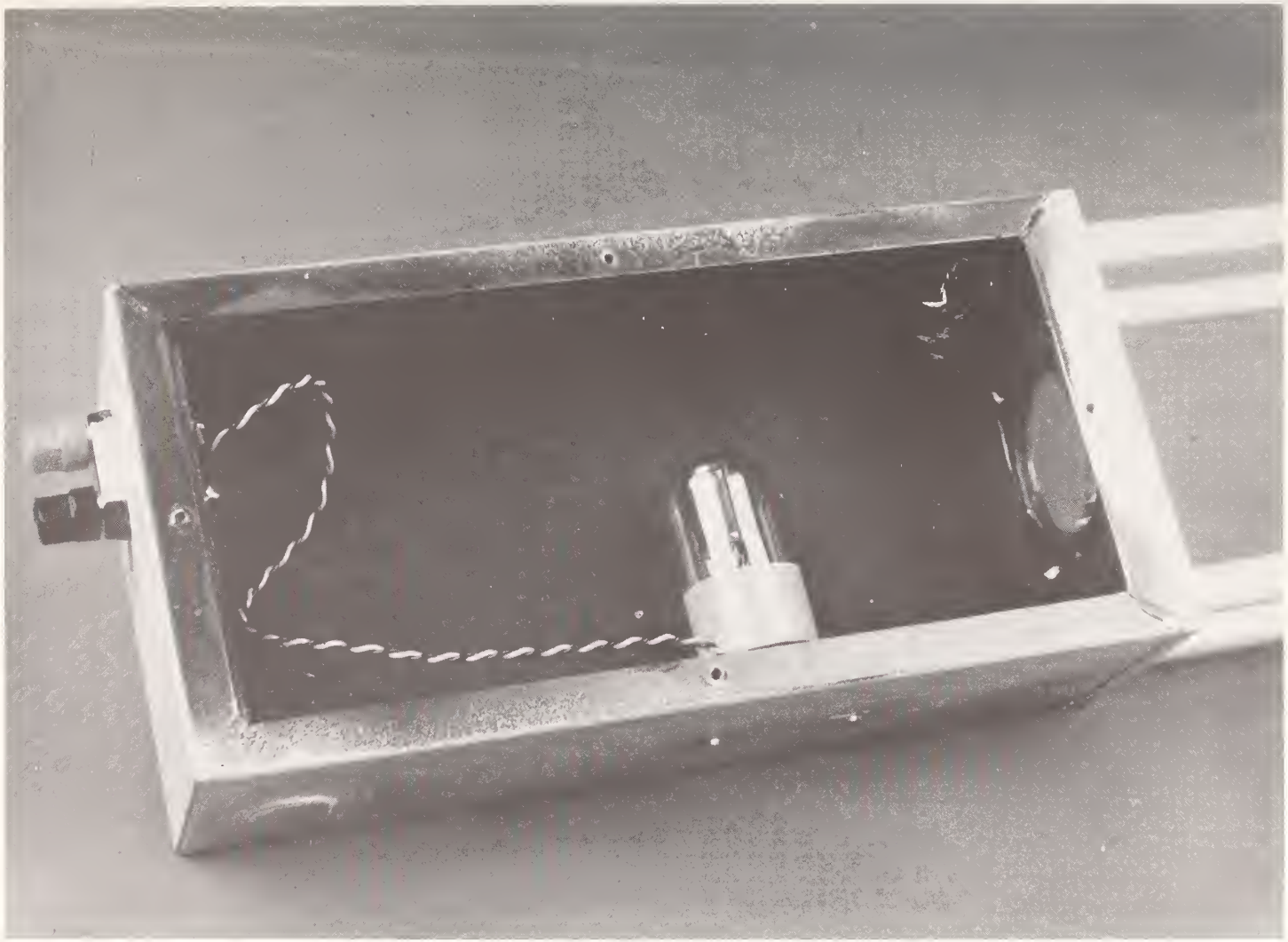

Figure 7. Photometer receiver.

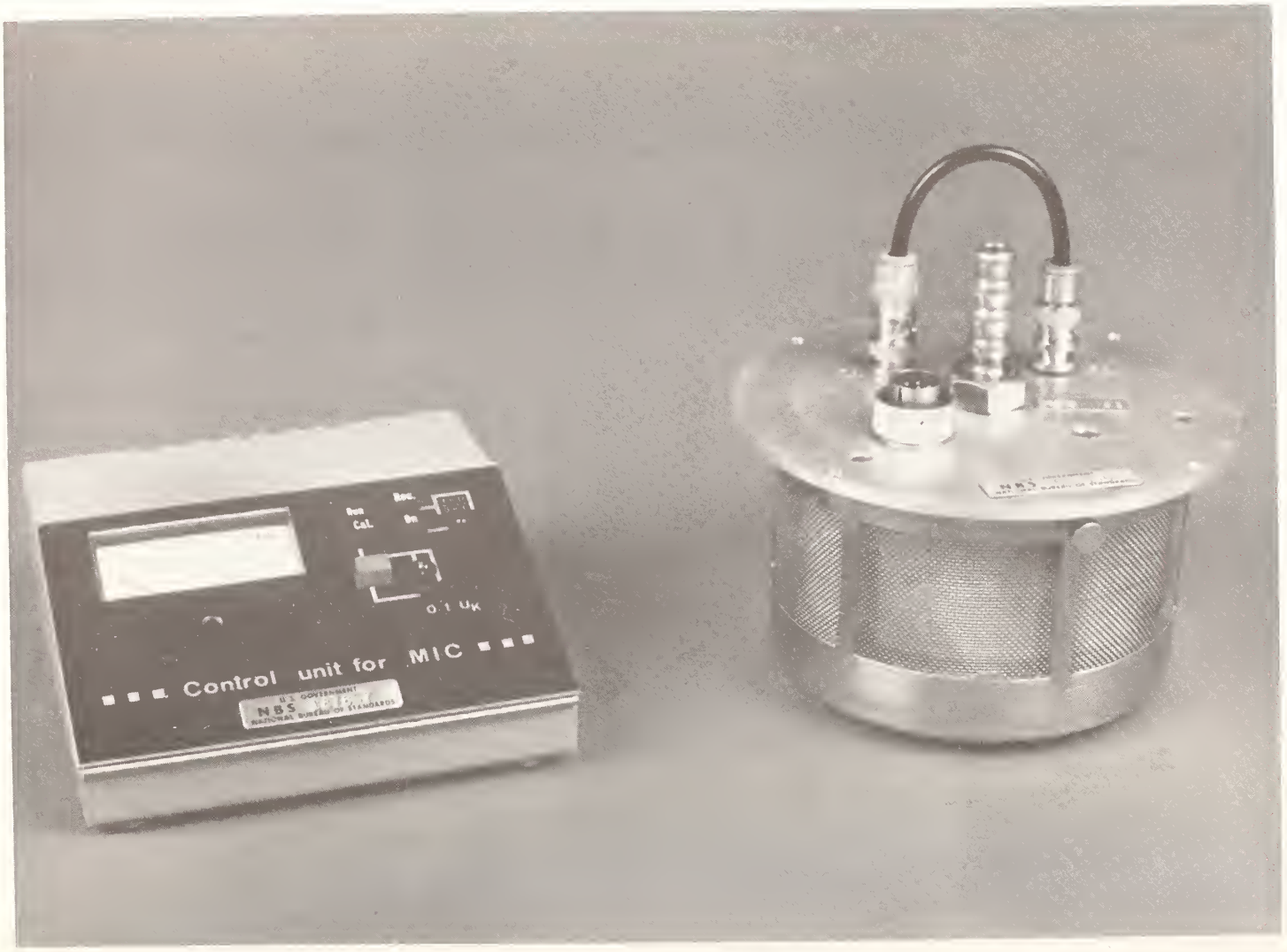

Figure 8. Measuring ionization chamber.

Photoelectric detectors are almost exclusively using long life light-emitting diode (LED) light sources, more efficient scattering angles, and light receivers and circuit designs which minimize time constant problems which had been encountered in earlier LED designs. More photoelectric detectors are using electronic ambient light rejection which eliminates the need for restrictive light-tight chambers which slow their response to fire produced aerosols. Photoelectric detectors in particular are also making better use of mechanical or electrical test features which allow testing of the entire detector circuit (including basic smoke sensitivity) simply by pushing an external button. This has come a long way from the original test buttons which did nothing more than connect the horn to the battery.

6. THEORETICAL WORK

Considerable emphasis in the Center for Fire Research (CFR) has centered on obtaining a better theoretical understanding of aerosol properties and design parameters which can affect the response of smoke detectors. To this end, the following summary of such theoretical considerations has been assembled from open literature reference sources, from results of tests conducted by CFR staff and others, and in some cases from observations by the authors.

7. IONIZATION DETECTORS

The general operation of an ionization chamber can be described in the following way. The chamber consists of a source of ionizing radiation positioned between two electrodes across which an electric potential is maintained (figure 9). The radiation source emits alpha particles (helium nuclei) or beta particles (electrons) at relatively high energies (e.g. 5.48 Mev for americium 241 alpha particles), creating positive ions by removing electrons from gas molecules along their path. The low energy electron released rapidly attaches to a neutral gas molecule which becomes a negative ion.

These ions are then drawn to the electrodes (positive ions to the negative electrodes and vice versa) where they give up their charge. This charge transfer represents a small ($\sim 10^{-11}$ A) current flow through the air space between the electrodes.

There are two ways in which an ion can be prevented from reaching the electrode and give up its charge. These are by recombination (random collision with an oppositely charged ion) or by being carried out of the chamber by convective airflow before reaching the electrode.

Some amount of recombination takes place in most ion chambers but is self-limiting. That is, the recombination rate is related to the ion density; the greater the density the greater the chance of a random collision. Thus, any chamber will have an equilibrium condition where the recombination rate and ion density will be constant.

Normally, the ion velocities are high enough and the convective flow rate low enough so that most ions reach the electrodes. When smoke particles enter the chamber, these particles capture ions, reducing their velocity by several orders of magnitude due to the increased mass of the particle-ion pair (figure 10). This reduced velocity allows the pair to be carried from the chamber before reaching the electrode, reducing the charge transfer and thereby the chamber current. It is this reduction in current which is used to trigger the alarm.

An alpha particle leaving the surface of americium 241 (Am) will create an equal number of positive and negative ions for a distance of about 4 cm (the mean range of an alpha particle of this energy in air at STP) [5]. If the electrode spacing in the chamber is 4 cm or less, a bipolar chamber results

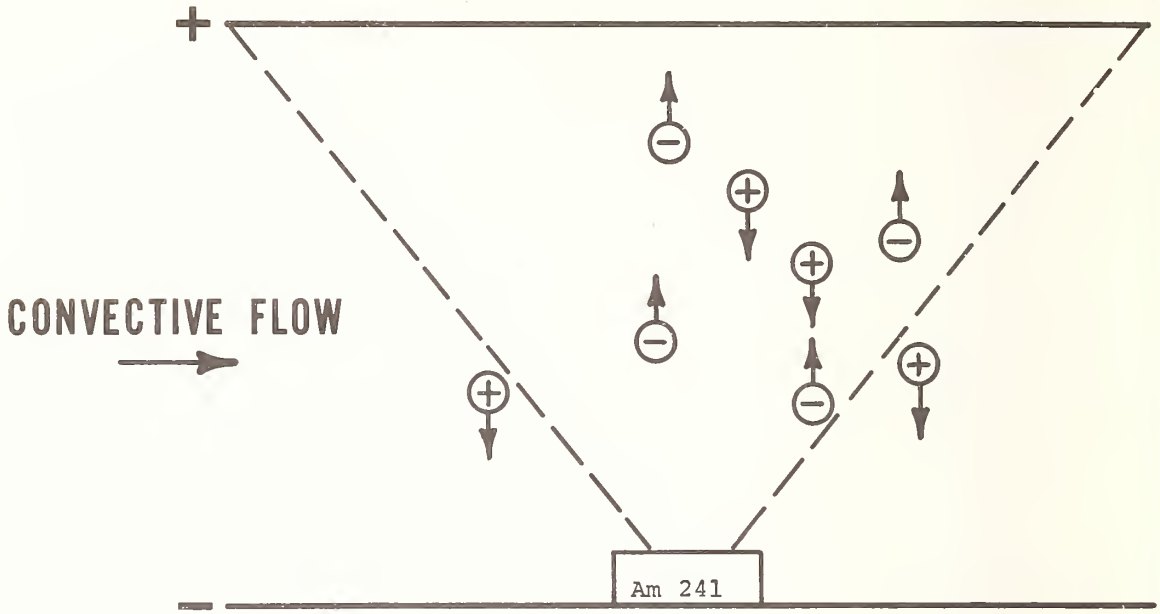

Figure 9. Ionization chamber operation - no smoke.

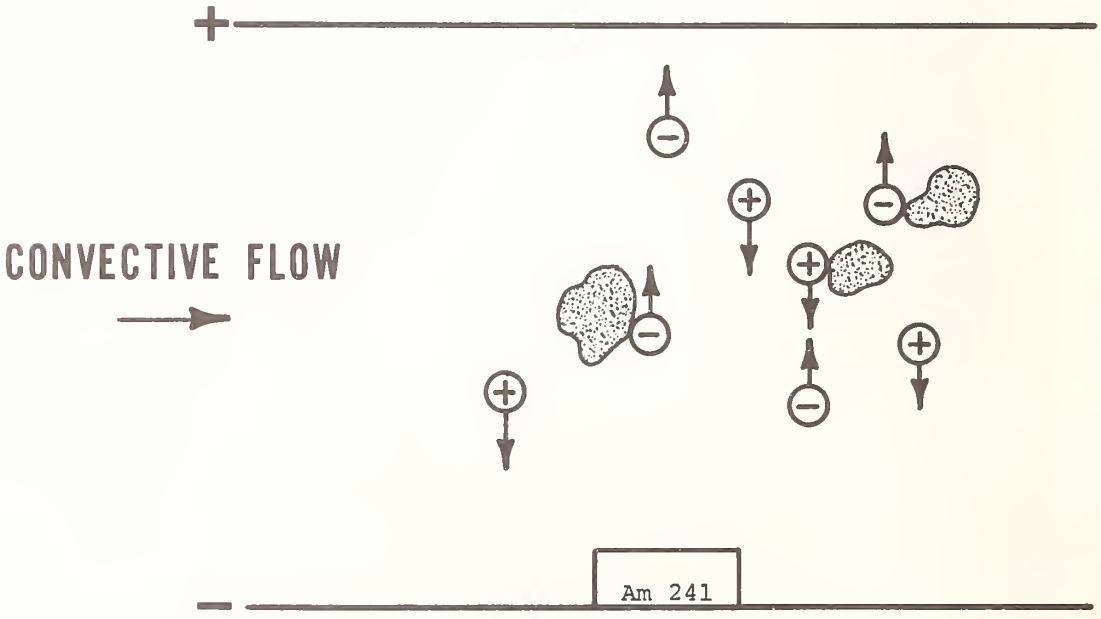

Figure 10. Ionization chamber operation - with smoke.

(figure 11). That is, ions of both polarities exist in the entire chamber. If, however, the electrode spacing is greater than 4 cm, a unipolar chamber is created (figure 12). The unipolar chamber has one region where both ion polarities are present (in this case in the first 4 cm from the source) and a region where ions of only one polarity are present. These two regions are separated by a space charge region which acts to stabilize the ion concentration in the unipolar region.

Another way of producing a unipolar chamber is to reduce the travel distance of the alpha particles to less than 4 cm by increasing the thickness of the outer gold plating on the americium. A gold thickness of 6.6 μm will reduce the alpha particles range to 0.45 cm in air [5].

7.1 Particle Size

Hosemann [6] derived a semi-empirical equation for the relative chamber signal of a bipolar ionization chamber. Scheidweiler [7] expressed this equation as follows:

$$S = \frac{Nd_p}{2\eta} + 1 - \sqrt{\left(\frac{Nd_p}{2\eta}\right)^2 + 1} \qquad (1)$$

and $$\eta = \frac{3\sqrt{\alpha q}}{C} = \text{chamber constant} \qquad (2)$$

where S = relative chamber signal $= \frac{\Delta I}{I_o}$

N = number of particles of size d_p

d_p = particle diameter

α = recombination coefficient

q = ion generation rate

C = Bricard capture coefficient

Litton has developed a detailed mathematical model for an ionization chamber [8] and finds that Hosemann's semi-empirical equation agrees within a few percent with his model results for all values of the quantity Nd_p/η. For low concentrations of a smoke aerosol equation (1) reduces to:

$$S \propto Nd_p \qquad (3)$$

That is, the output signal is proportional to the number of particles times the particle diameter. In this relation, the proportionality constant is a function of the chamber design parameters and would thus be slightly different for different chamber designs.

Equations (1) and (3) are for monodisperse aerosols. For polydisperse aerosols, equation (3) is simply summed over the particle size distribution as follows:

$$S \propto \sum_i N_i d_{p_i} \qquad (4)$$

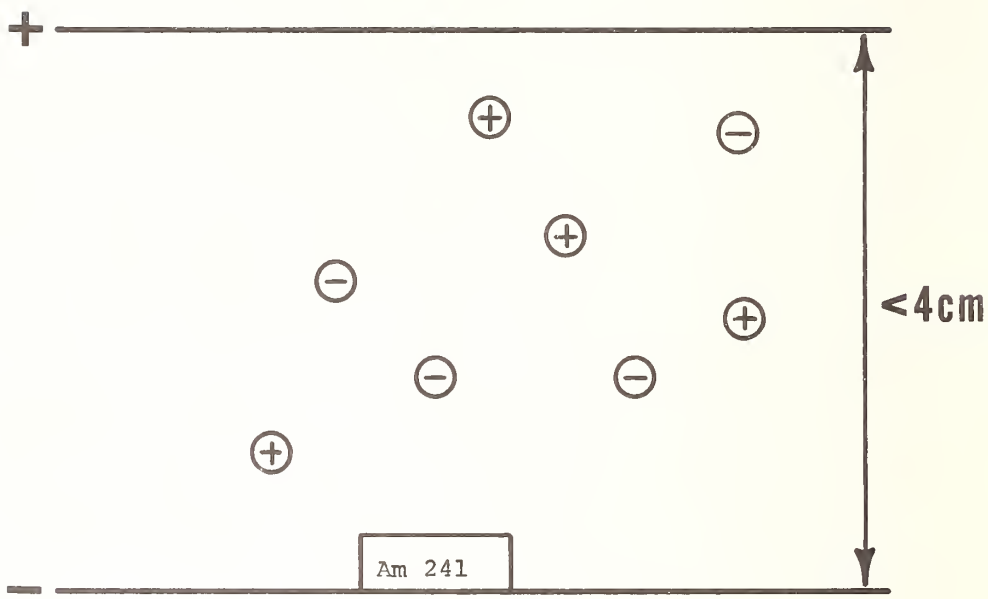

Figure 11. Bipolar ionization chamber.

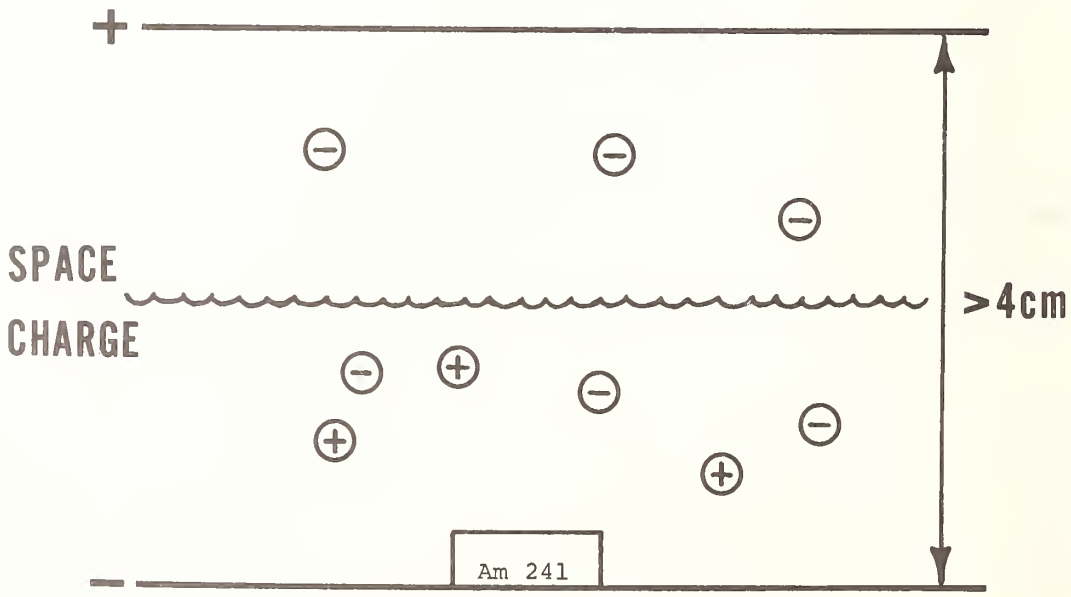

Figure 12. Unipolar ionization chamber.

When using this general relation, one must keep in mind that an aerosol particle size distribution is dynamic, varying with time and distance from the generation source. The particle diameter will tend to increase due to coagulation effects which are related principally to time and concentration. Also, particularly in combustion aerosols, the particle size distribution being generated can change as a function of temperature of combustion, material and its density, moisture content, and other factors.

When one looks at coagulation of liquid aerosol droplets or aerosols composed of solid nuclei with condensed liquid exteriors it can be seen that the number concentration for a fixed mass concentration is inversely proportional to the diameter cubed. Thus, if the aerosol diameter doubles, the number concentration would be reduced by 1/8 so that the overall effect would be the reduction of the relative chamber signal by a factor of 4. The effect of coagulation will be discussed in more detail in section 13.

7.2 High Air Velocities

Since the basic principle of operation of the ionization detector involves a small flow of current created by the transfer of charge across the chamber, any factor which interferes with this charge transfer will affect the chamber current and therefore the response. The effect of high air velocities is to blow the charged ions from the chamber before they can reach the electrodes and give up their charge. Since, under these conditions the charge transfer would be reduced, the chamber current would also be reduced, moving it toward alarm. This would have the effect of enhancing the sensitivity but can also cause a false alarm if the velocity is sufficient to remove enough ions. In his convective model, Litton [8] derived the following relation for the limits of convective flow in the chamber:

$$\left| Z_p \vec{E} \right| < \vec{V}_C < \left| \mu \vec{E} \right| \qquad (5)$$

where Z_p = mobility of charged smoke particle

$\vec{E}$ = average electric field

$\vec{V}_C$ = convective velocity in the chamber

μ = mobility of an ion.

Design factors which can compensate for this effect would be velocity shielding by mechanical means, increasing the ionic velocity (and therefore, the ionic momentum) through the use of higher electrode collection potentials or the use of the unipolar type chamber design. Since the unipolar chamber contains a space charge region, this region tends to act as a buffer, releasing more ions into the unipolar region when the ion concentration falls below equilibrium. This essentially stabilizes the chamber performance over a much broader range of air velocities than with a bipolar chamber design. A comparison of the change in chamber current with increasing air velocity was given by Scheidweiler [7] and is shown in figure 13.

7.3 Low Air Velocities

Equation 5 also shows that the effects of low air velocities are almost a converse of the high velocity effects. That is, low velocities can allow charged smoke particles to reach the electrodes and discharge before the convective flow through the chamber can move them out of the chamber. This

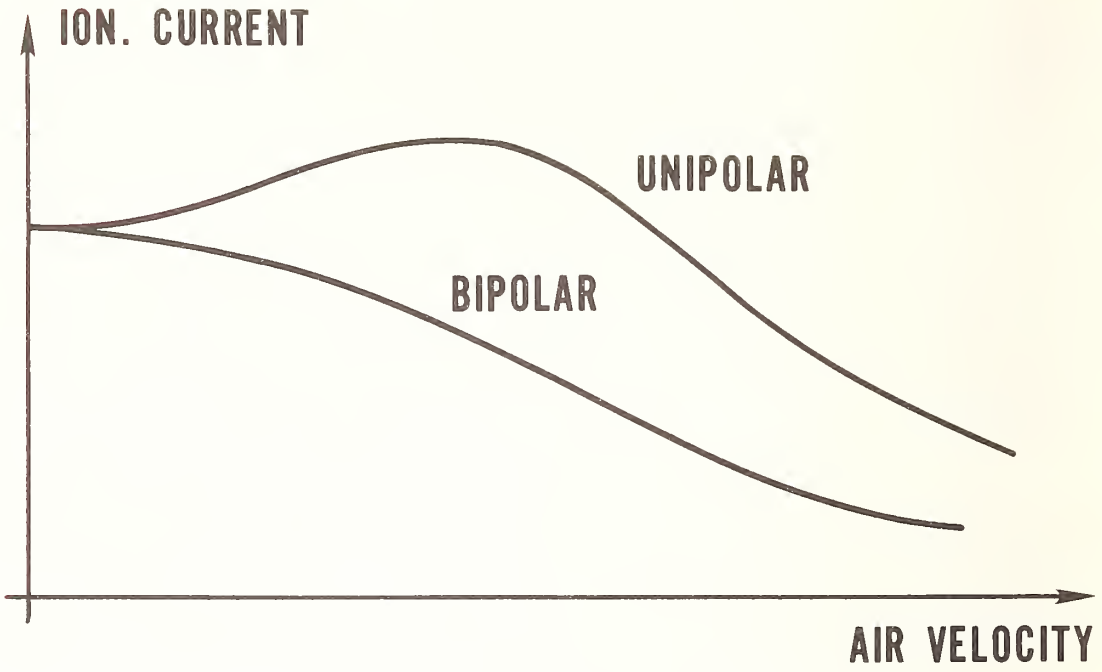

Figure 13. Influence of wind on a unipolar and a bipolar ionization chamber.

condition can result in an increase in chamber current and a corresponding loss of sensitivity. This effect may be a partial explanation (along with increased particle diameters and decreased number concentrations) of the apparent loss in sensitivity of ionization detectors to smoldering fires.

7.4 Chamber Design

7.4.1 Source Strength

The chamber constant (eq. 2) is a function of the volumetric ion generation rate, q (which is established by the source strength), the recombination coefficient, α, and Bricard's capture coefficient, C. The ion generation rate (q) is the only parameter which is affected by the detector design, the other parameters (α and C) being determined by the properties of the aerosol and ions.

From equations (1) and (2) in the limit of low particle concentrations it is seen that the detector sensitivity is inversely proportional to the square root of the ion generation rate and thus the source strength. In practice the advantage of the increased sensitivity with decreased source strength must be balanced against the reduction in the signal to noise ratio as the source strength is reduced. This effect can be seen in the new β source detectors which operate at very low source strength and chamber currents (several orders of magnitude below typical α source detectors). The β detector will detect the extremely small particulates from burning alcohol to which most α detectors will not respond. The β detector, however, has had to incorporate extensive RF shielding and, in addition to the normal sensing and reference chambers a third (balance) chamber is used to obtain acceptable stability.

7.4.2 Electrode Spacing

If the chamber electrodes are closer than the alpha particle path length, the alpha particles will not produce the maximum number of ion pairs possible.

If the electrode spacing is greater than the alpha particle path length, a unipolar chamber results. When determining proper electrode spacing, one must keep in mind that the thickness of gold outer foil plating of the ionization source greatly affects the alpha particle path length. As was explained earlier, an unplated source will have an alpha particle path length of 4.04 cm in air (at STP). Addition of a 6.6 μm thickness gold foil reduces the alpha particle path length to 0.45 cm. From this it can be seen that the plating thickness is extremely critical and that very small nonuniformities in the plating thickness can have great effects on the uniformity of chamber ionization.

Simon and Axmark [9] investigated the effect of electrode spacing on the ion chamber response both experimentally and theoretically for a parallel plate electrode design. The detector sensitivity, $\Delta I/I_o$, was measured as a function of electrode spacing, D, for a fixed value of the ratio of potential difference ϕ, to electrode spacing, ϕ/D = constant. As the plate separation was increased from 3 cm to 5 cm, the sensitivity increased by approximately 100%. For this experiment the range of the α particle was 3 cm so in one case the chamber is bipolar while in the other, there is a unipolar region in the chamber. The model calculation, which includes the effect of space charge in the field equation, was found to agree with the experimental results.

7.4.3 Electrode Bias Voltage

As shown in equation (5), if the bias voltage on the chamber electrodes is low, the ion velocity is low and there is more chance of recombination with opposite ions before the electrode is reached. Also due to lower ion momentum, the velocity at which captured ions can be blown from the chamber is reduced.

If the electrode bias voltage is high, there is less chance of recombination and less chance that captured ions can be blown from the chamber; but the radioactive source strength must be increased to maintain proper ion densities. This can be a problem in countries where maximum source strength specifications are set by law.

In the first case, the effect is an ion chamber inordinately sensitive to air movement. In the second case, the effect is to reduce the sensitivity of the chamber (unless the source strength is increased).

Litton [5] has studied the effect of the electrode bias voltage on the chamber performance. He finds that equation (2) is valid provided the chamber current is low compared to the saturation current ($I/I_s < 0.4$). As the current increases above this ratio, the chamber response depends on the electrode bias voltage as well as the source strength. For a given source strength and electrode geometry Litton found that there exists an optimum bias voltage for which the current difference is a maximum. He also found that an increase in the source strength S_α will shift the electrode bias ϕ_m at which ΔI is a maximum approximately as the square root of S_α.

7.4.4 Outer Shell Design

The design of the outer chamber shell relates to the high and low aerosol velocity effects. If the shell is too open, the higher aerosol velocity problem is enhanced and if too restricted, the low air velocity problem is

enhanced or the aerosol stream may take the path of least resistance and by-pass the chamber completely.

7.5 Detector Enclosure Design

The outer enclosure of the detector can also be critical. If too open, the unit may be susceptible to false alarm at high airflows and if too restricted, the unit may alarm slowly due to delayed smoke entry. This effect was demonstrated in an experiment conducted by NBS a few years ago. Two detectors (A and B), identical except for their enclosures, were tested for sensitivity to smoke at varying air velocities. One unit (A) would not alarm for any smoke concentration at a flow of 0.076 m/s (15 fpm), while the other (B) showed only a small decrease in alarm point at this velocity. Conversely, one unit (B) would give a false alarm at a flow of only 1.5 m/s (300 fpm) while the other (A) was stable to much higher velocities.

In addition to velocity effects, the following factors should also be taken into account in a proper enclosure design.

1. The electric fields generated in the peripheral detector circuitry can affect the chamber operation.

2. Current leakage paths on high impedence components or on insulators in the sensing chamber can cause false alarms or non-operation.

3. Adhesion of charged aerosol particles to external plastic parts that have acquired a static charge can reduce the number of the small particles reaching the sensing chamber.

8. PHOTOELECTRIC DETECTORS

Most photoelectric detectors in common use operate on the light-scattering principle. The sensing chamber contains a source of light and a light receiver at some angle to the light beam arranged so that the receiver does not normally receive any of the transmitted light (see figure 14). When smoke particles enter the scattering volume (the volume of space which intersects both the light beam and viewing region of the receiver), light is scattered onto the receiver. This increase in luminous flux on the receiver is proportional to the concentration of smoke particles and is used to trigger the alarm.

Early light-scattering detectors used short lived incandescent lamps (1-5 year average life) and photoresistive receivers. Newer designs use light-emitting diodes as the light source (30 year or more life) and silicon receivers (photodiodes, phototransistors, and silicon cells). Newer designs have also eliminated the need for a darkened sensing chamber (to eliminate effects of ambient light) by using pulsed LED's and electronic circuits which reject the ambient signal. Elimination of this chamber has greatly improved the performance by allowing much freer entry of smoke to the sensing optics.

8.1 Particle Size

The output signal from a scattering type detector optical assembly is affected by particle diameter, complex refractive index, scattering angle, scattering volume, light wavelength, and particle shape. In general, the basic theory of light scattering is only well defined for spherical particles. Some limited calculations are available for a few other shapes such as cylinders and ellipsoids.

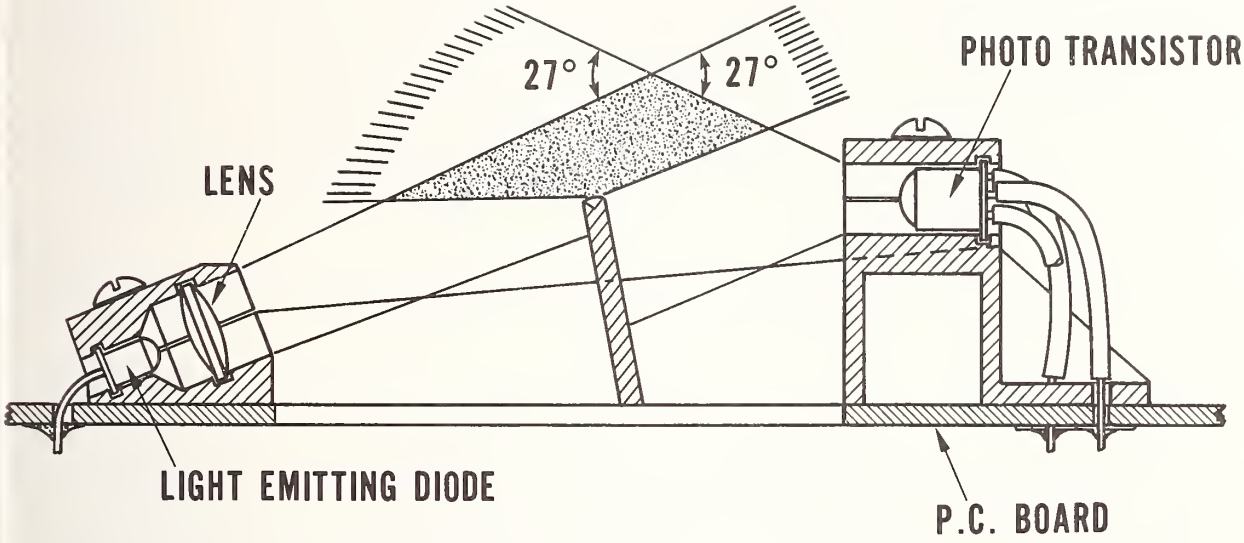

Figure 14. Light-scattering detector optics.

The effect of particle size falls into three regions defined essentially by the ratio of particle size to light wavelength [10]. These three regions are given below:

Rayleigh Region $d_p < 0.1\lambda$

Mie Region $0.1\lambda < d_p < 4\lambda$*

Bricard Region $d_p > 4\lambda$*

* Limit varies with refractive index.

In the Rayleigh scattering region, the output signal is essentially proportional to the 6th power of the particle diameter.

The upper limit of the Mie region is not clearly defined as it varies as a function of particle refractive index. At the Mie-Rayleigh boundary, the chamber output signal is proportional to the particle diameter to the 6th power and can oscillate in a damped sinusoidal manner until at the Mie-Bricard boundary it is proportional to d_p squared. The frequency of oscillation is a function of the refractive index of the particle.

For particles larger than about 4λ the theories of geometric optics (Bricard, Fraunhoffer diffraction) predominate. In this region the signal is essentially proportional to the particle diameter squared.

8.2 Scattering Angle

The angular intensity distribution of light scattered by particles varies with particle size (d_p), shape, and refractive index (M). An example of such an angular distribution is given in figure 15 [10]. This is for Mie scattering (particle diameter greater than one tenth of the wavelength) for a narrow band polydisperse aerosol with M = 1.33 (water vapor). While the distribution will vary with the above mentioned parameters for other size ranges, the same general characteristics are observed. That is, the greatest intensity is in the forward direction, decreasing to a minimum around 90°-100° and increasing again to a final value less than the initial value in the back scatter area. Only in the case of perfectly reflecting spheres is back scatter intensity greater than forward scatter.

From this characteristic one can deduce that a small, forward angle exhibits the best signal levels for most aerosols while angles around 90° would generally give the lowest signal levels.

8.3 Particle Shape

The effects of complex aerosol shapes are largely unknown. One can empirically determine the effective scattering cross section of a complex shaped particle but this parameter can change continuously as the particle tumbles randomly in an aerosol stream. If the aerosol concentration is high enough, it is valid in many cases to assume a random distribution of particle orientations.

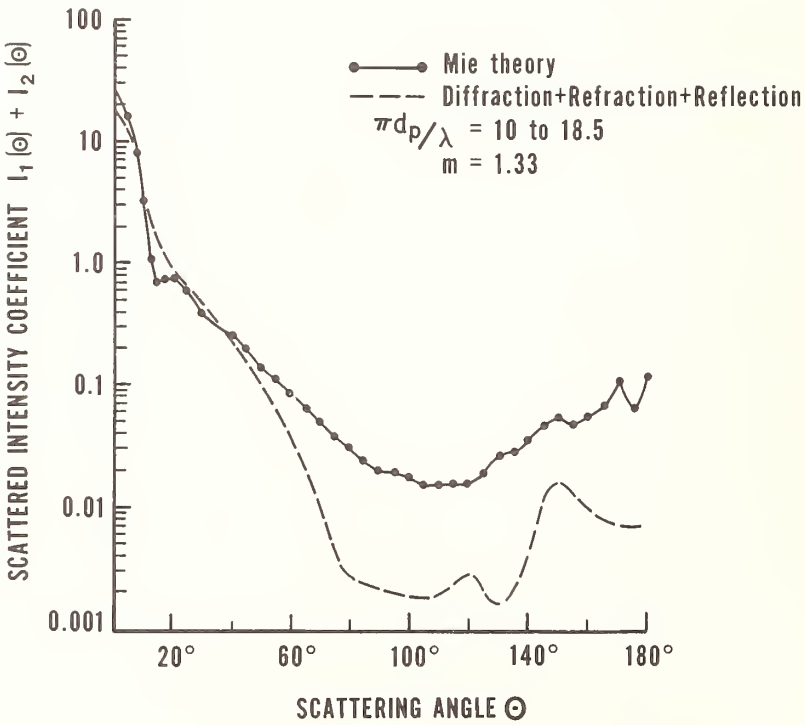

Figure 15. Mie scattering by polydisperse spheres, refractive index 1.33, compared with diffraction, refraction and reflection.

8.4 Refractive Index

Particle refractive index is a complex variable of the form:

$$M = M_o (1 - iK) \quad (6)$$

where M_o is the real part of refractive index

K is the absorption coefficient.

One should note that absorption is the imaginary portion of the term and the particle refractive index is only real where absorption is 0.

8.5 Wavelength

The principle effect of wavelength is to define the boundaries of the three scattering regions. Since the signal produced by an aerosol is strongest in the Mie and Bricard regions, wavelengths should be as short as possible so that a majority of the aerosol sizes to be measured are in these regions. This was not as much a problem when incandescent light sources were used since they are polychromatic and produce light over most of the visible spectrum, especially if driven at a relatively high color temperature. With the change to light-emitting diodes, however, red and infrared wavelengths became more common due to decreasing quantum efficiency of LED's at shorter wavelengths [11]. More recently, some improvement in yellow and green LED efficiencies have been made but new combinations of base materials may be necessary before these devices are usable at these shorter wavelengths.

8.6 Design Parameters

8.6.1 Entry

Ease of smoke entry into photoelectric detectors has improved greatly in the last few years. Careful study of low velocity flow dynamics and the more recent elimination of light-tight labyrinths by means of electronic ambient light rejection have been the principle causes of this improvement. It is now possible to actually scatter light from an aerosol outside of the detector enclosure. This obviously eliminates entry completely.

8.6.2 Circuit Time Constants

The change to light-emitting diode sources in photoelectric detectors also created time constant problems. This is because the total luminous flux from light-emitting diodes is only about 10% of that with incandescent sources. Thus, more sensitive photoresistive (Cd S or Cd Se) cells were necessary as light receivers. But the time constant of these photoresistive cells (to a step input) is inversely proportional to its luminous flux sensitivity. At normal LED light levels, time constants on the order of 5 minutes are common.

These time constant problems can and have been eliminated by the use of silicon devices such as photovoltaic cells, photodiodes or phototransistors. These devices, however, require more circuitry since they have no inherent gain and can increase the cost of a detector by as much as 30% over those using the photoresistive receivers. Hopefully, the cost savings associated with the newer large-scale integrated circuits now being designed for photoelectric (and ionization) detectors may offset the additional costs and result in better operating detectors with higher reliability.

9. SMOKE RESEARCH GOALS

Above we have discussed the general behavior of smoke detectors. From this point on we focus on properties of the smoke. In the United States there is interest in smoke properties for several applications in the field of fire protection:

1. Early detection of smoke to alert occupants.

2. The blockage of vision caused by smoke produced by the combustion of building materials.

3. The radiative heat transfer from smoke in the development of a fire up to flashover.

The major emphasis in smoke research at the National Bureau of Standards has been on the first application, which will be the focus of our discussion. The general goal of our research is to provide some of the basic data necessary for the development of improved smoke detectors and improved detector test methods. The first half of our presentation on smoke research will be concerned with the application of recently developed aerosol measurement techniqu and aerosol generation methods to the determination of the sensitivity of smoke detectors as a function of particle size. The second half will be concerned with the properties of smoke aerosols used in testing detector performance. These properties will include size distribution, optical density, and the aging of smoke.

10. AEROSOL INSTRUMENTATION

The measurement of the size distribution of smoke aerosols is a difficult experimental problem. Smoke aerosols encompass a broad size range from on the order of 0.005 μm for particulate from a propane torch to as large as 5 μm for well aged smoke generated from a smoldering source such as urethane foam. The three orders of magnitude in this size range are equivalent to the change in size extending from the diameter of a pin to the diameter of a beach ball. The order of magnitude range in particle concentration is even greater. The particle concentration of smoke drawn through a cigarette may be as high as 10^{10} particles/cm^3 while the concentration of an aged smoke may be as low as 10^4 to 10^5 particles/cm^3. In addition to the difficulty of measuring such wide ranges in particle size and concentration, there is also the problem that an aerosol is a dynamic, unstable suspension. As an illustration of the dynamic nature of smoke, the number concentration of smoke will drop by a factor of ten from an initial concentration of 10^8 particles/cm^3 in two minutes as a result of coagulation.

No single instrument is capable of handling the range of concentrations and particle sizes encountered in smoke analysis. We shall describe two instruments that we have found to be quite useful for smoke characterization at low concentrations, 10^3-10^6 particles/cm^3. Special emphasis will be placed on the calibration of these instruments. In our work we find that perhaps half of our time is devoted to instrument calibration. Even with this effort, it was found that a measurement accuracy of $\pm$ 30% is about the best that can be obtained.

The principal instrument used in our study is the electrical aerosol analyzer developed by Liu, Whitby, Pui and Clarke [12,13] to measure the size distribution and concentration of aerosols in the size range 0.01 μm to 1 μm. This instrument is similar in principle of operation to the ion mobility counter described by Watanabe at the 1976 UJNR panel meeting. As shown in figure 16 it consists of three major parts: aerosol charger, mobility analyzer, and electrometer current sensor. During a measurement, the aerosol

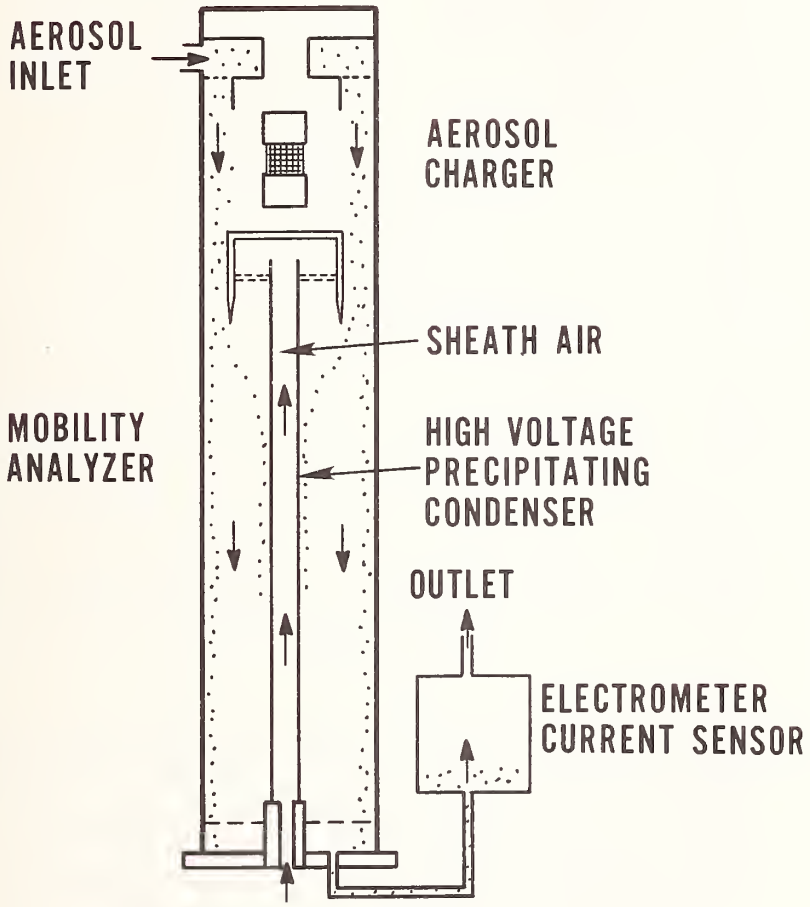

Figure 16. Electric aerosol analyzer.

is first sampled into the aerosol charger to expose the particles to unipolar positive ions produced by a corona discharge. The charged particles then enter a mobility analyzer where they are deflected through a laminar air stream in a cylindrical condenser. For a given voltage on the center rod, particles above a certain critical mobility (smaller than a certain critical size) are precipitated, while those with lower mobility (larger particles) escape and are sensed by the electrometer sensor. By changing the voltage on the center rod and measuring the corresponding electrometer current, the mobility and thus the size distribution of the aerosol can be determined.

A series of experiments was performed at the University of Minnesota and at the National Bureau of Standards [14] to determine the accuracy of the electrical aerosol analyzer (EAA) for the measurements of aerosol number concentration and volume concentration by comparison with a condensation nuclei counter (CNC) and a filter gravimetric method, respectively. A comparison of the total number concentration as determined by the two methods is shown in figure 17 for a polydisperse sucrose aerosol generated by an atomizer. It is seen that there is approximately a linear relationship between the number concentration determined by the two methods over the

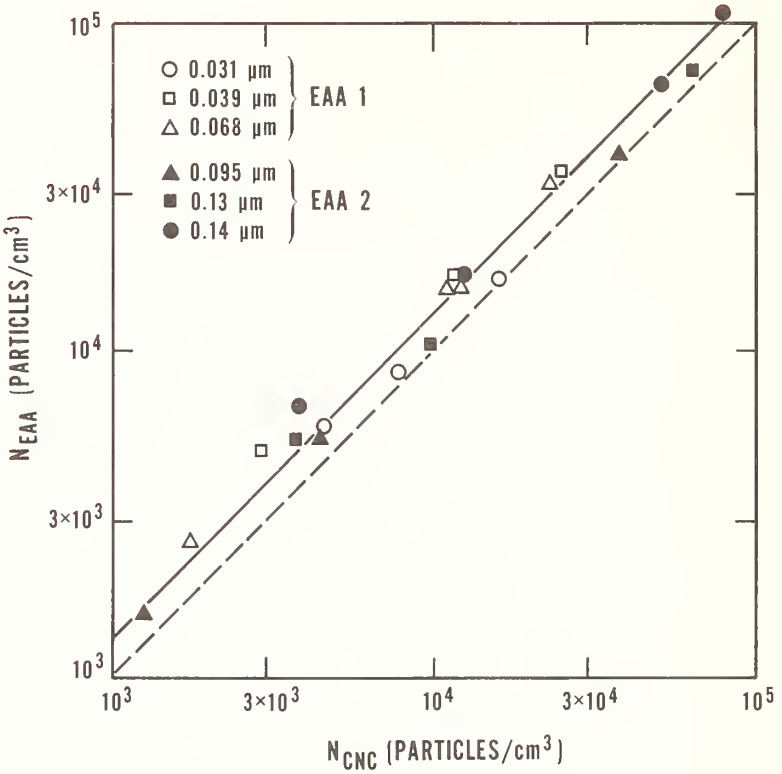

Figure 17. Comparison of the number concentration as determined by the electrical aerosol analyzer and the condensation nuclei counter for sucrose aerosols with various geometric mean number diameters [14]. (Two nominally identical electrical aerosol analyzers (EAA 1 and EAA 2) were used for the measurements. The dashed line corresponds to perfect agreement between the two instruments, while the solid line represents a least square fit of the data.)

concentration range 10^3 to 10^5 particles/cm^3. The data can be conveniently fitted to the following functional form:

$$\text{Log } N_{EAA} = \text{Log (const)} + \text{Log } N_{CNC} \qquad (7)$$

From a least square fit of the data to equation (7) it is found that the constant equals 1.3, which means that the EAA overestimates the number concentration by about 30%.

The size dependence of the volume measurement by the electrical aerosol analyzer is presented in figure 18 for dioctyl phthalate aerosols generated by a nebulizer. The most significant feature about the data is the rapid decrease in the ratio V_{EAA}/V_{FILTER} for particle sizes larger than 0.4 μm. There are two likely reasons for this discrepancy. First, particles larger than 1.0 μm will contribute to the aerosol volume collected on the filter, but will not contribute significantly to the aerosol volume measured by the electrical aerosol analyzer. Secondly, the mobility versus particle size characteristic of the aerosol analyzer is rather flat in the 0.4 to 1.0 μm diameter size range, precluding the possibility of making accurate size distribution measurements in this range.

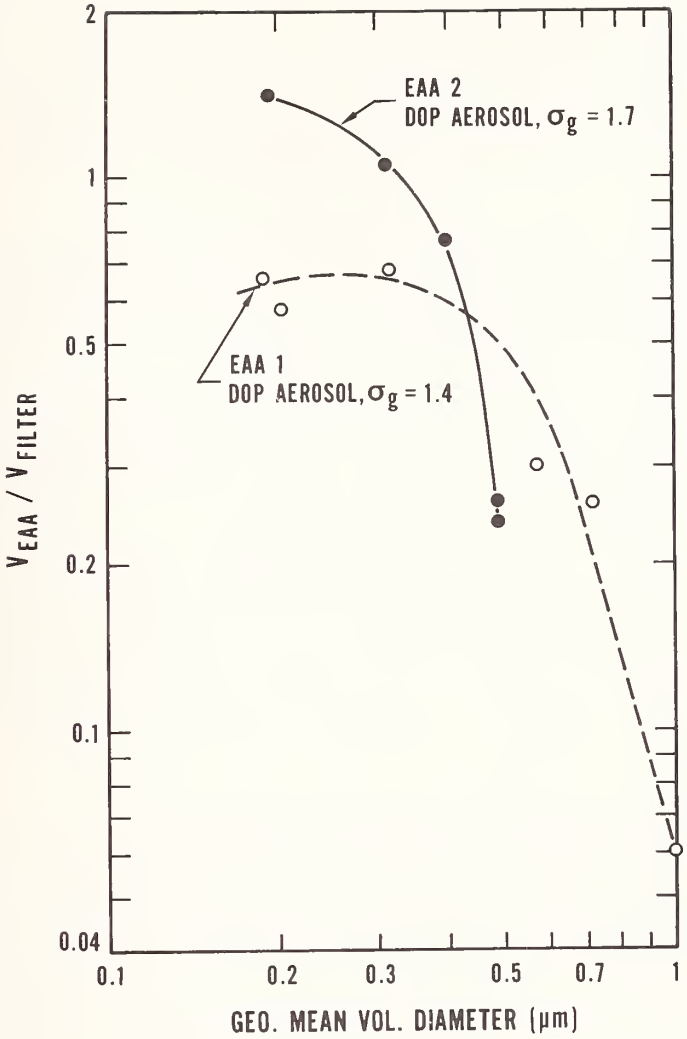

Figure 18. The effect of particle size on the ratio of the aerosol volume as determined by the EAA and filter collection method [14].

Particles with diameters in the size range 0.5 to 5 μm were measured by an optical particle counter that counts individual particles. In this instrument, a beam of light is focused into a small viewing volume through which the airborne particles pass one at a time. The amount of light scattered from each individual particle is measured by a photodiode detector. The detector signals (pulse height), which are related to the size of each particle, are then sorted and stored in channels of the multichannel analyzer of the instrument.

The conventional method of calibrating optical particle counters is with an aerosol formed by nebulizing a suspension of latex spheres of known particle size. This method was used in calibrating the optical particle counter. Later in this paper a new method for calibrating optical particle counters involving the laser doppler shift spectrometer will be described.

11. DETECTOR SENSITIVITY TO MONODISPERSE AEROSOLS

As was mentioned earlier, the particle size is an important parameter in determining the sensitivity of a smoke detector. In order to obtain accurate data on the size sensitivity of ionization and light-scattering type detectors, a joint National Bureau of Standards University of Minnesota study was initiated making use of the excellent capabilities at Minnesota for the measurement and generation of aerosols [15].

A major concern in the selection of an aerosol generation system was that it provide a stable, steady-state output to allow time for the smoke concentration in the detector to reach a steady-state and to allow time for the measurement of the concentration and size distribution of the aerosols. The aerosol generation system that was finally developed for the detector sensitivity measurements is illustrated in figure 19.

An atomizer was used to generate a polydisperse dioctyl phthalate aerosol, which was then made monodisperse by passage through an evaporation - condensation column. Next, the aerosol passes through conditioning equipment which controls the aerosol concentration, humidity, and charge, after which it enters the smoke detector chamber.

The resulting aerosol was quite monodisperse with a geometric standard deviation, σ_g, about 1.25. By varying the concentration of dioctyl phthalate in solution with isopropanol, it was possible to generate monodisperse aerosols over the size range 0.05 μm to 1.3 μm. The concentration range was about two orders of magnitude (2×10^4 to 3×10^6 particles/cm^3) for the generator. The concentration and particle size output of the generator were determined by the electrical aerosol analyzer, the optical counter, and by a filter gravimetric method.

The concentration dependence of the analog detector output is shown in figure 20 for particle sizes ranging from 0.15 μm to 0.57 μm. The detector is a light-scattering type with a nominal scattering angle of 21° and an infrared light-emitting diode with spectral peak around 940 nm. Over the concentration range studied, the analog signal was proportional to particle concentration and the sensitivity increased rapidly with increasing particle size. This detector did not respond to a particle size of 0.10 μm or less at concentrations as high as 3×10^6 particles/cm^3. The alarm voltage labeled in figure 20 corresponds to the detector signal produced by a polydisperse smoke aerosol with an optical density of 0.056 m^{-1} as measured in the Underwriters' Laboratories test chamber, which will be described in the next section. This value corresponds to the maximum threshold standard set by the Underwriters' Laboratories.

The detector sensitivity for the light-scattering type detector (S-2) and for an ionization type detector (R-2) are plotted versus particle size in figure 21. The detector sensitivity is defined as the detector output minus the background reading divided by the particle concentration and is expressed in the units μV-cm^3. The uncertainty in the determination of sensitivity is estimated to be ± 30% and is primarily attributed to the uncertainty in the measurement of the number concentration.

It is of interest to compare the experimental sensitivities with theoretical predictions. For the light-scattering type detector, the sensitivity is found to have approximately a six power dependence on particle size for the smaller sizes. This is in agreement with the theory of Rayleigh scattering, which is valid for particle sizes small compared to the wavelength of light. Qualitative agreement over the entire size range was obtained between the experimental sensitivity and the scattered intensity as calculated by Mie theory [15].

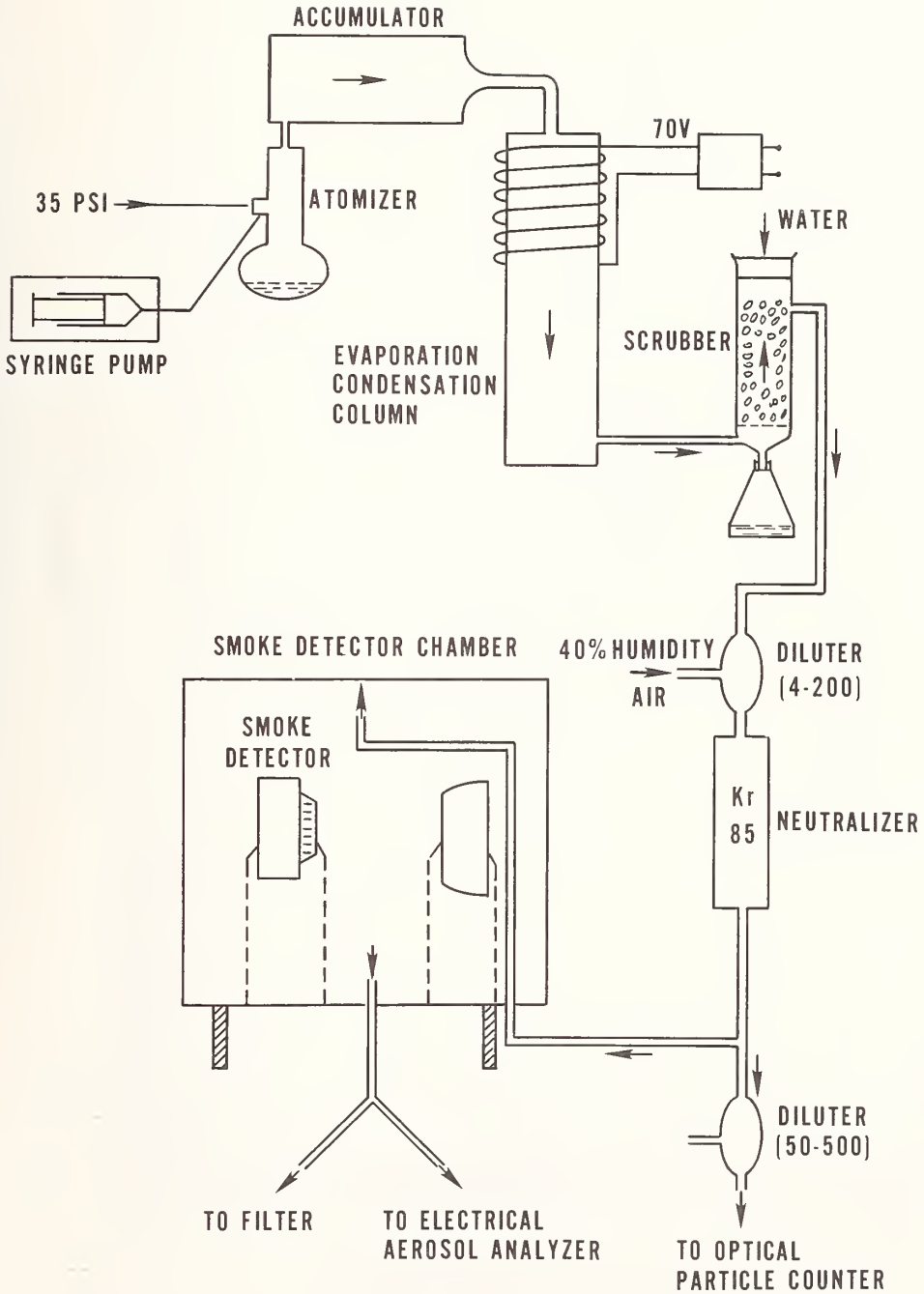

Figure 19. Monodisperse aerosol generation system [15].

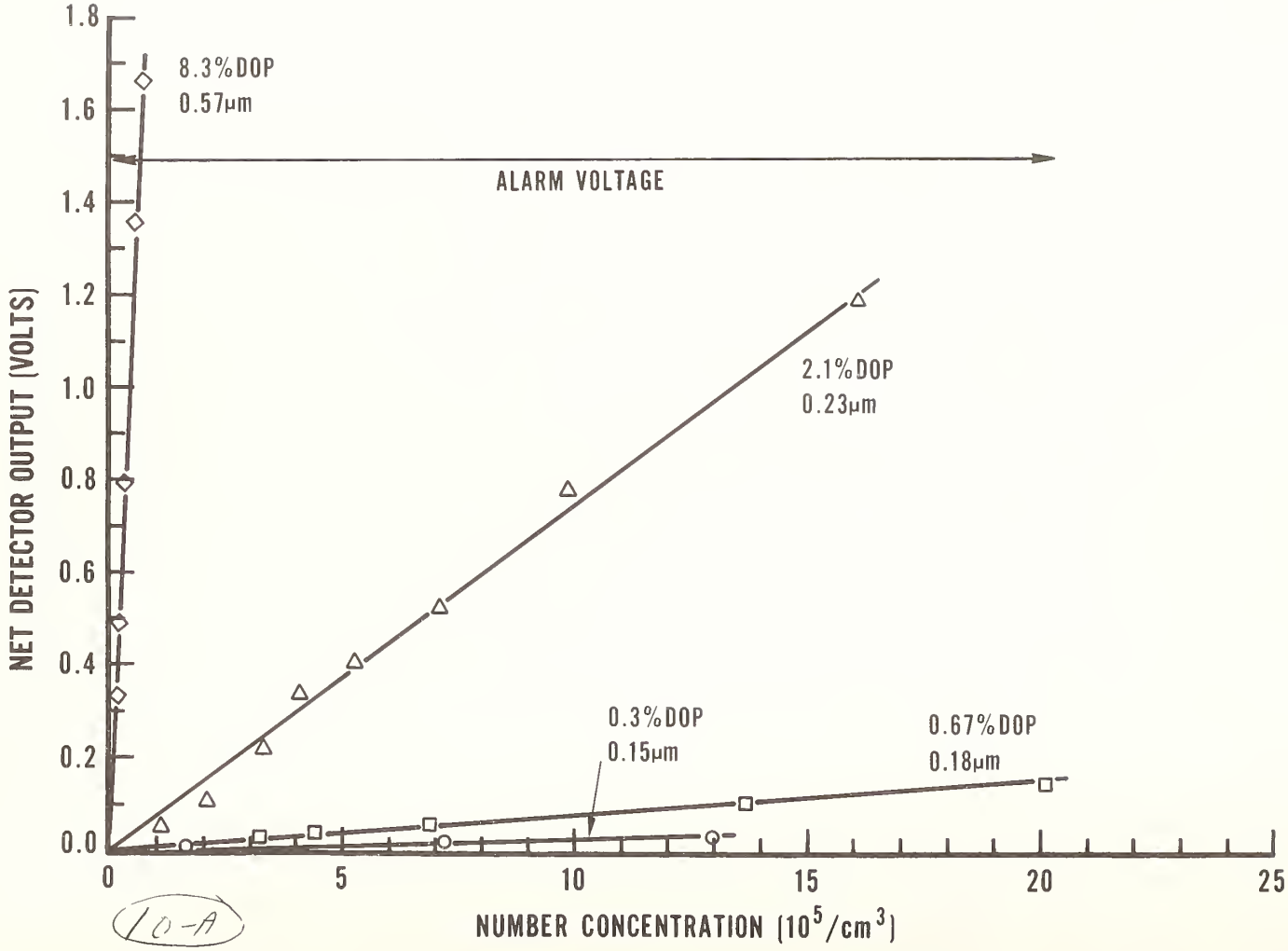

Figure 20. Response of a light-scattering type detector versus number concentration for monodisperse aerosol [15]. (The alarm voltage corresponds to the detector signal when exposed to a polydisperse smoke with an optical density of 0.056 m^{-1}.)

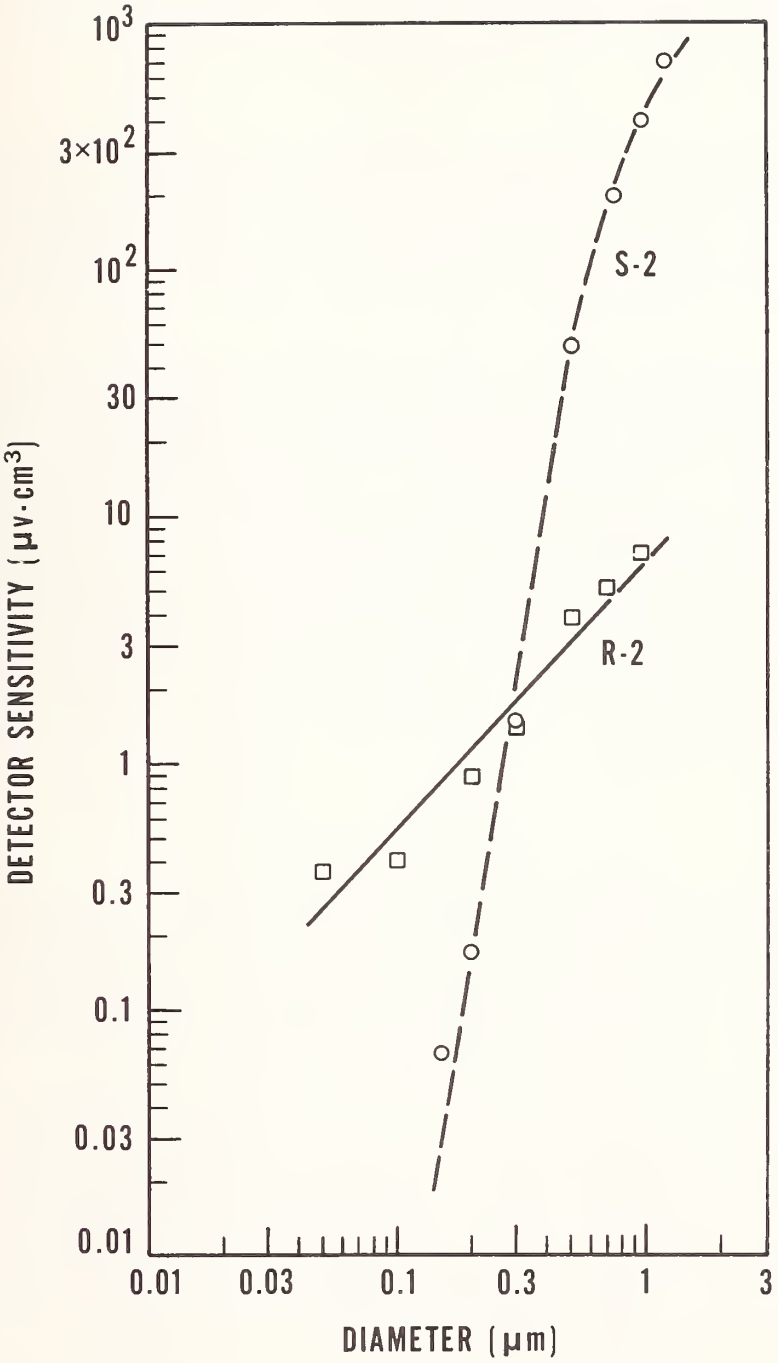

Figure 21. Detector sensitivity versus particle size for a light-scattering type detector (S-2) and for an ionization type detector (R-2) [15].

The ionization detector sensitivity data can be correlated with particle diameter by using a linear fit to a log-log plot as shown in figure 21. This indicates a power law relationship between detector sensitivity and particle size with the empirical relationship being:

$$S = 6.7 \bar{D}_g^{1.1} \quad (8)$$

where S is the sensitivity and $\bar{D}_g$ the geometric mean number diameter. Thus it is seen that the detector sensitivity is nearly a linear function of particle size rather than being linearly related to the surface area of the particle or to the volume of the particle. This result is in qualitative agreement with Hosemann's theory [16], which predicts a linear relationship between sensitivity and particle size for low particle concentrations (see equation (3)).

It is seen in figure 21 that the ionization type detector is the more sensitive for particle sizes smaller than about 0.3 μm, while for larger particle sizes the light-scattering detector is the more sensitive. This difference in sensitivity has important practical implications. There is evidence from work at Georgia Institute of Technology by Bankston et al. [17] that smoke generated in the flaming mode of combustion for Douglas fir, polyvinylchloride, and rigid urethane foam is generally smaller than 0.3 μm while the same materials undergoing combustion or pyrolysis in the non-flaming mode produce particles larger than 0.3 μm. Thus one would expect that the ionization detector would be more sensitive to smoke generated from flaming materials and that the light-scattering detector would be more sensitive to smoke generated by non-flaming materials. This expectation has, in fact, been demonstrated in the testing of smoke detector response to various small-scale fires by Consumer's Union [18] and to large-scale fires by IIT Research Institute and Underwriters' Laboratories under contract to the National Bureau of Standards [19].

12. SMOKE PROPERTIES

In this section we shall concentrate on the properties of those smokes used in smoke detector testing: smokes generated from smoldering lamp wick and punk (imported from the orient as incense sticks) and the black soot smoke generated from the diffusion burning of heptane. The properties of interest will be the number concentration, mass concentration, optical density, and size distribution. The aging properties of smoke will be discussed in the next section. A more extensive discussion of the properties of these smokes can be found in a report by Lee and Mulholland [20].

The measurement of smoke properties was made in the Underwriters' Laboratories (UL 217 standard) smoke detector evaluation chamber which is used for the testing of residential smoke detectors for approval. The detector evaluation chamber is essentially a 50 x 50 x 170 cm closed horizontal box in which the smoke detector is mounted on the center of the top surface as shown in figure 22. The chamber is partitioned into a top and bottom - half sections by a platform extending almost the full length of the chamber. Smoke generated in the lower section is circulated through the box in the direction indicated by the arrows in figure 22. A constant circulation velocity of 0.18 m/s is maintained.

A photometer which measures the optical density of the circulating smoke has a path length of 152 cm and a beam width of 5 cm. It consists of an incandescent lamp (GE-4515) source operating on 2.4 V (2370K $\pm$ 50K color temperature) and a photovoltaic cell (Weston 594 RR) detector.

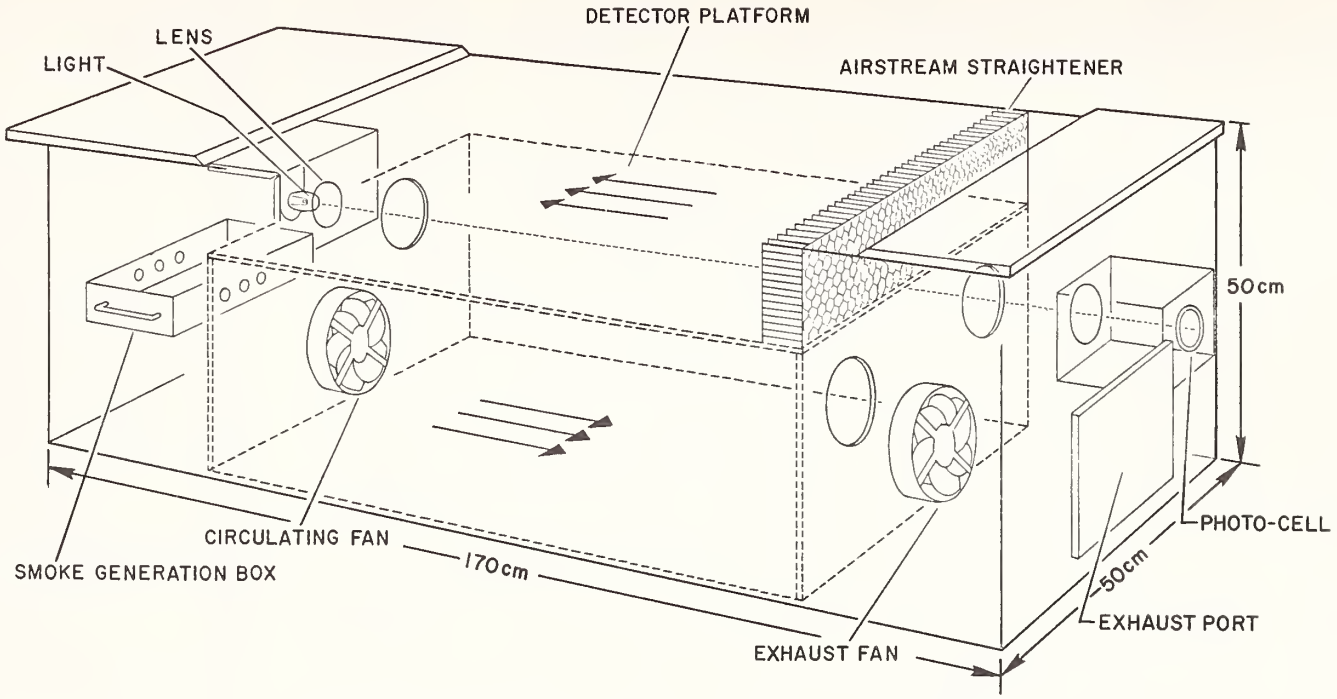

Figure 22. Smoke detector evaluation chamber.

In these measurements, a smoldering lamp wick or a heptane diffusion burner was placed in the burner end of the chamber and was withdrawn when the smoke reached a desired optical density level, ranging from 0.005 m^{-1} to 0.08 m^{-1}. After allowing about thirty seconds to insure uniform mixing, the aerosol was sampled by the analyzers.

The dependence of the optical density on mass concentration is shown in figure 23 for both smokes. The mass concentration for the lamp wick smoke and heptane smoke were determined by using the quartz crystal mass monitor [21] and the filter gravimetric method, respectively. The mass monitor was not effective in measuring the mass concentration of the sooty heptane smoke. The vertical bars in figure 23 represent the shift in optical density during the three- to four-minute sampling period required for collecting sufficient heptane smoke for precise filter weighing. Only a 20-30 second period was required for the mass monitor for the lamp wick smoke. The ratio of optical density per meter to mass concentration, termed the particulate optical density (POD), is an intensive property independent of concentration, at least over a certain range of concentrations. The POD for heptane smoke is 3.4 m^2/g and for cotton lamp wick smoke the value is 1.5 m^2/g. In an extensive paper reported at the Sixteenth Symposium on Combustion [22], Seader reports the dependence of optical density as measured in the NBS-AMINCO smoke density chamber [23] on mass concentration for high concentrations of smoke generated from the following materials for both flaming and non-flaming combustion: rigid polyvinylchloride, red oak, polystyrene, α-cellulose, Douglas fir, rigid urethane, and polyacrylonitrile-butadiene-styrene (ABS). All of the flaming combustion data can be approximately correlated by a linear plot with a POD of 3.3 m^2/g and the non-flaming combustion data, which appears to have somewhat more scatter, can be correlated by a linear plot with a POD of 1.9×10^{-3} m^2/g. Thus, both from our study of low concentration smokes and the work of Seader at high concentrations, the light-obscuring property of many smokes to white light can be placed in two categories depending on the mode of smoke generation - flaming or non-flaming. It should be stressed that the measurements were made under specific flaming conditions and specific non-flaming conditions; for example, the non-flaming combustion data reported by Seader are based on exposing a given size sample to a flux of 2.5 W/cm^2. It is not known whether the POD is independent of changes in exposure conditions such as radiant flux, sample size and ambient temperature.

The size distributions for the lamp wick smoke and the heptane smoke as determined with the electrical aerosol analyzer are presented in figure 24. The quantity ΔN represents the number of smoke particles in the particle diameter size range $\log D_p$ to $\log D_p + \Delta \log D_p$. The Δ presentation was used because data obtained from the measuring instruments were based on the average within each discrete range.

Two convenient parameters for characterizing the size distribution are the geometric mean number diameter, $\bar{D}_g$, as a measure of the average particle size and the geometric standard deviation, σ_g, as a measure of the breadth of the distribution.

$$\log \bar{D}_g = \sum_{i=1}^{n} \frac{\Delta N_i \log D_i}{N} \tag{9}$$

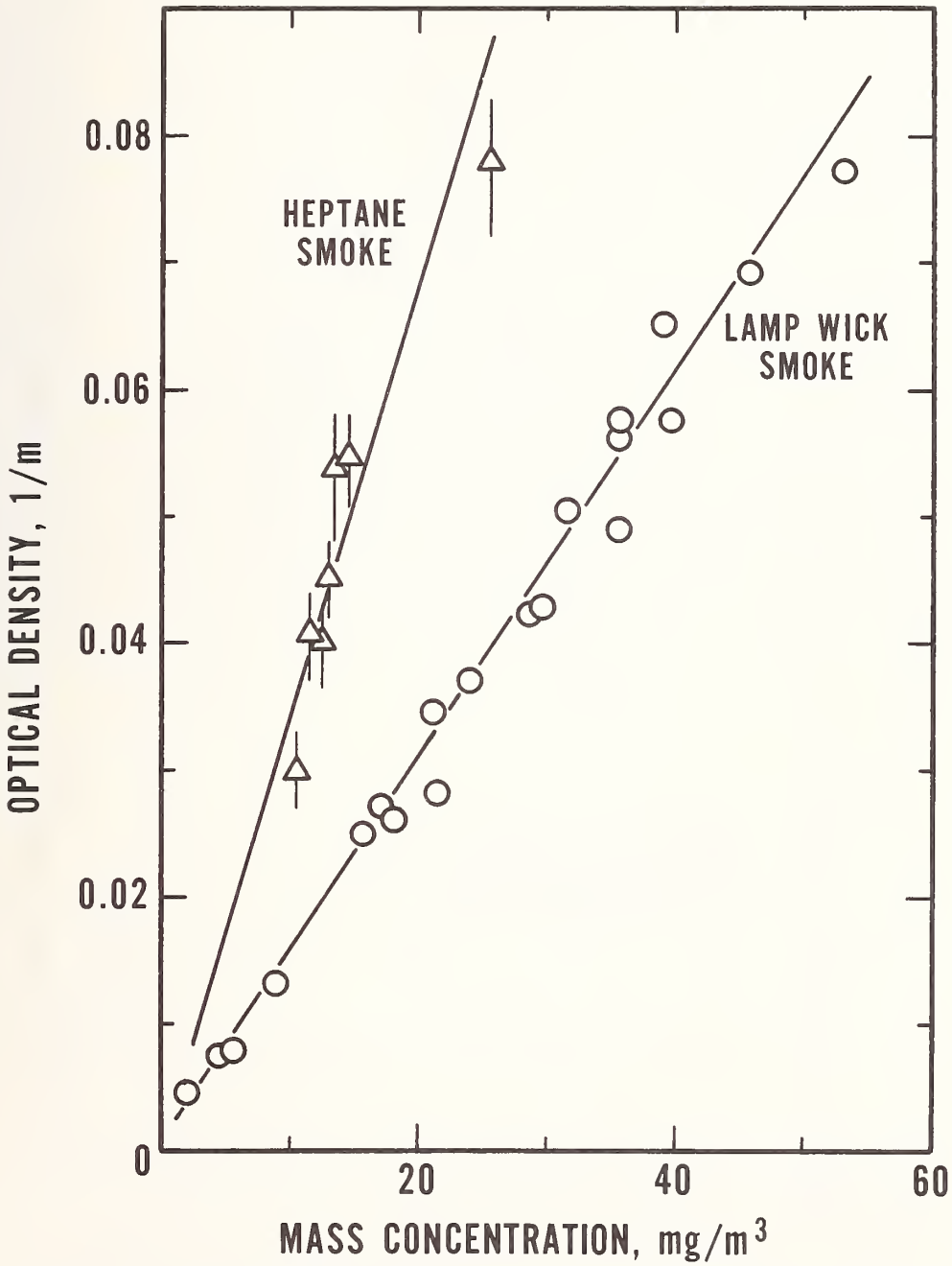

Figure 23. Optical density per meter versus mass concentration for lamp wick smoke and heptane smoke [20].

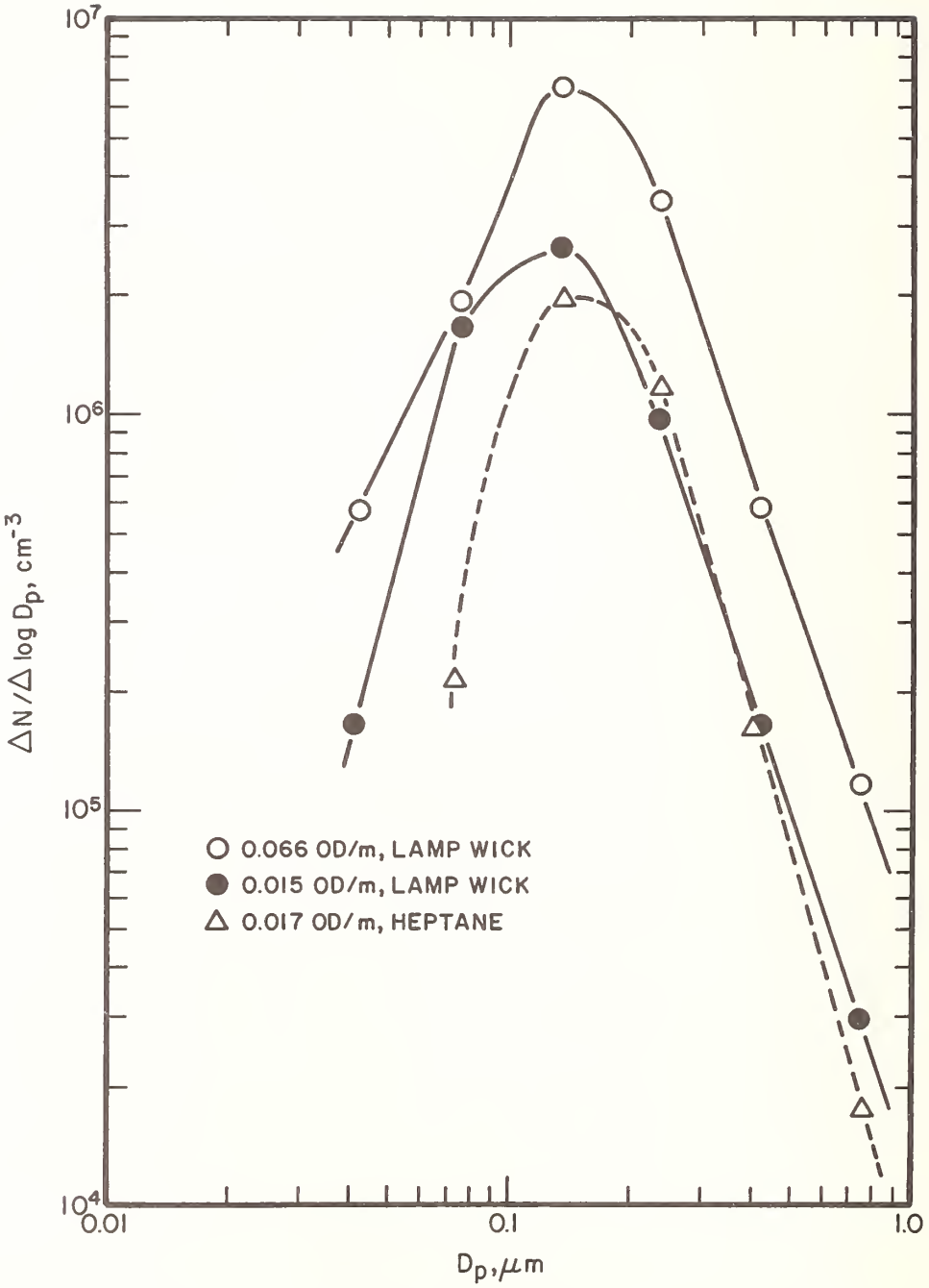

Figure 24. Particle size distribution for lamp wick and heptane smokes [20].

$$\log \sigma_g = \left[\sum_{i=1}^{n} \frac{\left(\log D_i - \log \bar{D}_g \right)^2 \Delta N_i}{N} \right]^{1/2} \qquad (10)$$

where N represents the total number of particles and n represents the number of size classes. Both smokes have a $\bar{D}_g$ between 0.1 and 0.2 μm; however, the heptane smoke seems to have a somewhat narrower size distribution than lamp wick smoke. A summary of all of the smoke data is presented in table 1. The values of σ_g found in our work for smoldering lamp wick smoke are significantly larger than those reported by Watanabe at the 1976 UJNR panel meeting (1.6 and 1.7 versus 1.4). It is known that the size sensitivity of the instrument used in measuring the size distribution, the electrical aerosol analyzer, decreases for particle sizes over a few tenths of a micrometer [24] and this may be responsible for the difference in the values of σ_g.

As discussed in a previous section, the electrical aerosol analyzer has been evaluated for the measurement of the number concentration and volume concentration. Its sensitivity to monodisperse aerosols has also been examined [24]; however, there is no comprehensive study regarding its performance for polydisperse aerosols such as smokes. While we cannot be certain of the size distribution in absolute terms, the instrument is very useful in detecting relative changes in size distributions. For example, the effect of exposure condition on the size distribution of smoke generated from the combustion of α-cellulose is shown in figure 25. In one case a small α-cellulose disc was ignited by a premixed flame while in the other it was in contact with a metal surface maintained at 500°C. The particle size distribution peaked at less than 0.01 μm for the flaming mode compared to 0.075 μm for the smoldering mode. The effect of time on the size distribution of the smoke, which is termed smoke aging, is another process that can be studied with the electrical aerosol analyzer and will be the subject of the next section.

Table 1. Measured and derived parameters of smokes in the UL 217 chamber test

Instrument	UL 217	PMM[a]	EAA[b]	EAA	CNM[c]		
	Optical density	Mass concentration		Number conc.		$\bar{D}_g$	σ_g
	m^{-1}	mg/m^3		$10^6\ cm^{-3}$		μm	
Lamp wick	0.066	42	21	3.4	2.5	0.14	1.7
Lamp wick	0.015	10	6	1.4	1.0	0.12	1.6
Heptane	0.017	5[d]	5	0.9	0.3	0.16	1.5

[a] Piezoelectric mass monitor

[b] Electrical aerosol analyzer, unit density assumed

[c] Condensation nucleus monitor

[d] Filter gravimetric measurement

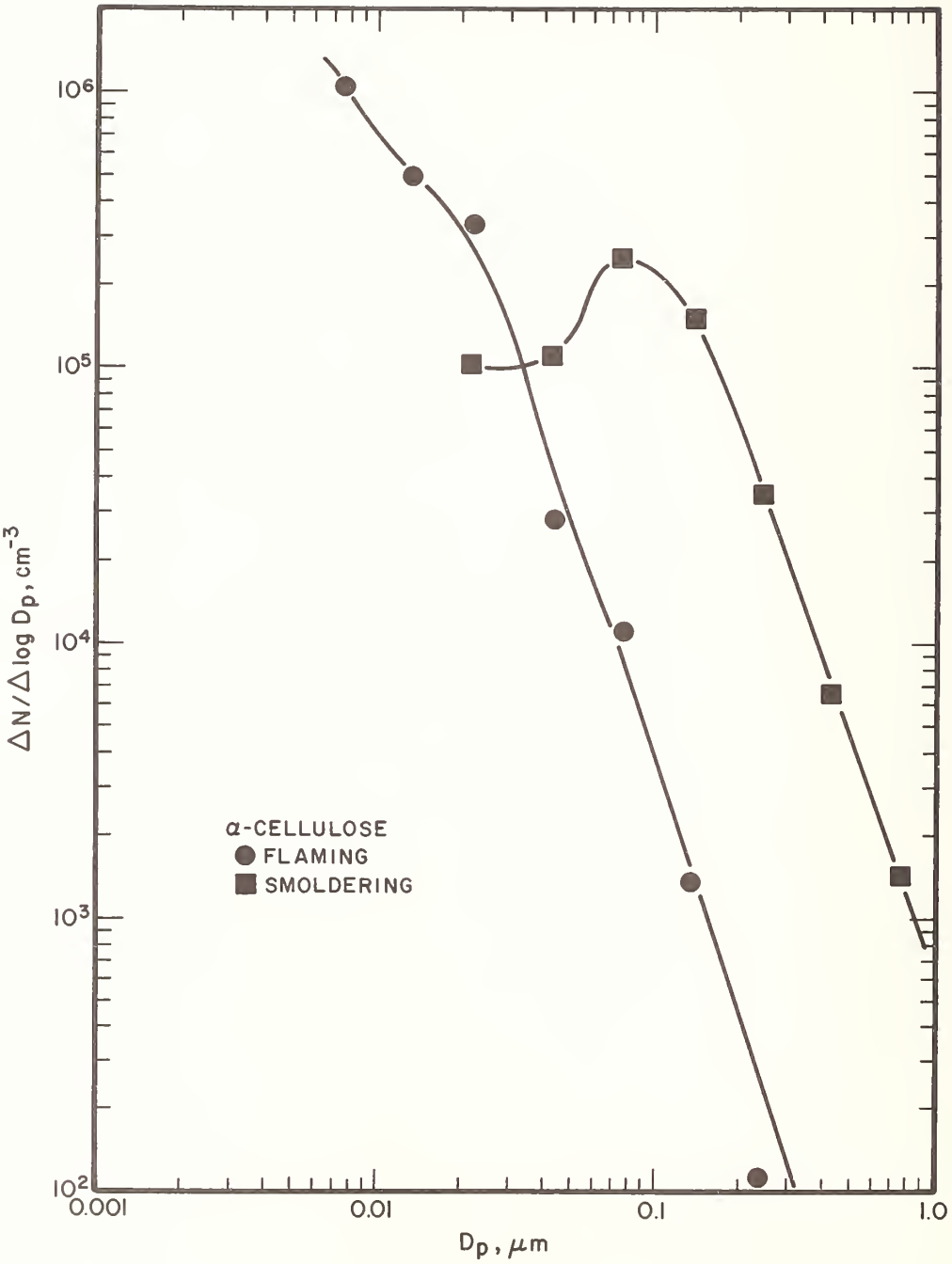

Figure 25. Smoke from α-cellulose under flaming and non-flaming exposure conditions [20].

13. SMOKE AGING

The behavior of smoke particles is dynamic from their formation to their transport to the walls or their dilution in the atmosphere. An experiment performed by K. Mniszewski at IIT Research Institute demonstrates the effect of aging of smoke detectors in the Underwriters' Laboratories test chamber. His data on the responses of a light-scattering type detector with a near forward scattering angle and of an ionization detector are plotted versus time in figure 26. The optical density of the light beam decreased about 5% during the eight-minute aging period. During this same time, the ionization detector response decreased by about 25% while the light-scattering detector increased by about 10%.

In a series of similar experiments at the National Bureau of Standards during which the number concentration and optical density were monitored versus time, a rapid decrease in number concentration occurred in a few minutes while the optical density remained essentially constant. This rapid drop in number concentration can be explained by the phenomenon of coagulation, which is simply the coalesence or attachment of aerosol particles as a result of collisions. The basic equation describing the rate of change of number concentration with respect to time is given by:

$$\frac{dN}{dt} = -\Gamma N^2 \tag{11}$$

Integration yields

$$N/N_o = 1/(1 + \Gamma N_o t), \tag{12}$$

where N_o is the initial concentration. For smoldering punk smoke, the coagulation frequency Γ equals 4.0×10^{-10} cm^3/s. Substituting this Γ into equation (12) one finds that an initial concentration of 3×10^6 particles/cm^3 decreases by a factor of two in 14 minutes.

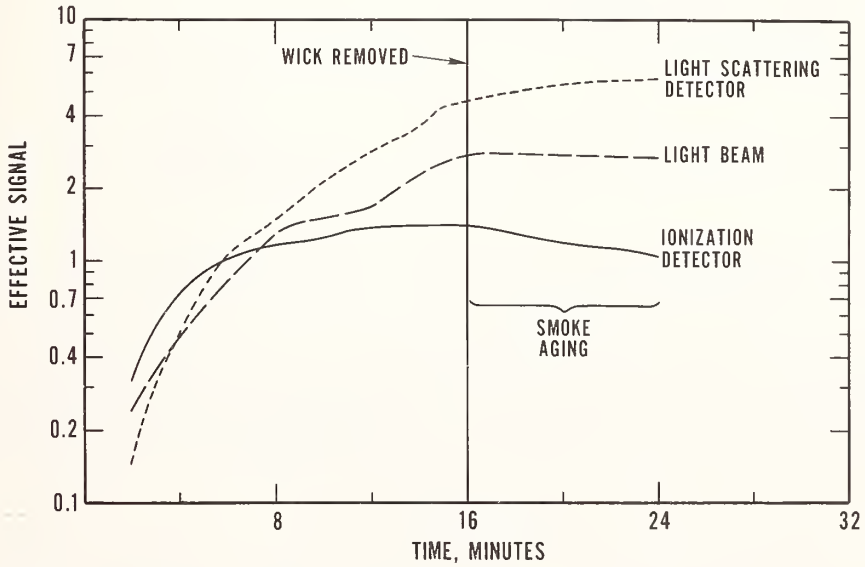

Figure 26. The effect of aging on smoke detector response.

The coagulation phenomenon creates two opposing effects on detector response. The decrease in the number concentration tends to decrease the detector output while the increase in particle size accompanying particle coalescence tends to increase the detector response. Which effect will predominate is determined by the size sensitivity characteristic for the detector.

The effect of aging on the size distribution of punk smoke is shown in figure 27. The smoke was generated in a 1.25 m cubical chamber and was allowed to age for up to 16 hours. The peak in the number distribution decreases by over two orders of magnitude while the particle size increases by about a factor of two. Coagulation is the dominant mechanism during the initial aging, but the mechanism of wall loss becomes the dominant process for the well aged, low concentration smoke.

All of the size distribution data in the previous figures plus the size distribution of punk smoke exposed to an air stream moving at a velocity of 2 m/s have been plotted in terms of Friedlander's self-preserving variables [25] ψ and η in figure 28. The number distribution is reduced by the total number of particles in the size distribution N(t), and the diameter is reduced by a quantity related to the average diameter for the size distribution, $(V/N)^{1/3}$, for that particular smoke. Thus

$$\psi = \frac{N}{\Delta \log N(t)} \tag{13}$$

$$\eta = D\, N(t)/V^{1/3}. \tag{14}$$

The data includes fresh smoke as well as aged smoke, smoke generated in both the flaming and smoldering modes, whitish smoke and black sooty heptane smoke, and smoke generated under different airflow conditions. There is qualitative agreement in the shape of the size distribution curves for all the data, especially for larger values of η. From the data for small η, it appears that the heptane smoke has a narrower distribution than the others.

Also shown in figure 28 are a reduced Junge like size distribution and a reduced log-normal size distribution.

$$\psi = 1.38\, \eta^3\, (\eta^3 + 0.2)^{-2}, \text{ Junge like} \tag{15}$$

$$\psi = 1.73 \exp - \left[\frac{\ln (1.23\, \eta)}{0.744}\right]^2, \text{ log-normal with } \sigma=1.7. \tag{16}$$

Equation (15) is a reduced version of the number distribution equation given in the 1976 UJNR panel meeting (p. 262). It appears that both the Junge like distribution and the $\sigma_g = 1.7$ log-normal distribution fit the data. It has been shown by Mulholland, et al. [26] in a coagulation calculation that the reduced algebraic distribution is only weakly affected by aging due to coagulation as is the case experimentally (see aging data in figure 28). This means that the algebraic distribution could be used as a model size distribution not only for a variety of smokes but also for smokes at various stages of aging. It is not known whether the log-normal size distribution also has this property.

14. LOOKING AHEAD

In our previous studies of smoke aging, we considered the highly idealized case of a perfectly mixed smoke. Our current theoretical work is concerned with the dynamics of smoke in a buoyant plume. To date our theory includes the effects of coagulation and of air entrainment in the plume and enables

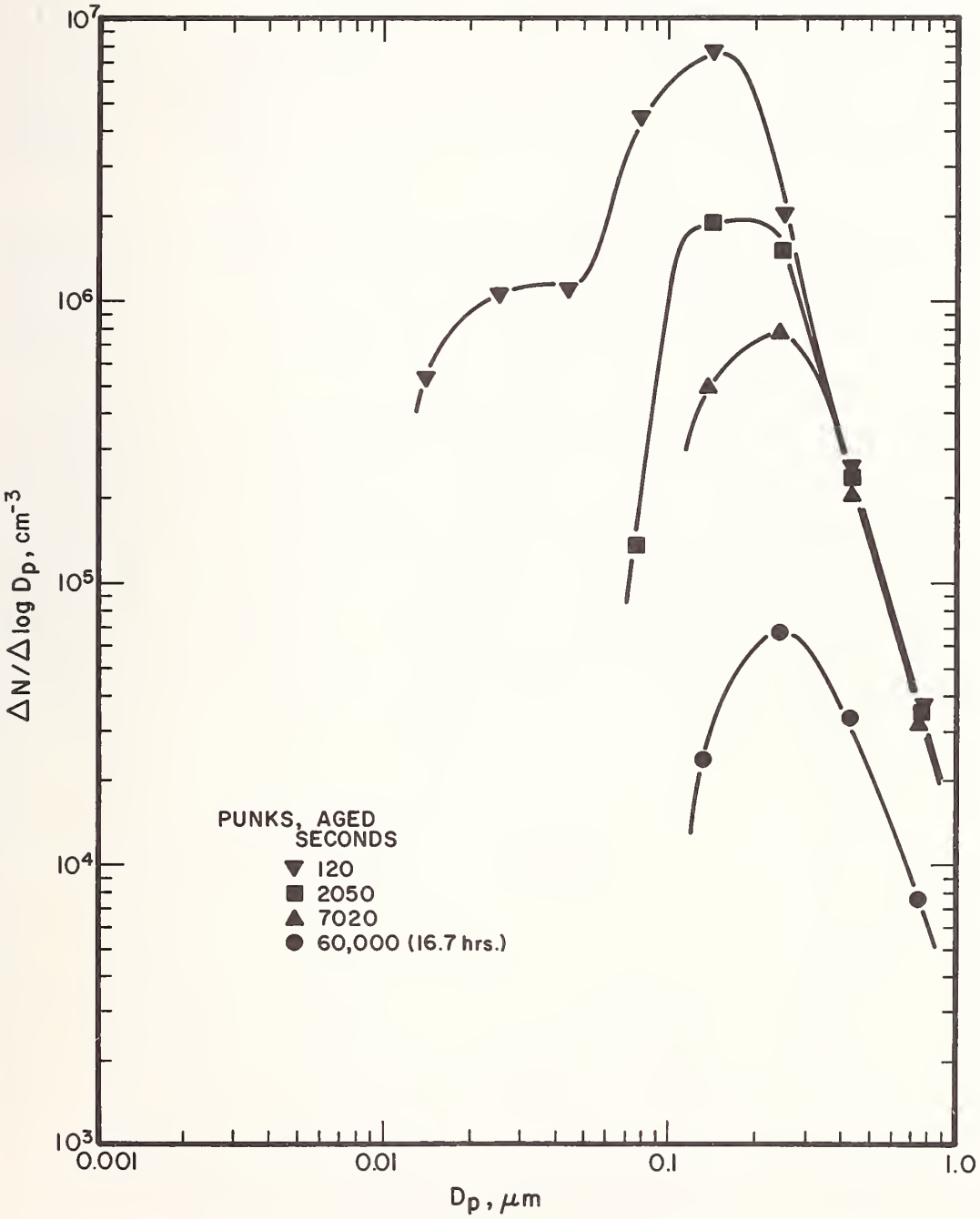

Figure 27. Aging of the punk smoke for up to 16 hours [20].

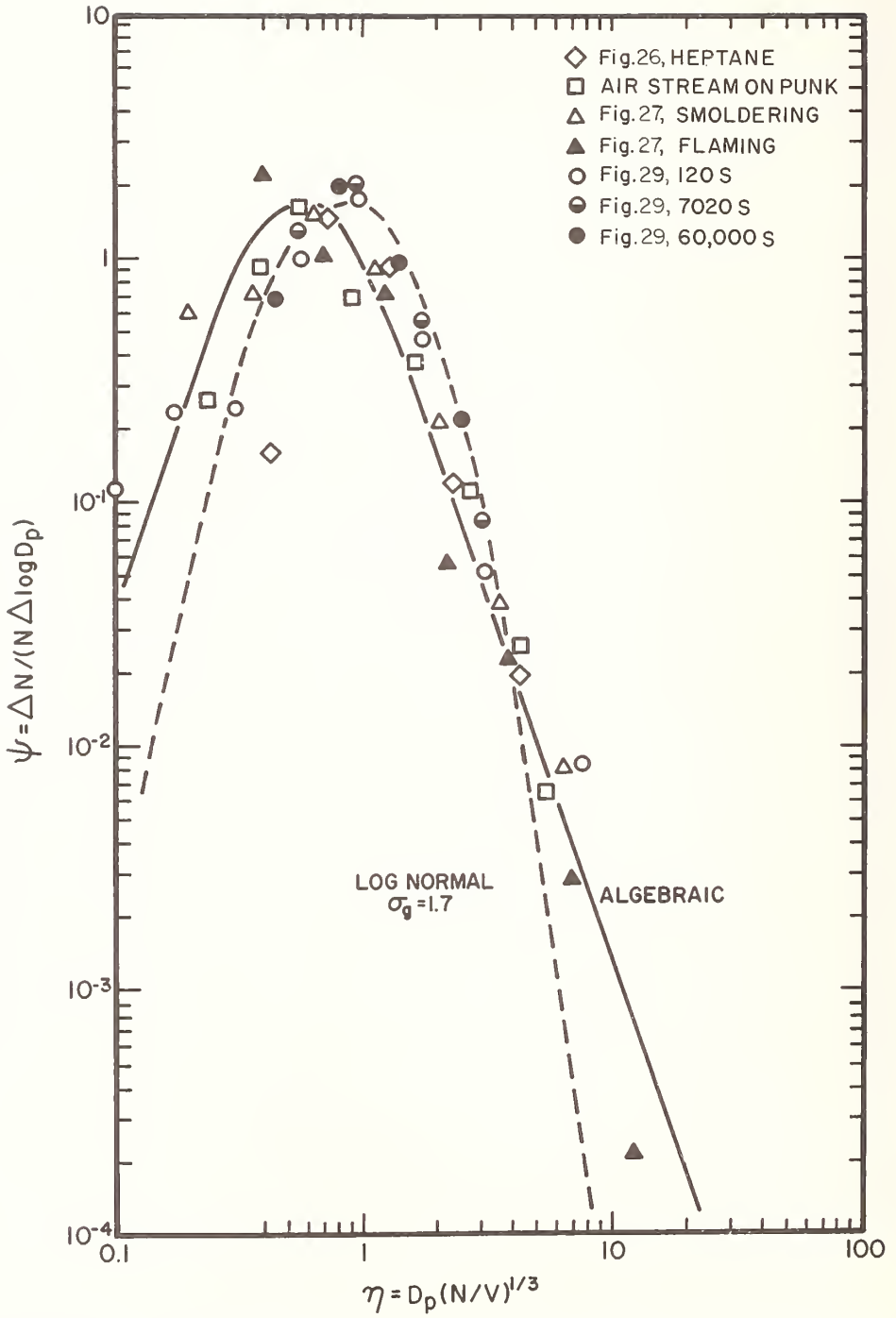

Figure 28. Size distribution in terms of reduced variables [20].

the calculation of the number concentration, mass concentration, and size distribution of the smoke particulate as a function of height. The relative significance of coagulation versus air entrainment on the particulate number flux is determined by a single dimensionless constant which we term the plume constant, A. Besides depending on the total rate of heat release and the rate of mass release, A also depends on the coagulation frequency, height and the number concentration at this reference height. For values of A greater than or equal to 0.1, coagulation becomes an important effect. In the future, we plan to include the mechanism of aerosol formation including nucleation and condensation in our study and to initiate an experimental study.

A second project of high priority is the development of a simplified version of the monodisperse aerosol generator for testing the sensitivity of installed smoke detectors. A prototype version of the tester is shown in figure 29 [27]. Some of the major design features are a repeatable, steady-state aerosol source; adjustable aerosol concentration over a range from 10 to 60 mg/m^3; mass median diameter of about 0.5 μm; and formation of the aerosol from the atomization of the pure liquid dioctyl phthalate.

A third project in progress is the absolute calibration of our optical particle counter using a laser Doppler size spectrometer developed by Chabay in the NBS Analytical Chemistry Division [28]. The principal of operation for the instrument is illustrated in figure 30. Light scattered out of a horizontally propagating laser beam by falling particles is collected at one angle in the vertical scattering plane. Beat frequencies in the photocurrent of the detector due to the Dopper shift of the radiation scattered by the settling aerosol are analyzed to determine particle velocities. The slip - corrected Stokes law settling velocity gives the particles size for a known particle density, while the amplitude of the beat frequency contains information on the number of particles of that size. The technique has a sizing accuracy of $\leq$0.16 m diameter for measuring particle sizes over the range 2 to 20 μm. The Berglund-Liu vibrating orifice generator [29] is being used for generating monodisperse ($\sigma_g \sim 1.05$) dioctyl phthalate particles for the calibration.

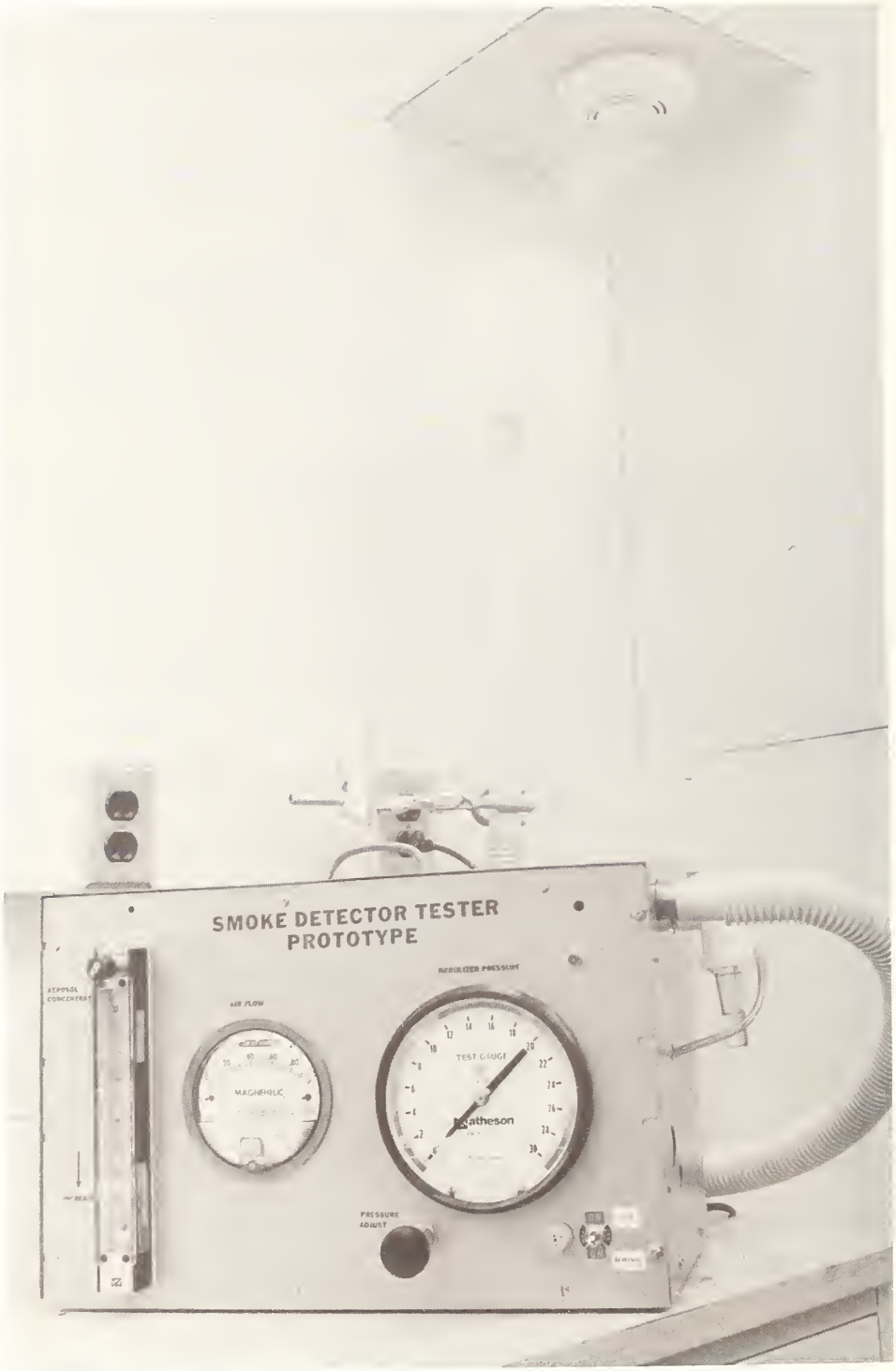

Figure 29. Smoke detector tester [27].

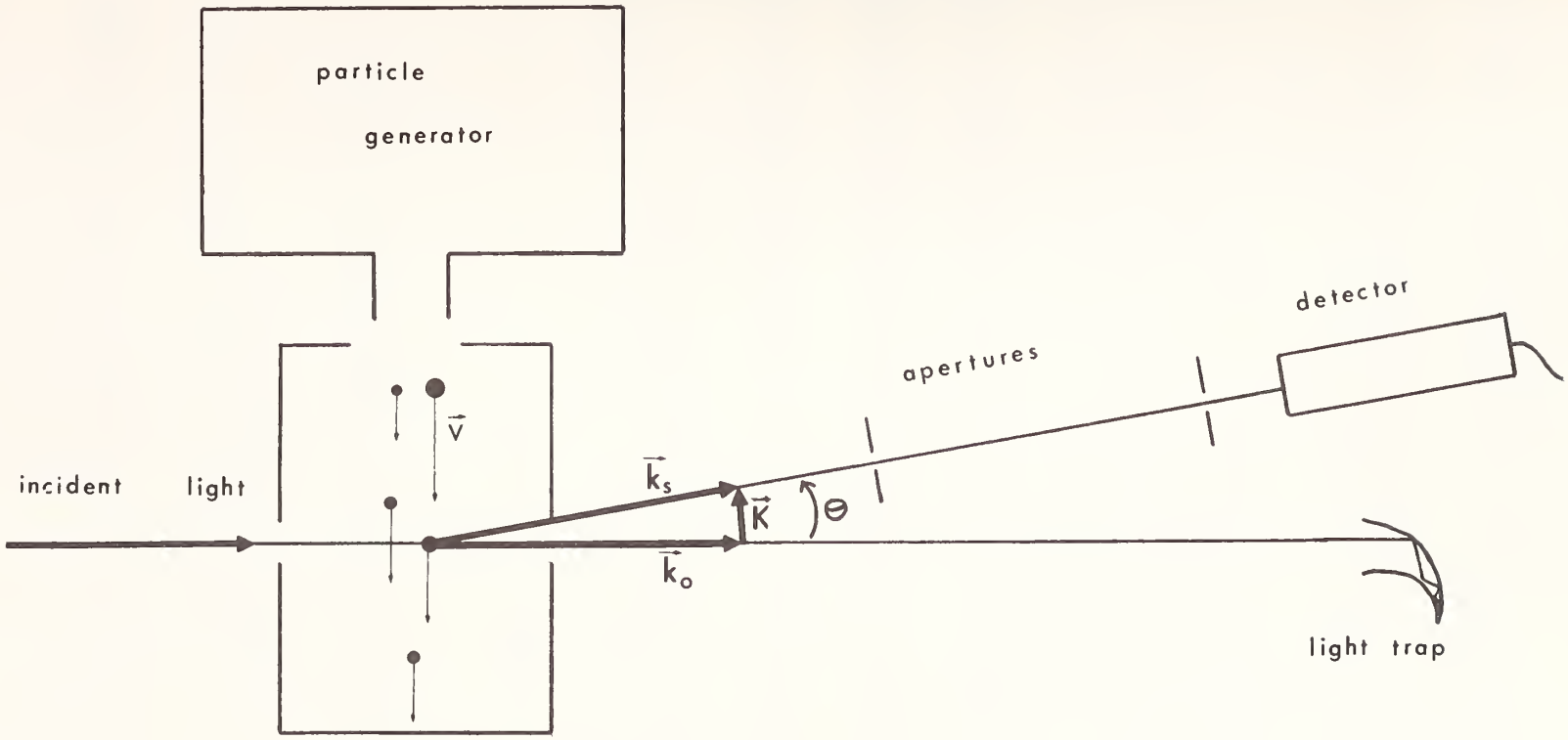

Figure 30. Laser doppler size spectrometer [28].

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FALSE ALARM OF SMOKE DETECTORS

by

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Engineering Institute of Japan

The causes of false alarm of smoke detectors are described together with the standards for device and installation of smoke detectors, and the means to avoid false alarm are presented.

INTRODUCTION

In Japan, several millions detectors are yearly manufactured and installed, and then, there are not a few statistics on the production of fire detection systems[1] However, after the installation, the responsible executive of the building does not like to report the actual performance of detectors even when the system is properly operated. For this reason, it is pretty hard to collect an objective information on facts which gave false alarm or failed to give alarm. We can easily prove the high reliability of the devices themselves, but a statistical analysis on effectiveness of fire detection systems will be a matter of considerable difficulty without knowledge on negative aspects of the system such as design inadequency, human-initiated error and down-time.

The statistical data which have so far been reported concern mostly with thermal detectors. But, recently, the Fire Alarm Committee, the Illuminating Engineering Institute of Japan received interesting information on the false alarm of smoke detectors. The authors wish to summarize the reports.

REQUIREMENTS

The smoke detectors are tested by the Japan Fire Equipment Inspection Corporation according to the technical standards[2].

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* Professor of Sophia University (Chairman of the Committee)
** Chief of the Third Research Division, Fire Research Institute

The standards are provided by the Ministry of Home Affairs, and include the following function tests of smoke detectors;

-- Ambient temperature test in which the function is ascertained after being subjected to the temperature of - 10°C and 50°C for a period of 1 h, respectively,

-- Aging test in which the detector is kept at 50°C for 30 days,

-- SO_2 corrosion test,

-- Endurance test in which the detector operates 1 000 times,

-- Vibration test in which the detector is subjected to 1 000 cpm vibrations of 4 mm peak-to-peak amplitude for 1 h under unenergized condition, and to vibrations of 1 mm peak-to-peak amplitude for 10 min under energized condition,

-- Impact test in which a detector is subjected 5 times to a shock equivalent to 50 times the gravitational acceleration,

-- False alarm test to confirm that the detector does not operate when subjected to the illumination of 5 000 lux for 5 min or to the air current of 5 m/s, and,

-- High temperature test in which detectors are exposed for 30 s to the air current having a temperature of 150°C and velocity of 1 m/s.

The smoke detectors are divided into photoelectric type and ionization chamber type by the detecting principle, and into three classes by the sensitivity; the typical detector operates at the light-obscuration of 10 %/m when smoke is generated by smoldering a filter-paper at 500°C.

The testing consists of a 'type test' of several samples from the first production lot, and a 'factory test' which is carried out at the time of shipment. The type should be finally approved by the Minister of Home Affairs.

Fire detection systems are obligatorily installed in the buildings for specific uses having a floor area above a certain value according to fire law and ordinances[3,4]. Local fire departments or other authorities inspect fire detection systems at the stage of planning and after the installation.

Japanese fire law and ordinances[3-5] require that smoke detectors should be installed within 60 cm beneath the ceiling surface, and that they should not be placed within 60 cm from the walls and beams, or within 1.5 m from air-inlet openings but rather near the openings for outgoing air.' Although the rooms where smoke detectors

must be used are limited to those in underground floors, floors exceeding 11th floor and windowless buildings, it is also noted that the maximum coverage area of a typical smoke detector should be 150 m^2 for a ceiling-height less than 4 m, 75 m^2 for the height between 4 m and 8 m, and 40 m^2 for the height between 8 m and 15 m. As for other spaces which should be protected by smoke detectors, the detectors should be placed at a travelling distance up to a maximum of 30 m for corridors and gentle ramps, and at a vertical distance up to 15 m for stairways, steep ramps, and escalators; smoke detectors should be also used at elevator-shafts and vertical pipe-shafts having a cross-section of larger than 1 m^2.

Smoke detectors having sensitivity other than that of typical one are used for protecting space with high ceilings and for triggering rolling shutters, but the false alarm of such detectors is not included in the next paragraph.

FALSE ALARM OF SMOKE DETECTORS

Since 1972, the Association of Fire Alarm of Japan and the Tokyo Fire Alarm Maintenance Corporative Association have investigated false alarm of smoke detectors in response to the request of the Fire Defence Agency and the Ministry of Construction. The factors relevant to false alarm were examined to facilitate statistical tabulation. At present, the factors include the cause of false alarm, occupancy, building construction, maximum number of stories, the floor and specific area giving alarm, month, hour, weather, detector-type, detector-sensitivity, maintenance interval, action taken for solving false alarm, down-time, etc. Both associations collected 2 787 reports on false alarm and analyzed statistically them[6]. Among the finding, Table 1 shows the causes of false alarm, which occurred between 1973 and 1975 in Capital Region. In the table, the causes of about a half of false alarm are still unknown, but it is noted that false alarm caused by meteorological factors and artificial factors accounts for 31 % and 27 %, respectively.

By comparison of false alarm of ionization detectors with that of photoelectric detectors, we can find that the percentages for many causes almost agree, but false alarm caused by defective photoelectric detectors is out of proportion to that of ionization detectors; this may be attributed to the use of incendescent lamps,

and this tendency is decreasing by the use of LED light sources. The out-put of smoke detectors between 1969 and 1974 is 2 511 488 for ionization type and 390 018 for photoelectric type, while the numbers of the reported false alarm are 1 010 for ionization type and 112 for photoelectric type. From these figures, it can be said that the frequency of false alarm of photoelectric detectors may be about the half of those of ionization detectors.

By comparison of the figures in Table 1 with those of 1 648 reports on false alarm occurred in 1972 in the whole land, it seems that false alarm due to the externally-induced transient voltage on power supply line and due to the insects reduced remarkably.

Figure 1 shows a change of the frequency of false alarm with month. A dotted line in the same figure shows the mean monthly humidity in Tokyo. Humidity in July is the highest as in the figure due to the rainy season. Figure 2 shows a change of the frequency of false alarm with hour. As will be seen from both figures, humidity and human activities seem to affect the number of false alarm.

There is a doubt that this report might not include all the false alarm in premises where smoke detectors are installed. Therefore, more detailed analysis would be the subject of future research.

For reference, the statistics of false alarm on heat detection systems[7)] will be described here. In 1967, 485 reports on false alarm were submitted to the Tokyo Fire Alarm Maintenance Corporative Association from the responsible executives of the buildings. The devices from which false alarm was initiated were given as follows ; heat detectors 72 % ; manually-operated devices 12 % ; wiring 14 % ; control boards 1 % and unknown 1 %. The causes of false alarm by thermal detectors were ; rapid change of metecrological factors such as temperature, wind and atmospheric pressure 44 % ; leakage of water 17 % ; mechanical damages 9 % ; change of sensitivity 30 %. It was revealed through these statistics that 95 % of false alarm due to leakage of water and 97 % of false alarm due to mechanical damages occurred in spot type detectors. Based on these facts, the standards for devices and their installations were revised in 1969[2)]

MEANS TO AVOID FALSE ALARM

Based on the above statistics, what kinds of the means have been selected to avoid false alarm?

In Japan, most smoke detectors now in use are the products made in 1969 or after, and the manufacturers have made a constant effort to improve the performance of smoke detectors. For example, Mr. Iwami, a research member of a private company reported the combined effect of humidity and dirts on electric insulation of polymeric materials.

The Fire Defense Agency revised the technical standards of smoke detectors according to the report in the preceding paragraph[2], and added the following tests;

(1) Dust test in which a detector is exposed for 15 min to dusty atmosphere having light-obscuration of 20 %/ft,

(2) Transient voltage test applying the following 100 pps (pulses per sec) pulses to the detector for 15 s, respectively;

-- a peak voltage of 220 V with a width of 1 ms applied by the pulse generator having an internal resistance of 600 ohms,

-- a peak voltage of 500 V with a width of 1 μs applied by the pulse generator having an internal resistance of 50 ohms, and

-- a peak voltage of 500 V with a width of 100 ns applied the pulse generator having an internal resistance of 50 ohms, and,

(3) Humidity test in which the energized detector is exposed for 4 days to moist air having a relative humidity of 95 % at a temperature of 40°C.

Fire Defense Agency also revised the maintenance standards[8,9]; it is prescribed in the notification that operation test using smoke from joss sticks and appearance check shall be performed every six month and that the sensitivity of smoke detectors shall be checked every year by a qualified person.

The figures obtained by statistical analysis may differ from these in USA, because they are influenced by the sensitivity and placement of the detectors, climate, type of building construction, the way of handling heat and so on. However, the above means to avoid false alarm will be useful to determine proper sensitivity and to decide placement of detectors.

The authors wish to express our thanks to Fire Prevention Division of the Fire Defense Agency and the members of Fire Alarm Committee for their constant advice and encouragement.

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TABLE 1. CAUSES OF FALSE ALARM

CAUSES OF FALSE ALARM	TOTAL		Ionization type %	Photoelectric type %
	No.	%		
TOTAL	1139	(210.5)	(218.1)	(177.8)
KNOWN	541	100	100	100
UNKNOWN	598	(110.5)	(118.1)	(77.8)
Design Considerations	15	2.8	3.2	0
location	14	2.6		
sensitivity	1	0.2		
Engineering Work	6	1.1	1.1	1.6
connection	1	0.2		
insulation	2	0.4		
installation	1	0.2		
others	2	0.4		
Device	37	6.8	3.9	30.2
Local Factors	6	1.1	1.3	0
seaside district	2	0.4		
corrosive gases	4	0.7		
Meteorological Factors	166	30.7	33.0	23.8
strong wind	90	16.6	17.5	14.3
high humidity	61	11.3	12.3	9.5
atmospheric pressure	1	0.2	3.2	0
lightning	14	2.6		
Environmental Factors	52	9.6	8.9	11.1
insects	11	2.0	1.3	4.8
condensation of steam	6	1.1	7.6	6.4
air conditioning system	8	1.5		
mouse	1	0.2		
others	26	4.8		
Artificial Factors	144	26.6	24.0	19.0
intentional mischief	6	1.1	0.4	3.2
smoking	27	5.0	5.2	3.2
mechanical damage	1	0.2	18.4	12.6
portable heater	1	0.2		
smoke	59	10.9		
steam	19	3.5		
bon-fire	4	0.7		
combustion gases	10	1.8		
others	17	3.1		
Maintenance	82	15.2	14.5	11.1
Building Management	26	4.8	4.5	1.6
remodelling	3	0.6		
leakage of water	15	2.8		
change of building use	1	0.2		
ignorant manager	4	0.7		
others	3	0.6		
Others	7	1.3	5.6	1.6

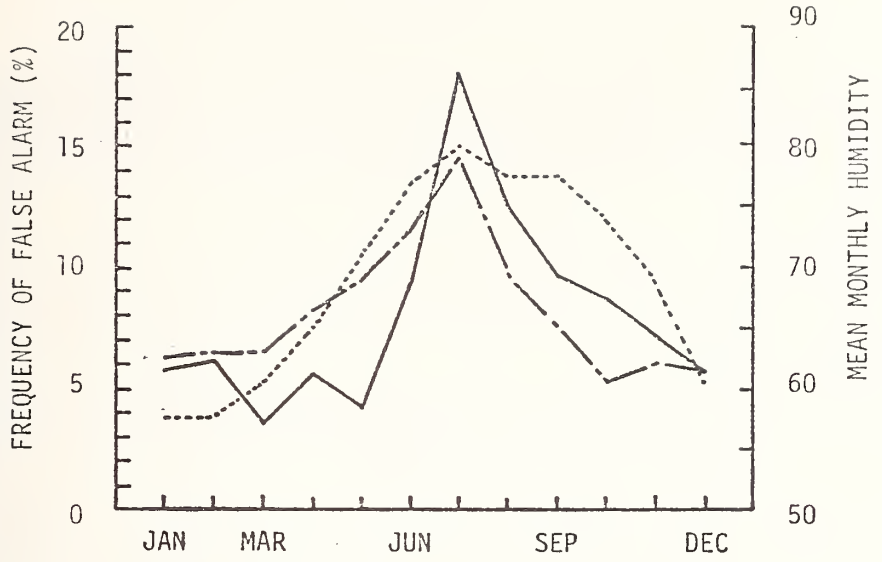

Fig. 1 Change of the Frequency of False Alarm with Month

Solid line, Values between 1973 & 1975 in Tokyo area;
Chain line, Values in 1972 in whole land;
Broken line, Mean monthly humidity in Tokyo

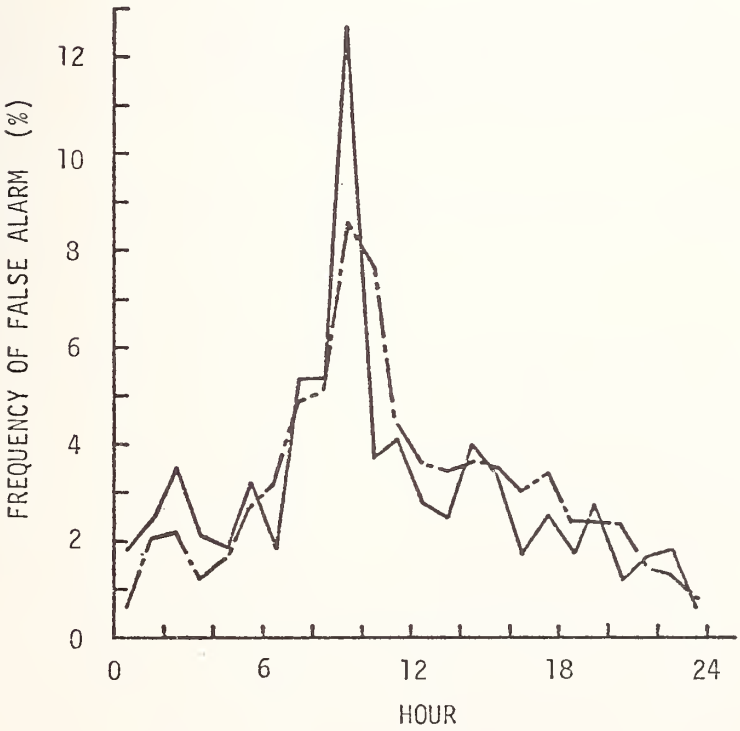

Fig. 2 Change of the Frequency of False Alarm with Hour

Solid line, Values between 1973 & 1975 in Tokyo area;
Chain line, Values in 1972 in whole land

Theme

SMOKE PROPERTIES
AND DETECTION

RESEARCHES IN SMOKE PROPERTIES IN JAPAN

BY

SMOKE AND GAS TOXICITY LOAD COMMITTEE

JAPANESE ASSOCIATION OF FIRE
SCIENCE AND ENGINEERING

Third Joint Meeting
U.S. - Japan Panel on Fire Research and Safety
UJNR, Washington, D.C., March 13 - 17, 1978

PREFACE

The countermeasures to smoke produced in fires of buildings are very important for the safety of people. An effective design for fire safety is required to establish the reasonable countermeasures based on the knowledge of characteristic of smoke released.

There may be two categories for countermeasures of smoke in fires. That is, one is to control the generation of smoke and the other is to control the flow of smoke released in buildings.

The methods of the study of the former subject are essentially different from those of the latter
The cooperative studies between the two categories have been carried out for many years by fire research people.

The committee of Japan Association of Fire Science and Engineering involves a subcommittee which studies on smoke and toxic gas load relating to the countermeasures to smoke in fires. Information on mechanism of generation, property, and quantity of smoke from various materials in fires have been exchanged and the fundamental studies on characteristic of smoke have been studied for many years at the subcommittee.
The smoke behaviour in compartment fires have also been studied.

This report is the summary of some main reports which have been discussed at the subcommittee on mechanism and generation of smoke from materials and smoke generation in compartment for the contribution to the 3rd Panel Meeting UJNR Panel on Fire Research which involves Technical Session on "smoke property and detector".

The main reports have been presented by the members of the subcommittee under Japan Association of Fire Science and Engineering.
The members are as follows.

Chairman :	F. Saito	Building Research Institute, Ministry of Construction
	T. Jin	Fire Research Institute, Ministry of Home Affairs
	H. Suzuki	Building Research Institute, Ministry of Construction
	K. Endo	Nohmi Bosai Kogyo Co. Ltd.
	K. Oguni	Takenaka Technical Research Laboratory
	A. Takahashi	Takasago Thermal Engineering Co. Ltd.
	T. Nagashima	Science University of Tokyo Department of Chemistory
	T. Hirata	Government Forest Experiment Station, Ministry of Agriculture and Forestry
	A. Takemoto	Fire Research Institute, Ministry of Home Affairs

1. GENERATION OF SMOKE

1.1 Behaviour of Smoke and Measuring Methods

Various kinds of methods have been taken for the study on smoke which are produced from organic building materials when heated. Smoke dealt in this report was generated in some experimental electric furnaces, burning a small amount of various organic materials, which were devised for the fondamental study of smoke particles. 1)-8)

Sedimentation method is more useful for the measurement of such small particles as those from cigarett than usual optical microscope. Electron-micro scopic methods were used by Suzuki. Smoke particles were collected on glass plates coated with oil layer or collodion membrane using cascade impactor by Jin, and then were counted with naked eyes on the photoes which were taken by optical microscopes. (Fig 1)

The scattered light at an angle of 90° to the beam by smoke particles was measured with "Royco Particle Counter" shown in Fig 2 and the experimental light scattering apparatus shown in Fig 3 for taking the size distribution of smoke particles when materials were burned in an electric furnace, or another furnace controlled by a high-frequency. Disymmetric method was used for the measurement of the changing of light intensity scattered by smoke particles during combustion.

An experimental electric furnace shown in Fig 4 has been used for the generation of smoke and an optical microscope has also been used. For the mesurement of invisible particulates of smoke, an ion mobility counter was used as shown in Fig 5.

1.2 Behaviour of Smoke

Smoke generated in an experimental electric furnace controlled by a high frequency shown in Fig 6, contains various kind of products -- gaseous, liquid and solid, however, only liquid and solid products have been treated as smoke particulates in this paper. Smoke particulates during smoldering at lower temperatures before catching flame are mainly round and lightly coloured.

The colour of smoke could be regarded as that from smoke particles, because normally gaseous products are colourless.

Even the furnace is controlled at a fixed temperature, the temperature of a material in it is always changing by the conduction of heat by the combustion of the outer part of the materials. Therefore it would be difficult to get the uniformalized particles by combustion of materials. Colour of particles may depend on the chemical structures of the materials and on the temperature in the furnace, however most particulates generated are coloured in light yellow or light brown at the lower temperatures. Then the colour turns into brown or dark brown and black at the higher temperatures.

The colour changing during combustion mainly depends upon the dehydrogenation of the materials, affects the indexed of the refraction and also affects on the scattering of the light on the surface of particles. The oxygen concentration will also affect the colour of the smoke particles. When the combustion is completed in the innert atmosphere, the smoke particles will much lighter in their colour than in a oxygen rich atmosphere. The colour of smoke particles from wood is gradually changing from light yellow to dark yellow, light brown, dark brown, gray and black when particles collected on filter papers after the combustion at the fixed temperatures as 350°c, 400°c, 450°c, 500°c, 550°c, 600°c.

Fire retarded wood with ammonium bromide and ammonium phosphate will release much darker particles than untreated wood.

1.3 Estimation of Smoke Density by the Light Obscuration Coefficiency

Smoke density can be represented in various expression. One of the popular methods is to measure the light obscuration in a box where smoke density can be estimated by the following formulae,

$$I = I_0 \exp(-Cs \cdot L)$$

$$Cs = (1/L) \ln(I_0/I)$$

$$C = Cs \times V$$

Where I_0 is the initial light intensity in the box which does not envolve smoke, and I is the experimental light intensity. L is the light path (m), V is the volume, Cs is the extinction coefficient (m^{-1}) and C is the amount of smoke.

The results obtained in the relation between weight loss of materials and amount of smoke (C) are shown in Fig 7, 8, 9, and 10. 7) These tendency is the same as Suzuki's results. 6) Sugahara has also studied with evaluation of smoke as the same principle. 8) The smoke density in a chamber seems to be proportional to the weight loss of materials, although the total amount of smoke produced depends on the conditions where a material was burnt.

The relation between the amount of smoke (C) and weight loss is experimentally shown as follows.

$$C = K(T) W + A$$

Where K (T) is the smoke generation coefficient, W is the weight loss and A is the time log of smoke diffusion at the initial stage in the chamber.

The relation between smoke generation coefficient (K) and the ambient temperature (T) is written as follows.

$$K(T) = A - B T^n$$

The smoke particles produced under the lower temperatures mainly consist of liquid particulates while the ones obtained under burning with flame contain soot.

The burning rate (r) of materials depends on the temperature and is supposed to have the following relation.

$$r = \frac{dW}{dt} = KoWo \exp\left(-\frac{E}{RT}\right)$$

Where Wo is the weight loss of a material, R the gas constant, E the activation energy, T the absolute temperature and Ko the coefficient.

The Arrhenius plots on the smoke generation are shown in Fig 11.

The rate of smoke generation (Csk) is written as follows.

$$Csk = K \times r$$

$$= (A - BT^n) \times (KoWo \exp(-E/RT))$$

and shown in Fig 12.

1.4 The Procedure of Generation, Growth and Decrease of The Average Number of Smoke Particles

Smoke particles generated by smoldering of wood are coagulated each other and grown to increase the diameter.

This phenomena in a box filled with smoke, shown in Fig 13, will continue for hours. The coagulation rate will depend on the initial concentration of smoke in the collection box.

The number of smoke particles has a linear relation to the extinction coefficient (Cs), therefore the declination of smoke will be described as follows.

$$-\frac{dCs}{dt} \doteqdot \beta C_s^2$$

or

$$\frac{1}{Cs} - \frac{1}{Cso} \doteqdot \beta t \quad \ldots\ldots (1)$$

Where Cso is the concentration of smoke in the box at the initial stage (at arround 3 minutes after the generation) and β is the coagulation coefficient.

The changing of the coagulation coefficient can be calculated by the above formula (1).

In the case of smoldering of wood, the coagulation coefficient (β) could roughly be considered as a constant value of 0.09 in the range of over 1.5/m as shown in Fig 14.

The difference of the values of β will not give a big difference to the result, although β is changable in a small range due to the initial concentration (Cso). The results from calculation concerning the particles from plastics at their smoldering are given in Fig 15.

The value of β obtained from plastics seems to be a little bit smaller than that from wood. This means that smoke particles from wood may apt to coagulate than that from plastics.

In order to pursue the behaviour of smoke particles at production, Z value, scattered light intensity ratio of $I_{135°}$ and $I_{45°}$, was used.

Smoke particles produced from wood and commercial rigid polystyrene in an electric furnace controlled by the high frequency, were lead into light scattering apparatus by vaccum as shown in Fig 6.

The Z value obtained from scattered light by particles which are released during combustion of wood is continueously changing as shown in Fig 16.

The Z value is influenced by the initial temperature of the furnace. The phase (1) at a furnace temperature of 400°c cannot be seen at 450°c in Fig 16, and the phase (2) starts instead of phase (1). Likewise at 500°c

The Z value is also influenced by the oxygen partial pressure of the atmosphere.

The change of Z value are basically caused by the following reasons.

1. Change of the size of particles by oxidation in the atmosphere
2. Change the refraction indexes
3. Initial diameter of particles released at the temperature in the furnace.

Fig 17 shows the diagram of the Z value from wood at an innert atmosphere of 0.1 of partial pressure of oxygen.

The Z values become smaller in the innert atmosphere and the period of production of smoke are extended.

The Z values obtained from plastics, and commercial rigid polystyrene are shown in Fig 18.

The shapes of the curves in Fig 18 are different from those of wood shown in Fig 16 and 17.

1.5 Size Distribution by The Sedimentation Method

The modal diameters of smoke particles are obtained by the measurement of the falling velocities in a smoke chamber using a experimental cell which involves 3 windows for light beam for detector and for inlet of smoke with 2 plates of platinum inside. The 2 pieces of plates are located in the cell with the horizontal distance of 2mm between them. Combustion products are generated by heating 0.5 or 1 gramme of thin speciment in a furnace controlled at a constant temperature or a constant rate of temperature rise. The chamber ($1m^3$) was filled with smoke until the extinction coefficient (Cs) become $1m^{-1}$.

The observation of smoke particles which were led into the cell by vaccume have been made using high pressure mercury arc being cut off the infra-red reagion.

The particle size are obtained by sedimentation method using the formula by Stokes-Cunningham

$$r = -\frac{\beta \ell m}{2} + \sqrt{\left(\frac{\beta \ell m}{2}\right)^2 + \frac{9 n v}{2 \rho g}}$$

and the light scattering method for visible smoke particles and an experimental ion mobility counter for invisible particles. The size distribution diagrams obtained by counting particles for ten minutes in the chamber are shown in Fig 19. The modal diameters of particles produced from Japanese cedar, pine, filter paper, melamine resin and polyurethane at various conditions were between 0.6 and 1.0 μm.

The size distribution obtained again with the same method for 10 minutes between 22 and 32 minutes after the initial stage of the measurement at the furnace temperature of 340 ℃ does not show any change with filter paper, but Japanese cedar increased the diameters of particles by 0.12 μm. The mean specific gravities of particles has been obtained to be between 0.95 and 1.15, as the number of electrons on particles are estimated from the electric field necessary for balancing a particle between the electrodes.

1.6 Size Distribution by The Scattered Light Intensity by Single Particle at 90

The concentration of smoke in the chamber was measured by light extinction at the same height as smoke inlett port. Combustion products are generated by heating of 0.5 or 1 gramme of specimen in an electric furnace controlled at a constant temperature or at a constant rate of temperature rise. The combustion products were collected in a chamber, 1 m^3, and then led to the Royco particle counter to be counted the size and number of particles.

The size distribution curves obtained were approximated by Junge's formula when smoke was diluted by one fifth of the original concentration. The Fig 20 shows the isopleth of the relative concentration counted in number.

These diagrams represent the following phenomena.

i) The diameters of particles increase themselves relating to the increase of concentration of smoke in the chamber.

ii) The floating particles, about 0.3 μm in diameter, which were recognized in the initial stage of smoldering decreased.

iii) Particles of 0.3~0.9 μm in diameters increase in their numbers during the furnace temperature between 50°c and 160°c when filter papers were heated at the constant rate of the temperature rise, then total number of particles decreased until 250°c.

Fig 21 shows the size distribution diagrams obtained.

At the initial stage of collecting the smoke in chamber, the size distribution diagram corresponds to normal or lognormal distribution, and at the later stage lognormal.

The medium diameter of particles increase with smoke density.

The particle size distribution obtained may correspond to such situation as stages when smoke floats in a room for minutes or travel long distance through escape routes. 1.4 of geometric standard deviation was obtained as the size distribution diagrams in the chamber in which extinction coefficient is 0.1 m^{-1}.

The effect of smoke density to particle size is shown in Fig 23. The size distribution was represented by the percentage of the number of particles of 0.35 μm in diameter to the total number of smoke particles. The relation between P35 and the concentration of smoke (Cs) was shown in Fig 24, in which more than 70% of P35 decrease rapidly and less than 60% of them show the milder decrease curves at their tail than the reciprocal diagram of 4th power to the number.

If smoke is extreamly diluted with clean air in the collection chamber until the particles do not change, the modal diameters of various smoke produced have fallen to 0.3 μm or less.

Modal diameters like these are likely to be real diameters for thin smoke or for smoke at the initial stage of smoke generation. The dense smoke will not only due to the growth of particle size, especially for smoke obtained from cellulosic materials heated at a low temperature.

1.7 Measurement of Invisible Particulates

Ion mobility distribution has been determined by an ion mobility counter which is a cylindarical condenser with an inner electrode subdivided into two parts, then it has been converted into size distribution diagrams.

In most cases of the experiments, alph-ray has been radiated in order to charge the neutral particles.

The voltage applied has been changed in every 9 seconds, in order to obtain the size distribution whose mobility spread in wide range.

The valtage between the electrode are controlled in the stage which is determined by being graded into 19 stages by the logarithm scale over the range between 0 and 200 volts.

The measurement has been done in every other stage in the above 19 conditions.

The density of ion to the every unit of mobility measured has been obtained by the method which has been presented by E C Whiple 6) with a hypothesis of not changing for 9 seconds while the voltages applied were changed in every 9 seconds.

Fig 25 shows the results of the size distribution of the particles which were counted at the second electrodes by its intensity of the electric current.

The more invisible particles were counted in their number at the stage of production of smoke than at the latter stage where smoke particles are decreasing.

The size distribution curves obtained show some peaks between 3 μm and 200 μm in the diameter of particles and these curves change with time.

The results on invisible particles are summarized in Table 1.
The diagrams presented in number of particles charged in either positive or negative are shown in Fig 26.
Each area involves the same concentration represented in number.
(a) in Fig 26 shows the each concentration with 10% of deviation from filter paper burnt at 500 c. Others in Fig 26 are shown in size distribution f(d) in number.

1.8 Coagulation of Smoke by Corona Discharge and Particle Size Distribution

Possibilities in developing the technique of eliminating smoke by corona discharge have been explored at Nohmi Co. in collaboration with Handa, Kaneko at Tokyo Science University and Suzuki at Building Research Institute 6). Therby, the evaluation on the efficiency has been pursued by the reduction of the turbidity which has been endorsed by the change in the size distribution of particulates in smoke for the in-depth study. The outline of the research is as follows; Single set of corona discharge apparatus made of 10 electrodes with each aperture of 25 cm and with the supplied voltage of 25 Kv, is placed in the full scale corridor (L=150m, B=3.3m, H=1.65m). For the smoke generation, 0.5 Kg of PVC, 0.5 Kg of polyurethane, 0.5 Kg of FR. polyurethane with each 100 cc of methanol for the ignition source, and 1.2 liters of gasoline for the fuel have been used as the flaming fire source, respectively. The size measurement of particulates have been pursued at every 12 sec. for smoke before and after corona discharge by the submicron size optical counter (Hitachi laser dust monitor TSI 500) covering the range of particulate's diam. from 0.1 μm to 10 μm and by the microscope photographic observation of particle diam. above 5 μm to 50 μm for those deposited on the glass plate. Because of the dense concentration of the particulates in the system, the particle number counted by the counter has been corrected for the coincidence loss and

cross-channel sensitivity above 10 $^{11}/m^3$. From the preliminary experiminary experiment, it is confirmed that there is no indication of any obvious changes in the size distribution of the aforesaid smoke during the travelling. However, very remarkable changes have been recognized in the size distribution of smoke before and after corona discharge and it is particularly enhanced in smoke composed of soot as represented by the smoke from the burning fuel in Fig 27. It should be mentioned that the technique is characterized by two different methods regarding the processing after discharge to eliminate the coagulated smoke. The one concerns with the ordinary method in terms of the collecting electrodes, while the other concerns with the deposition of the coagulated smoke particulates by water sprinkling. Therefore the size distribution shifts to the larger diam. by the intense of corona discharge. As illustruted in Fig 27, the former can eliminate all particulates except those with diam. below 1.0 μm, while the latter can eliminate the larger particles induced above ca. 8 μm by coagulation, especially those coagulated ones with their maximum of 40 μm. The corresponding change of the extinction coefficient are illustrated in Fig 28. The change in the size distribution of particulates of smke from various burning polymers (PVC, FR polyurethane, Polyurethane) before and after discharge are illustrated in Fig 29 and Fig 30, respectively. The expected elimination efficiency of smoke volume or weight on both methods are shown in Table 2. The practical apprication of smoke elimination to the full-scale buldings have been pursued by T. Ueno of Tokyo Fire Department. 11)

2. SMOKE LOAD AND COMBUSTION BEHAVIOUR OF FIRE RETARDED MATERIALS

2.1 Introduction.

The main factors of fire spread in building are fire load and its ignitability. The air supply ratio and an oxygen partial pressure of the atmospher also control the fire-spread. 12), 13), 14), 15) On the basis of the above general conceptions, the building materials are regulated in buildings by Japanese Building Standard.

The above purpose is to be decreased smoke-road from the materials, for the easy escape from fire in buildings and to protect buildings at the early stage of fires.

The ignitability, combustibility and smoke concentration accumulated in the smoke chamber are evaluated by the fire tests which are used for grading of materials.

High-rise buildings are also enforced to install smoke evacuating facilities.

Through the basic study on the combustion behaviour, heat release and smoke-load, the correlation amongst the factors are introduced concerning fire retarded materials and the dynamic combustion behaviour is also discussed.

2.2 Experimentals.

The longitudinal type of furnace was designed to control the temperature of hot-bath, the flow rate of the air-supply and the oxygen partial pressure of the atmosphere. 21) The test furnace consists of an electric heater, air supply pump, air-N_2 gas mixer, and smoke chamber as shown in Fig. 31.

The weight loss of samples were measured by the combination of a chemical balance and a strain gauge, the smoke concentration was evoluated as the extinction coefficient by the trans-

mission of light pass-length of 50 cm using a tungsten lamp and detector of CdS cell.

The smoke in the chamber was stirred by a small fun. The temperature distribution of test furnace along the vartical direction and the hot-bath near the sample boat located in the middle of the furnace were measured by using CA thermocouples.

All of the informations were recorded on the charts by recorders.

The filter made by a felt was placed on the top of the chamber for keeping a constant pressure within the chamber.

Smoke released in the chamber was collected on the glass filter and then the weight was measured.

Smoke particles were also collected on a glass plate in the bottle as showed in Fir. 31.

After collection of smoke particles on the plate, the size of smoke particles was observed by the optical microscope. The size distribution of smoke and number of smoke particles per unit m^3 were measured by an experimental He-Ne Gas LASER Dust Monitor.

2.3 Samples.

The behaviour of smoke from plastics, carpets, furnitures may take place one of the most important role during building fire. Hence, in this report, polypropylene, polystyrene and the other typical plastics and those treated ones by various fire retardants were used for test species as follows.

1) Polypropylene (PP) and fire retarded one (FR-PP) with 30 parts of bromine (2,3-dibromo-pentabromophenyl ether) and Sb_2O_3 in various Sb/X weight ratio from 1/9 to 1/1.
2) Polystyrene (PST) and fire retarded one (FR-PST) with Br_3-ϕ RBr_2.
3) Phenol resin and fire retarded one with 7.5 W% of TCP.

4) Beech and γ -ray irradiation W.P.C treated by Vinyliden Dichloride on the basis of beech.

2.4 Smoke Behaviour from Fire Retarded Materials.

The extinction coefficient from PST and plywood representing a typical plastic and wooden materials were showed in Fig. 32 under the various hot-bath temperatures respectively. Those materials represented clearly combustion modes from oxidative thermal decomposition process to flaming combustion process. Fire retarded wooden materials decreased smoke and tended to become noncombustible.

However, fire retarded materials based on plastics did not decrease smoke even if it became flaming combustion based on the original materials. In particular, polyvinyle chloride which is one of the most effective fire retarded materials showed a linear increase of the extinction coefficient accompanied with the increase of hot-bath temperature. 16)

The extinction coefficient per unit area (C_A) and burning rate decreased in the reverse relation with the amount of inorganic fire retardants as shown in Fig 33.

$$C_A = \frac{1}{\ell} \log {}^{Io}/_{I} \quad \frac{V}{A} \quad \text{[Dimensionless]}$$

Where ℓ is the light path, Io and I are intensity of light at initial and final stages, respectively, V is the volume of smoke chamber and A is the area of specimen heated.

FR-PP is one of plastic materials which shows clear flaming and smoldering combustion. The extinction coefficient from these materials was illustrated in Fig. 34. The weight of smoke generated from the same materials corresponding to a physical measurement were showed in Fig. 35 under the various hot-bath temperatures.

Specific weights of smoke on the basis of PP (Ws/Wspp) change depending on the amount of fire retardant as showed in Fig 36. However, from the evidence of above results about the specific smoke concentration (Cs/Cspp), the increase of smoke concentration is considered to show a fire retardant effect on the microscopical observation. Therefore, the optimum and effective amount of fire retardant may be able to estimate as illustrated in Fig. 37. While, a constant gasification factor is apparently defined at the each material. The correlation between the weight of smoke from PP and PST and the initial weight of samples (Wo) were illustrated in Fig. 38. Moreover, the smoke evolution characteristics of fire retarded phenol resin treated by TCP was showed in Fig 39.

The linear relationship between the extinction coefficient (Cs) and weight of smoke (Ws) from various fire retarded materials was showed in Fig. 40 (a), (b), and (c).

The extinction coefficient (Cs) was proportional to the weight of smoke and the initial weight of samples. 16), 18)

However, the extinction coefficient (Cs) is expressed as a function of the scattering cross section area, number of particles and the scattering coefficient. Weight of smoke is exactly expressed as a function of number, volume and density of smoke particles. 18), 19) Therefore, it was necessary to measure the size of smoke particles and number of particles and to evaluate the scattering coefficient as a function of color of smoke and size of particles.

2.5 Correlation among the Size, Number of Smoke and Optical Smoke Concentration.

The utility of fire retardant for materials was already estimated from the increase of the extinction coefficient in the smoke chamber. From the information of the optical microscopic observation, the size of smoke particles from fire retarded materials was recognized to become smaller than that from the untreated materials. 16), 20)

For example, the correlation between the mean surface volume diameter of smoke from PP and FR-PP and the mean scattering coefficient estimated from the following relation on the basis of the optical microscopic observation was illustrated in Fig. 41(a). 16), 18), 20).

$$\bar{k} = \frac{\sum^{i} k_i d_i^2 N_i}{\sum^{i} d_i^2 N_i}$$

$$Cs = \frac{Fm^2 \pi \bar{k}}{4\ Vs} \sum^{i} d_i^2 N_i$$

$$Ws = \frac{\pi \rho}{6} \sum^{i} d_i^3 Ni$$

d_i : Diameter of smoke particles (m)

N_i : Number of smoke particles (-)

K_i : Scattering coefficient of each particle (-)

$\bar{k}$: Mean scattering coefficient (-)

m : Relative refractive index (-)

V_s : Volume of smoke chamber (m^3)

ρ : Density of particles (gr/m^3)

F : Shape factor (F=1) as spherical particles (-)

From the same analysis of smoke particles, the correlation between the size of particles and mean scattering coefficient was obtained in the same oder of value as showed in Fig. 41(b). The nice coin-

cidence of mean scattering coefficent for the size parameter on the basis of mean surface volume diameter of smoke particles was recognized. 16), 18), 19), 20)

A size of smoke particles from fire retarded materials become bigger by the coagulation to be proportional to the number of particles at the earlier stage of generation by Smolnch Owski relation. However, after this, the growth of smoke particles was inhabited by an electrostatic force, so it was considered that the extinction coefficient from fire retarded materials increase it in the smoke chamber. 16) The above behaviour of smoke particles was recognized by the aging of size distribution of smoke particles using the previous LASER Dust Monitor. 19) The time dependent changes of smoke concentration from PP and FR-PP in the smoke chamber was showed in Fig 42. The aging of the size distribution of smoke particles and number of particles from PP and FR-PP at the various sampling time was obtained by the LASER Dust Monitor as illustrated in Fig 43(a) and (b), respectively.

In comparison the aging of smoke particles of PP with FR-PP, the smoke from FR-PP was distinctly recognized the inhibition of the growth of smoke particles under the smouldering was recognized in the lower oxygen partial pressure of the atomospher. 16), 20), 21)

2.6 Mechanism of Effect of Fire Retardant

The consumption mechanisum of fire retardant was pursued by the detection of HBr in gas phase and by a chemical X-ray analysis for the smokes and residues in solid phase.

As illustrated in Fig. 44(a) and (b), the released amount of HBr detected in gas phase ($W_{HBr,\ gas}$) showed the complicated changes accompanying with the increase of the initial weight of Br in the sample (Wo, Br) for PP-dibromopropylpentabromophenylether-Sb_2O_3 and illustrated its maximum of Sb/X ratio at ca. 1/4 and 1/3 with $W_{o,Br}$ of 50 mg and 170 mg per unit weight of samples W_o, respectively. On the other hand, the released amount of Br detected in the smoke, most HBr was adsorbed onto smoke and partly combined with Sb, and increased linearily accompanying with $W_{o,Br}$ irrespective of the change of Sb/X ratio as illustrated in Fig. 44(a) 22)

However, Sb detected in the smoke ($W_{Sb,smoke}$) behaved differently from $W_{o,Sb}$. The linear increase of $W_{Sb,smoke}$ was observed for the series of FR-PP at the definite Sb/X ratio of ca. 1/3. $W_{Sb,smoke}$ from the series of FR-PP with variation of Sb/X ratios from 1/9 to 1/1 showed a maximum at Sb/X ratio of ca. 1/3 accompanying with the increase of the Sb/X ratio as illustrated in Fig. 44(b) and (c). This suggested that Sb was released from the sample only in the form of $SbBr_3$, while Br was released in the form of HBr and $SbBr_3$ via multiple reaction cycles among Sb_2O_3, SbOBr, $Sb_4O_5Br_2$, Sb_3O_4Br, $SbBr_3$ and HBr. 22)

Following reaction scheme as illustrated in Fig. 45 was suggested by these evidences and by taking into consideration of the results of X-ray diffraction analysis on the form of Sb remained in the residue (Sb_2O_3, SbOBr, $Sb_4O_5Br_2$, etc. 23)) and on the products of the model reaction of Sb_2O_3 with HBr at the hot bath temperature of 400°C.

By the same method, the consumption mechanisum of phosphate in fire retarded phenol resin is being pursured.

2.7 Correlation between Combustion Parameters and Smoke-load.

The reverse relation between the smoke concentration (Cs) from the FR-PP and the heat release in gas phase was illustrated in Fig. 46. 9), 21) This relation was generally known as Burgess Relationship. The role of HBr gas is to inhibite flaming combustion in gas phase or reaction interface and to be cycled successfully Br compounds in solid phase as illustrated in Fig. 45.

The characteristics of combustion behaviour about the fire retarded materials was arranged as the linear relation of the extinction coefficient (Cs) per unit weight loss and C_A per unit weight loss. 24), 25) As showed in Fig. 47, the constant gasification factor under the smouldering and flaming combustion was also recognized from the dynamic analysis. 16)

Therefore, the smoke-load from materials was evaluated by the inclination angle or the smoke weight coefficient obtained from the above analysis.

The extinction coefficient is proportional to the weight-loss. Hence, the linear relationship between burning rate of samples and smoke released rate will be obtained when mean relative refraction index and scattering coefficient are constant or the changes of those depending on time is negligiblly small during combustion process. The co-relation among the released rate of weight of smoke, $(1-f)\frac{dW}{dt}$ and maximum extinction coefficient C_s^{Max} were summarized in Fig 48. Therefore, it was considered that the following relation would be discribed, 16), 20)

$$(1-f)\frac{dW}{dt} = \frac{2\rho V_s \overline{D}_{vs}}{3 Fm^2 k} \times \frac{C_s^{Max}}{T_3}$$

$$\overline{D_{vs}} = \frac{\sum^{i} d_i^3 Ni}{\sum^{i} d_i^2 Ni}$$

f : Gasification factor (-)

$\overline{D}_{VS}$: Mean Volume surface diameter (-)

T_3 : Time-lag for smoke evolution (sec)

2.8 Correlation between Oxygen Partial Pressure in the Atmosphere and Smoke Concentration.

The correlation between the oxygen partial pressure in combustion air and smoke concentration have been pursued for the connection from the study of material-level to the one of compartment fire. From the results of the aging of smoke particles under the various oxygen partial pressure of the atmosphere, the smoke concentration from materials enhanced generally. The evidence of the above consideration was recognized as illustrated in Fig. 49.
The changes of the smoke concentration measured by the extinction coefficient were illustrated in Fig 50. 19) It was known that air-fuel ratio for combustion in a fire room was small in actual fires. Therefore, the smoke generated from building materials in the room without openings increase very much.

The above problems have been studied in different sections. Finally, the many studies on the smoke-load of the various building materials will be necessary to obtain the optical smoke-load for the smoke control technology.
In particular, it is convenient that those informations are summarized as the weight of smoke or weight-loss vs smoke ratio, burning rate vs initial weight of samples and burning rate vs smoke concentration from the various materials by a test furnace modifying full scale fires.

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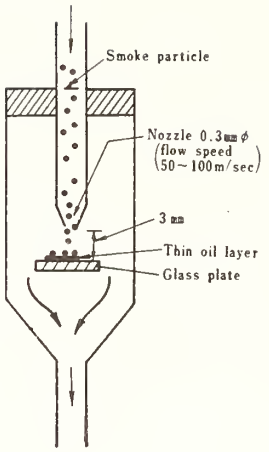


Fig. 1 Impactor for sampling of smoke particles

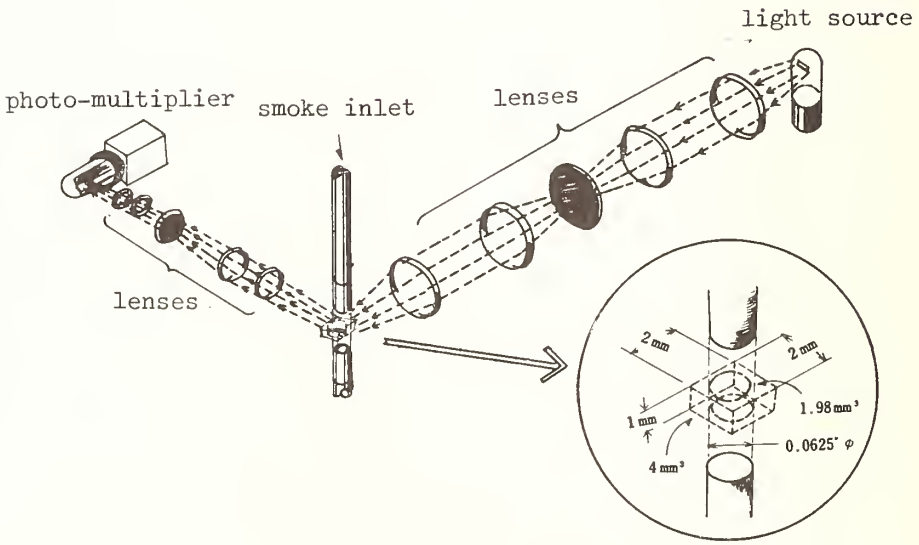
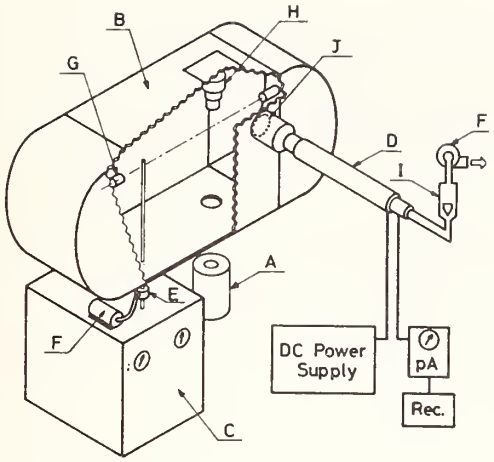


Fig. 2 Apparatus for measurement of light scattering.



A: electric furnace, *B*: smoke chamber, *C*: particle counter for visible smoke, *D*: ion mobility counter, *E*: outer dilution chamber, F: pump, *G*: smoke density meter, *H*: head for combustion products analyser, *I*: air flow meter, and *J*: radioisotope

Fig. 3 Apparatus for particle size measurement

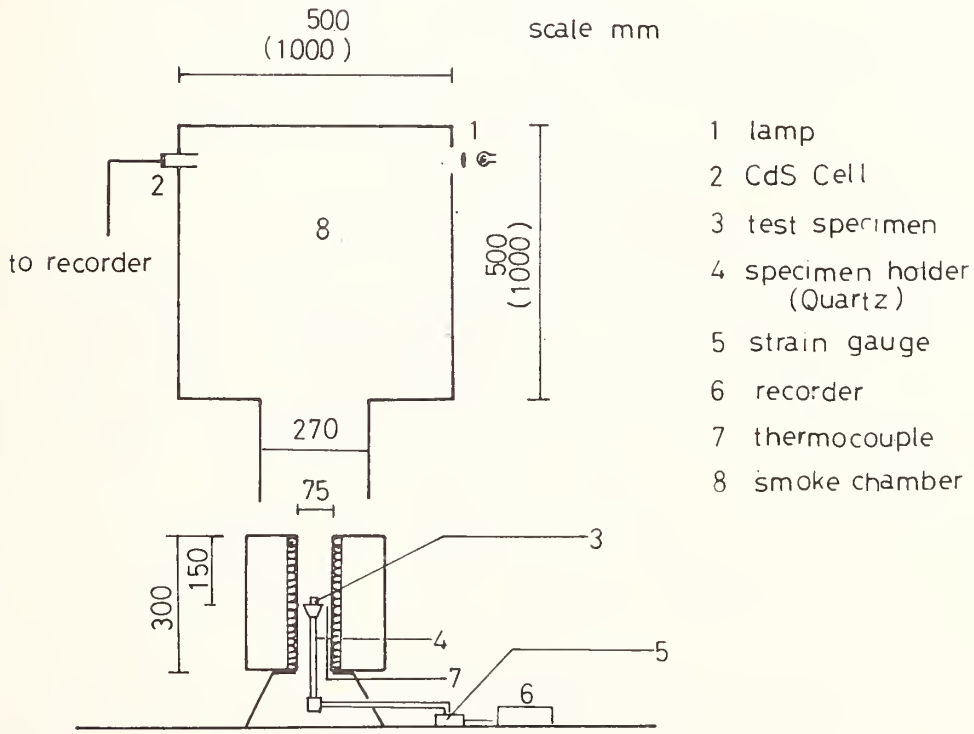


Fig. 4 Test apparatus

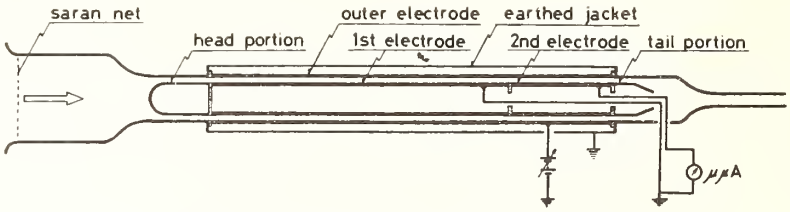


Fig. 5 Ion mobility counter
inside diameter of outer electrode: 65.8mm
outside diameter of inner electrode: 50.7mm
length of first or second inner electrode: 450mm
or 150mm, respectively

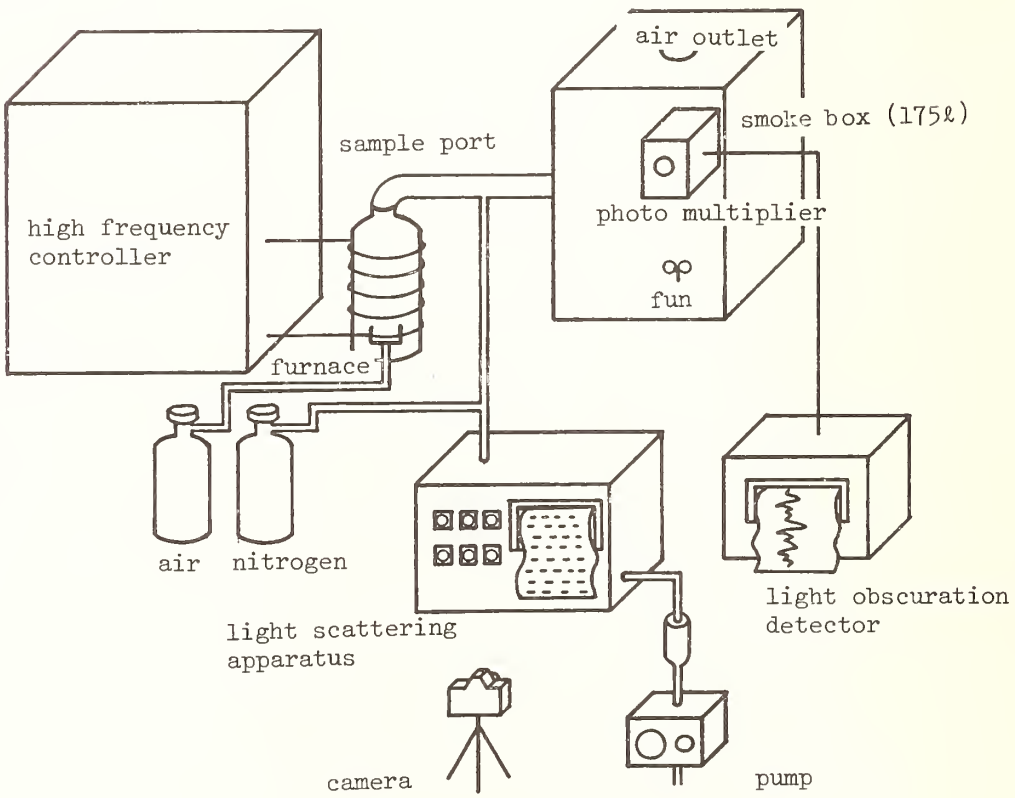


Fig. 6 An Experimental apparatus for production of smoke

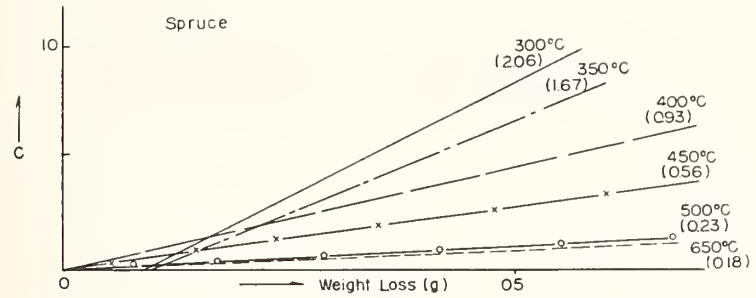


Fig. 7 Relation between C and W

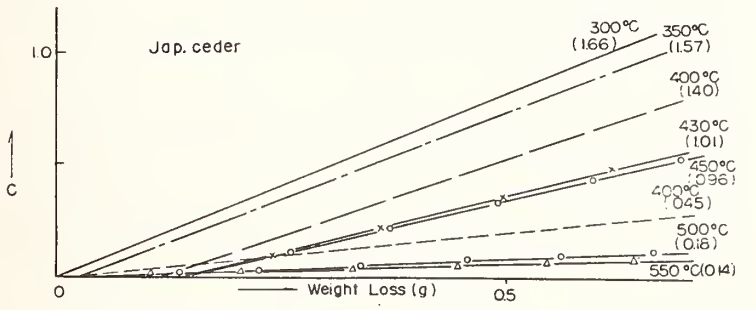


Fig. 8 Relation between C and W

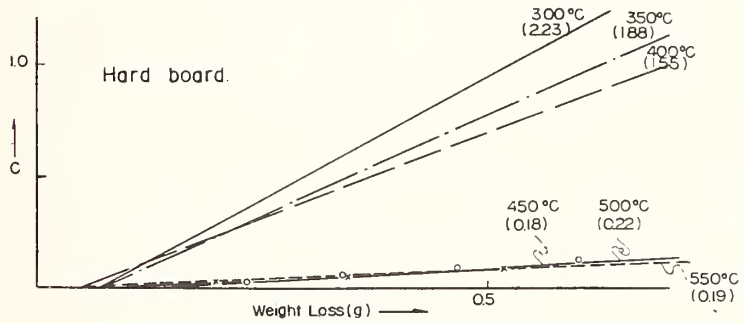


Fig. 9 Relation between C and W

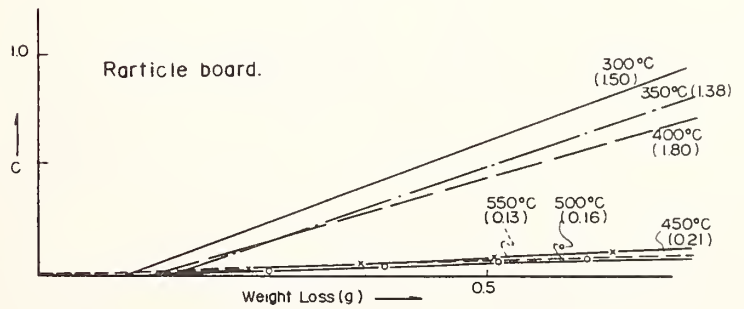


Fig. 10 Relation between C and W

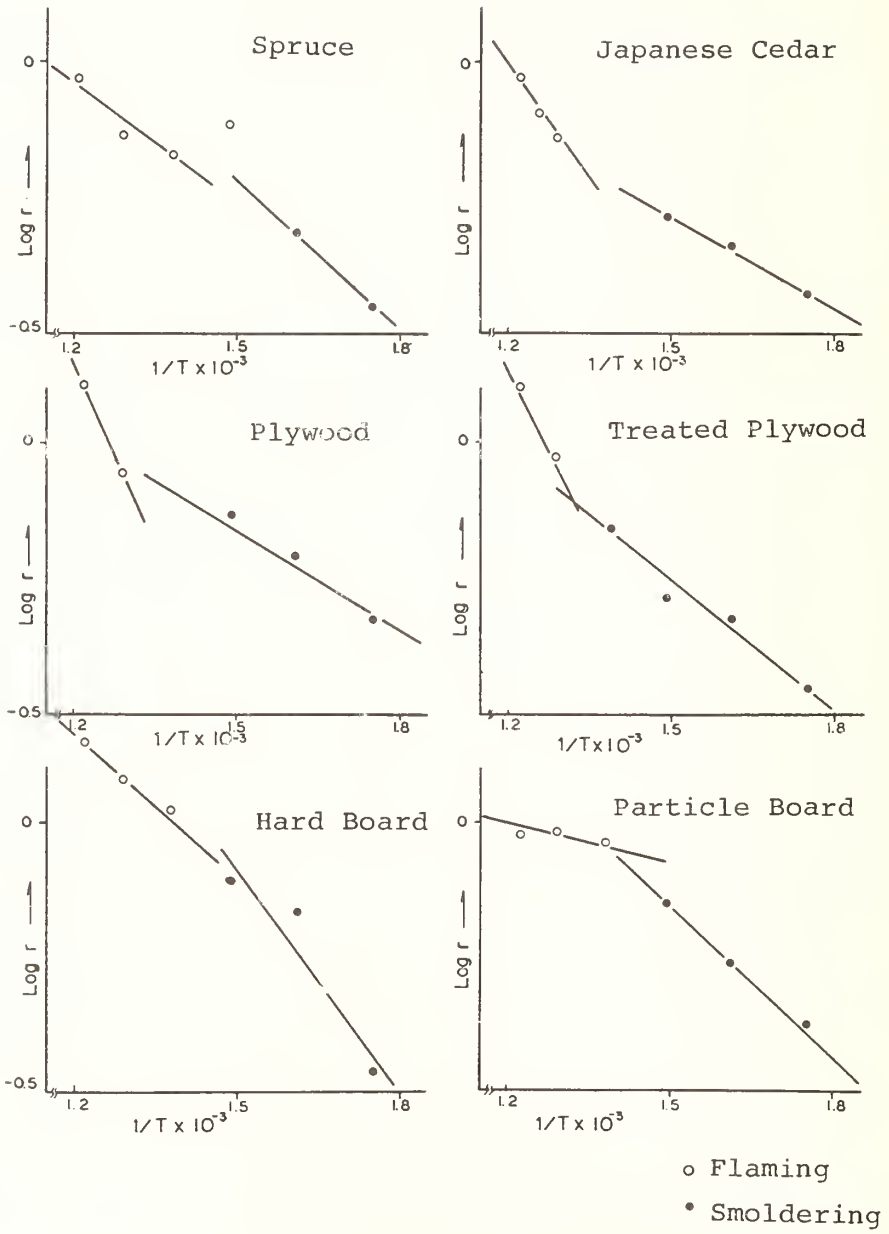


Fig. 11 Arrhenius plot of cellulosic materials

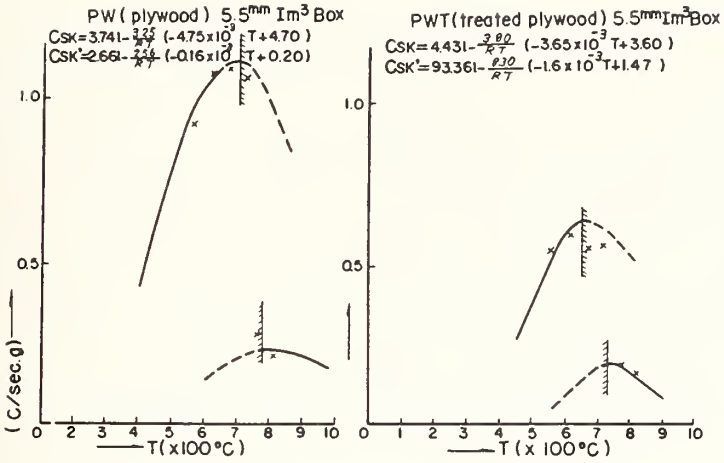


Fig. 12 Rate of smoke generation accrding to empirical formulae

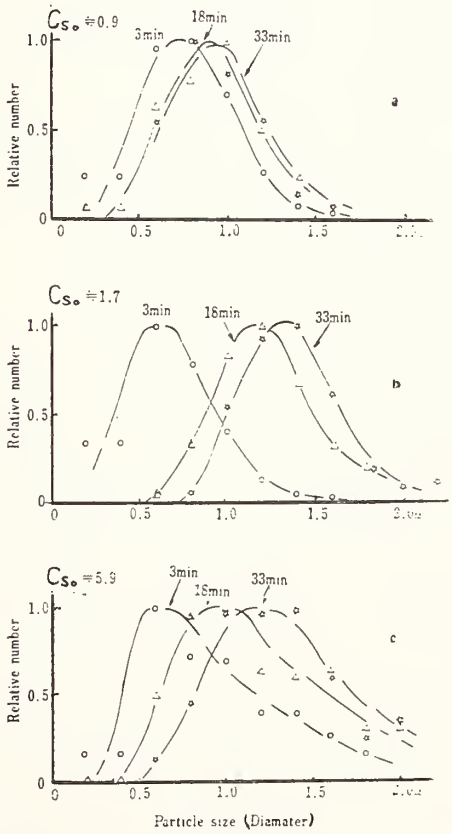


Fig. 13 Particle size distribution of smoldering wood smoke (Heating temp. 500 ℃).
C_{s_0}: Initial smoke density in smoke chamber

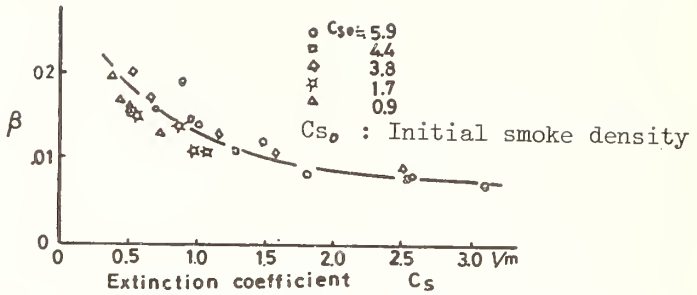


Fig. 14 Relation between apparent coagulation coefficient and extinction coefficient for smoldering wood smoke

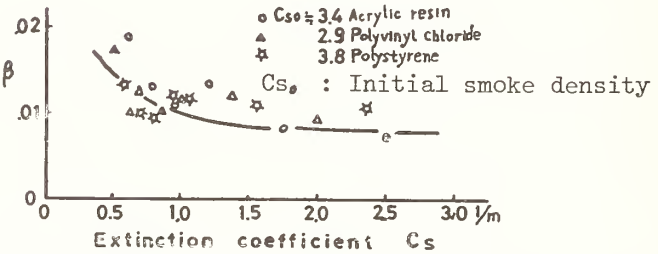


Fig. 15 Relation between apparent coagulation coefficient and extinction coefficient for various smoldering plastic smoke

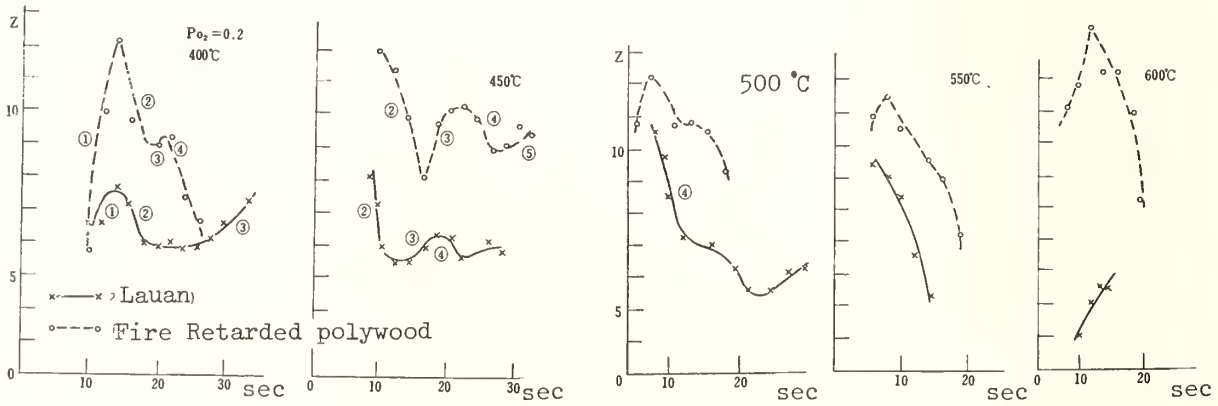


Fig. 16 Changing of the Z value at various furnace temperatures in the atmosphere of 0.2 of oxygen partial pressure

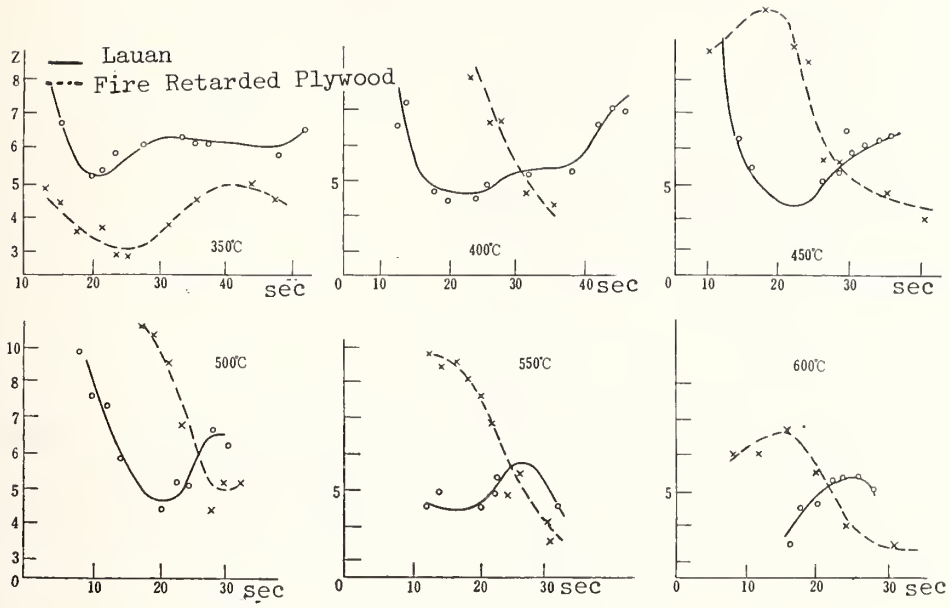


Fig. 17 Changing of the Z value at various furnace temperatures in the atmosphere of 0.1 of oxygen partial pressure

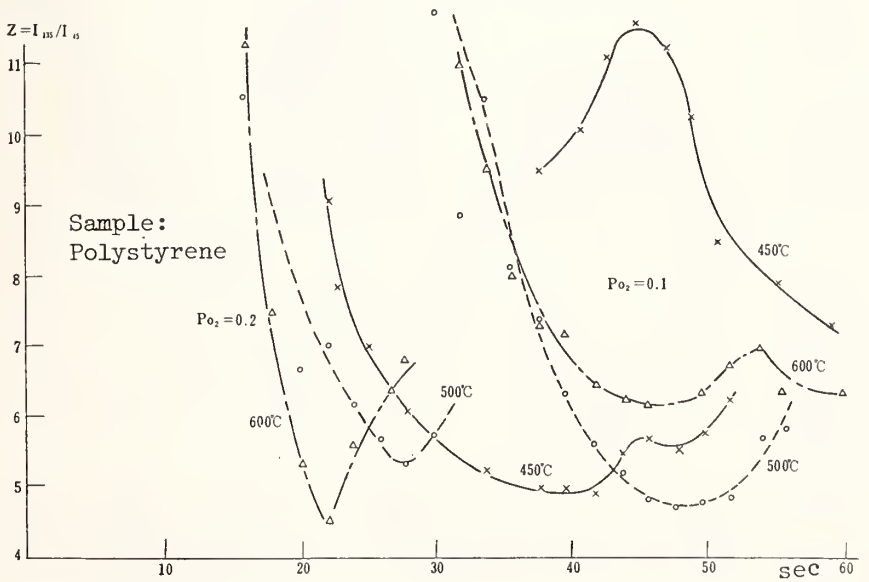
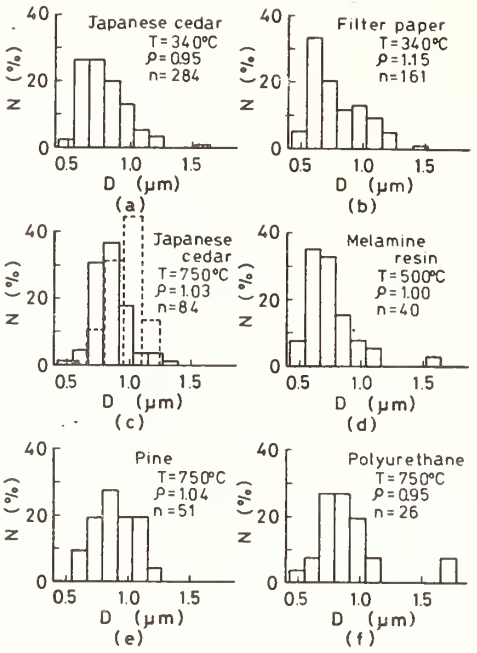
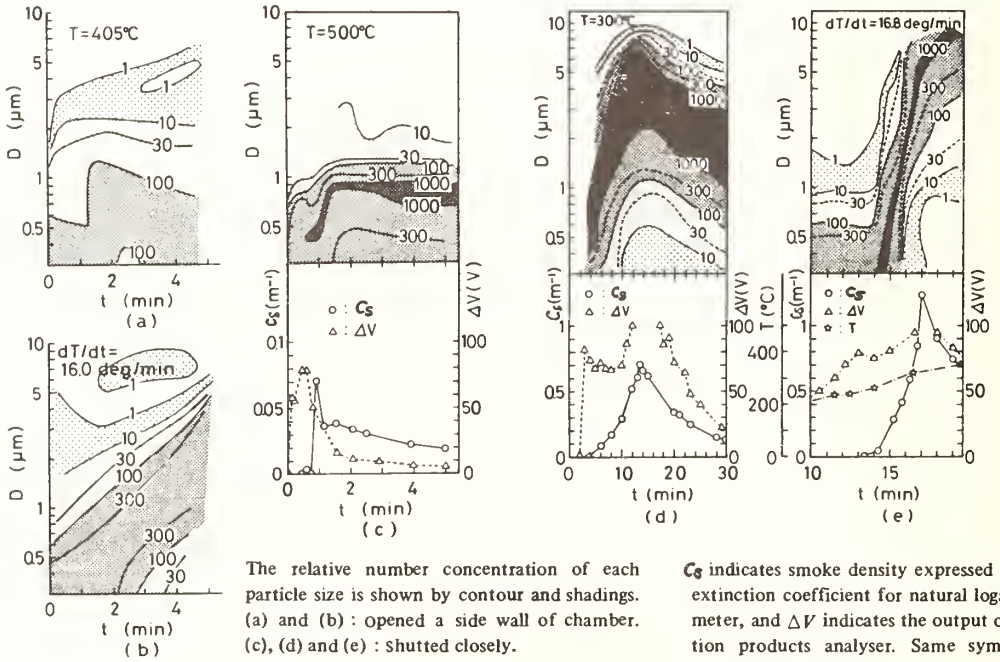


Fig. 18 Changing of the Z value at various furnace temperatures in the atmosphere of 0.1 and 0.2 of oxygen partial pressure



N: relative number of particles, *D*: the diameter of particles, *ρ*: the mean specific gravity, and *n* number of observed particles.
Broken lines represent the result obtained by microscopic photograph (Jin, 1971)

Fig. 19 Size distribution measured by sedimentation method



The relative number concentration of each particle size is shown by contour and shadings. (a) and (b) : opened a side wall of chamber. (c), (d) and (e) : shutted closely.

C_S indicates smoke density expressed in term of extinction coefficient for natural logarithm per meter, and ΔV indicates the output of combustion products analyser. Same symbols used throughout all figures.

Fig. 20 Time variation of size distribution of filter paper smoke measured with light scattering-type particle counter (Dilution ratio: 10)

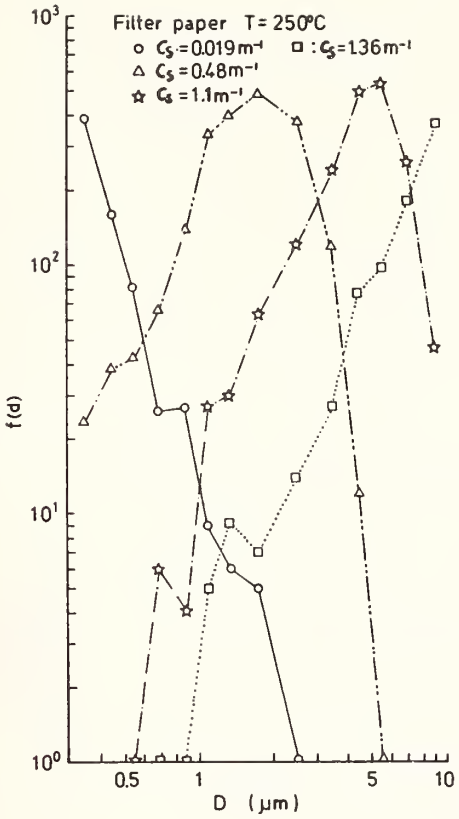


Fig. 21 Particle size distribution vs. smoke density

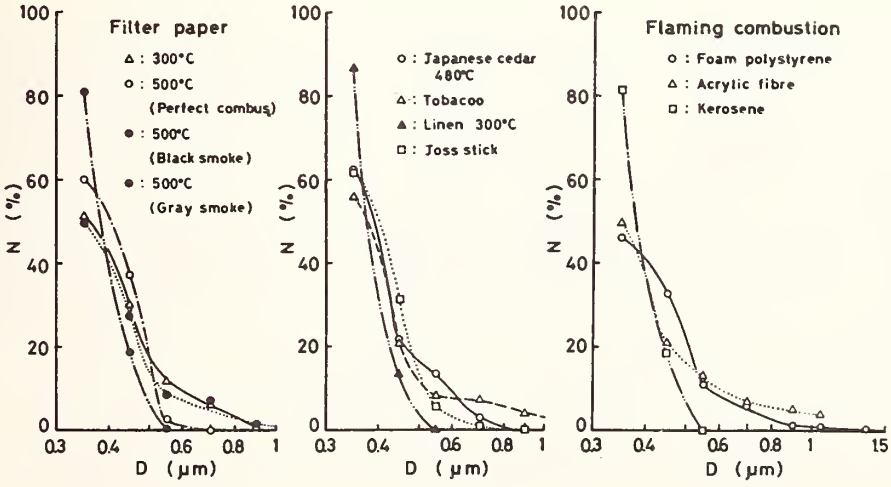


Fig. 22 Particle size distribution of various smoke vs. the extinction coefficient of $0.1m^{-1}$ (Diluted by a large quantity of clean air)

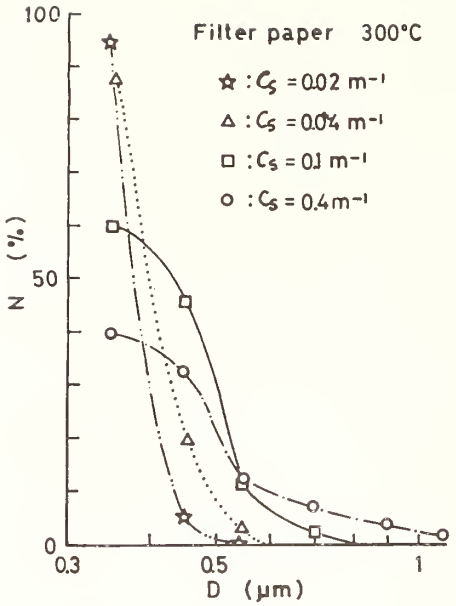


Fig. 23 Effect of smoke density to particle size distribution

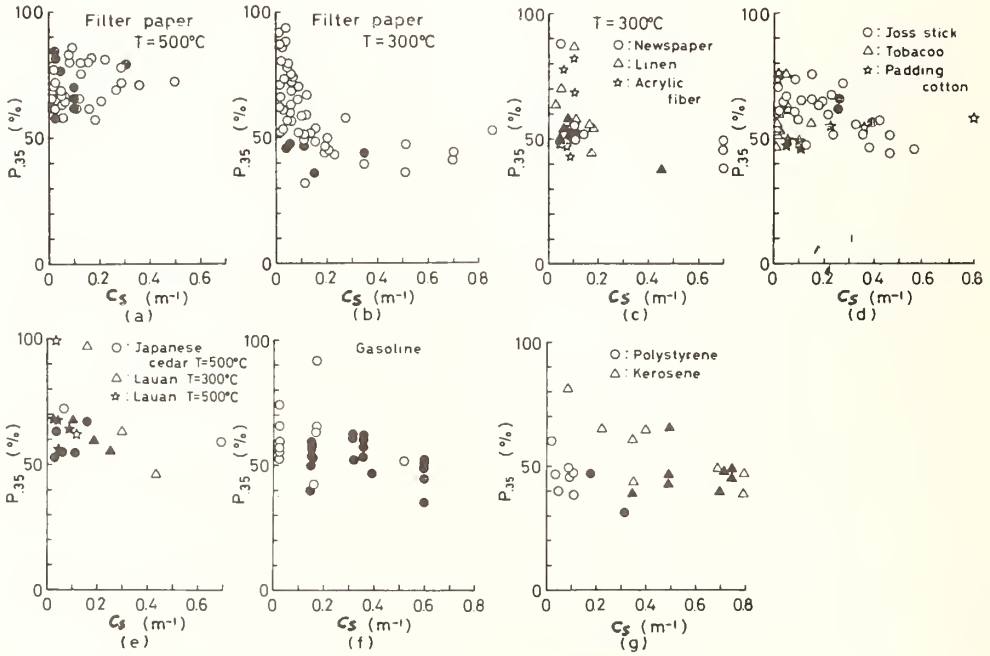
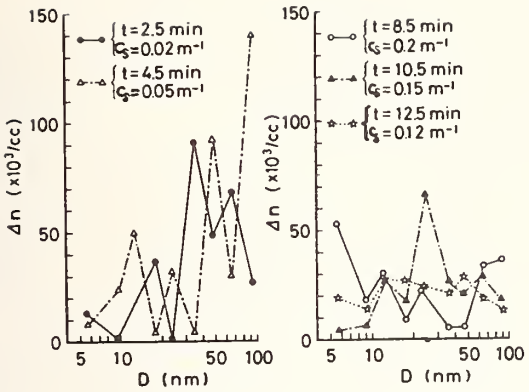
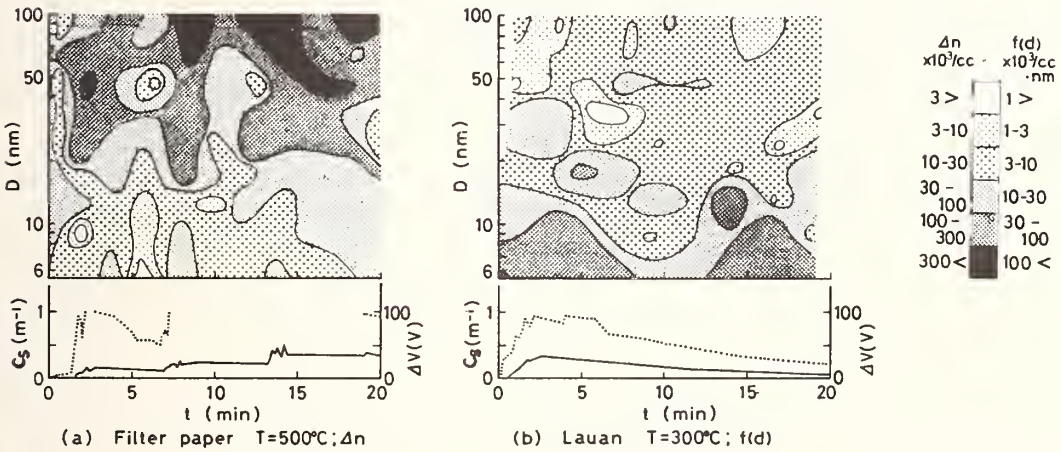


Fig. 24 Relation between smoke density and the percentage of the number of particles 0.35 μm in diameter to total number of smoke particles
open symbols : the values for fresh smoke
solid symbols : those for aged smoke



burning condition: filter paper 300°C
open symbol: positive-charged particles
solid symbols: negative-charged particles

Fig. 25 Variation of number concentration (width of ± 10% of the diameter) n with time and smoke density



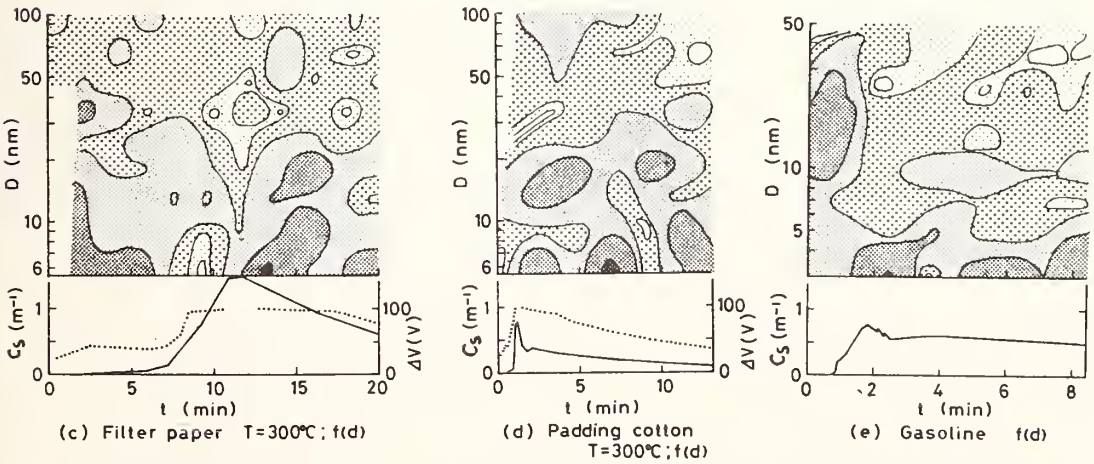


Fig. 26 Dynamic size spectrum
The number concentration of positive-or negative-charged particles measured is shown by contour and shadings in the same figure.

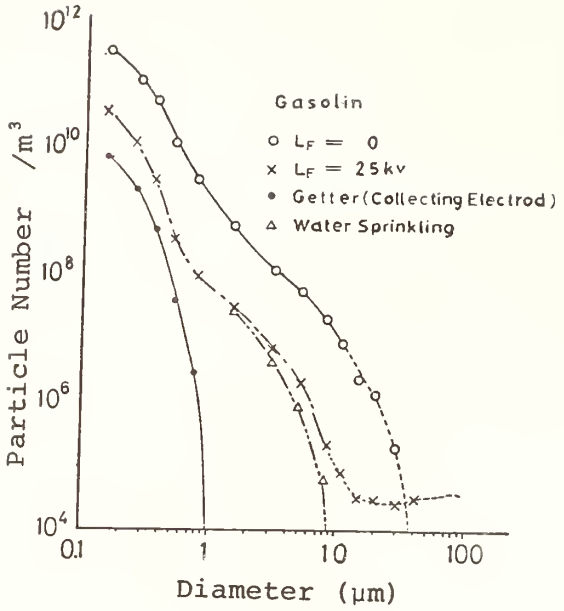


Fig. 27 Particle size distribution.

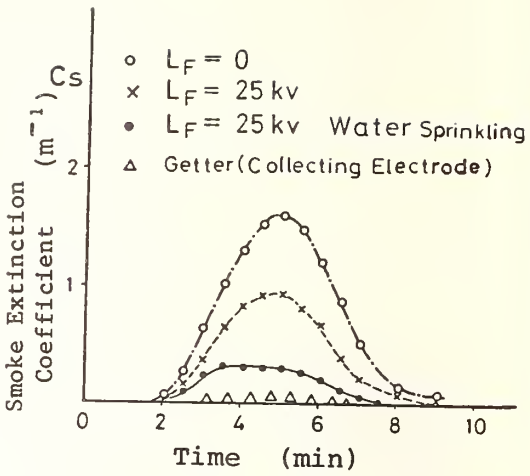


Fig. 28 Smoke extinction coefficient change

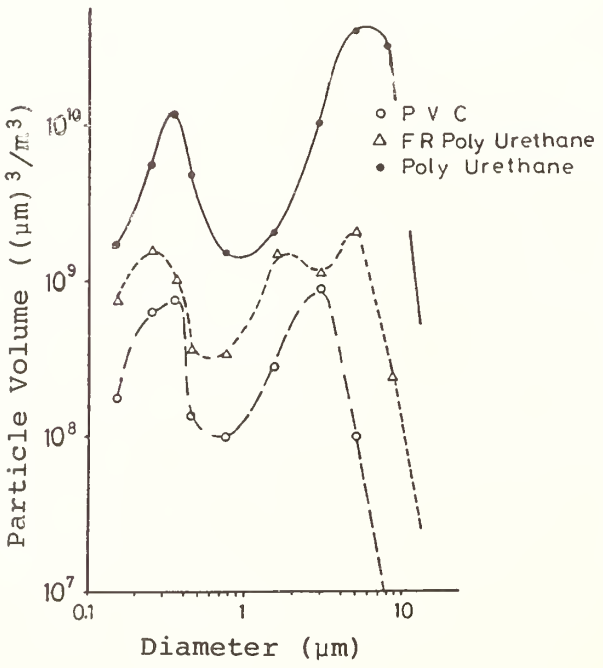


Fig. 29 Particle volume distribution.

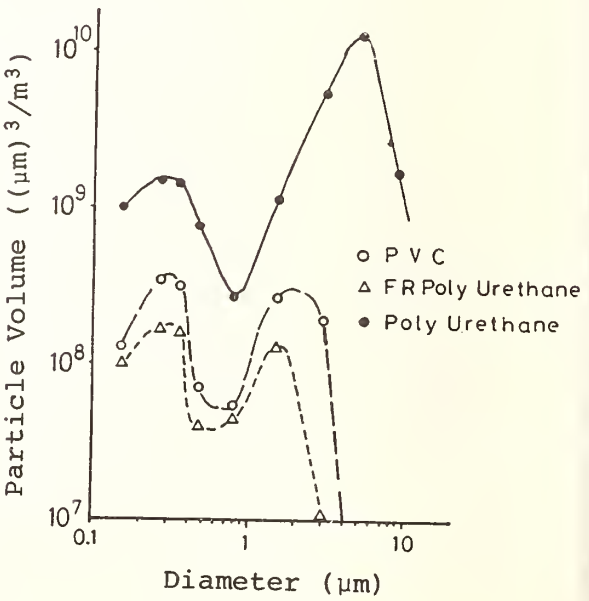
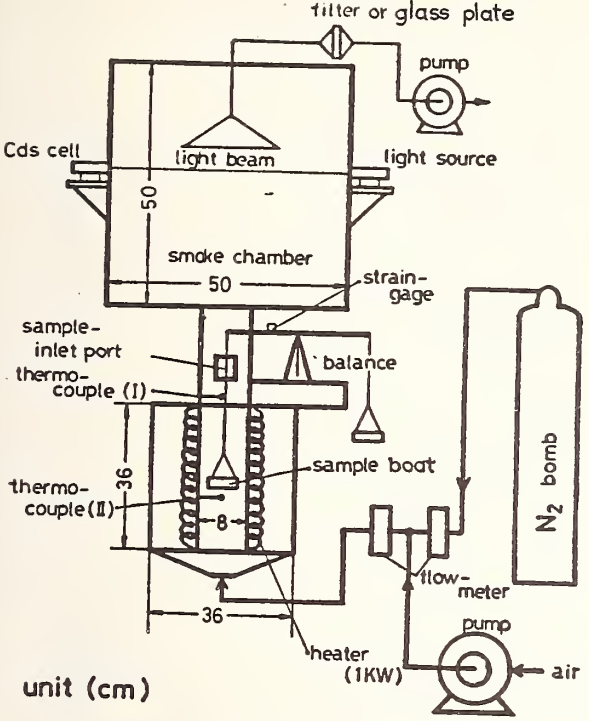


Fig. 30 Particle volume distribution after corona discharge.



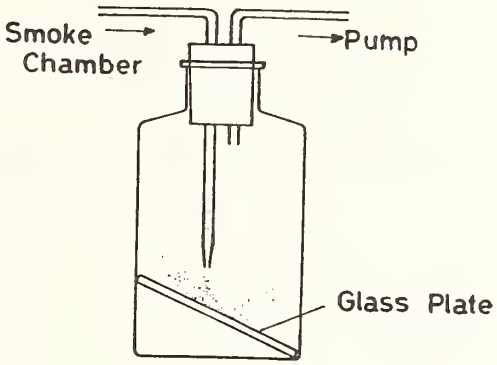


Fig. 31 Outline of the longtudinal type test furnace for the analysis of the weight loss, heat evolution and the smoke evolution in various ratio of O_2/N_2. Apparatus for collecting the smoke particle.

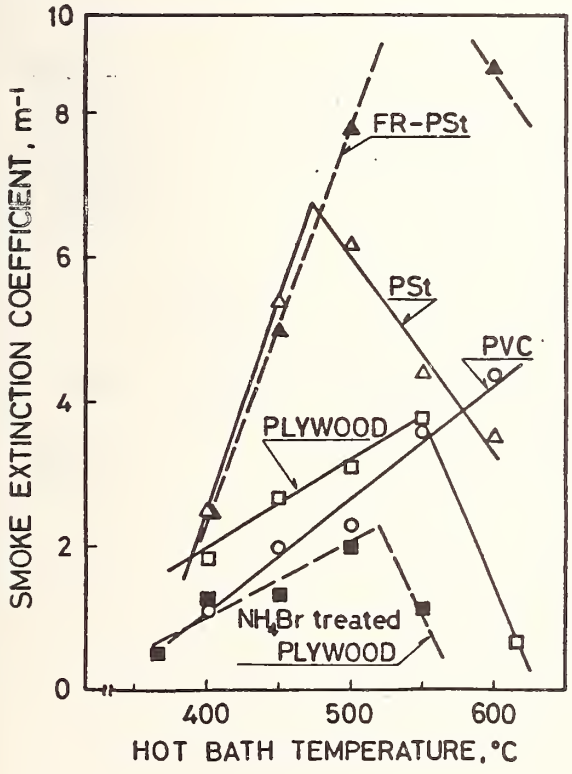


Fig. 32

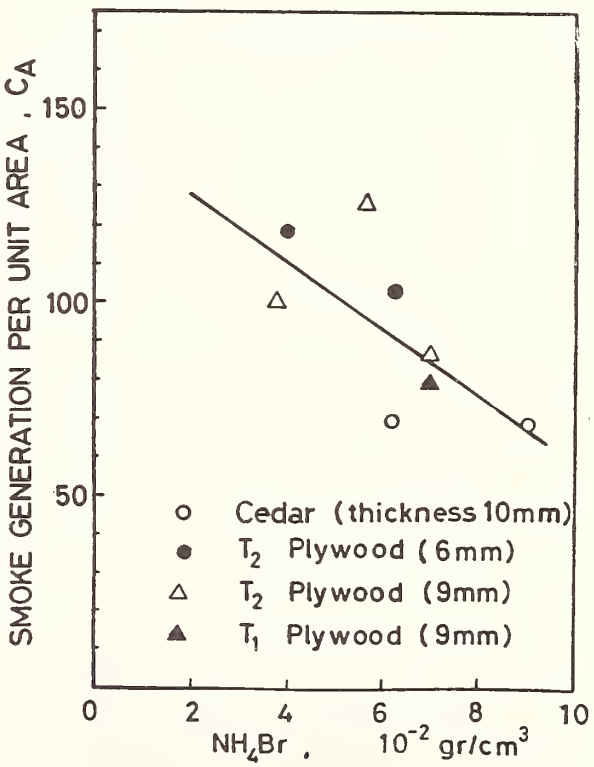


Fig. 33

Fig. 32 Relation between smoke extinction coefficient (C_s) and hot-bath temperature in various samples.

Fig. 33 Relation between smoke generation per unit area (C_A) and added amount pf NH_4Br, where

T_1 Plywood; using melamine resin as the adheisive agent.
T_2 Plywood; using urea resin as the adheisive agent.

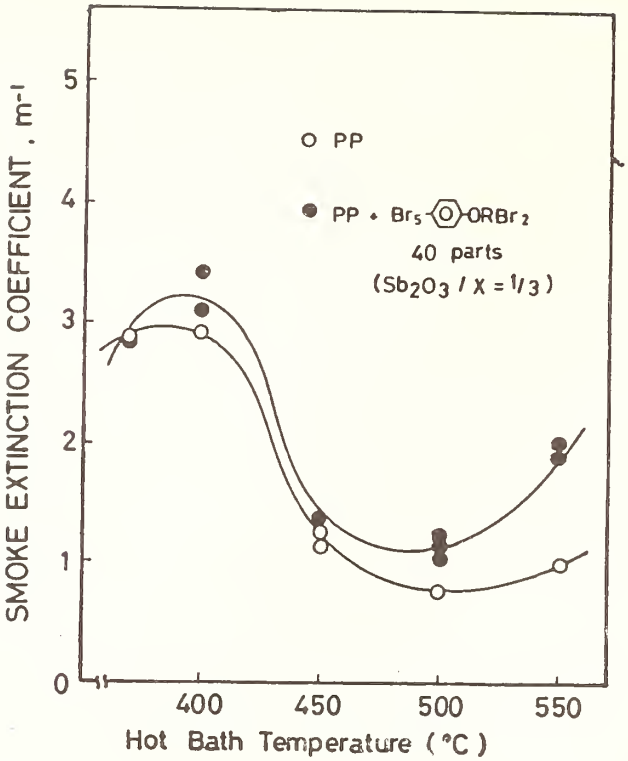


Fig. 34

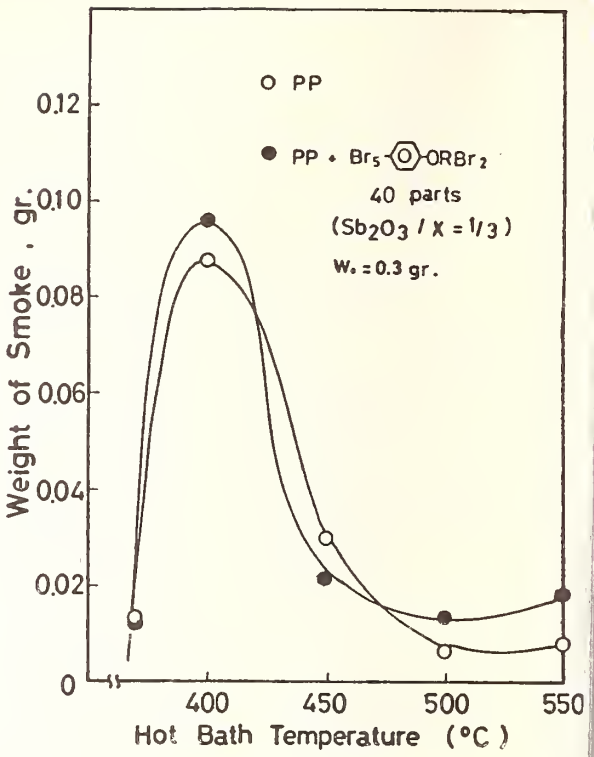


Fig. 35

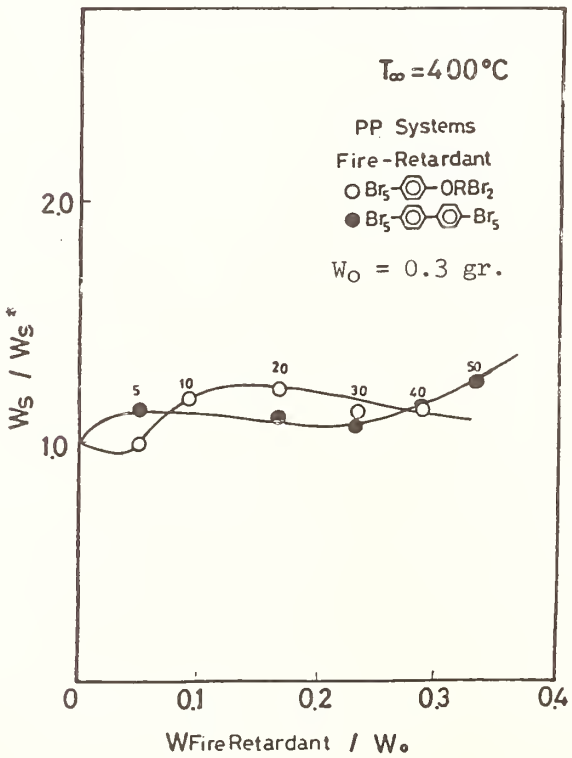


Fig. 36

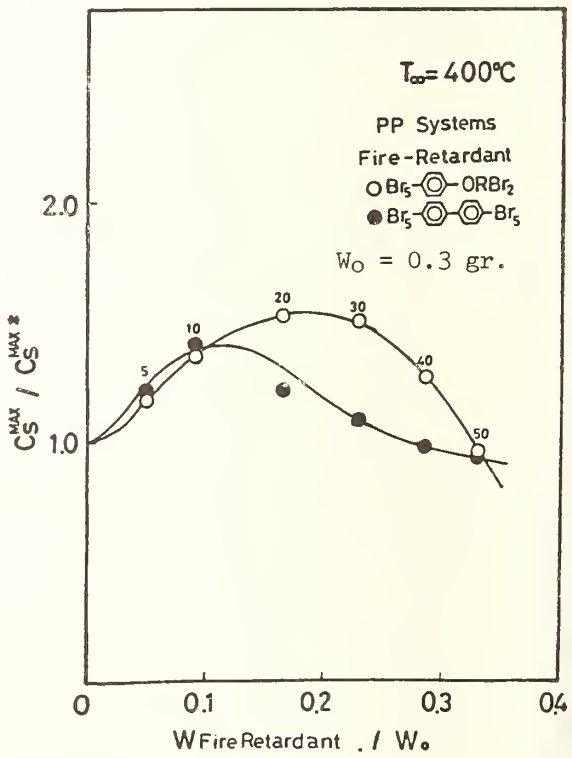


Fig. 37

Fig. 34 Smoke extinction coefficient (C_s) vs. hot-bath temperature.
Fig. 35 Normalized weight of smoke vs. hot-bath temperature.
Fig. 36 Normalized weight of smoke vs. added amount of fire retardant in the PP systems. W_s*; weight of smoke from PP resin.
Fig. 37 Normalized smoke extinction coefficient ($C_s/C_{s\ pp}$) vs. added amount of fire retardant in the PP system.

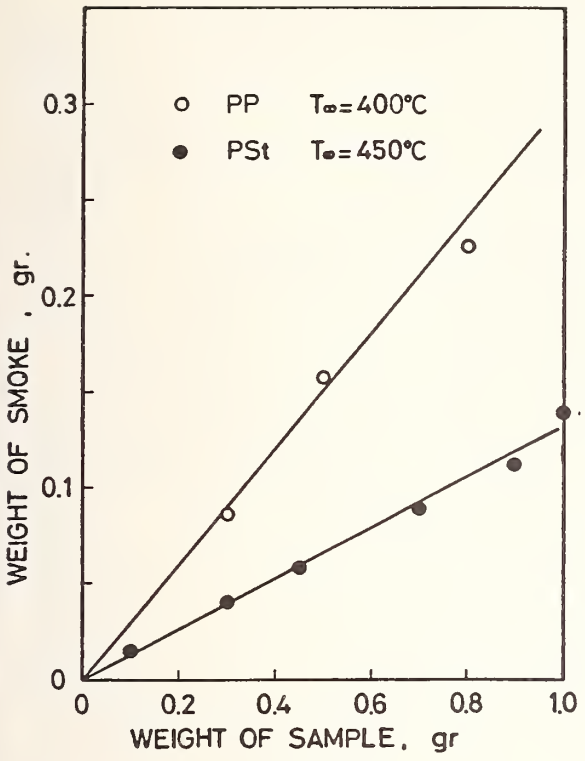


Fig. 38

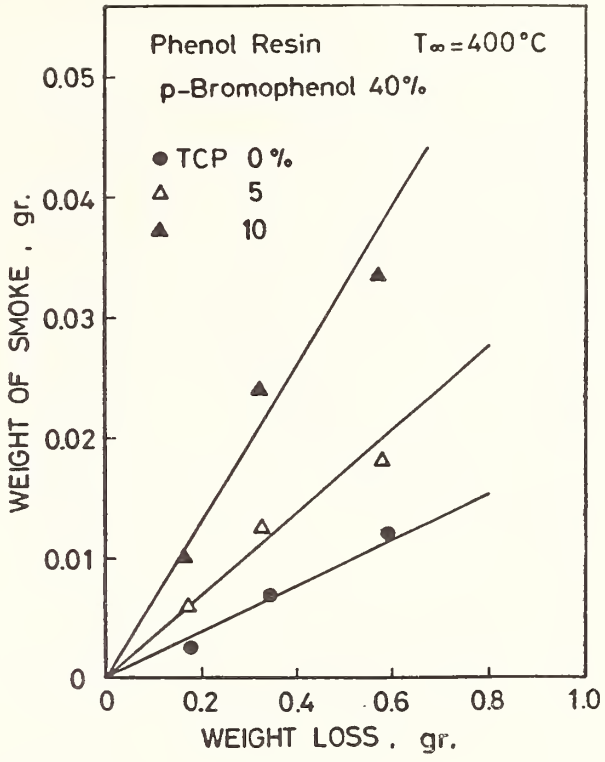


Fig. 39

Fig. 38 Correlation between the weight of smoke vs. initial weight of sample. (PP, PSt)

Fig. 39 Relation between the weight loss of sample and the weight of smoke. (Phenol resin)

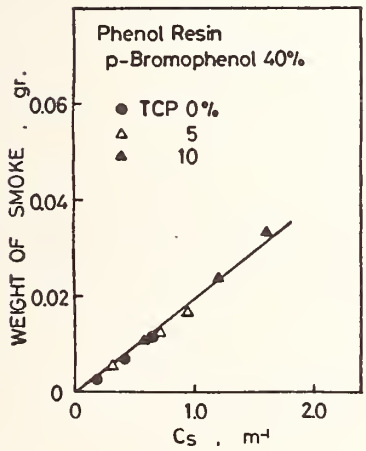


Fig. 40(a)

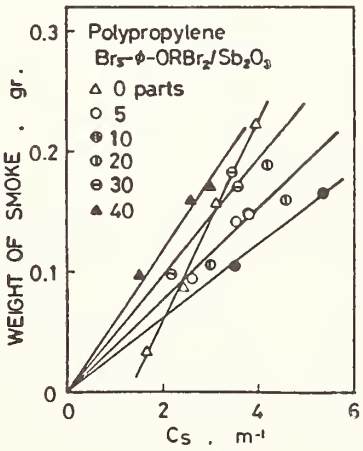


Fig. 40(b)

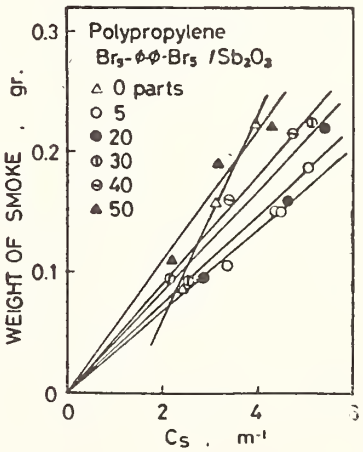


Fig. 40(c)

Fig. 40 (a) The relation between the extinction coefficient (Cs) and the weight of smoke. (Phenol resin treated by TCP)

Fig. 40 (b) The relation between the extinction coefficient (Cs) and the weight of smoke. (PP-Br_5-φ-OBr_2-Sb_2O_3 systems)

Fig. 40 (c) The relation between the extinction coefficient (Cs) and the weight of smoke. (PP-Br_5-φ-Br_5-Sb_2O_3 systems)

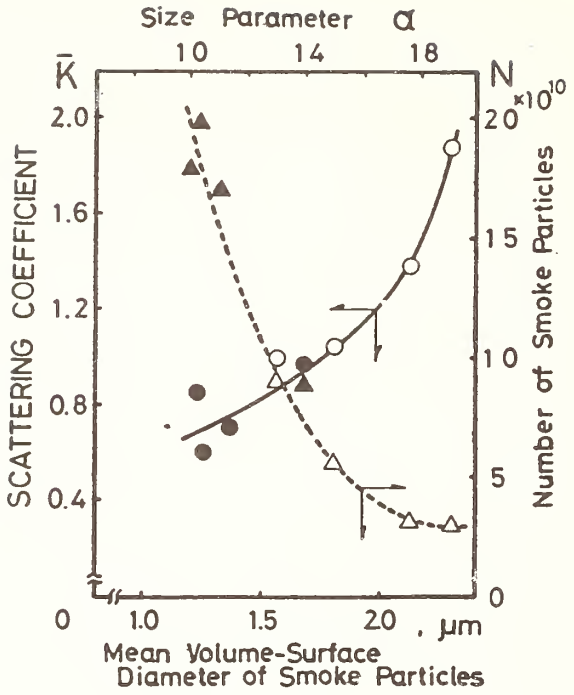


Fig. 41(a)

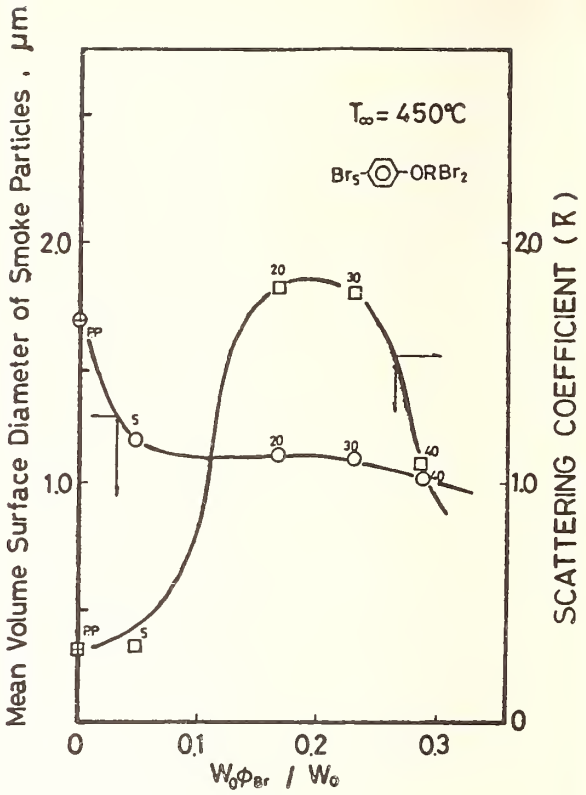


Fig. 41(b)

Fig. 41(a) Changes in the mean scattering coefficient and the particles number vs. the mean volume-surface diameter of the smoke perticles. 0 Δ:PSt per of 1 gr. 0 Δ:FR-PSt (10%) of 1 gr.

Fig. 41(b) Changes in the mean volume-surface diameter of smoke particles and the scattering coefficient vs. added amount of the fire - retardant.

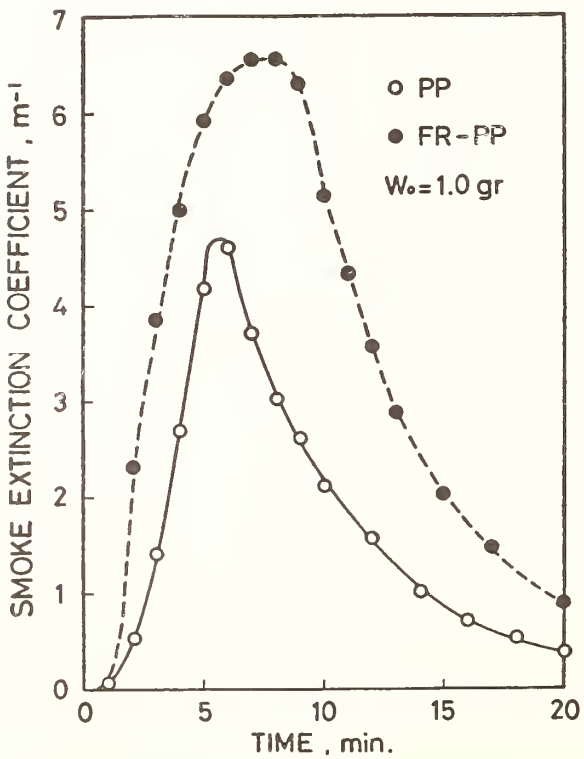


Fig. 42. Time dependent of smoke extinction coefficient.

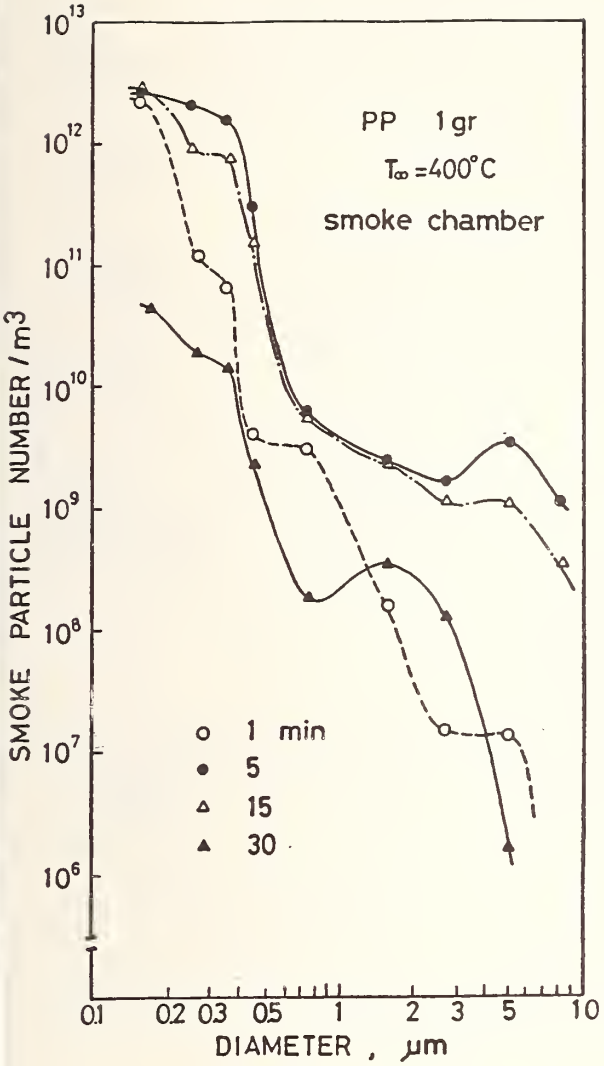


Fig. 43(a)

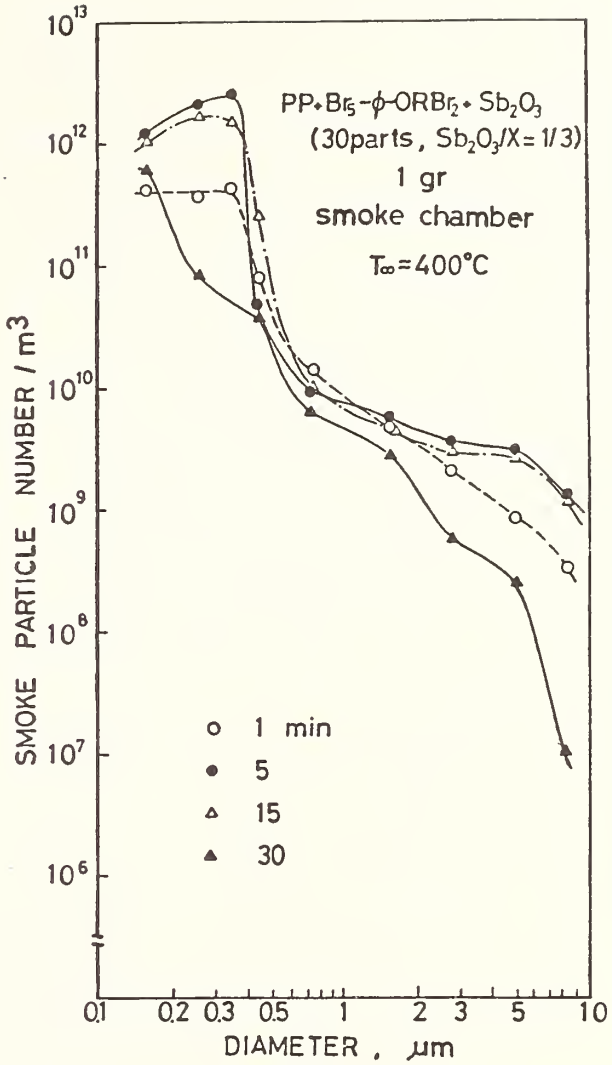


Fig. 43(b)

Fig. 43(a) Time history of the particle size distribution of smoke from PP.
Fig. 43(b) Time history of the particle size distribution of smoke from fire retarded PP.

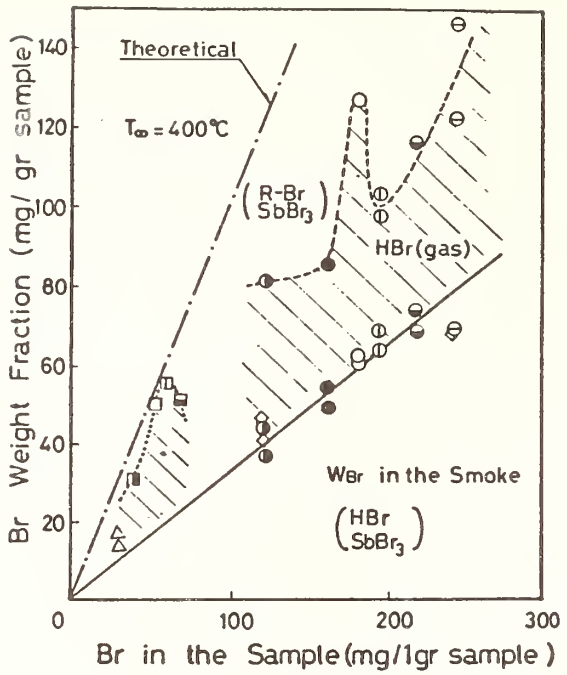


Fig. 44(a)

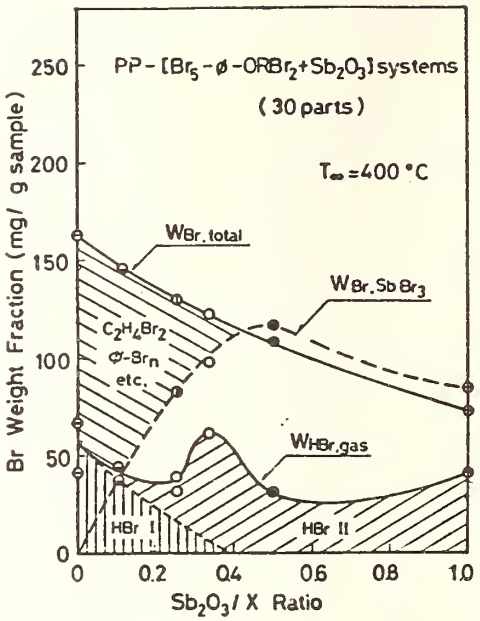


Fig. 44(b)

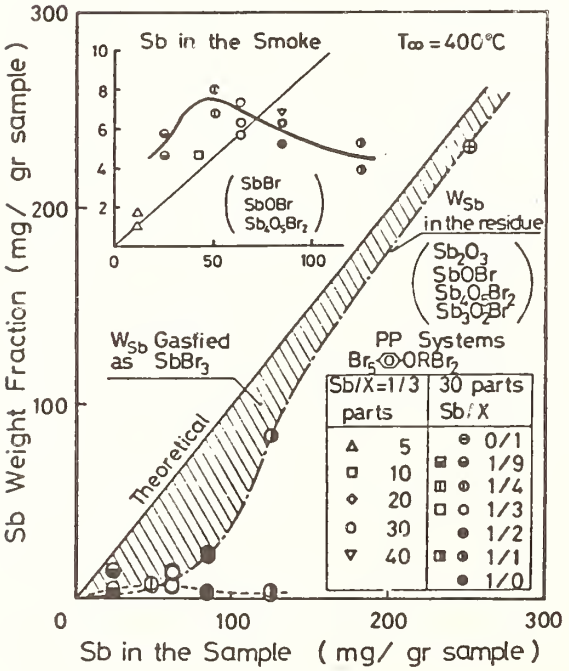


Fig. 44(c)

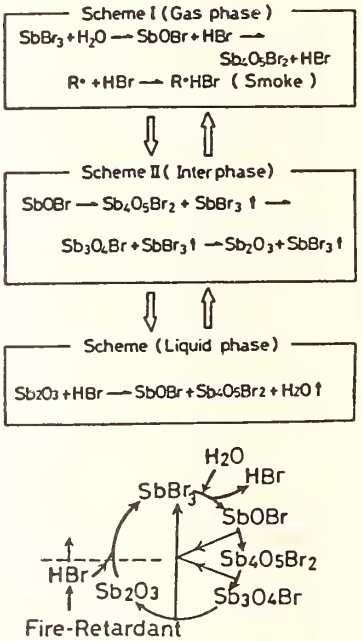


Fig. 45

Fig. 44 **Substantial balance and release pattern of Br and Sb from** PP-dibromopropylpentabromophenylether-Sb_2O_3. Correlation among $W_{HBr,gas}$, $W_{HBr,smoke}$ and $W_{o,\phi Br}$ (a). ○, □, ◇ etc on solid line —— and ●, ■, ◆ etc on broken line –– refer to $W_{HBr,total}$. ○, □, ◇ etc referred to Sb/X = 1/3, ●, ■, ◆ referred to various Sb/X. The height among ●, ○, □, ◇ on broken line –– or —— and those on thick solid line ▬ across the shaded area referred to $W_{HBr,gas}$. (b) Correlation among $W_{Sb,smoke}$, $W_{R,Sb}$ and $W_{o,Sb}$. ●, ■, ◆, etc on broken line – • – and those on —— referred to $W_{R,Sb}$ and $W_{Sb,smoke}$, respectively. ○, □, ◇ referred to Sb/X = 1/3 and others ●, ■, ◆ etc referred to Sb/X of various values. (c) Release pattern of Br for system of 30 parts add-on with various Sb/X. Sb and HBr in the shaded area meant the fraction of retardants and HBr emitted directly excess to Sb by Sb and Br balance.

Fig. 45 A scheme of the Br release mechanism.

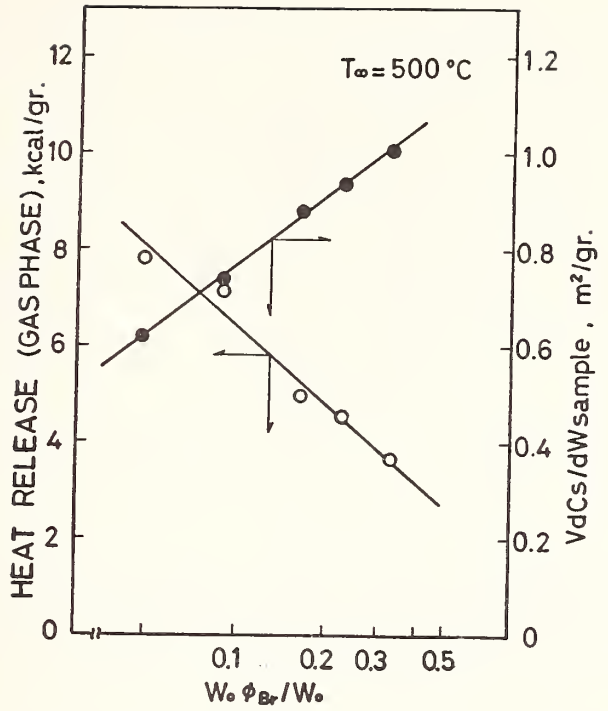


Fig. 46 Reverse relation between the heat release and the smoke extinction coefficient from fire retarded PP vs. added amount of the fire retardant.

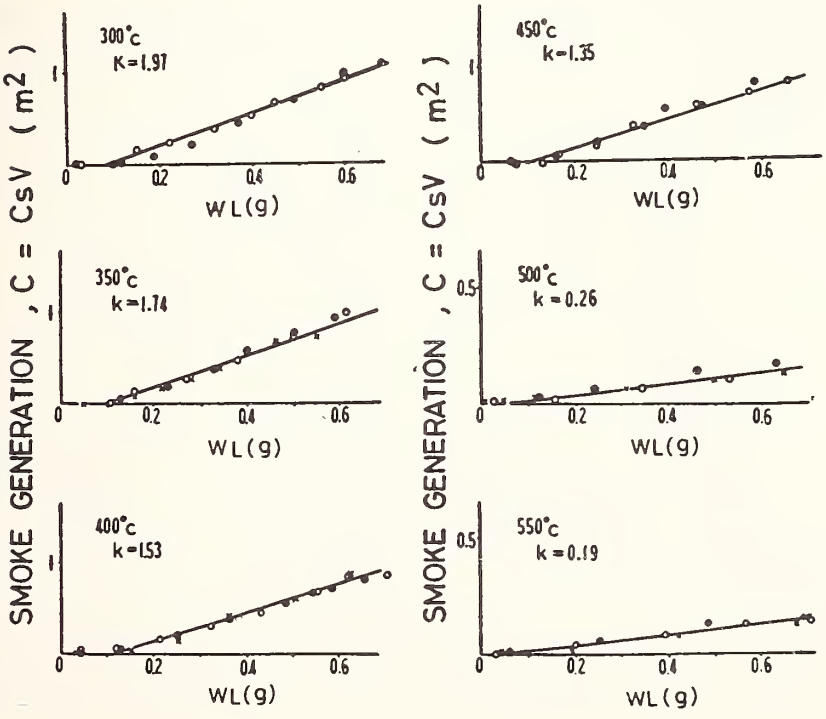


Fig. 47 Relation between the weight loss and smoke generation (plywood).

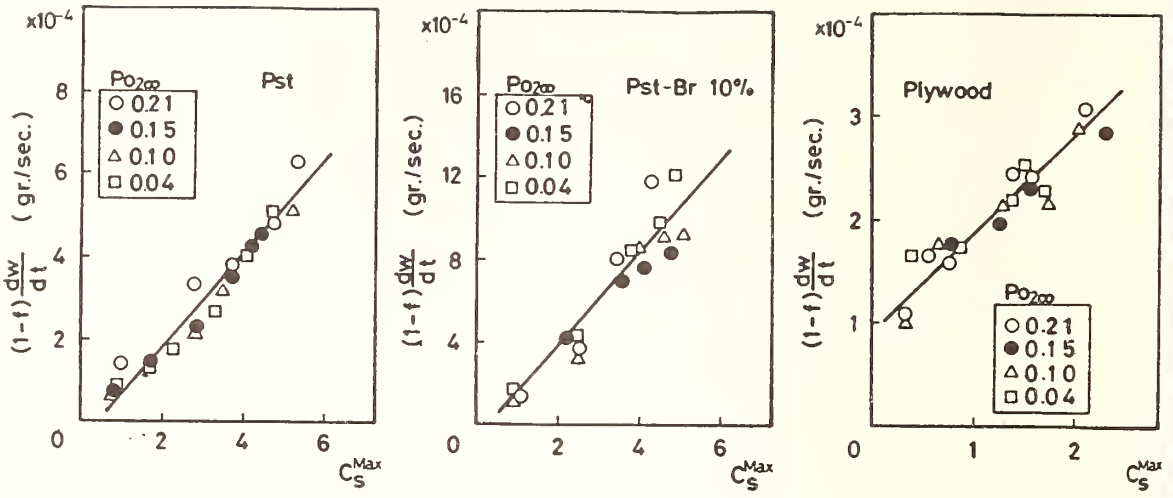


Fig. 48 The smoke generation rate by weight (1-f)dW/dt vs. the maximum smoke extinction coefficient C_s^{MAX} plots for PSt, the fire-retarded PSt and plywood at the various $P_{O_{2\infty}}$ and to of 450°C

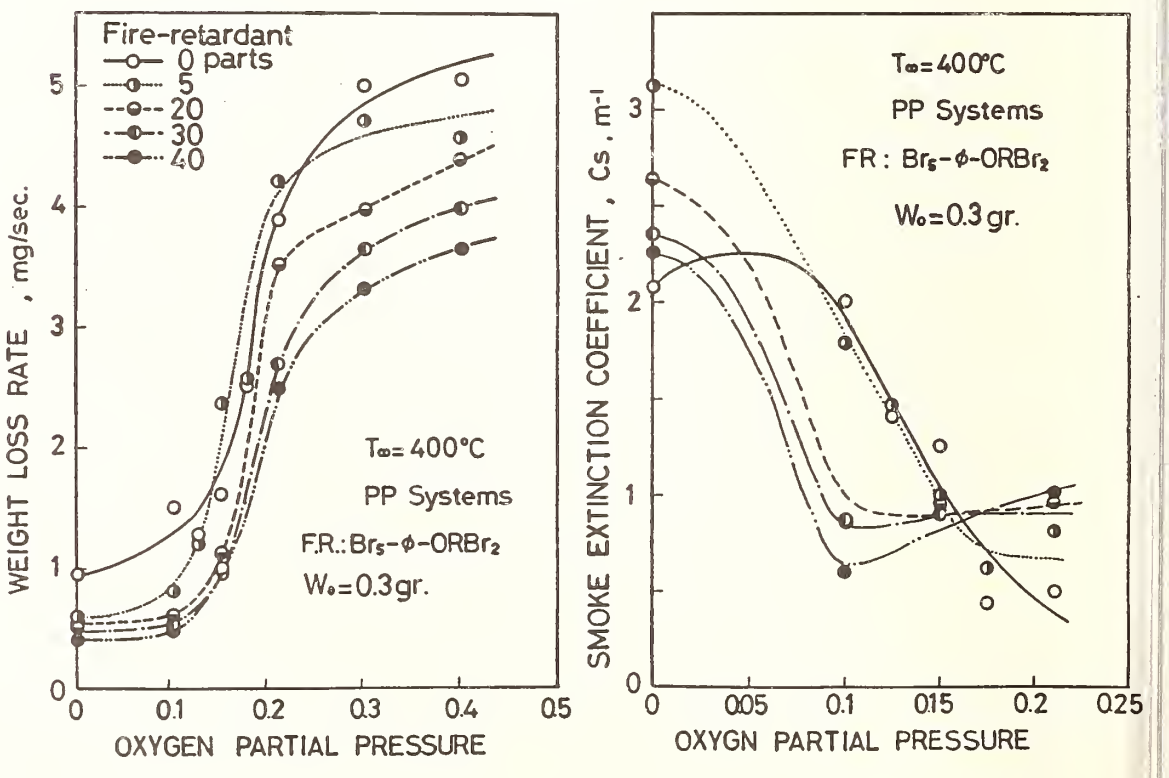


Fig. 49 Changes of weight loss rate and smoke extinction coefficient vs. oxygen partial pressure of atomosphere.

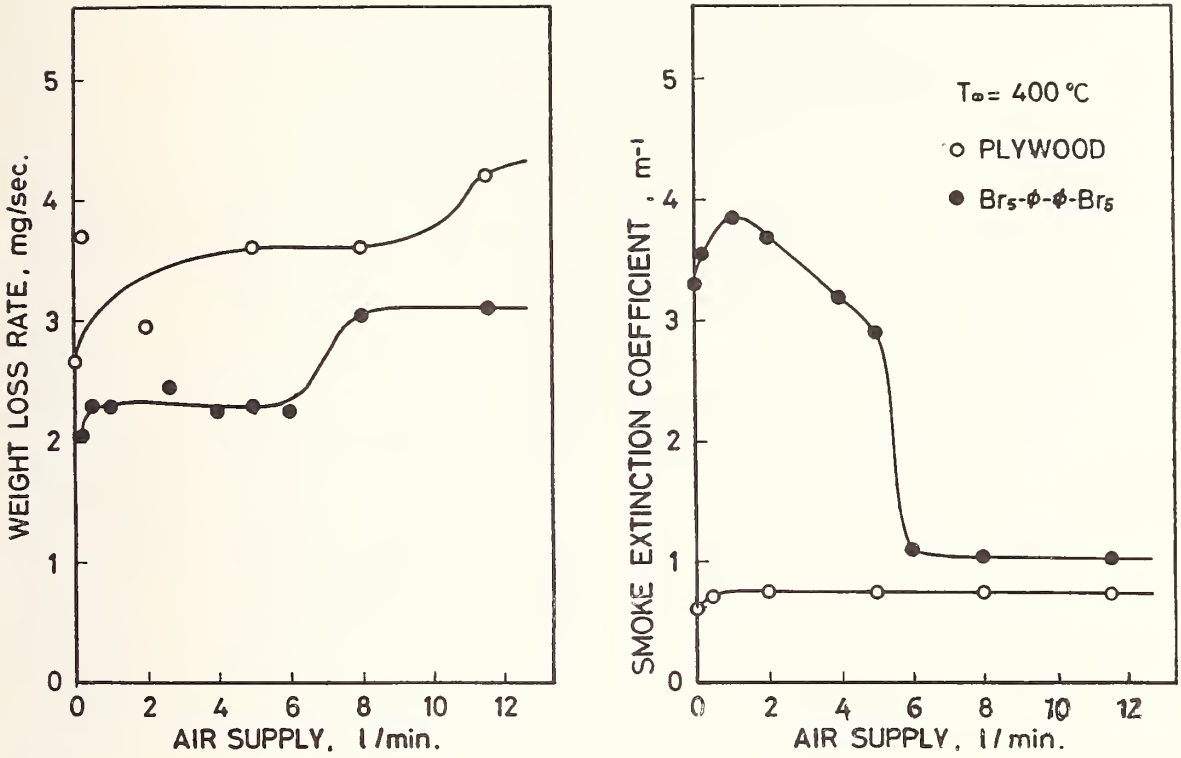


Fig. 50. Canges of weight loss rate and smoke extinction coefficient vs. air supply.

Table 1. Summary of results on invisible particles

Burning condition	Measured size (nm)	α-ray ionisation	No. burnt	N_+/N_-	D_p (nm)	D_d (nm)	Z_i (× 10^6/cc)	Cs max (m^{-1})
Padding cotton 300°C	3–50	○	2	0.59 0.68	5, 12, 34	(3), 13, 64	1.3 1.5	0.6 0.01
	5–100	○	2	2.5* 1.62 1.04			2.6 2.9	0.79 0.12
Joss stick	5–100	○	2	1.14 1.00	(5), 13, 18	48, (91), 24	1.9 2.0	0.56 0.28
Tobacco	5–100	○	1	1.13	(5), 34, 13	64, 9, (5)	3.7	0.16
Filter paper 300°C	5–100	×	3	– 1.13 1.17	(5), 9, 13	64, (91), 48	2.0–2.8	0.18–1.12
	3–50	○	1	0.7	7, (3)	34, (3), 48	2.1	2
	5–100	○	4	aver 1.14	5, (91), 13	34, (91), 48	1.5–4.1	0.23–1.95
Newspaper 300°C	3–50	○	1	1.23	5, (3), 13	24, 18	0.6	0.18
	5–100	○	1	0.76			2.7	1.04
Linen 300°C	3–50	○	2	0.94 0.78	(3), 7, 13	64, 34, (3)	0.9 0.8	0.33 0.03
	5–100	○	2	1.30 1.48			3.7 1.9	1 0.2
Acrylic fibre 300°C	3–50	○	1	0.94	5, 34, 24	9, 13, (91)	1.0	0.19
	5–100	○	1	1.74			4.4	0.12
Lauan 300°C	5–100	×	1	0.94	(5), 9, 13	34, 64, (91)	2.0	0.33
	5–100	○	1	0.76			2.1	0.99
Filter paper 400°C	5–100	○	3	aver 1.81	(5), 18, 13	34, 64, 9	0.5–2.8	0.012–0.84
Filter paper 500°C Perfect combus.	3–50	○	1	2.2* 1.05	5, 7, (3)	34, 9, 5	0.9	0.2
Filter paper 500°C Imperfect combus.	5–100	×	1	7.1* 1.35	7, 9, 18	34, 9, (5)	2.5	0.31
	3–50	×	1	1.66	5, 9, 7	34, 9, 15	4	0.47
	5–100	○	3	aver 1.43			4.2–15.6	0.15–1.9
Linen 500°C	3–50	○	1	0.62	(3), 7, 9	64, 24, 9	2.4	0.56
	5–100		1	0.49			3.3	0.92
Lauan 500°C	5–100	×	1	1.94	(5), 24	18, (91)	3.9	0.17
Cedar 500°C	5–100	○	1	1.87	(18), 5	64, 47	4.0	0.84
Gasolene tray burning	3–50	×	1	1.55	10, (3), 24	89, 45, 25	2.0	0.8
	9–200	×	1	–			–	0.82
	3–50	○	1	0.72	(3), 10, 24	89, 24, (180)	2.6	0.78
	9–200	○	1	1.56			12.2	0.8
	5–100	○	3	aver 1.24	(5), 13	34, 47	4.9–7.7	0.8–0.86

Notes

N_+/N_- : Ratio of number of positive-charged particles to that of negative-charged particles.

D_p or D_d : Diameter, being apt to appear peak or dip on size distribution curves $f(d)$, shown in order of frequency.

Z_i : Estimated total number concentration in region described in "Measured size"

Cs_{max} : Maximum extinction coefficient

A circle or cross shows the presence or detachment of radioisotope, respectively, and a value obtained at the appearance of smoke is marked with an asterisks.

Table 2 Smoke particle elimination ratio after above 8μm, 4μm, 1μm particle size dime was eliminated respectively.

	Gasoline	F.R.Polyurethane	Polyurethane	P.V.C
8μm	0.97	0.98	0.74	0.75
4μm	0.945	0.95	0.60	0.73
1μm	0.95	0.87	0.81	0.48

Bukowski-Mulholland Presentation

Handa: I would like to ask Mr. Bukowski to talk to us about "Detection and Smoke Properties. I would like to ask what is the standard in the United States on Figure 15. I see on the American side you have a figure of 4 meters. In Japan I think it's about 1.5. I would like to know, what is the standard--if you have any such standards. It's about Figure 15 from your presentation.

Mulholland: .....there are no numbers here.....

Handa: Dr. Bukowski has the 4 meter figure. In Japan it's 1.5 meters; but what is the American standard that is used in getting the air velocity at the time when the units for the (cannot distinguish) degree? Now what would be the distance there? What has been developed here?

Mulholland: I'm afraid I don't know that one.

Bukowski: We've got various detector design theories. The formulas from Litton quantify the range of convective air flow through the sensing chamber for which ionization theory holds. This will be a function of the outer enclosure design and the shell design of the chamber itself so this will vary from detector design to detector design.

Mulholland: Professor Handa, are you asking, "Is there a specified airflow at which the ionization detectors are tested in the U.S.?"

Handa: Yes.

Mulholland: I see.

Bukowski: The maximum air velocity used in the detector testing is 150 ft/min.

Handa: What is that in terms of meter?

Mulholland: .....about three-quarters of a meter per second. .75.

Handa: Is the aerosol used, paraffin? What is it based on (that figure)? Is it aerosol?

Bukowski: That is the aerosol used in the Underwriters' Laboratory test which is the smoldering cotton lamp-wick.

Watanabe: I would like to ask a question of Mr. Bukowski about the obscuration meter. On the average, at NBS in the Fire Detection Group, the meter that has been used here and the ones that are used by the Smoke Generator Group, I think that the same kind of meter has been used. But what is the relationship between those two meters? In fire research I see that there is a handicap in using a different kind of meter. I personally think that if the same meters are not used, I think that there is a handicap being experienced. Mr. Gross, I think, used a voltage of 134 volts. I think you used 1.5. I think it was a very small one. I would like to know if you check or exchange opinions between the two groups on what kind of an electric current has been used in the different research groups.

Bukowski: Yes, I agree completely with Dr. Watanabe's comments. We have just recently developed the extinction photometer which I mentioned and we are hoping that all the organizations in this country and around the world would consider this instrument for these applications. All of the work done in the detection area now uses this meter design, and we hope to change the meters used in the other groups within the Bureau to this design, also.

Rockett: In relation to this question, I would like to emphasize that the work of Mulholland makes it very clear that in using any broad spectrum meter which measures total obscuration only, the results will be extremely complicated to interpret if you do not know the spectral transfer function of the meter and if you don't know something about the smoke that you're measuring. Without some kind of smoke distribution knowledge it is very difficult to make any meaningful comparison between these instruments.

Chaiken: I would like to make a comment with regard to the use of any smoke detector and this relates to the phenomena of being able to detect the desired thing which is a fire at a very early stage. Here, we have to be concerned with, not so much sensitivity in the true sense, but the signal to noise ratio and have a device which is quite sensitive but may false alarm at a very high rate due to atmospheric particles and particles having nothing to do with the thing that they're trying to measure. And at this point, I'm not sure any of the discussion I heard was given to that point.

Handa: On Figures 16 and 17. These concern the two Figures 15 and 17. Figure 17 is on the scattering angle. The dotted broken line on the bottom of that figure. I would like to ask if this is a flickered line. Is this the actual light collecting angle? I would like to know what is the actual light collecting angle in this case?

Bukowski: In this diagram the data was calculated for Mie theory and this is the solid line; and the dotted line is the comparison with the calculated defraction-refraction-reflection components at various angles. It's basically all calculated data.

Handa: What is the actual light collecting angle?

Bukowski: All of the different angles in the range shown were used in the calculation.

Handa: I think there is a misunderstanding. I would like to explain further. I'm not talking about the observation angle. I would like to know what is the actual light collecting angle, not the observed collecting angle. Can you give me what that is?

Mulholland: I'm not sure I understand. Figure 17 is a theoretical calculation and I guess your question is, in doing the theoretical calculation, what range of angles do they average for each of these points? Is that your question?

Handa: Yes.

Mulholland: And I think the answer is that Dick and I don't know, in this calculation, what range of angles were averaged to get this curve. Dick, do you know?

Bukowski: No. This is not NBS data. This was taken from a book on aerosol properties.

Handa: Thank you very much.

Watanabe: There was a question from the American side for smoke detectors. If you look at smoke detectors from a person who is selling such things, I think he said that it is something in the area of signal to noise ratio. In the case of Japan, we think that the standard of the heat system is about .5 to 1. In the case of smoke detectors this becomes SN, S to N. Signal to noise becomes very bad. However, I think that it should be taken to about 3.1. The ratio of signal and noise should be about 3 to 1 minimum. That means that if it's too sensitive, in Japan, if there are many detectors in one building then there are cases of false alarms. This is my opinion that was expressed earlier on smoke to noise ratio.

Chaiken: I concur with that, and that was the point I was trying to bring up. I would like to say that Figure 17 in the NBS paper may be a good example of part of the problem. One would say from looking at this figure that you would perhaps like to look at the light scattering in the forward direction since it has the highest scattering tendency coefficient. The little experience I've had with forward angle scattering is that--that is the area where background scattering from your optical system is also the greatest and find it is sometimes better to discriminate the signals by going to side angle scattering or even back-scattering.

Jin: I would like to ask a question of Mr. Mulholland. In Figure 17, you said these were calculated values. Are these values calculated based on actual burning? I have done some kind of experiments that are very similar and, according to my experiments in the case of flaming and smoldering, I have seen a big difference between the two cases. And I think that this is also related to the sensitivity of photoelectric detectors. I would like to know if you have compared the values in the case of smoldering fires and flaming fires. Do you see any similarities or do you see a big difference between the two values of the two cases?

Mulholland: First, for clarification--Is Dr. Jin referring to Figure 17? Figure 17 is not for smoke aerosol. It's for water droplets so that the effect of the imaginary part of the refractive index from a black soot smoke to a transparent smoke is not indicated. This is just water drops which have no absorption coefficient (imaginary part of refractive index is zero).

Jin: I would like to know if you have the results from actual experiments that you conducted on different materials.

Mulholland: My colleague, Tom Lee, has some data at 30°, 60°, 90°, 120°, and 150° for smokes generated at various situations. It has not been a comprehensive study. Perhaps I should let my colleague comment on the problem.

Lee: If you will talk to us later we'll be glad to explain this work. We do have data.

Jin: I have some data, also. However, my data is in Japanese. So perhaps we cannot discuss it directly but I would like to exchange data with you.

Rockett: For the rest of the group's information, the measures in gathering polarized light in the parallel and perpendicular planes for a variety of angles we have data on the scattered intensity on the two types of polarized light for a limited number of angles.

Handa: On Figure 24, in the evaluation chamber what is the maximum wind velocity in the United States when you use this? What is the maximum wind velocity in your researches?

Bukowski: 150 ft/min. 3/4 meter/sec.

Watanabe: In Mr. Bukowski's presentation, I was not able to follow it completely. If there is less radiation source, did you say that there is less sensitivity? When we see the researches in Japan, I think that sensitivity increases. IO . The problem is the ratio between IO and ΔI. If IO is less then sensitivity increases. I have seen such a reverse relation so I would like to make this point clear because in your presentation I understood that its sensitivity decreases. However, in my experience its sensitivity increases.

Bukowski: Our experience is similar to yours. As the source strength is lowered, the sensitivity increases; but this must be balanced against the problem of electrical noise and external influences as the chamber current is decreased to smaller values.

Handa: On Figure 26, the curve on this figure is something spectacular! For values of over 1.2 microns and if coagulation is present, I think that perhaps there is another peak if we compare this figure to Figure 30. Do you have any detailed researches that have been made in this respect? If you compare the results in Figure 26 and Figure 30, I would like to know if there is another curve or--in this kind of concentration--that there was no such kind of coagulation present? Did such coagulation take place in this kind of concentration? Is that why there is no more curve--an additional peak?.....I'm not criticizing your researches at all. It's just a question I had in mind.

Mulholland: Professor Handa asked a good question. In Figure 27 and also those in reduced form in Figure 28 the size distribution is determined for particle sizes up to 1 micrometer. We do not have data for the particle data for particle sizes greater than 1 micrometer. We have difficulty using the optical particle counter which saturates at higher concentration. We would be very interested in your results for particle sizes larger than 1 micrometer in finding out whether or not the reduced size distribution is universal.

Miyama: We have about 10 minutes more for questions and answers. I would like to take up one more question from the Japanese side to that presentation _____ Mr. Jin.

Jin: On Figure 24 you used a punk-type of incense and you have said that reproducibility was very good. Do you think that this is the best way to make research so that we can prevent fires _____ in fire research? I would like to know if the usage of this incense type stick is the best way, the most appropriate way for research, in fire research.

Bukowski: We feel that the punk method is a good method in the present but it also suffers from many of the flaws of other combustion generated aerosols. We feel that the optimum method of generating test aerosols, particularly in small scale tests such as this, is the mechanically generated artificial aerosol. These artificial aerosols will give us much less variation of the basic aerosol parameters than any combustion generated aerosol could. The cotton lamp wick, for example, used by Underwriters' Laboratories in this country has a severe problem with moisture. The cotton being very hygroscopic, the aerosol changes considerably with very small fluctuations of the relative humidity. While the punk sticks are less hyperscopic, they still suffer from problems in variations in density from punk stick to punk stick and also our not knowing from what they are actually made.

Watanabe Presentation

Benjamin: I was struck by the large difference in sales between photoelectric and ionization detectors and I'm wondering, no. 1, if you have any reason for this? The second question I would ask is whether you feel the amount of data for the photoelectric does give a basis for comparison of the two detectors?

Watanabe: Thank you so much for your question. There are not too many photoelectric detectors in Japan. First of all, there is the question of patent. There are various patents existing for the detectors for fire prevention and the patent problem seems to interfere with the effective sales of such detectors being installed. The second reason is that the photoelectric type has not been mass produced in Japan, therefore it is more costly than the ionization type detectors. As for the second question regarding the data, there are abut 5,000 reports of false alarms just taking place in my demonstrator today. In Japan the fires defense agency is rather powerful and they do have a large influence and therefore if they try to exert their influence then we can collect more data, so we have about 5,000 reports concerning the false alarm.

Benjamin: I observed in the paper of Dr. Watanabe that there were only 112 reports of the photoelectric type.

Watanabe: I feel that is quite a considerable number of false alarms in order to look into the causes of the false alarm. If you can see the figure which is cited in the report, the number of detectors already being installed amount to 3 million, the main body of data is about 70,000 detectors.

Einhorn: I would like to ask a question of Dr. Watanabe. Do you have information as to whether the number of false alarms increase over a period of time--3, 4, or 5 years?

Watanabe: There is some data for 1972. The figure for 1972 is for the products which were manufactured right after the smoke detectors were developed and therefore there were more false alarms and more failures for those which were newly marketed. However, in Japan that type of new introduction type of failure decreases as time passes. It reaches a certain stage where there won't be that much increase or decrease in the number of failures. I feel that the detectors should be maintained. The maintenance should be conducted before we have revised the standards for the maintenance. I have felt that at least once a year there should be a checking conducted for detectors so that would exclude the ones that are not operative.

Einhorn: Do you have any studies or information pertaining to fire injury? If an alarm went off - failed to go off, as compared to if there had been no alarm? How effective in reducing loss of life or serious injury? Can you comment on this type of information?

Watanabe: Thank you. Perhaps during the course of discussion on the building system we might go into that area. Of course it is only a part of the research that I have been conducting in this field. Regarding the fire detector, we have taken into account 4,000 incidents and we looked into the effectiveness of the detectors based on these 4,000 incidents. However this research is still in progress and, therefore, I might not be able to give you the detailed figures. But roughly speaking for those buildings with the fire detectors about 10% of the incidents have failed to detect the fire, that is, the detector did not go off. The discovery of the fire is not limited to the detector. Human detectors are also one of the means of detecting a fire and, therefore, when we look at the fire system we have to take into consideration not only the mechanical detector but also the human detector. Although there has been a 10% failure it does not mean that there would be 10% more injury or 10% more damages done because of the fire.

Handa: I would like to add a few words to the presentation. At the initial stage of the development there are of course more failures in the case of the ionization type as far as I have found out. Unlike in the United States you have a good insulation. For instance there is a Hydesol Company. There has not been that type of material in Japan. Japan has very high

humidity and the protection for the MOSFET has not been appropriate and therefore there has been a lot of failure at the beginning. I'm doing work in the semiconductor area on MOSFET's and all these electronic companies use the Hydesol material for insulation and this has more or less stabilized the detector; but until we start manufacturing that material for insulation we have more cases for failure or false alarm.

Bukowski: I have a question for Dr. Watanabe. In his presentation he mentioned that the rate of false alarm for photoelectric detectors was greater when they used incandescent lamps. Does this mean that in Japan a lamp failure of an incandescent lamp results in a false alarm of the system?

Rockett: You had a correlation of false alarms against the time of day, which I believe peaked very strongly at around 8 o'clock in the morning. Have you examined behavioral patterns that would explain why this strong peak would occur at this time of day?

Watanabe: Electrically speaking, all the electrical appliances start working around 8 o'clock. For instance, at the department store all the lights go on at 8 o'clock and this will create noise. Further, there is the fresh air being introduced before the human beings start moving around or at the outset of putting on the heaters and other air conditioning facilities which would introduce very tiny dust. Perhaps this would be one of the reasons. Therefore, at the time when people start moving around this particular human behavior seems to trigger more false alarms.

Mulholland: In the United States I suspect that cooking is a significant contributor to false alarms. I was looking through the list of causes of false alarms that Watanabe has, and found cooking to be omitted and I wonder if that's because of the different habits of the United States and Japan.

Watanabe: Within the Japanese figures about 10.9% is from cooking related factors. I think there are various patterns of cooking. First, what amount of vapor would be released from cooking or the heat--what amount from that would be the contributing factor to the false alarm? When we look into these itemized causes it is difficult to generalize it as just being cooking. Therefore, because of that fact, we have conducted heated discussion on what should be the optimum cause of the actual false alarm. These generalized items of cooking have been omitted but we have to look into the ultimate cause of the false alarm rather than just giving the general terms of cooking. We have calculated the vapor which is emitted from cooking and we have also looked into the heat which is actually generated from cooking.

Mulholland: What is the Japanese distribution of detectors installed in offices, public buildings, and private residences?

Handa: First of all, the residential figures are very low. In Japan the house is smaller than in the United States; therefore if you cook at home that would trigger the false alarm. Secondly, the Japanese just love bathing and this practice does create an enormous amount of vapor and steam, and as well in the cooking area, we eat lots of Chinese dishes and therefore lots of grease deposits on the detector. Recently Japan has set a standard for the residential detector. What you have seen on the slides are the standards on the office building and on the public facilities such as department stores, etc. where a large number of people go in and out. In the case of private residences the detector is limited to the high-rise apartment. And this is the thermal detector rather than any other type of detector that we install for the high-rise apartment buildings.

Lee: I am interested in your data on detector failure, you mentioned 10% of all reported fires are due to detector failure.

Watanabe: The figure 10% as I have mentioned earlier includes the human initiated error and therefore as far as the reliability of the equipment itself is concerned we do not take into consideration what kind of interplay is seen between the equipment and human aspect and whether the equipment will work or not. We just don't look at the equipment itself when we look at the reliability of the equipment.

Bukowski: Is the fire defense agency in Japan keeping data on failure rate of detectors?

Watanabe: Are we talking about the reliability portion of the equipment when we talk about the failure rate or are we just talking about the actual situation of the alarm not going off?

Wukowski: Yes, the reliability of detectors.

Watanabe: The fire defense agency has conducted the failure rate research or the follow-up study of the detectors which are installed in areas which might induce that type of failure and therefore we have that type of failure. However, the figures for the detectors which were influenced by environment which might induce the failure we have to really reduce or bring it over to the general condition in order to get more appropriate reliability rate. Therefore, what kind of figure we should take for K, the function right, would be quite a problem. When we talk about just the reliability as we mentioned by R's as the humidity rate goes high the failure rate would be about 4 times more. And therefore with regard to the reliability forecast conducted in the United States, we have to really compare our notes regarding what type of conditions we are using in order to compare notes with you.

Einhorn: Since our last meeting in Japan we have studied approximately 40 fires in the Salt Lake City area. Of these 40 fires there were 15 cases where detectors were installed in homes. Of these two were cooking fires, two were TV fires, and 11 were cigarette fires, where the presence of the detector actually awakened someone who had been sleeping. We feel detectors contributed in preventing injury. There were 3 fires where there were no detectors present, where we think that in 2 of the 3 fires detectors would have saved lives. In both cases the fires were TV fires where one or more parents had gone to sleep and within 40 to 50 minutes the fire occured and they smelled smoke and came downstairs and went back upstairs to take the children out. In the case of a double fatality the mother was carrying one child and the two young ones following turned around and she was not able to go back and rescue them. And a similar case happened where we lost one life. We felt if we had had 3 or 4 minutes more warning we would not have had a loss of life.

Watanabe: As I have mentioned earlier, we do not believe from looking at the actual statistics that the fire alarm would work perfectly when it is needed. The fire should occur under the normal conditions but it all goes on under the abnormal conditions and under abnormal conditions lots of things happen. There is one unique case. For instance there is one person who did not pay his electric bill, so the electric company stopped the electricity but the battery would be exhausted in 3 or 4 days. And therefore they used the candlelight. This might create fire, so the actual cause of the fire is not normal. These are abnormal situations which create the fires. For instance the cigarette fire starts when someone visits you and leaves the cigarette in the places that you would never think of leaving cigarettes. So this is the kind of environment where the fire occurs and therefore the 10% failure. If we really look into the details, the ultimate reasons for such failures are various things that contribute to that type of figure and we cannot just say it failed 10% of the time.

Handa: Dr. Watanabe talks from the supervisory position or the supervisor side. I talk from the side of the detector manufacturing company. As Dr. Mulholland pointed out earlier, cooking is one of the main factors in the United States for false alarms. In Japan, until recently, the law has not stipulated that residential homes require smoke or fire detectors. However, in the case of the high-rise residential buildings or apartment buildings, the biggest single factor contributing to the fire is the cigarette left in the conference rooms. Including myself, we have a fond taste for cigarettes. For instance, if anyone should make a request to hold a conference at the fire defense agency, we request them to submit what kind of detector they have within the facilities where they hold conferences. However, as it has been mentioned by Dr. Watanabe, we have a biological sensor being a human being and therefore I don't think it is asking too much to ask for a report. In the case of other high-rise buildings, I am very often asked by manufacturing companies what the state of affairs is at the moment or the fire from the cleaning area, as well as the top floor restaurants from cooking seem to be the big causes and therefore recently our thinking regarding the false alarm has been changing and we have been thinking along the same line as the United States, more so now. I am sure that in the near future more and more residential homes will be installing detectors. And, unlike the United States, Japan has very high humidity and therefore we have to use some resin that has a very high insulation rate. Unless we come up with the material which would give adequate insulation we would be creating

more false alarms at the residential homes. American detectors, I have looked into some of the imported ones in Japan. The cheapest kind the protection of the MOSFET does not seem to be adequate for Japan. This seems to be because the humidity in the United States does not seem to be a problem. But the MOSFET would not work in Japan because of the high humidity. In the case of residences, installing these detectors in the residential home would cause one single problem.

Benjamin: I would like to find out if Professor Handa maybe has has not seen some parts of the U.S. where we have over 80% relative humidity all year round. I an thinking particularly of the area around Houston and Galveston and so forth. So, yes, we do have a problem and, indeed, there was a detector on the market which had to be recalled because it wasn't working when the humidity went above a certain level. So we do have areas like that in addition to areas like Arizona where the humidity is always below 30%.

Handa: Thank you very much.

Robertson: We know I think that in Japan there has been a long term concern about fires in the homes and I think we have considered it a criminal offense to have fire in your homes. But I wonder if the loss records that you are collecting now really justify the emphasis on industrial and office use of fire detectors. In our country we think that most of the life loss is in the home residential occupancy. Is this not so in Japan?

Watanabe: There does not seem to be much difference between the United States and Japan in the causes of fire which might result in a casualty. In order to minimize the casualties, the Tokyo Fire Protection Agency about 8 years ago had created a campaign to promote installation of fire detectors at home. Unfortunately the detectors at that time were still very primitive. It was the photo-electric simple type detectors. Therefore after the installation there have been lots of failures as well as the false alarm cases. Because of the high frequency of these incidents, it has not been successful. The wishes of the installation of the detectors is on the part of the government rather than the general public, so this did not work too well. Therefore we did not see the results we wanted to see. Because of the high failure rate this has created strong criticism among the general public and it required 3 years for us to calm down the people and correct the criticism which was created by our campaign. Because of the failure we had, we are allergic to the residential type detectors. There is a different environment existing in the United States and Japan. Therefore we feel we have to put every effort to develop a detector which would be suitable for home use. However, unlike in the United States where the husband would do the Sunday carpenter-like work of installing the detector himself, Japanese are not too keen on do-it-yourself type affairs. Therefore it might be difficult to promote the installation of the detectors in Japan. Perhaps we should learn from the United States as to how best we could create initiative on the part of the general public to install detectors at home. I would like to add to that statement, even in the United States, how often do you repaint the walls? Will the detectors get very dusty? And beside the fact that we know we have to repaint the walls a number of times every so often --you seem to go without maintenance for 20 years or 30 years. This seems to be just an understatement. It is difficult for us to understand why you would let them go without the maintenance for that long period of time. If I may add I would like to give you a more concrete figure regarding the question which was raised earlier. In 1977 there were 63,953 cases of fire. The building fires amounted to 39,286 cases. Residential houses, 16,445 cases. According to the occupancy rate the residential fire seems to be the highest out of the total figure. Of 1,909 about 105 people are dead because of suicide and there are the people that were killed because of the fact that someone wanted to commit suicide. For instance someone would release the city's gas and then set fire to it. Not only the person who wants to commit suicide but also the people around that person will be involved in the incident. Perhaps there are more people committing suicide in Japan, but there might be more arson cases in the United States. For instance, in Washington, D.C. and New York there are cases where arson is commissioned on certain types of buildings.

Chaiken: Thank you, I'd like to make a comment in regard to possibly an extreme example of how environment will affect the use of these smoke detectors. We at the Bureau of Mines are interested in detecting fires in underground mines and as far as a hostile environment goes, probably the worst example of an environment for a detector. A couple of years ago we had a contract for research with Gillette here in Maryland to carry out a study

of all available commercial detectors for possible use in a mine or mine environment. I don't have specific data to give you but the conclusion of the study was that there is no commercial smoke detector other than possibly one--the ionization detector manufactured in South Africa for the use in South African mines. Not one of these commercial smoke detectors here in the United States would be suitable in a mine environment because of failure, false alarms or whatever. One assumes that a home environment is a fairly clean one and the mine environment is a very dirty one. The detectors that may be suitable for one environment are not going to be suitable for the other and since we have a whole range of office and industrial activity between say those two extreme environments, we may have to discriminate between what is effective in what places. There may not be a universal detector.

Benjamin: I feel there is a basic philosophical difference between the American approach and the Japanese approach to the detector. It is our intent and our goal to develop detectors that will essentially be maintenance-free for a period of maybe 30 years. We do not feel that it is practical to maintain a residential detector. We don't have 30 years' experience We do have maybe 10 years of experience in many cases, where we've had detectors with no maintenance. Now I don't think it's because the American homes are any cleaner. In fact, if you would ask my wife she would say the walls should be painted every year. In fact, in certain parts of the country, particularly in the Mid-West during the drought period, one could walk around and actually taste the sand and dirt blowing. So we have dust, we have dirt in some places, we have other pollutants and yet we are striving for about 30 years' maintenance-free. We feel that it is realizable and this is obviously in great contrast to the approach that I hear the Japanese talking about. I think this is something that we can't discuss now but should be discussed in greater detail as to why we have this convergence.

Lyons: Is it still the policy of the government in Japan not to recommend or approve ion chamber detectors in private residences?

Watanabe: There is no law which states you can not use the ionization type detector at home. I do not know if I can answer your question. Recent requirements in the home detectors show that the radiation from that detector should be less than 1 microcurie. As you will know this figure was decided last June in connection with the OECD conference. If I remember correctly, during the course of the OECD conference, it was decided that the home detector should be less than 1 microcurie. I think the United States has decided not to keep the standard for their existing detectors which have already been installed.

Einhorn: During our visit to Japan we noticed the wide utilization of detector/suppression systems in public hearings. Not having the chance to visit hospitals and health care facilities, are detectors and/or suppression systems required in such facilities?

Watanabe: When we look at the causes of fire--if I can give you the figures again. In the case of residential areas, about 42%. The next one is schools, according to the high occupancy rate, followed by hotels. In the case of the British Fire Research Institute, in the hospitals and so forth, the comparison to Japan has a high frequency of incidence of fire than in Japan. I do not remember the exact figure but in comparison to the figure which was given by the British authority the intervals of instances is longer for Japan by about 5 to 10 times. Although this is of course a very important topic for the handicapped people it is true we have already installed the detectors in these facilities and the large hospitals are now equipped with the automatic sprinkler systems. However, the smaller version of the hospitals like clinics and so forth--this is not within the framework of the laws and regulations.

Miyama: One last question. Just two last questions.

Handa: Since in the position quite contrary to Dr. Watanabe's and more on the side of the manufacturers than the authority, we are trying to develop a detector that would last for at least 15 years and unless we can develop something like that it will be difficult in an actual situation to install them at home. It would be almost impractical to conduct inspections for the home installed detectors. Dr. Chaiken has mentioned earlier gas sensors and ion sensors. These are combined for the detector to have dual sensing capabilities in order to prevent the explosion type fire as well as the suicide type fire that we have been mentioning. We hope we can develop that type of sensor that would be in-

stalled in residential areas. However, the traditional type detector, because the heating plate consumes a large amount of electricity. And therefore, we are trying to develop and use semi-conductors which would be able to control the voltage without having to use the heating plate. This does not consume too much electricity and because of the fact that there would be on digit voltage decrease when the carbon monoxide is introduced, perhaps in the very near future we might make this type of detector available. Thank you.

Chaiken: Again, referring to the work the Bureau of Mines has carried out on fire detection, particularly with work done in Great Britain dealing with fire underground. There are two approaches. One is to have multi-point detectors at various locations and the other a point called a two bundle concept, an atmosphere sampling device you can sample the atmosphere from various points and bring the atmosphere to a single point for detector purpose. There would be some cost benefits and depending on how many detectors are required to detect, and whether you go to the multi-detector or to the sampling. I personally think that for something like a high-rise building or a large office or hospital complex where you have to examine or protect many rooms, the concept of sampling and bringing in gas to the same point has some very real advantages in terms of reducing the reliability control and you can get rid of a lot of problems that local environment might impose upon a detector. One other comment I would like to make is in regard to residential, this is my personal view. It seems to me that the biological sensor is very good and you really have to protect the home when you are sleeping. I don't think that consideration with regard to cooking is very important at this point in time. This poses another series of constraints or design criteria that you can have on a residential detector. Whereas for an underground mine detection system or in a large office building you probably would want to be able to protect unattended areas by a local sensor. That is another set of design criteria. I guess this refers to the fact that one should not necessarily strive to develop the universal detection system for every condition in every environment.

Miyama: Thank you so much for the very lovely discussion. I hope that you would consider having more discussions during lunch. Thank you so much.

Saito Presentation

Einhorn: Do you know why the increasing amount of treatment fire retardants? And you also showed the relationship of changing amounts of smoke. Do you see a change in the kinds of smoke evolution? And if you do, do you find that this comes out rather rapidly and then levels off?

Saito: I hope Dr. Einhorn asks me on speed of the smoke generation is that it? (yes) As for the speed of smoke generation, it depends on the smoke generation coefficient and it is times the smoke generation coefficient times the burning rate. These two factors have to be multiplied. Therefore, if a material is chemically treated, the burning rate comes down and is decreased and thus the smoke generations speed also comes down. And in many experiments we have seen this.

Einhorn: If you have a polymer the temperature at which vaporization starts in our studies is earlier and a lower temperature. We see on many materials that we will have a lower degradation temperature which we find initial products of decomposition and then a more rapid rate which forms more or less a parallel, maybe lower, then a material that is not treated.

Saito: I think it depends on the materials that are used. We do see this kind of phenomenon according to some kinds of materials. The coagulation of smoke occurs and when temperature is higher as termperature increases an electric phenomenon takes place. A charged induced coagulation takes place and I think that when this takes place the charring of materials or decomposition is governed by the decomposition rate and charring rate.

Mulholland: A comment and a question regarding figure 40. As I look at the figure 40A, there is a flux on one axis, the weight of smoke. I interpret this to be the mass concentration of the smoke particulates. And the other axis, the optical density. The log of the transmitted light--that's correct? (yes) Then my comment is, there has been work at NBS, also work at the University of Utah by Professor Einhorn and Professor Seador on the dependence of the optical density on the mass concentration and the qualitative conclusion that one can divide smoke into two classes, depending on the mode of the combustion. One mode is a flaming mode. The other, a smoldering mode. The studies at NBS and Utah were restricted to specific combustion conditions in terms of the heat flux and the size of the sample that was being exposed. I wonder whether in your measurements you see a similar correlation in terms of the qualitative behavior of these two different classes of smoke, or whether you see many different types of correlation depending upon specific combustion conditions.

Saito: On the question that was just raised. The group led by Dr. Handa did make such experiments. This chart is rather insufficient. I think it was on page 38, yes, figure 40. These are the values that were taken, or the results conducted on that apparatus the value is 0.3. Sample weight was 0.3 grams and this was put into a box 0.125 cubic meters. I think therefore that we really have to correct or adjust some of the figures. In Japan building materials are being tested and in many cases the temperature taken as a parameter and we use an electric furnace and so at NBS and also in research conducted by Dr. Einhorn. I think that the units used are not the same and perhaps they have to be viewed differently. Smoldering and flaming have not been correlated in our cases.

Chaiken: With regard to the types of smoke that are produced during combustion, our experience in corridors or tunnels lined with wood suggests that the combustion phase can also be classed by the two types of smoke generations. And it seems to be directly related to oxygen concentration in the propagation of the fire along a simulated mine logging or wood mining tunnels. As the fire propagates from some ignition source at one end the rate of generation of volatile matter increase greatly with aerodynamic throttling of the intake air, this is an under force ventilation with a fan. At that point in time there is a very remarkable and drastic increase in smoke production which relates to a fuel rich burning condition and at that time in a 9" tunnel you actually prevent all optical transmission across the tunnel. The same observations have been seen in larger scale tunnel fires; an 8 foot wide tunnel, several hundred feet long. Not only would temperature be an important aspect of quantities of smoke but also the amount of oxygen. These results are for charring materials like wood and coal.

Saito: I do understand your point very well. When we think about fire I think that we should take another approach. There is more smoke that is generated from these materials when it happens at a lower temperature. However, when a real fire takes place what is most important is the rate of generation of smoke. Which means that the heating composition rate I think is an important factor. So in other words, I think that because of a large combustion taking place, then there is more flame generated too. I think this is the point of view that should be taken into account. I would like to entertain one more question.

Einhorn: May I use the blackboard? If we take douglas fir, which is a given type of wood which is used quite often. As we consider that a range from 1 to 10 watts per centimeter square and the corrected optical density at a 10 rate with a pilot flame of about 1.2 we are #1100, #550, and #250. These are corrected optical density 2.5, this is approximately 5.5, 5.7 ignition, 6.3. So we have smoke down and the weight could be plotted another way in flux one through ten. We have increasing and then decreasing. This is pre-ignition, ignition, and past ignition. Now there are some very interesting underfactors that come in. If we look at a material first of all with no pilot flame, we will find if we plot 5 watts, 2 1/2 watts. This will be 37,000 PPM CO_2 and this will be about 750 PPI. If we look at CO we see virtually no CO we have a pilot, let's make this pilot point. If we have a flaming ignition the CO_2 drops drastically and so one sees in the early phases as if we have no flaming, but only smoldering. High this is 5 - 2.5 CO and we have very high aldehydes, that an aldehyde may be at the level of 160 parts and 2 1/2 may be 70 parts. Actually another very interesting point, I should point out just a little bit. There is an induction period on the CO if you look at animals, this is very important because this is a CO generation which is slow in time, but in class of physiological response, such as blood pH, it drops drastically, the oxyhemoglobin drops drastically long before CO comes up. When we look at the CO hemoglobin the animals are incapacitated here, but then out here the CO's hemoglobin at a rate as if the aldehyde should not have been present. So in wood very early incapacitation in a smoldering mode is due to the aldehydes. And then CO loading and this relates between the ignition and the smoldering changes. We'll talk more about it tomorrow.

Saito: Perhaps my explanation was not enough. I would like to add a few words to what was just explained. As you pointed out there is such a relationship, when there is a flaming burn the quantity of smoke comes down that is true. However, what I am trying to say is that the issue is that when we take weight loss here and CSXV (observation) coefficient, this is the smoke generation coefficient K. I think that these are the values. If there is a fire in a room and there is a flashover taking place, then this comes down. But I think the issue is the temperature profile inside the room. Depending on the place in the room this K is different, changes when this becomes larger. It means that the space where the fire is taking place has been enlarged also. When this value is smaller if the space is larger then there will be more smoke that has been transmitted to outside the room.

Handa: I would like to explain to you again about 40A. I think that something is missing here. I would like to add to it. In the electric furnace that we use sometimes we do use radiation but in this case we changed the temperature from 400C to 600C. There is a window here and we put this in. The specimen. The curve of the temperature of the specimen goes down and then goes up. This is the actual scattering cross section. This is time we measure this in Japanese experiments. Dr. Einhorn said that the temperature changes go up and then come down. In size distribution surface volume diameter has the same kind of curve. The number of particles is very high. Why does this phenomenon happen? When this comes down the other goes up. By using an optical counter or optical pulse counter we have counted and seen these results. However, when we consider building materials we do not consider size distribution. We only think about the results from these experiments. Charged induced coagulation is taken into account more when we consider smoke generation. We take into consideration the differences in charges. We treated with fire retardant boite and inside the smoke the fire retardant is in proportion in a straight line. The fire retardant is not treated in this way. HBR is in the gas phase, this occurs in a radical fashion. We have had a very active participation in the discussion and I would like to thank all of you for your very active participation. As chairman of this meeting I would like to make a summary of the discussion that took place this morning and this afternoon. And if necessary I would have to contact you personally and re-check on what kind of questions you raised and if I should go to you personally to ask what questions were raised, I would like to ask your full cooperation. I am sure you have more questions on your minds. If that is the case, I would like the presentors of the reports and those participants to get in contact with each other, pri-

vately and have more active discussions on these issues. At this time I would like to close this gathering of this technical session of Detection and Smoke Properties.

Thank you very much.

The Progress Report
on
HUMAN BEHAVIOR
Prepared for the Third United States-Japan Panel on Fire Research
by

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The progress report on Human Behavior reflects the intensive and increased activity on human behavior in fire situations which has occurred since the second United States-Japan Panel on Fire Research meeting in Tokyo during October, 1976. There were two meetings at which a number of papers relating to human behavior were presented. At the Fifth International Fire Protection Seminar in Karlsruhe, West Germany, September, 1976 three interesting papers related to human behavior were presented. Probably the most significant meeting since Tokyo, was the Invitational Seminar on Behavior in Fires, at the University of Surrey, Guildford, England, conducted from March 23 to 25, 1977. This meeting was arranged by the human behavior fire research group in the Environmental Psychology Department of The University of Surrey. A second invitational seminar is currently being planned by the Program for Design Concepts of The Center for Fire Research to be held at the National Bureau of Standards, from October 30 to November 1, 1978.

The subject areas currently under intensive development related to human behavior in fire situations primarily involve evacuation studies, the investigation of the behavior of occupants of buildings in fire incidents, and the development of interaction models to relate the human behavior to the fire development. It appears more academic interest and international cooperation is developing toward the study area of human behavior in fire situations. It is to be expected this intensive study leading to the development of descriptive models from the case study observations of human behavior will result in the formulation of models in agreement with current concepts. The essence of such model formulation as developed at the Center

for Fire Research to enable the examination of the individual's action related to the fire development is attached as Figure 1.

Research projects which have been completed at the Center for Fire Research since October, 1976 involve the areas of emergency communications, behavioral response in fire situations, design implications of human behavior in fire situations, and an assessment of the technical literature related to emergency egress. Additional studies not completed involve the development of computer simulation models, sleep arousal and response to alarms, and the determination of behavioral response patterns in fire situations.

The research projects which have been completed are identified below with a summary of the project.

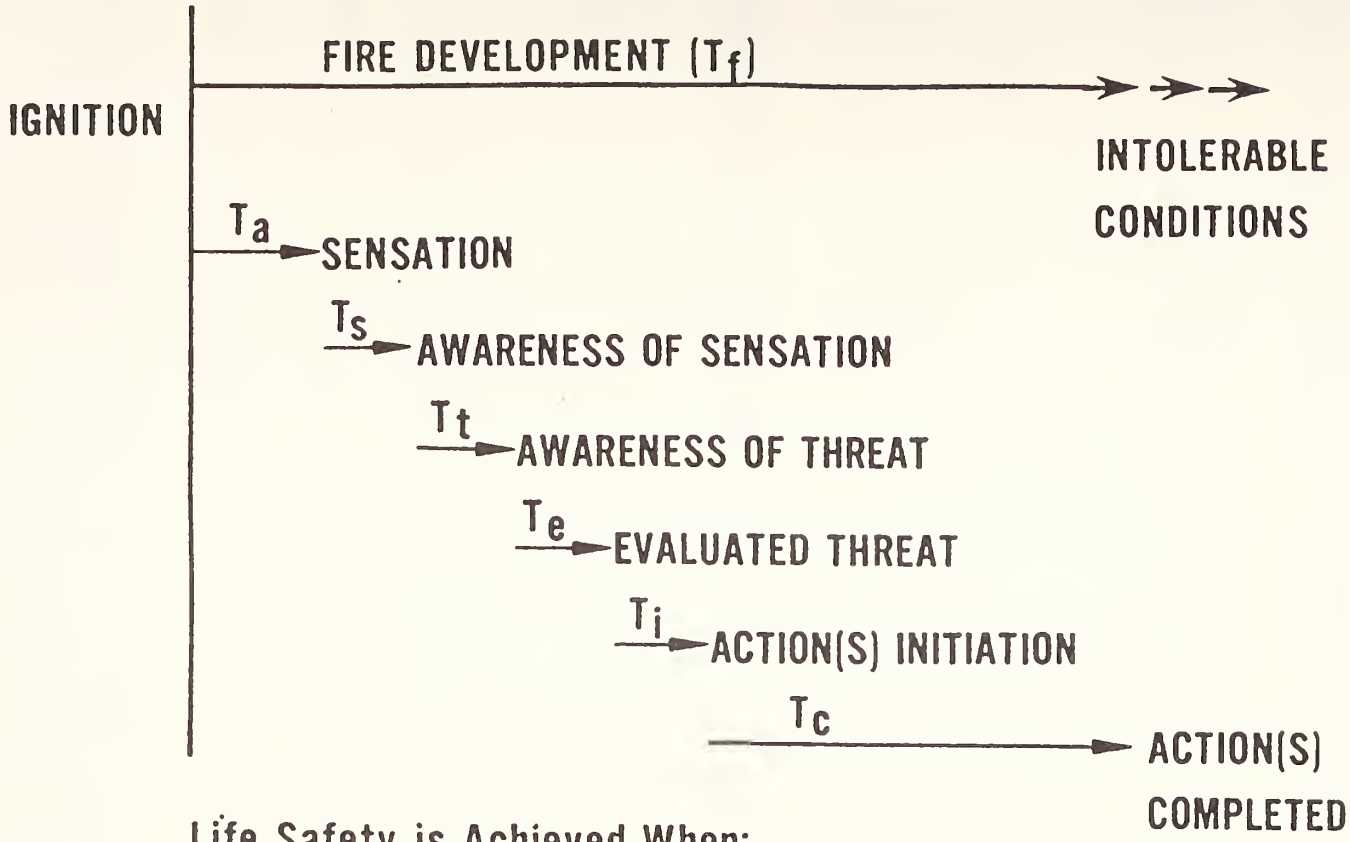
NBS-GCR-77-94 Smoke as a Determinant of Human Behavior in Fire Situations, (Project People). J. L. Bryan, University of Maryland, Fire Protection Curriculum, NBS Grant No. 4-9027, June 30, 1977.

The study involved the interviewing of 584 participants in 335 fire incidents, primarily involving residential occupancies. Variables related to the occupancy, amount of smoke spread, time of the fire, height and the previous alarms in the building were compared to the participant variables of age, sex, occupation, previous fire training and experience, location in the building, means of awareness of the fire, the response actions of participants, and the belief in the safety of the building. The study provided verification of many of the results of previous investigations and provided data on the differences between British and American populations.

NBS-GCR-77-102 Vocal Emergency Alarms in Hospitals and Nursing Facilities: Practice and Potential. John P. Keating and Elizabeth F. Loftus, University of Washington, Department of Psychology, NBS Grant no. 6-9106, July, 1977.

The project reviewed the usage of vocal emergency alarms in nursing homes and hospitals in the State of Washington. The project developed guidelines for the development of fire alarm messages and a sample message. The project recommended the vocal messages be: specific and directed exclusively to staff, disguised or coded, specifically directed to nursing staff, as simple and as

Life Safety-Time Relationship



Life Safety is Achieved When:

$$\frac{T_a + T_s + T_t + T_e + T_i + T_c}{T_f} \leq 1$$

FIGURE 1

brief as possible form of the message be focused on the fire situation, the code to be standardized, and the entire staff be alerted from the initial alarm. The project recommended the usage of the code: "Nurse Blaze".

NBS-GCR-77-106 People in Fires: A Manual For Mapping. Lars Lerup, University of California, Berkeley, Architectural Life Safety Group, NBS Grant no. 5-9016, 1977.

This project was a manual prepared for the fire investigator and presents the theoretical and technical procedures involved with the adaptation of this mapping technique by the fire investigator. The technique presented is useful as an analysis tool in developing a sequence of the fire and smoke development, as related to the behavioral actions of the participants. The procedures developed appear to be most valuable in relating the interaction between the physical environment of the building and the social environment of the occupants of the structure.

NBSIR-77-1313 An Assessment of the Technical Literature on Emergency Egress From Buildings. Fred I. Stahl and John Archea, Center for Building Technology, National Bureau of Standards, October, 1977.

The study involved a technical assessment of the literature related to the current emergency egress regulations utilized by the Occupational Safety and Health Administration. The following three research areas were identified: The carrying capacity of exitways; The design and use of signs, lighting, and visibility through smoke; and The research on occupant response and experiences in building fires. It is indicated the research on the behavioral responses in the fire incidents must also include data on the building arrangement and exit facilities, to be of value in the development of emergency egress regulations for buildings.

NBS-GCR-76-73 Mapping of Recurrent Behavior Patterns in Institutional Building Under Fire: Ten Case Studies of Nursing Facilities. Lars Lerup, David Greenwood, and John S. Burke, University of California, Berkeley, Architectural Life Safety Group, NBS Grant no. 5-9106, May, 1976.

This study involved the development of the mapping technique for the behavior of the occupants and the developmental stages of the fire.

The project involved a case study approach for ten nursing home fires in the United States. The procedures and techniques developed were utilized to illustrate the man-environment relations in the dynamic fire situation. The techniques initiated in this study were refined and futher developed in NBS-GCR-77-106 and NBS-GCR-77-93.

NBS-GCR-77-93 Human Behavior in Institutional Fires and Its Design Implications. Lars Lerup, David Cronrath, and John Koh Chiang Liu, University of California, Berkeley, Architectural Life Safety Group, NBS Grant no. 6-9013, February 28, 1977.

This project was an examination in further detail of the relationship between the actions of the personnel in nursing homes and the physical environment of the home during the fire incident. The human behavior was examined in sequences of behavior identified as episodes and was related to the developmental stages of the fire. Two recurrent types of behaviors were identified: The staff called the fire department even when it had already been notified, and investigated to verify the existence and severity of the fire.

The progress report also included the preliminary attempts at model formulation to indicate the interaction between the intervention strategries and the human behavior as developed at the Center for Fire Research and shown as Figure 2.

NBS-GCR-77-92 Simulating Human Behavior on High-Rise Building Fires: Modeling Occupant Movement Through a Fire Floor from Initial Alert to Safe Egress. Fred I. Stahl, Design Research Consultant, Order Number 512223, June 26, 1975, publication date August, 1977.

A Markov-based model has been developed to simulate the occupant movement patterns in response to life threatening situations on a single floor of a multi-floor office building. The factors influencing occupant movement in the model include: The location of the fire incident in both time and space; the occupants knowledge of egress routes; the occupants' perception of the location and severity of the fire threat; the occupants' perception of available alternatives; the occupants' threat-reducing

Fire Safety Intervention Strategies
vs.
Human Behavior Factors

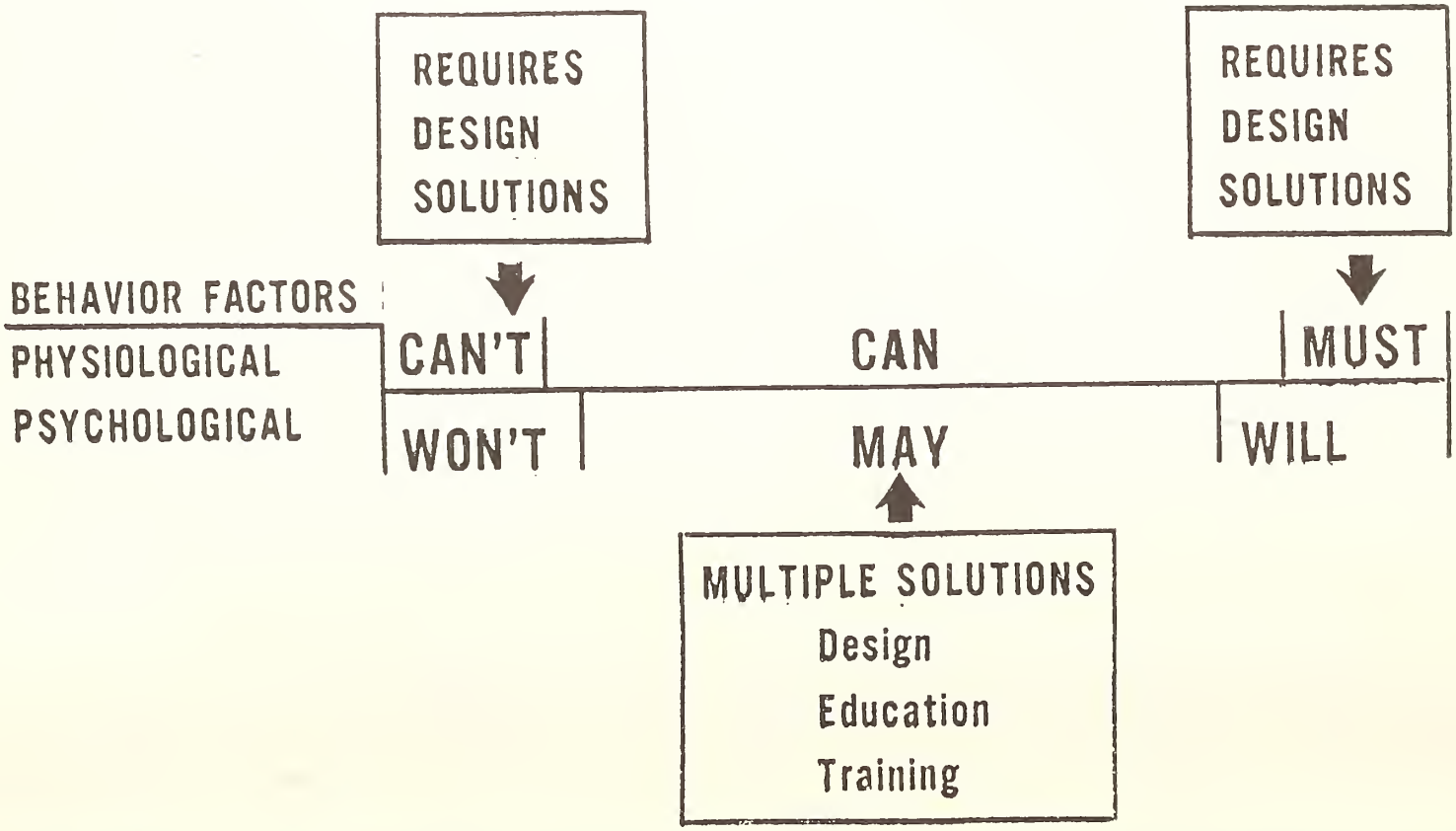


FIGURE 2

experience prior to the current movement decision; and the interjection of sudden interruptions to the occupants goal-directed behavior.

The research reports, NBS-GCR-77-94, NBS-GCR-77-102, NBS-GCR-77-106, NBSIR-77-1313, and NBS-GCR-77-92, were distributed to the members of the Japanese delegation. Following a presentation of slides describing the Beverly Hills Supper Club fire, copies of the National Fire Protection Association report, Reconstruction of a Tragedy, was also distributed. A bibliography of 192 citations was prepared and distributed to all the participants at the meeting.

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Progress --- Report on "Human Behavior" in Japan

S. Horiuchi, T. Jin

Studies on the "Human Behavior" in Japan are classified into the following three parts.

(A) Evacuation behavior through the analysis of investigations of real fires.

(B) Dynamic evacuation by computer simulation.

(C) Experiments of evacuation behavior.

However, although about each of the above items studies have been made intensively, exchange of information among workers has not been so active because of few opportunities for contacts.

In this report, we can only list concerned papers and reports published in the past year.

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M. Homma

(3) A Study on a City - Man System Simulator
S. Horiuchi and M. Kobayashi

(4) Visibility through Fire Smoke (Part 5 Allowable Smoke Density for Escape from Fire)
T. Jin

(5) Statistical Research on Stair - Accidents
K. Kinoshita and H. Nagata

(6) Fundamental Dissertation on the Curvature of Footpath (1) - Its humane radius according to a change of the direction -
M. Kishizuka

(7) Fundamental Dissertation on the Curvature of Footpath (2) - Relative chiefly to its human pattern "Slalom" -
M. Kishizuka and T. Goto

(8) Effects of Police Presence to Crossing Behavior of Pedestrians
M. Kobayashi and K. Koyama

(9) Study on Complicated Passenger Flow in a Railway Station
Y. Naka

(10) The Effects of Physical Environments upon Pedestrian Behavior
K. Nakamura

(11) The Cost - Benefit Analysis of Traffic Safety Measure Based on Behavior Analysis
K. Sakurada

(12) A Study of Pedestrian Environment Planning in a Residential Area
H. Takatsuji

(13) Investigation of Functions to guide Pedestrians in Public Institution
- On the stairs in railway station -
T. Uehara, Y. Kuriyama, K. Kato and M. Kato

(14) A Simulation Model of Crowd Flow in Emergency
I. Yoshihara, M. Ohnari, K. Nakao and M. Oguri

[Group C]

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CURRENT U.S. SYSTEMS ACTIVITIES IN FIRE SAFETY DESIGN

Harold E. Nelson

Third Joint Panel Meeting
UJNR Panel on Fire Research and Safety
Progress Report
General Reports, Topic 2-Building Systems

Background

The subject of Building Systems was covered by general reports numbers 3 and 4 at the Second Joint Panel meeting.

Report number 3, "Directions to Improve Application of Systems Approach to Fire Protection Requirements for Buildings" by Harold E. Nelson (U.S.) briefly reviewed the background of fire safety systems approaches in the U.S. and discussed a potential approach based on the states transition model.

Paper number 4, "What Should be Architectural Safety Planning Against Fire," T. Terai (Japan) outlines fault tree and other event logic analysis approaches to an analytical fire safety evaluation of building systems. Professor Terai emphasizes the formal concepts of Failure Mode and Event logic and reliability theory.

Work in amplifying and applying the approaches discussed in both of these reports is underway. As with the two papers most of the present work continues to be the development of methodologies. Implementation of the methodologies however requires either the application of extensive judgment or the development of significant new data.

The work on the mathematical modeling of fire growth, the simulation of human behavior, and other deterministic modeling will eventually provide an improved data base. In the meantime existing data must be incorporated with experience and professional judgment in the application of any of the probabilistic approaches covered under the general title of Building Systems.

Organization of Report

This report consists of brief abstracts and source references for 16 ongoing activities related to the application of probability systems in evaluating the level of safety or determining the fire safety requirements for buildings. In order to organize the scope of the ongoing efforts and their relation to each other, Figure 1, a matrix comparing the purpose of the effort against the type of analysis system has been prepared. The definition of each matrix title follows:

1. Purpose. Sphere or areas of use most appropriate for the application of the product or systems approach involved.

a. Broad policy (technology assessment). The evaluation of the impact of policy decisions affecting many facilities, locations, products, or activities. Frequently the questions involved relate to the impact of a single subordinate requirement (e.g. the combustibility of furniture, provision of detection, requirements for emergency drills, etc.) on an otherwise uncontrolled or varied inventory of facilities.

b. Code or regulation preparation or analysis. The evaluation of the overall impact of a comprehensive fire safety code or set of regulations on the inventory of all buildings so regulated. This concern differs from the technology assessment impact in that the concern is normally for the complete spectrum of requirements prescribed by a code type document.

c. Design or renovation of individual facilities. The development of the maximum design flexibility and discovery of all potential satisfactorily safe alternatives available to the designer. The objective may be to discover alternatives that meet the minimal legal requirement or may be a search for the most cost effective means of optimizing fire safety.

d. Evaluation of existing facilities. Mechanisms for evaluating either the actual or comparative level of safety in an existing structure.

2. Type. The data and probability handling approach involved.

a. Decision analysis. This covers formal decision probability approaches of the type described by Howard Raiffa in his book "Decisions Analysis, Introductory Lectures on Choices under Uncertainty."* This approach has the capability of combining technical, economic, social, and any other factors of uncertainty in a single decision tree. The approach eliminates all factors that do not vary between the alternatives being considered regardless of their individual impact. This approach requires that the alternatives to be compared are fully described before designing the specific decision tree or executing the concept.

b. Event logic analysis. This may be described as fault tree, reliability analysis, or fire safety decision tree analysis. The approach is designed to either determine all of the available alter-

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* Raiffa, Howard, Decision Analysis, Introductory Lectures on Choices under Uncertainty; Addison Wesley; Reading, Massachusetts; 1968.

natives or to describe all of the potential mechanisms for failure. This approach initiates with either a description of the objective level of safety or a description of the event (fault) to be avoided.

c. State transition. This approach is primarily designed to utilize potential outputs from event logic analysis or other sources and to relate them to the envisioned state by state (realm by realm) growth of fire.

d. Evaluation (grading) systems. Pragmatic, stochastic, or other approaches directed at producing an answer based on the measurement of arrangements or conditions and a relative simplified grading system.

e. Input data. Approaches at establishing the variables and other inputs required for the probabilistic systems. In general this report omits mathematical modeling approaches in view of the extensive coverage elsewhere in this joint meeting. The modeling approaches will eventually provide the base for the development of the most accurate system inputs.

Abstracts of Current Building Systems Projects

The following is a list of abstracts of ongoing projects in the area of application of probability concepts to building systems. Those selected are felt to be of current significant importance. The relationship of these projects to each other in terms of their purpose and type of approach is shown in figure 1. The numbers shown in figure 1 correspond to the subparagraph numbers listed below.

1. Upholstered Furniture Fire Losses Project; B. Buchbinder and S. G. Helzer, Center for Fire Research, National Bureau of Standards and F. L. Offensend, S.R.I. International. This is a pilot project to evaluate the worth of decision analysis techniques in determining the impact of major regulatory or code decisions on the U.S. national cost plus loss impact of fire and the cost of protective measures. The initial analysis compares continuance of current regulations with the impact of a mandatory cigarette ignition prevention requirement for upholstered furniture or mandatory smoke detector requirements in all residences. The report of the first phase has been published. The report title is "Preliminary Report on Evaluating Alternatives for Reducing Upholstered Furniture Fire Losses", Buchbinder, B.; et. al. (NBSIR-77-381) National Bureau of Standards, Washington, D.C., 1977.

2. Evaluation of Automatic Residential Fire Suppression Systems; Rolf Jensen and Associates, Inc. The Jensen firm has as part of a contract to evaluate the potential of automatic sprinklers and other extinguishment systems for residential facilities produced a decision tree analysis of the variables involved. Principle drafting of the tree

and production of the variables was by Peter L. Yukonis. This project uses a complete event logic tree as a mechanism of determining broad policy impact. Two trees were developed, one for property protection impact and one for life protection impact. Both trees are very extensive and are supported by approximately 150 probability distributions. About half of these distributions are presented as input data and about half are derived from functions in the trees. These trees propose mechanisms for combining dis-similar elements in a single risk probability statement. The final report has been submitted to the National Fire Prevention and Control Administration but it has not yet been published.

3. National Fire Protection Association Committee on the Application of Systems Design to Structures; Henry Roux, Chairman. This NFPA committee has been an important element in the development, encouragement, and distribution of information and concepts on systems approaches to fire safety in the U.S. The committee has produced the "NFPA Decision Tree" a widely used event logic tree. The committee also has operating task groups working on projects to relate existing standards and regulations to the NFPA decision tree, to develop and promote education in basic systems concepts, to identify and evaluate other systematic approaches to probability analysis to fire safety aspects of structures, and the development of the probability of events described in the tree. The Event Probability Task Group is attempting to both develop the basic concepts and requirements for determining event probability from data of all types. A specific objective of this task group is the use of the technical committees of NFPA as judgment cells that will combine data and information with judgment and experience to produce estimated probabilities of events. The NFPA decision tree is available from the National Fire Protection Association, Boston, Massachusetts. The other activities of the committee were most recently reported in the Technical Committee Reports of the NFPA Fall conference, Atlanta, Georgia, November, 1977.

4. Fire Protection Engineering Systems Design, the State-of-the-Art; Society of Fire Protection Engineers under grant from the National Fire Prevention and Control Administration. This project, initiated in 1977 is directed at the development of a general fire protection engineering design text book. Phase I, now underway, will be primarily directed at the presentation of one basic methodology of applying fire protection engineering principles to determine building requirements or evaluate fire safety of existing facilities. The basic approach planned by the SFPE editors is derived from the concepts of the goal oriented systems approach as modified through the experience of the editors and other sources. The editorial staff consists of Dr. Robert Fitzgerald, Worcester Polytechnic Institute, principal editor; Rolf Jensen, Rolf Jensen and Associates, review editor; and Rexford Wilson, FirePro, Incorporated, review editor. The Phase I textbook on the methodology is targeted for completion during 1978. The project monitor is Mr. John Ferguson, National Fire Prevention and Control Administration, Washington, D.C.

5. The Study of Fire Safety Effectiveness Statements; University of Maryland under grant from the National Fire Prevention and Control Administration, Mr. Jack Watts, Principal Investigator. The contract target completion date is October 1978. This study deals with the development of guidelines for preparing fire safety effectiveness statements as charged by the Fire Prevention and Control Act of 1974. The first step is the definition of such statements in terms of the historical development of the concept, and proposed scope and objectives. The next step is to identify the variables which are significant to fire safety. This will be undertaken in the sequence of enumeration, nominal classification, ordinal classification, quantification and selection. Following this, the various approaches which appear to have potential for creating the statements will be evaluated. These are presumed to fall into the categories of analytical, probabilistic and simulation approaches. These approaches will be compared to the identified key variables for their comprehensiveness. Selected approaches will be further evaluated in terms of facility for application, cost/benefit and legal ramifications.

6. A Theoretical Rationalization of a Goal Oriented Systems Approach to Building Fire Safety; Jack Watts, University of Maryland. This project conducted under grant from the Center for Fire Research undertakes a methodological analysis of GSA Goal Oriented Systems Approach to develop a more theoretically based probability approach to fire safety in structures. The final report is now in preparation. This report will include a review and an analysis of an existing goal oriented systems approach in terms of recognized operations research concepts. The author has developed revised models that he believes enhance and improve the approach. He has also examined distribution forms, sensitivities, and various principles of parameter estimation. A final report including the proposed revised model is targeted for the first half of 1978. It is expected that it will be published as a contract grant report by the Center for Fire Research. An interim report covering both background explanations of the present goal oriented systems approach and an appendix describing that approach in detail is currently available. This report is NBS-GCR-77-103, The Goal Oriented Systems Approach, Jack Watts, University of Maryland issued by the National Bureau of Standards, Washington, DC.

7. Learning from Fire, A Fire Protection Primer for Architects; Lars Lerup, David Cronrath, and John K. C. Liu; Architectural Life Safety Group, University of California, Berkeley. This primer prepared by the Architectural Life Safety group for the NationalFFire Prevention and Control Administration presents a qualitative, graphic model and analysis of fire growth in residential space. It is principally directed at architects, public officials, and others who are interested in the concepts of fire growth rather than specific quantitative measurements. The primer describes fire in a state transition concepts using the event logic tree to explain fire development at each state (realm) of fire development. The report has been published by the National Fire Prevention and Control Administration.

8. Development of Engineering Models and Design Aids to Predict Flame Movement and Fire Severity Within a Room; Dr. Robert W. Fitzgerald, Worcester Polytechnical Institute. This is the report of a grant to Dr. Fitzgerald from the Center for Fire Research. The report describes a framework of an engineering model approach developed by Dr. Fitzgerald for determining the probability of flame movement and fire severity within a room. The material is directed at producing probability predictions as needed for the goal oriented systems approach or other event logic and state transition models. Dr. Fitzgerald does not provide the mathematical modeling or any other deterministic approach to the establishment of specific numerical relationships between variables or the actual calculation of probable spreads or severities. Instead Dr. Fitzgerald lays out an approach for analyzing the impact of the existant physical conditions using best available data in combination with formal academic and engineering committees as a final judge. He uses the development of civil engineering as the model to be followed. Report of Dr. Fitzgerald's work is currently being printed and will be issued as a contractor/grant report by the Center for Fire Research in the near future.

9. Risk Management and Reliability; Myron J. Miller, Factory Mutual Research Corporation. Mr. Miller presented a paper which is published as part of the proceedings of the Third International Systems Safety Conference sponsored by the Systems Safety Society and held in Washington, D.C. in October, 1977. Mr. Miller analyzes the use of probability in fire safety design from the standpoint of major industrial risks. His area of concern is high-value, highly-protected risks. The basic premise of Mr. Miller's paper is that mechanical or man induced failures of automatic fire control systems is the overwhelming determinant of fire risk management in such facilities. Mr. Miller develops a much more numerical approach (as compared to other work in probability systems) by concentrating on the system reliability factors and obtaining data from fire loss statistics.

10. An Introduction to the Measurement of Fire Safety in Buildings; Rexford Wilson, FirePro, Inc. The current work and concepts of Mr. Wilson in application and use of the goal oriented systems approach were presented in the subject paper and published in the Proceedings of the Third International Systems Safety Conference. Wilson has progressed extensively in the development of worksheets and guides for handling and manipulating the variables in the probabilistic approach. It is expected that significant portions of this presentation will reappear in the SFPE text book covered in item 4 above.

11. Fire Safety System Approach Courses. Over the past several years Dr. Fitzgerald and Mr. Wilson has conducted a total of 19 courses for both graduate and undergraduate engineers in the goal oriented systems approach. Approximately 400 students have completed the course. It is understood that a number of graduates who are engineering professors have included fire safety systems probability concepts in their

course work. It is felt at this stage that the impact of these courses has been intensive in at least the qualitative aspects of improving understanding the concepts of event logic trees and their application to the fire safety design of buildings.

12. Fire Safety Systems Analysis for Residential Occupancies; National Fire Protection Association. The National Fire Protection Association's Research Division is undertaking evaluation of fire safety systems analysis and their application to residential and other types of structures under contract from the Department of Housing and Urban Development. The first report of the project has been published in two volumes with the subject title by the Department of Housing and Urban Development. (HUD-PDR-268-2 November, 1977). The work of the NFPA has been one of the lead activities in developing the states transition concept as discussed in Nelson's paper at the Second Joint Conference. The approach of the NFPA research is multi-directional. Currently the model studies both the development of fire in a spatial (realm) and temporal (time in realm) probability analysis. The model attempts to simultaneously handled the variables of space and time. Test runs of the model have concentrated on predicting the extent of fire spread against time and the rate of obstruction of egress routes from fire or other fire caused effects against time. A strong emphasis is being placed by the NFPA Research Division on analysis of statistical fire incident data and fire test data to select the form and parameters of the best fit distributions at each potential fire transition (i.e.: from realm to realm.) One of the principles of the NFPA model is to separate data which may take various forms and have various levels of confidence from the actual working model. The project director for the NFPA is Mr. Joe Swartz, the principal investigator is Dr. Jeffrey Berlin, the monitor at the Department of Housing and Urban Development is Mr. William Werner.

13. RFIRES Model (IITRI, Ron Pape, Principal Investigator). This model is primarily a mathematical model of fire development and as such will be more extensively covered in the mathematical modeling section of the joint meeting. The model however is designed to handle probabilistic distributions of burning rate inputs. The model is designed to handle either deterministic to probabilistic data. This is currently available in the existing computer code for the model. The concept of the model is a state transition concept. It is equipped to handle only a single environmental condition at a time. It is therefore primarily suitable for evaluating specific detailed environments. While several preliminary reports of the model have been published it is in a constant state of development. Any interested parties should contact Mr. Pape directly at IITRI.

14. Fire Safety Evaluation System for Health Care Facilities; Center for Fire Research, National Bureau of Standards. This rating system is being developed to evaluate the relative equivalency of different arrangements of recognized life safety features in buildings that do not necessarily conform with the specific requirements and allowances of specific codes. The approach involves a combination of data and a focused consensus on the specific relative worth of individual protection sub-systems compared to other approaches. Equivalency is judged to exist where the total impact of risk factors and compensating safety features produce a level of safety equal or greater than that achieved by rigid conformance to the specific requirements of a code. The criteria for equivalency is measured in both of terms of overall safety impact and depth of redundancy. The product is visualized as an applicable system distinctly advanced beyond current code concepts but still within the range of present technology and reasonable judgment decisions. The initial approach addressing health care facilities is in an advance state of completion. The final working package consisting of the necessary forms and manual along with a background report to support the approach is targeted for completion in the third quarter of 1978. Harold Nelson, Center for Fire Research is the responsible program officer.

15. Analysis of the Technological Base for Evaluating the Rate of Growth of Fire Risk Versus Egress Time in the Workplace; Center for Fire Research. This work is part of a project studying egress hazards being conducted for the Occupational Safety and Health Administration. It is directed at developing the best statement of the current technical knowledge and fire growth theory presently available to either determine the rate of growth of fire risk or to assist those responsible for filling technical gaps with judgment decisions. The areas of prime interest include both the development of fire within the room of origin and the spread of fire and fire effects from that room. This project is a partial attempt at undertaking the organization and expression of knowledge proposed by Nelson in his paper at the Second Joint Conference. The initial phase is targeted for completion in the fourth quarter of 1978. The responsible program officer is H. E. Nelson.

16. States Transition Modeling; University of California, Berkeley, Dr. R. Brady Williamson. Dr. Williamson has proposed a series of states transitions based on his observations during room fire tests conducted at the University of California and elsewhere. He has proposed that establishment of the time between these points of transition should be a recorded item in each test. The collected distribution of times would then have the potential of providing a frequency distribution that could be used to determine the probable time of realm transition in a states transition model. Dr. Williamson proposes that the impact of variables such as ignition source, fuel, room volume, ventilation, and the thermal characteristics of the bounding surfaces be varied and that a distribution be established for the variables. Dr. Williamson's

concepts are reported in his paper entitled "Quantitative Fire Hazard Analysis" published in the Proceedings of the Conference on Designing to Survive Severe Hazards sponsored in November of 1977 by Illinois Institute of Technology Research Institute in Chicago.

Conclusions

There is a significant amount of activity in the U.S. centered around several different approaches to probabilistic and analytical system approaches to building design. In general the more sophisticated and detailed approaches have concentrated on qualitative overviews and the methodology involved in quantitative measurements. For the most part these systems have either used hypothetical values for the variables to produce examples or have used the judgment of "experts" in establishing the values of the input variables.

While progress is being made and the various system approaches are having a degree of impact on fire safety design in U.S. they generally face problems related to:

A. Proofing of the inherent appropriateness and internal consistency of the systems elements, arrangements, and system calculations. Proofing of such systems is difficult and there is no existing protocul or guide for this.

B. Obtaining sufficiently valid event probability data. Many of the building design systems demand data that either does not exist or is of less than varifiable quality. The softness of the data tends to erode confidence in the results. Currently most calculated systems approaches are considered to be supplemental design assistance rather than an individual and unique determiner.

C. Understanding the meaning of the outputs. In many systems the results are expressed in probabilistic terminology. The meaning and relevance of such probabilistic statements to the economic sociological goals of fire safety building design is vague. There is a need to examine and rationalize the expression of fire safety objectives and risk management goals in terms that are meaningful to both the responsible administrators and to the systems concepts.

TYPE \ PURPOSE	BROAD POLICY (TECHNOLOGY ASSESSMENT)	CODE/REGULATION PREPARATION ANALYSIS	DESIGN OR RENOVATION OF FACILITIES	EVALUATION OF EXISTING FACILITIES
DECISION ANALYSIS	CFR/SRI (1)			
EVENT LOGIC ANALYSIS	RJA (2)	NFPA Systems Committee (3)	NFPCA/SFPE (4) CFR/Univ. of MD (6) CFR/WPI (8) Wilson (10) Wilson/Fitzgerald (11)	NFPCA/Univ. of MD (5) FM/Miller (9)
STATE TRANSITION			NFPCA/Lerup (7) RFIRES/IITRI (13) Univ. of California-Berkeley (16) Williamson	
EVALUATION (GRADING) SYSTEMS			CFR (14)	
INPUT DATA			CFR (15)	

FIGURE 1. PURPOSES AND TYPES OF BUILDING SYSTEMS EFFORTS

PRESENT STATUS OF RESEARCH ON FIRE SAFETY SYSTEMS FOR BUILDINGS

K. Kawagoe
Y. Morishita

I. Introduction

An outline of the recent research conducted in Japan on fire safety systems for building is presented in this paper, which is centered on the studies done by the Committee of Fire Safety Systems founded in April 1977 in the Japanese Association of Fire Science and Engineering. The Committee of Fire Safety Systems is a committee aimed at the development of a General Evaluation System for the fire protections of buildings and is the first organized research group to conduct research of this field. In addition to the discussions that are being carried out on the method of composition of fire safety systems and the concept of safety, this committee has done studies with regards to the method of evaluation of subsystems such as the smoke control system and fire extinguishment system, etc. with several successful results.

Further to the results of these research conducted by the Committee of Fire Safety Systems, the studies carried out by the Committee of Fire Safety Performance of Houses arranged by the Ministry of Construction on the evaluation of fire safety performance of houses are also introduced in this paper. In this research, attempts are made to grade the risk of fire into several steps, thus calling for deep interest as a method of evaluation of the degree of fire risk of houses.

II. Background of the Research

It may be meaningful to discuss the background of the necessity for these research on the fire safety systems for buildings in Japan, prior to the discussion of their results, in making a clear view of the aim of these research.

When looking back at the research so far carried out in Japan on fire protection, one could see that researches are made on subdivided field such as the combustibility of materials, fire endurance of structures etc., and the results of these researches are applied in actual design of buildings only by applying the results in each field to the each regulation for the specification of planning.

However, very few studies is made on the interrelationship among the research on each field and how the safety is maintained as a whole and therefore, the regulations are formed by the accumulation of regulations for the specifications of planning in each field. Under these present circumstances, the construction of buildings is done to satisfy the regulations with respect to fire safety, but without having a knowledge of the degree of danger against fire as a total system. Such stiffened regulations relevant to fire safety have become a hindrance to the flexibility of design and recently, a tendency is seen that the architectures are demanding to give the interchangeability to fire safety measures. In addition to the anxiety of the architectures for research on fire safety systems, 1) administrative intention to systematize the regulations with scientific backing and 2) anxiety for the systematization of fire safety

research and there by to confirm the direction of future research, are considered to exist potentially.

As a reply to the interests shown with respect to such research, Toshio TERAI has already done studies on the topic "What should be the architectural safety planning against fire?" while Yoshio MIMURA has made a study "On an acquirement of fire safety in buildings". These studies were already published at the UJNR Second Joint Session held in October 1976. Be the matter what it may, very little research has been carried out in Japan regarding fire safety systems, and with the establishment of the Committee of Fire Safety Systems of the Japanese Association of Fire Science and Engineering, it can be said that a start is given to the research on this subject.

III. Research by the Committee of Fire Safety Systems

"Research on the General Evaluation System of Fire Protection of Buildings"; April 1977 -

This Committee was founded by the Japanese Association of Fire Science and Engineering in April 1977 for the development and research of general evaluation system for fire protection, and consists of six working groups as shown in the figure 1.

The four groups, namely, Compartment Fire Group, Smoke Control Group, Detection and Extinguishment Group and Evacuation System Group carry out research on the composition of fire protections within each subsystem and the quantification of system, while the remaining two groups of Total System Group and Maintenance System Group conduct research on the composition method

of subsystems and the goals of fire safety.

In starting with the research, the method of evaluation was not unified among these groups, so separate evaluation systems were prepared by each group. For example, the Smoke Control Group makes an attempt to evaluate the Smoke Control System from the sequences of main causes and their results and from the probability of generation of these sequences, while on the other hand, Evacuation System Group makes an attempt to evaluate with the ratio of evacuable persons as the scale using a deterministic simulation, showing little resemblance among the evaluation methods of the subsystems. However, considering the fact that fire hazards are multifarious, development of these various systems are rather desired, and by discussing the problems that were made clear during the development procedure of these systems, knowledge of fire hazards as a whole could be deepened and further, it may be possible to arrange finally as a total system.

The results of the research carried out by each group are described below.

(1) Total System Group

This group conduct research centered on the two topics; a) How to assemble the subsystems as a whole, b) How to establish the goals of fire safety.

With regards to a), consideration is made on the already available research on total system and systems that are considered possible to be developed in the future. The

types of total system were categorized into (i) Decision Three System*1, (ii) Sensitivity system*2, (iii) Category Value System*3, (iv) Sequence System*4 and (v) Stochastic System*5, and the characteristics and problems of each system were observed. It is considered that in addition to these systems, their combinations also could be taken up as total systems.

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*1. A general evaluation system for fire protection developed by G.S.A., N.F.P.A.
The probability of success of the total system is determined by probabilistic calculations from the static probability of success with respect to each event.

*2. After graphical representation of the composition of elements with respect to the total system, the relative importance of the elements is calculated by comparing the variation of elements with the variation of total system.

*3. A score is given to each element that composes the total system and the score of total system is determined from the score of elements by a predetermined calculation method.

*4. The sequence of uncertainty factors within the systems is first assumed and then the system is evaluated by adding up the products of the output (for example,

success or failure) of the system with respect to the sequence and the probability of occurrence of the sequence.

*5. A stochastic model is prepared with respect to evacuation, smoke movement, fire spread and extinguishment, and simulation is repeated many times as much as required, using the values obtained from the probability distribution of the parameters of this model as the input data.

With regards to (b), a questionnaire survey was done as to how the people evaluate loss of life and loss of property. Results of the survey made clear that (i) some people have psychological resistance towards the comparison of human life with money, (ii) more than half of the people evaluate the magnitude of the disaster by the number of lives lost. (iii) some people evaluate the size of disaster considering both the loss of life and the loss of property. From these results it is concluded that most important in the evaluation of disaster is the human life, that this is a basis for evaluation convinced by more than half the people, and further, that pecuniary losses also should be considered to a certain degree as a factor in the evaluation.

(2) Maintenance System Group

This group studied the methodological problems in making a fire safety system and suggested the following as the steps for the preparation of a fire safety system.

(i) Clarification of the frame, constituent elements and input of the system, (ii) development of the evaluation method, (iii) standardization of the inputs for the system, (iv) clarification of capability of the system, (v) clarification of reliability of the system, and (vi) application of the evaluation system.

Further, this group has pointed out the following with respect to the maintenance problems of the fire safety system.

[1] The problems related to fire incidents are not necessarily caused by the imperfection of engineering system in the planning, but rather by careless mistakes in the maintenance. [2] Therefore, a standard maintenance conditions are to be established first and the system is to be planned based on these conditions. On the other hand, the reliability of the maintaining of these standard maintenance conditions becomes the most important point in a practical system.

(3) Compartment Fire Group

This group has made an attempt to evaluate the fire spread taking the development of fire phases as the measure. In other words, compartment fire is categorized into five phases, namely, (i) Ignition Source Phase, (ii) Primary Ignition Phase, (iii) Partially Burning Phase, (iv) Whole Compartment Burning Phase and (v) Inter-compartment Burning Phase, and the evaluation is made by taking the transition probability from one phase to the next as the measure. The transition probability from one phase to the next is

calculated by the procedure shown in the figure 2. Out of these steps, the part showing the making of a mathematical model of burning is the principal object of the immediate work, and currently, the preparation and improvement of mathematical model of burning and mathematical model of materials temparature rising is being carried out.

(4) Smoke Control Group

This group is making a study to determine a value corresponding to the capability of smoke control system using the possibility of smoke entering the stairs area. To put it concretely, by assuming a highrise building with 50 floors, sequence of various factors such as season, wind direction, wind velocity, floor where the fire started etc., that govern the smoke movement, and the probability of these sequences are calculated. Further, a method is adopted by which a judgement is given whether or not the smoke enter the stairs area with respect to each of these sequences based on the results of the calculation of smoke movement. According to the results of calculations, the probability of smoke entering the stairs area is 50% when there is no forced smoke control and it reduces to 19% when there is forced smoke control.

(5) Detection and Extinguishment Group

The aim of research carried out by this group is to determine

quantitatively the system effectiveness of equipments for fire extinguishment, as function of hardware capability of the equipments and human reliability. In this case, statistical methods are adopted based on data relevant to inquiries of fire incidents.

First of all, a total of 120,000 cases of building fire in the whole country were subjected to a preliminary analysis of the extinguishment activity in early stage of fire spread. From the results of this analysis, it was clarified that there is a difference in means to report according to the reporter and the region which cause several problems in a statistical analysis, showing that there is necessity to determine the effectiveness of the equipment for fire extinguishment based on a fire survey conducted by the same authority by the same method. Therefore, this group is now working to determine the hardware capability and human reliability of the equipment for fire extinguishment based on data of 4,000 cases of fire, for which the operational conditions of equipment for fire extinguishment were investigated and reported by a single authority. Further, when data are not available or not sufficient for the operational condition during actual fire period, the effectiveness of the equipment is determined by a technique for prediction of equipment reliability based on data of ordinary times. For example, in the case of smoke detectors for which data are not sufficient, the effectiveness was estimated by two methods of prediction and it was found that their failure rate is $2.6 - 7.5/10^6$ hour.

(6) Evacuation System Group

This group is preparing an evaluation system by which the escape routes can be evaluated using a deterministic simulation of evacuation. In this case, ratio of persons who could evacuate to the safe zones such as the stairs area without being involved in smoke gives the measure in the evaluation system. In other words, by taking the velocity of smoke spread, number of occupants, walking velocity, and floor area as the evacuation conditions and assuming the number of exits from the room, their disposition and width as the variables that could be adjusted at the stage of planning for evacuation, comparison among several plans is made by simulation using the ratio of the number of persons who could evacuate without being involved in smoke as the measure. At present, an evaluation system is ready with respect to the evacuation from the floors of fire occurrence in buildings with wide space, such as department stores and offices.

Above is the present state of development of research done by each working group. As mentioned earlier, the methods used by these groups are not necessarily the same, so it is necessary to debate how these results of research done by each group could be arranged in a single total system in order to make a general evaluation of the fire protection of buildings.

IV. Research by the Committee of Fire Safety Performance Houses

"Research on the evaluation of fire safety performance of houses" April 1974 - March 1978.

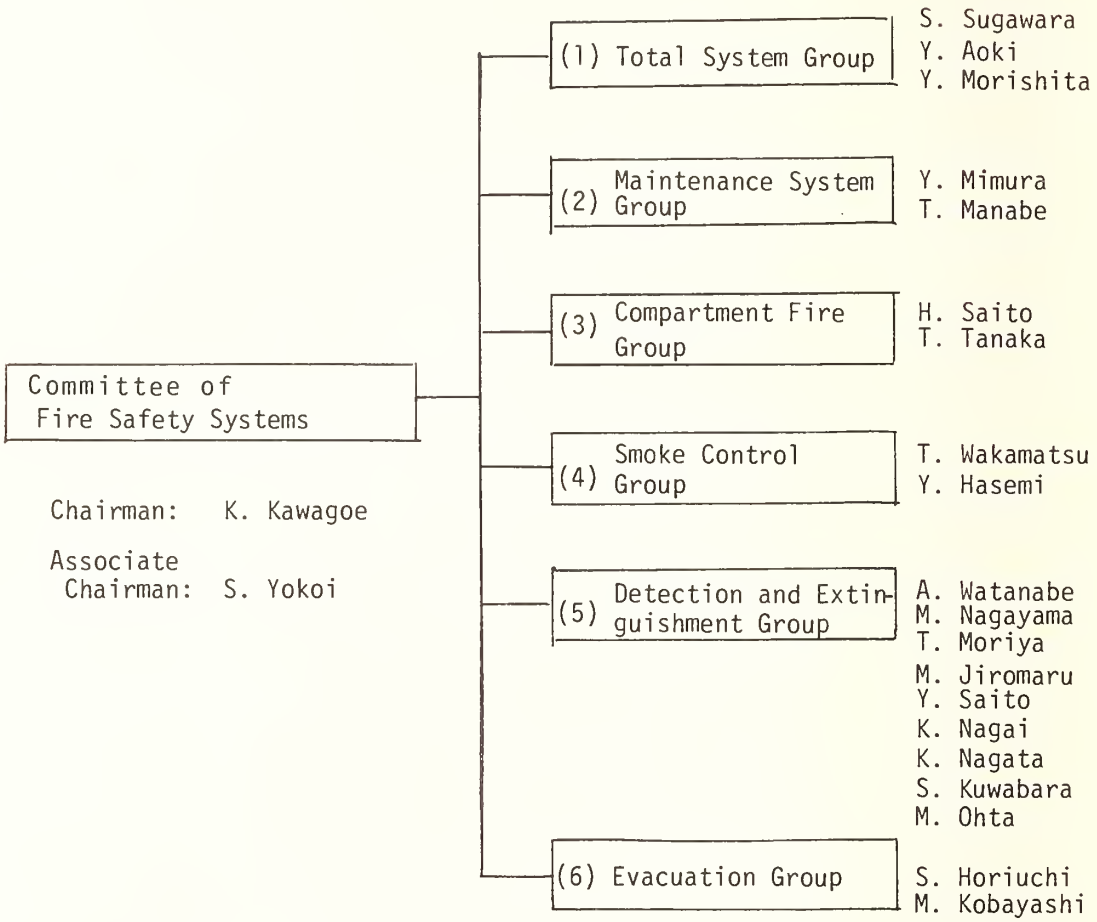
The Ministry of Construction arranged this committee in 1974 in order to develop a method of evaluation of fire safety performance of houses with the aim of providing houses to the users after clearly distinguishing the grade of fire risk. The Committee is expected to report the results of their work in March 1978, and at present a draft for the evaluation system of fire safety performance of houses is being prepared.

In the preparation of this evaluation system, factors that are related to the fire risk are evaluated in individual stages, namely, 1) Ignition stage, 2) Early stage of fire spread (before flash over), 3) Fire propagation stage in whole house, 4) Inter-houses propagation stage and 5) Evacuation stage, and the results of the evaluation gives the data for grading fire risk. For example, at the 1) Ignition stage, the heat sources are evaluated with the ratio of annual rate of outbreak of fire in the subject to the average rate of outbreak of fire in a house as the measure and the results of this evaluation are then graded. 2) In the Early stage of fire spread, scores are given to the interior finishings, live fuel and equipments for fire safety according to their type with due consideration given to the fire risk, and the total score obtained by a certain calculation method is graded. 3) In the case of fire propagation stage in whole house, the elapse of time of the fire propagation in a house is determined after establishing the relationship between the fire

propagation time and the factors such as live fuel, fire protection performance of partitions etc., that are related to the fire propagation risk between rooms, and the results thus obtained are then graded. 4) In the case of inter-house propagation stage, the fire protection performance of outer walls, insides of eaves, openings etc., are graded and further, based on this grading, the required distance between two houses is specified. 5) In the evacuation stage, the reliability of passages, doors, windows etc., that compose the escape route are first established and the reliability of a given escape route is then calculated and the results thus obtained are finally graded.

In addition to the preparation of a draft for the evaluation system, this committee carried out research on the statistical analysis of fire incidents, fire tests of furnitures and mathematical model of fire, in order to obtain the fundamental studies for the preparation of the system. Out of them, the fire test of furnitures were conducted on 27 types of furniture and appliances that are generally used in houses and the burning rate, smoke density, temperature distribution in plume, and the wind velocity in plume were measured in these tests. The results of the tests are now being analyzed. The main results of the statistical analysis of fire incidents and mathematical model of fire will be reported in the Session for Fire Modeling.

Fig. 1 Committee of Fire Safety Systems



Note: T. Terai is involved in this Committee but he does not belong to any group because he has been overses.

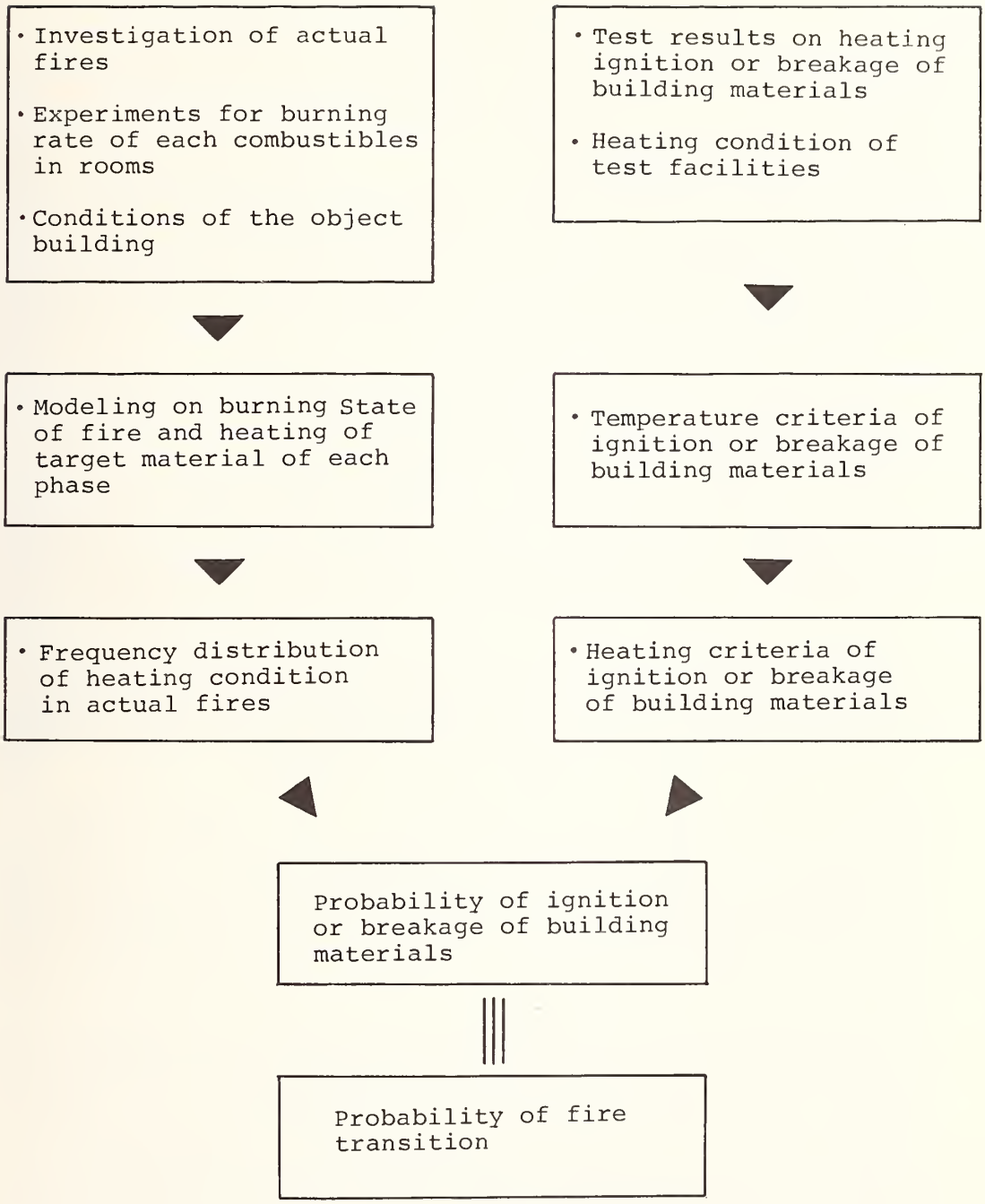


Fig.2 Procedure of Estimating Probability of Fire Transition (with Phisical Modeling)

Progress Report

Smoke Control

Irwin Benjamin

1. Design Developments

The generation of new building designs with smoke control systems reflects the growing interest of the mechanical engineers in such systems and their willingness to experiment. The philosophical approach that was used is discussed for each of several of the buildings which were completed in this past year.

Of interest are 3 hotels done by the same design engineer, using different approaches to the pressurization. The Peachtree Plaza hotel in Atlanta is 74 levels high, claimed to be the tallest hotel in the world. This building has a sprinkler system throughout and is of concrete structural frame. One stair in the building was made into a smoke proof tower, by imposing a negative pressure on the vestibule at each landing. The vestibule was built with a deep soffit and a exhaust slot on top of the soffit which empties into a shaft running along side the vestibule. A fan on top of the shaft maintains the negative pressure in each vestibule.

A hotel by the same designer, opened in 1977 in Detroit, used pressurized stairways. In this case the building has a scissor stairway near the central core; and there are two separate pressurization systems, one for each stairway. They used a separate blower to maintain pressure in each stairway. The building is fully sprinklered.

Another hotel, opened in 1977 in Los Angeles, uses a combination of a vented and pressurized stairwell. No vestibule is used. In this case pressure is fed in from the bottom and exhausted at the top when the pressurization system goes into operation. These three hotel buildings, with the three different solutions, illustrate the range of approaches that is currently being used in the U.S. on pressurization of stairwells.

As examples of office buildings: a new one which opened in 1977 is the 34 story Bechtel Office Building in San Francisco. This building has both a total sprinkler system and a smoke control system. Because of the City of San Francisco requirements the building used a vestibule at the entrance to each landing. The stairway pressurization system was designed to maintain a positive pressure by having a 600 cfm input and 300 cfm output for each door opening. In addition, the vestibules were maintained with 60 air changes per hour supply and 90 air changes exhaust, to maintain negative pressure in the vestibule. Both the stairwell system and the vestibule system are separate systems from the rest of the building. The stairwell pressurization system uses multiple blowers and multiple injection levels to get more even distribution of the pressures. The balance of the building is designed to develop pressurization in case of fire. In time of fire the system can be switched over manually so as to provide 100% exhaust from the fire floor and 100% input to all floors other than the fire floor. The use of a manual change over rather than automatic was at the request of the fire department.

Another office building is the IDS Center in Minneapolis. This building was built in 1971 and was retrofitted in 1977 to provide a pressurization system. The stairwell is 58 stories high and was divided into 4 separate vertical compartments with a normal fire rated partition and door dividing each stairwell compartment. The air is introduced near mid-height in each of the compartments. This design did not use any vestibules. The design of the blowers is based on the assumption that a maximum of 3 doors would be opened at any given time. The stair pressurization is manually operated by the fire department. The stair compartment has been measured to have about .06 inches of pressure at the doors. In addition to the pressurization of the stairwells the building itself is pressurized. At time of alarm the dampers all close, shutting off the perimeter induction units below the fire floor level and shutting off the interior supply at the fire floor. The rest of the supply system in the building, other than below the fire floor is maintained on.

In general, the stair pressurization systems which have been used have basically been designed on the assumption that 3 doors would be open at a time. This requires a zoned alarm so that only the fire floor and the one above and below is evacuated. In a general alarm all the doors would be open and the pressurization of the stairwell would be defeated. There also seems to be a trend to get away from an automatic switch over of the pressurization system and back to a manual control operated by the fire department. However, both types are being used at this time. Some designers have also noted that the inclusion of motorized dampers for energy conservation purposes, reducing night time flows, has made possible the use of a pressurization system for smoke control with little additional cost.

2. Field Studies

Work continued at NBS on field studies to measure both smoke movement and effective pressures and leakage in buildings. A report by Dr. Fung, Smoke Simulation Correlations in a Dwelling (in draft), studied the movement of smoke in a typical two-story residence building. This report studies the effect of the forced draft heating system on movement of smoke in the residence. It also correlated the SF-6 technique, which has been used extensively by NBS to measure smoke movement, with actual smoke generated by real fires. The correlation showed good qualitative agreement. Direct quantitative agreement is not possible since the SF-6 provides a step function input to the smoke system, whereas the normal smoldering fire has a long slow incubation period during buildup. One of the important results of the experiment was the indication that the effect of bedroom doors in a single family residence, either in the open or closed position, is immaterial if the heating system is in operation; since the major mode of smoke distribution is by the heating system, rather than through convection or dispersion.

Additional field studies were done on a Federal office building in Roanoke, Virginia, and at the National Institute for Health Clinic in Washington, D.C. In both of these cases SF-6 was used to measure smoke movement throughout the buildings. These measurements were then correlated with analytical studies on the computer and have been used as the basis for suggestions on modification of the building designs.

3. Code Developments

Although some of the building codes in the United States now require smoke control systems there are no criteria generally accepted for the design of such systems. For this reason the buildings mentioned above and other buildings which have been designed with smoke control systems are still being designed on an individual basis, with the judgement of the designer being the major criteria. The NFPA (National Fire Protection Association) Committee on Air Conditioning has revised the standard 90A to include general information on smoke control systems in an appendix. The TC 5.6 Committee of ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) has drafted a design guideline for smoke control systems and has suggested its adoption to several local jurisdictions. However, the draft has not been adopted as a document by ASHRAE at this time and is still in the evolutionary stage. The model code groups, which provide the guide for many local building codes, have changed their standard to state that when mechanical ventilation is used the system should provide a minimum of one exhaust air change each 10 minutes.

4. Analytical Studies

Development work has continued on the analytical model for predicting behavior and movement of smoke in buildings. This model was reported at the last meeting of the panel and has been further developed. The major change to the model has been the addition of an unsteady thermal state routine. This work is an extension of the approach which has been used by Wakamatsu. In this program the building is divided into 3 areas: a burn room, rooms adjacent to the burn room, and rooms separated from the burn room area. In the burn room area a temperature program or rate of burn program can be introduced to develop a temperature profile for the burn room. By using a heat balance equation the temperatures of the air leaving the room and entering a corridor or adjacent connected spaces is then calculated. The smoke in the burn room is superimposed as a step function on the temperature rise within the room.

For the non-fire rooms connected to the fire room the model uses a heat balance equation which represents the heat conduction from the volume of hot air to the walls, floor and ceiling of the space.

For those spaces not connected to the fire space a simpler model is used, in which the thermal properties of the walls and ceilings are neglected.

In addition, improvements have been made to the air movement part of the program, and the smoke concentration model has been made compatible with the air movement program. At this time the model does not handle stratification of smoke in the corridors adjacent to the fire room. Neither does it handle diffusion in a large space, since it assumes that any compartment is homogenously polluted. The model can be used for an atrium, and will handle the vertical movement of smoke in the atrium. However, if the atrium is very large it will not handle the horizontal movement. This would require a horizontal diffusion model which is not presently available. However, no additional work is planned at this time on development of the model.

In summary, we believe we are now reaching the stage where the shift is being made from conceptual theory and analytical development to generating field experience with the design of various types of systems. Much of the future work will be on design guides and on evaluating experience with various designs.

Japanese Progress Report on SMOKE CONTROL

Prepared for

Third Joint Panel Meeting
UJNR Panel on Fire Research and Safety

As reported at the 2nd joint meeting, the studies on smoke control in Japan have advanced with the main object of developing design methods of smoke control systems, and those have been supplemented by large scale field tests.

In order to prepare an appropriate or optimal smoke control system for a building, as we have already argued elsewhere, it will be indispensable to assess the validity of the systems proposed for the building through quantitative predictions of the movement of smoke under possible fire situations, taking account of various conditions required in the building other than those concerning fire safety matters. As important part of the work necessary for attaining this goal, a series of studies has been performed to develop calculation methods. Up to now, three calculation Models different with precision and simplicity have been developed, and the accuracy of each model has been confirmed, comparing the results attained from full scale tests or those from other models. In summary, we may regard the calculation methods for predicting the smoke movement as developed enough for the practical application to assessment of smoke control systems.

By the way, a smoke control system should without doubt be validated in correspondence with the environmental conditions under which the system may be operated. The conditions consist of the external ambient air, fire situation and severity, temperatures and flow resistances throughout the building and so on. So, if we evaluate a smoke control system by taking account of the occurrence probability of the sets of the environmental conditions under which the smoke safety may be ensured by the system, the next subject we should do is to calculate the probability and to

develop a method to advance the validity of the system perspicuously. While the problem how to determine the standard or goal of the probability defined above will be left still even by those studies, it is evident that the above-proposed subject occupies anyway the essential part of smoke safety planning.

The smoke safety probability in the sense of the former paragraph can be obtained basically by the computer simulations for the movement of smoke on the whole sets of the environmental conditions supposed, the judgement of their results and the multiplication of the occurrence probabilities of respective sets. As such an approach may require innumerable calculations because of enormous number of the cases or environmental conditions supposed, the way to research the critical conditions for smoke safety that permit us to omitt the simulations for evidently safe or danger cases should be developed. Besides, a proper optimization method will be necessary for practical designing of smoke control systems.

Consequently, there remain several problems to be solved for applying the calculation methods of the smoke movement to the assessment or designing of smoke control systems, even though the validity of the calculation methods have been enough verified already. Here, we summarize the recent progress of the studies related to those problems mentioned above.

1) Quantitative Assessment of Smoke Control Systems

This study compares the calculation results of the smoke safety probabilities for the case with a properly designed smoke control system and the case without it in consideration of the fire floor, condition of fire room, reasons, and wind conditions as factors of the environmental conditions in the sense mentioned formerly, and proposes a way to make such an assessment perspicacious.

The building here studied is a 50 storied sky scraper*[1], and the environmental conditions are assumed to be distributed discretely.

The judgement upon smoke safety is made, after the simulation for the smoke movement, by whether the smoke generated in fire compartment would enter into staircases or not. The calculated smoke safety probability for the case with the smoke control system is 90% by a possible fire situation, whereas that for the case without any smoke control equipments is about 50%. In the study introduced above, the calculation was made for about 600 sets of the environmental conditions for each of the two cases. A trial and error method to estimate the critical conditions for smoke safety is also proposed for the purpose of decreasing the cases to be computed and calculating the probability efficiently. Provided that the result of a simulation for a certain environmental condition is judged as "safe", it is not necessary to simulate the smoke movement for the sets of conditions that are evidently safer than it. While the stack effect, wind pressure effect and some other effects will count among the factors that have major influences on the smoke safety of a building, the value of the pressure difference due to the stack effect that may be a cause of the smoke flow from fire compartment into the shafts through corridors is adopted as the major factor for smoke safety, and the critical sets of the conditions that have influences on it like seasons, the elevation of fire floor or opening condition of vertical shafts are searched in a trial and error method. If only the sets of the conditions are classified into two categories, namely safety side and danger side, the judgement on smoke safety can be performed by summing the occurrence probabilities in each region, and so the number of the cases on which we should make calculations will be considerably decreased.

2) Analytical Studies on Smoke Control Equations

This study purposes to generalize the optimization and the assessment method of smoke control systems.

Even if the result on a certain environmental condition is judged as "safe", the smoke safety may be broken easily by the change of

some capricious factors like the conditions of doors. In this sense, the safety under a certain environmental condition involves always some vagueness, which should be assessed as one of the indices of the adequacy of smoke control systems.

On the other hand, so as to make optimizations of smoke control systems, it is important to attain the insight what devices will result in the most effective advancement of smoke safety from a calculation result.

In order to make such detailed and concrete studies as those introduced above, it will be efficient to obtain supplementary informations like the sensitivities of parameters on smoke safety as well as direct results like flow rates out of a simulation result. As common bases to those studies, the sensitivity equations for smoke movement equations are deduced and the parameters that correspond to the environmental conditions are classified and normalized according to the sorts of vagueness.

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*1 Wakamatsu, T. "Calculation Methods for Predicting Smoke Movement in Building Fires and Designing Smoke Control System" FIRE STANDARDS AND SAFETY ASTM/NBS

SUBPROGRAMS: A STATE-OF-THE ART REVIEW

PREPARED FOR THE

MATHEMATICAL FIRE MODELING COMMITTEE

AND THE

3rd JOINT MEETING OF THE

U.J.N.R. PANEL ON

FIRE RESEARCH AND SAFETY

TABLE OF CONTENTS

INTRODUCTION (J. de Ris)

Preface

Comprehensive mathematical models of fire growth need to draw upon information from a wide range of research specialties. To foster communication between builders of comprehensive fire models and specialists in other areas of fire research, the subprogram subcommittee has prepared this state-of-the-art review of the specialized fire research areas. In each case the topic reviews are generated by experts in the areas from the standpoint of providing essential information to builders of comprehensive fire models. It is envisioned that individuals from each of these specialized areas will eventually prepare algorithms (computer subprograms (or simple algebraic formulae), data and concepts) which can be directly used by comprehensive model builders. An important outcome of these reviews are their recommendations for assembling existing knowledge or obtaining new concepts and data needed for comprehensive model predictions.

The status for each referenced work is categorized as follows:

A. At least a Fortran listing and enough description of the logic so that a typical user will not have to rewrite the program. This should include a table of Fortran variables, separate specification of input and output parameters, and a test case. Documentation explaining the physical-chemical model used in the code should be provided.

B. Published or broadly distributed technical report.

C. In progress with a definite projected date of release.

The remaining part of this introduction provides some overall comments on: (1) the importance of more basic flammability research and (2) the relationship between field and zone models for predicting enclosure fire development. This is followed by John Lloyd's State-of-The-Art Review of Field Models. The final section provides brief summary reviews for each zone model subprogram research area.

Some Remarks on the Importance of Fire Growth

At the present time, computer models of enclosure fire development appear capable of predicting the time to flashover and other quantities of practical importance provided the model is supplied with the initiating item's empirical rate of fire growth and the effect of external radiation on this rate of fire growth. However, at present, we cannot predict the initiating item growth rate due to our relatively poor understanding of basic combustion mechanisms. Indeed we cannot even predict the rate of burning of a constant area (i.e. non-spreading) fire of hazardous scale in terms of basic measurable fuel properties. This is clearly the most important fundamental problem in the field of fire research.

In recent years, considerable progress has been made in predicting burning rates. We now can accurately predict the burning rates of small laminar fires for a wide range of geometries (vertical, sloping, and downward facing single surfaces as well as vertical parallel surfaces). These predicted laminar burning rates depend primarily on the fuel's convective B number. Recently such calculations have been extended to include turbulence effects; but upon comparing the results with experiment, we have found that the burning is dominated by the radiative heat transfer and does not correlate solely with the convective B number. Generally almost all fires of hazardous scale are controlled by their flame radiation. This is unfortunate since we have a relatively poor fundamental understanding of radiation from turbulent diffusion flames. Current investigations of this flame radiation suggest that it can usually be described in terms of: (1) the effective flame radiation temperature, (2) the mean flame absorption-emission coefficient (per unit length), and (3) the overall time-averaged flame geometry. Surprisingly little data exists for these crucial quantities.

We still must perform much more research before our treatment of fire growth rates can match our present understanding of the rest of the enclosure fire development problem. In particular: (1) we must develop convenient and reliable techniques for measuring flame radiation temperatures and absorption-emission coefficients; (2) we must gather and correlate such flame radiation data in terms of fuel combustion and chemical properties; (3) we must obtain accurate correlations of flame shapes for the many fuel geometries of practical interest; (4) we must develop convenient formulae for describing flame radiation heat transfer and burning rates for these geometries, and finally (5) we must extend these calculations to predict fire spread and growth rates.

This is clearly a large undertaking. It will require major commitments from at least half a dozen research institutions over a period of about five years before we have a general ability to predict fire growth rates. The problem has the additional challenge in that almost all current standard flammability tests are too small to be controlled by flame radiation and consequently are insufficient in themselves to characterize hazardous scale burning rates. This means that we have little practical data to draw upon for estimating fire growth rates in terms of fuel properties. It also points to the need for encouraging and guiding fire test engineers toward developing standard tests which are sensitive to the flame radiation generated by the material itself. Tests which subject materials to different levels of controlled external radiation can provide valuable information on material response to radiation; however in themselves they do not provide the necessary flame radiation data.

Finally, while awaiting development of meaningful standard flammability tests and/or sounder scientific predictions, realistic "standardized" fire test procedures should be formulated for empirically measuring the rate of fire growth of isolated initiating items. The results from these empirical tests should be helpful for indicating the relative flammability of items and can be used as inputs to the computer models for evaluating item hazards in different use situations.

Some General Comments on Field and Zone Models

There are two general approaches to mathematical fire modeling: field models and zone models. Field models express the fire development in terms of general partial differential equations at each point in space. Zone models describe global mass and energy transfer relations with algebraic equations (or ordinary differential equations in transient situations) for each principal zone: walls, ceiling, ceiling gas-smoke layer, fire plume, burning surfaces, as yet unignited target surfaces, neighboring room, etc.

Field models in the long run should provide the most general, accurate, and detailed prediction of fire development. They are particularly well suited for predicting complex three dimensional phenomena which may be overlooked by the more intuitive ad hoc zone models. However, at present field models: (1) are limited by computer capacity and speed, (2) do not yet properly treat action-at-a-distance radiative energy transfers, and (3) are still awaiting a rigorous treatment of buoyancy influenced turbulence. As a result, it will take several additional years of fundamental research before field models can be expected to provide reliable comprehensive predictions of hazardous fire development. During these years, we also expect computer development to alleviate the problems of capacity and speed.

Zone models represent a nearer term engineering approach which is closely tied to experimental observations. Present comprehensive zone models usually assume the fire is in the lower half of a room. The fire acts as a pump by driving a mixture of unburnt fuel vapors, smoke, flames or hot combustion products and unburnt entrained air into the hot smoky ceiling gas layer which subsequently flows out of the enclosure windows or doors according to classical hydraulic flow equations. Global heat and mass transfer ordinary differential equations are developed for each zone: ceiling gas layer, ceiling and wall surfaces, fire plume, lower ambient gas layer, unignited target surfaces, burning fuel surfaces, etc.; together with general action-at-a-distance radiant energy interchanges between all relevant zones.

This zonal approach has several important advantages: (1) computational simplicity, (2) ease of decoupling zones for independent investigation by geographically separated researchers, (3) simpler comparison of theory and experiment for individual zones, and (4) easier conceptualization of the interaction between zones. As a result, one is likely to have more confidence in the predictions for situations similar to the experiments. At this time, the zonal approach appears to be much closer to practical application.

In the course of time, the treatment of each zone will become progressively more sophisticated and complicated according to the demands of generality and accuracy in predicting observed behavior. For example, it would be advantageous to predict the vertical and horizontal ceiling gas layer temperature gradients because of their strong influence on the critical interior radiant fluxes. As these and other improvements are implemented, the zone models will appear progressively more like field models. Similarly as field models are developed to the point where they can be directly compared with actual room fire experiments, they will likely incorporate the zonal treatments of fire growth, fire plumes, radiant interchange, etc. Thus the present pronounced differences in approach will likely decrease in time.

II. GENERAL REVIEW OF FIELD MODELS (J. R. Lloyd)

The category of field models is an all encompassing area which by rights must include all those delineated under zone models. Previously this area was in large part limited to modeling of turbulence. However, this should not be the only topic considered. Areas of radiation, combustion, species transport, flame spread mechanisms, smoke generation, etc., should also be included since these physical phenomena also require finite difference equation formulations for their incorporation into numerical solution schemes. In this light field models should be defined as models which are used in numerical solutions of the recirculating flows characteristic of the fire spread problem. By numerical, it is meant solutions using discrete approximations to the governing equations for the recirculating flows.

Historically the use of these techniques began with the advent of the computer, but was given a special emphasis relative to enclosure fires by Torrance and Rockett(1). While their solutions did not include turbulence, radiation or combustion, it was a landmark which signaled a movement to the use of numerical techniques in looking at the fire problem. The work of D. B. Spalding and his co-workers (eq. 2-5) has pioneered the use of numerical techniques in furnaces. Today, there are several groups who are making significant contributions to the use of field models for fire predictions. The discussion which follows outlines their work, but due to space limitations cannot include a comprehensive review.

Two different approaches have been taken by the researchers in this area. One is to use the governing equations in the stream function - vorticity form and the other is the physical variable approach involving actual velocities and pressures. Both have their advantages and disadvantages. Those studies employing the stream function - vorticity approach are limited to two dimensions, and without pressure appearing explicity in the governing equations, handling of variable density flows is inconvenient at best. (It has been demonstrated quite clearly that variable density must be maintained in the governing equations where fire is involved). Various boundary conditions are also difficult to handle with this approach. The physical variable approach easily handles this problem provided an appropriate pressure correction scheme is employed.

Several works require specific comment. Larson and Viskanta (6) looked at the laminar two dimensional enclosure problem using the stream function - vorticity approach. Their work included effects of radiation and demonstrated that, at least for laminar flows, radiation from surfaces and soot must be included. Trent and Welty (7) published a study discussing the vector potential-vorticity and velocity-pressure approaches which included two and three dimensional calculations and an algebraic turbulence model based on Prandtl's mixing length theory. They applied the vorticity transport technique to the axisymmetric vented enclosure. In a rather extensive program, Knight (8) published a computer code based on the stream function - vorticity approach with the Boussinesq approximation for the steady state two dimensional laminar flow enclosure

problem. His major conclusion was that computer finite different problems for accurate calculation of fire scenarios are not practical at the present time.

A rather strong movement was given momentum by D.B. Spalding and his co-workers at Imperial College when they began to use physical variables in their solution to the furnace problem (2-5). Their SIMPLE algorithm enabled them to solve the pressure correction problem which is inherent in this solution technique. They have since included the effects of radiation using the flux methods (two, four and six flux methods). The group has been instrumental in bringing about the wide use of differential field models for including turbulence. While these turbulence models seem to work fairly well in predicting fully turbulent flows, they are not applicable to the regions in enclosure fires which appear to be partly laminar because the model is valid only for fully developed turbulent flows. Recently, Spalding has been working on a new turbulence model called ESCIMO (9). This basically is a particle history concept wherein an age distribution or eddy breakdown history is described. While this model is currently only good for steady state problems (which is a draw back) it may overcome the objections of assuming fully developed turbulence.

The Fire Research Group at Notre Dame has developed a computer code named UNDSAFE (10,11). This code employs physical variables and full variable density to solve the transient fire and smoke spread problem for enclosures. The program currently includes one-dimensional gas, soot and wall radiation which is extremely important. In this study an algebraic turbulence model is employed which accounts for buoyancy effects on turbulence, and also allows the dynamic flow condition to generate turbulence. It thus can reduce to a laminar value in the absence of buoyancy and the absence of velocity gradients. The ability to handle the transition from full turbulence in wall and in very buoyant regions to laminar flow is significant. The importance of including transient effects has been clearly pointed out in newly developed computer movies from the UNDSAFE predictions where wave phenomena are observed which could not be seen if only steady state solutions were available.

Workers in Japan have also started working on field model programs. The work by Hasemi (12) is especially significant. This work uses physical variables in an unsteady solution of two and three dimensional enclosure fires. The concept of eddy viscosity is used but is based on fully turbulent flow conditions. Radiation is not included in this study.

RECOMMENDATIONS

Field model solutions to the enclosure fire problem will become increasingly valuable in the future. As the various models are developed and improved, and more efficient solution techniques are developed, these techniques will become more and more significant and practical. Primary focus must be directed to the following areas in the next few years if this is to become a reality:

1. Turbulence models must continue to be developed so that they can account for buoyancy generated turbulence. The mechanism for transition between laminar and turbulent flow must be included so that enclosure fires can be properly predicted. The turbulence models must be three dimensional.

2. The field models developed must allow for the transient character of fires and should be adaptable to three dimensional analysis. Variable density must be maintained in the analysis.

3. Models of surface, gas (non gray) and soot radiation must be developed, including interaction effects. It is very important that the analysis techniques can handle two and three dimensional effects better than the current techniques, such as the most popular zone and flux techniques, are capable of doing.

4. Combustion or chemical reaction models must be developed beyond the volumetric heat and mass source which is so convenient and commonly used in the field model solutions. Heat and smoke generation must be a part of the combustion model. Details down to the level of pyrolysis will be important, especially in defining ignition conditions. Of course, flame spread mechanisms and their models must be developed for the complete field program.

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III REVIEW OF SUBPROGRAMS FOR ZONE MODELS

IIIA. FIRE GROWTH (P. J. Pagni)

Fire growth is here defined as either: (1) the rate of change in size of a preflash-over fire of arbitrary configuration, or (2) spread of a turbulent flame across an ignitable solid surface. Liquid fuelled spread[1,2] has been excluded since it is less crucial to compartment applications. Those portions of the fire growth problem which are specifically treated in other sections of this review are also excluded. Their output serves as a possible input to this section, i.e., (b) FIRE PLUME, is expected to supply the fire geometry as a function of time; (d) PREFLASH-OVER CONVECTION provides the local ambience; (c, d and parts of k) RADIATION provides functional forms for radiative flux to the unburnt fuel from both the fire and the ambience. What remains then in this section is the energy balance incorporating these inputs and outputting the fire growth rate or spread rate.

(i) Fire Growth Rates

Berkeley: Pagni, et al[3, 4], Empirical histories of fire mass loss rates, temperatures and geometries. Calculation of flame radiation. B.

Harvard-FMRC: Emmons[5], Semi-empirical transient radial fire growth in response to external radiation. C.

Emmons, et al[6-10], Empirical compartment fire histories to flash-over. Preliminary analyses of mass, momentum and energy balances on compartments. B.

Dayton: MacArthur[11], Fire growth code for arbitrary geometries including ignition, charring and flaming and response to specified radiation and fuel burning rates. A.

Borehamwood: Thomas[12], Turbulent spread of crib fires. B.

U. S. Forest Service: Rothermal, et al[13-15], Flame geometries and spread rates through porous cellulosic materials under controlled conditions. B.

(ii) Turbulent Flame Spread

FMRC-Harvard: Markstein, et al[16-19], Transient turbulent upward spread on PMMA, turbulent spread on fabrics at various inclinations, radiation effects. B.

Brown: Sibulkin, et al[20,21], Upward turbulent spread of PMMA. B.

Berkeley: Pagni, et al[22,23], Turbulent spread through porous fuels with empirical geometries and radiation as input. B.

Other related papers by Albini, Putnam, Hottel and Stewart.

(iii) Background Studies (Laminar Flame Spread)

Tarifa, et al,[24]
Magee, et al.[25]
de Ris[26]
Campbell[27]
Pagni, et al.[28]
Pello and Williams[29-32]
Sirignano[33-34]
Kashiwagi[35-36]

Recommendations

1. Develop transient, free and forced, turbulent fire growth models for a wide variety of fuel geometries, initially in an unconfined environment.

2. Extend this development to include the effects of vitiated oxygen, flow fields and external radiation expected in a compartment.

3. Extend that development to spread beyond the compartment of origin.

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IIIB. FIRE PLUME (G. M. Faeth)

Fire Plume Theories

(i) Combusting Plumes

FMRC: Tamanini[1,2], A full k-ε-g model for axisymmetric buoyant flames, using algebraic stress modeling and a simplified consideration of radiation. B.

Australia: Kent and Bilger[3], A full k-ε-g model for turbulent axisymmetric flow, using Favre averaged variables. B.

Imperial College: Lockwood and Naguib[7], An axisymmetric k-ε-g model employing a modified version of GENMIX[8], B., A.

Imperial College: Lockwood and Ong[9], An eddy viscosity model for a plume along a wall. B.

DCW Industries: Wilcox[4], An integral model for turbulent axisymmetric buoyant flames including an ad hoc modification of the entrainment expression to treat conditions near the source and allowing for diffusion within the plume. B.

Canada: Masliyah and Steward[5], and Steward[6], An axisymmetric integral model assuming instantaneous combustion of oxygen entering the plume. B.

USA: Escudier[10], An integral model of a free plume in crossflow. B.

Berkeley: Pagni and Shih[11,12] integral and series expansion solutions for two-dimensional buoyant and forced flames in free and wall plumes. A full k-ε-g model for two-dimensional forced turbulent wall and free wakes. B.

Penn State: Ahmad and Faeth[13], finite difference model for laminar wall plumes. B. Integral models for laminar and turbulent wall plumes are also being developed. C.

(ii) Noncombusting Plumes

FMRC: Alpert[14,15], An integral model for axisymmetric turbulent plume impingement on a ceiling in the absence of a hot ceiling layer. B.

Tamanini[16], a k-ε-g model for axisymmetric turbulent plumes with algebraic stress modeling. B.

Harvard: Emmons has developed an integral model which computes mass and energy inputs to the hot ceiling layer. B. Earlier work[17,18] provides integral models for two-dimensional and axisymmetric flows including stratification. B.

Notre Dame: Kanury and Lloyd are developing a model for interactions of multiple turbulent plumes. C.

Penn State: Faeth and coworkers[19-21], integral models for turbulent wall plumes, finite difference calculations for laminar adiabatic wall plume. B.

MIT: Hoult, Fay, and coworkers[22,23], An integral model of plume rise in a crossflow, correlated with a large number of measurements. B.

(iii) Background Studies

- Turbulent Plumes

FMRC: George, Alpert, and Tamanini[24]

NBS: McCaffrey and Rockett, effective plume entrainment from enclosure flow measurements. C.

Japan: Yokoi[27]

Cal Tech: List, Brooks, Koh. B.

Other: Rouse, Yih, and Humphreys[25]. B. Morton, Taylor, and Turner. B.

- Turbulent Flame Heights

England, FRS: Thomas, Baldwin, and Heselden[28]. B.

Japan: Yokoi[29]. B.

Recommendations

1. Develop an improved turbulent combustion model, preferably an integral technique in the short term, which allows for near source effects, stratification, crossflow, and radiation (e.g., an extension of the approach of Wilcox[4] and Steward[5,6]). Verify the model by comparison with measurements.

2. Measure and correlate entrainment coefficients for flames in terms of reduced plume density. Consideration should be given to near source effects (retarded flows) and fire geometry.

3. Develop a new model for plumes and flames impinging on ceilings, including the effect of stratified ceiling layers (e.g., an extension of Alpert's model[14,15]. Complete measurements on flows of this type for model verification.

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IIIC. FLAME RADIATION (C. L. Tien)

(i) Radiation Calculation for Actual Flame Shapes

Berkeley: Dayan and Tien[1], Algebraic formula for radiation from a right circular flame volume. B. (Used by Reeves and MacArthur[2] and others).

FMRC: Modak[3], Numerical prediction for radiation from an axisymmetric flame volume of arbitrary radius vs. height. B.

Modak[4], Algebraic formula for radiation from a conical flame volume. B.

Harvard: Emmons[5], Semi-empirical calculation of radiation feedback from conical flames. B.

(ii) Flame Radiation Temperatures and Absorption Coefficient Measurements of Solid Fuels

FMRC: Markstein[6], PMMA, PS, PU, PP, PE. C.

Sweden: Hägglund and Pearson[7], Wood Flames. B.

Berkeley: Buckius and Tien[8], PMMA, PS, PE. B.

(iii) Background Studies - Models and Calculation Methods

- Flame Emissivity Calculations

Berkeley: Felske and Tien[9]. B.

Yuen and Tien[10]. B.

FMRC: Modak[11]. B.

Sheffield: Taylor and Foster[12]. B.

- Infrared Mean Absorption Coefficient Calculations

Berkeley: Hubbard and Tien[13]. C.

- Radiation-Convection Interaction in Flames

Notre Dame: Negrelli, Lloyd and Novotny[14]. B.
Lloyd, Yang, and Liu[15]. C.

Recommendations

1. Develop more validated algebraic formulae for radiation from flames of various shapes.

2. Develop correlation formulae for flame shapes and sizes in terms of burning rates and fire geometries.

3. Develop simple yet accurate techniques for determining flame radiation temperatures, absorption coefficients and soot concentrations for real world fuels.

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IIID. PRE-FLASHOVER ENCLOSURE CONVECTION (E. E. Zukoski)

(i) Two-Layer Room Convection Models

Cal Tech Zukoski[1]: Brief review of calculation schemes. B
Zukoski and Kubota[2-3]: Simple, steady single opening, no heat transfer to walls, point or line plume source. B. Generalization to arbitrary number of openings and external pressure field. C.

Harvard Emmons and Prahl[4]: Two-layer flow through an opening, theory and experiment. B.
Emmons and Mitler (unpublished): Transient two-layer flow with heat transfer, two openings, point source plume. C.

NBS Rockett[5]: Steady two-layer, one opening with wall heat transfer, point source plume. B.

UDRI MacArthur Et Al[6]. Documented problem for above. A.

IITRI Pape Et Al[7]. Documented for above. A.

Cal Tech Kubota and Zukoski: Extension of models to two rooms with common external pressure field. C.

(ii) Background Studies

Kawagoe[8]: Convection through openings.

Baines and Turner[9]: Model for transient multi-layer room convection driven by a plume source but without room opening, theory and experiment. B.

Zukoski[10]: Transient multi-layer temperature profiles, analysis of experimental results. B.

Recommendations

1. Extend models to treat multi-layer transient vertical temperature distributions.

2. Model interlayer turbulent mixing at openings.

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IIIE. POST-FLASHOVER BURNING (T. Z. Harmathy)

All mathematical models are related to fire in a single compartment with one ventilation opening. (See Refs. (2) and (4) for procedure to be followed in case of several openings at different heights.) In all models, except Ödeen's, the rate of entry of air is calculated on the assumption that the stationary gas in the compartment is at uniform temperature except near the opening. (Ödeen did not consider the effect of ventilation.) Some other frequently used assumptions:

(a) uniformity of process variables within compartment ("well-stirred reactor" model),

(b) combustion confined to the inside of compartment,

(c) constancy of thermal properties of compartment boundaries,

(d) fire ventilation-controlled,

(e) constancy of rate of heat evolution,

(f) rate of heat evolution determined by a constant "velocity of penetration" of fire into the fuel particles.

1. Kawagoe and Sekine (1,2): assumptions (a),(b),(c),(d),(e), finite difference method, B.

2. Ödeen (3): assumptions (a),(b),(c),(f), stoichiometric combustion, finite difference method, B.

3. Magnusson and Thelandersson (4): assumptions (a),(b),(d), time-dependent rate of heat evolution, fully developed and decay periods covered, finite difference method, B.

4. Tsuchiya and Sumi (5,6): assumptions (a),(b),(c),(d) for fully developed fire, (f) for decaying fire, rate of combustion and fire atmosphere functions of temperature, finite difference method, A.

5. Harmathy (7): assumptions (c),(e), zonal burning in ventilation-controlled fires, separation of fuel-surface-controlled and ventilation-controlled regimes, possibility of flaming combustion outside the compartment, predominantly radiant heat exchange, "fire severity" parameters calculable analytically, B.

6. Nilsson (8): assumptions (a),(b), time-dependent rate of heat evolution, porosity of fuel bed considered, fully developed and decay periods covered, finite difference method, B.

7. Babrauskas and Williamson (9,10): assumption (a), combustion either ventilation or fuel-bed controlled, (f) for fuel-bed controlled fire, partial combustion outside the compartment if fire ventilation controlled, fully developed and decay periods covered, finite difference method, A.

8. Tanaka (11): assumptions (a),(b), combustible-compartment boundaries, radiant heat interchange between boundary elements, finite difference method, B.

Recommendations

1. More experiments should be performed on fires involving substantial amounts of plastic materials. These experiments should be performed with both charring and non-charring plastics.

2. Particular attention should be given to measurements outside the enclosure.

3. Understand better the mechanisms of oscillatory combustion in enclosure fires.

IIIE. REFERENCES

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IIIF. CONVECTIVE HEAT TRANSFER COEFFICIENTS WITHIN ENCLOSURES (F. Tamanini)

(i) Idealized geometry: Horizontal ceiling.
FMRC: Alpert[1], Fire plume impinging on unconfined ceiling, B.
Cal Tech: Zukoski et al[2], Fire plume impinging on confined and unconfined ceilings. B.

(ii) Real geometrics.
NBS: Quintiere et al[3], heat transfer to the ceiling of a corridor: model and full scale. B.

FMRC: Tamanini[4], heat transfer to the ceiling and walls in a full-scale enclosure fire.

(iii) The classical literature[5] on convective heat transfer coefficients should be consulted.

Recommendations:

1. Develop guidelines for selecting convective heat transfer coefficients, applicable to real fire environments.

IIIF. REFERENCES

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5. Rohsenow, W. M. and Hartnett, J. P., "Handbook of Heat Transfer", McGraw-Hill, 1973.

Notre Dame: Lloyd, Yang, and Liu,[8] surface nongray gas and soot radiated in enclosures. C

(iii) Selected Background Material

General - Hottel and Sarofin,[9] B; Seigel and Howell,[10] B; and others

Configuration Factors or Transfer for Specific Configurations - Hamilton and Morgan,[11] B; Dayan and Tien,[12] Blackshear[13] B; and others

Scattering by Small Particles - Mie,[14] B; VanDeHulst,[15] B; Kerker,[16] B; and others

Recommendations

1. Determine limitations imposed by simplifying assumptions (done by Modak[16, 17] to some extent)

2. Include transient smoke concentration (done approximately by Pape[2] and by Reeves and MacArthur[3])

3. Include ceiling and layer temperature distributions

4. Provide full program documentation

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IIIG. RADIATIVE HEAT TRANSFER WITHIN ENCLOSURES (R. Pape)

(i) Room Fire Computer Model Subprograms for Radiative Interchanges Inside Enclosures

NBS: Quintiere,[1] energy balances on hot gas layer includes radiative transfer to ceiling and adjacent walls and to floor. Energy balance on fire plume includes radiative losses to the surroundings and influx from the hot layer. B

IITRI: Pape,[2] separate subprogram to compute interchange areas between specified horizontal and vertical surfaces (based on 11). Radiative interchanges considered between specified horizontal and vertical surfaces, the hot layer, flames, and the background assumed to be at a specified surface's temperature. Transient model for surface temperature rises. A

URDI: Reeves and MacArthur,[3] radiative feedback from flames and upper layer influence flame spread and release rates. Energy balance on upper layer quite similar to NBS approach. B

Harvard: Emmons and Mitler,[4] subprogram to give total radiative flux from every object, plume and hot layer. Components of this subprogram give irradiation of vertical and horizontal surfaces by the hot layer, radiative tranfers from room walls, hot layer, and flame to the fuel surface, and a transient model for surface temperature rises. B

Japanese BRI: Tanaka,[5] primarily concerned with wall finish. Includes radiative transfer between enclosure surfaces with attenuation through flames and indoor air. Hot layer not considered (view factors same as those used by Pape from Ref. 11). B

FMRC: Modak and Mathews,[6] numerical model giving radiative flux from hot layer and enclosure surfaces to any arbitrarily oriented surface within the enclosure. Considers accurate attenuation through upper layer and gives analytical expressions for most cases. B

Documented program[18] is being used in the Harvard fire model. A

Expansion to include smoke mass concentrations and arbitrary ceiling layer temperature profile. C

(ii) Independent Analytical or Numerical Models

Notre Dame: Novotny,[7] formulation on one-dimensional radiative flux for nonhomogeneous nongray gases and soot. B

7. Novotny, J. L., Formulation of One-Dimensional Radiative Flux for Nonhomogeneous Nongray Gases and Soot, TR-37191-74-1, NSF RANN Grant GI-37191, February 1974.

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IIIH. WALL THERMAL RESPONSE (H. Baum)

FMRC Tamanini[1]: Transient finite difference, finite thickness variable property with arbitrary boundary conditions on both surfaces. Model includes pyrolysis (evaporation) and interval convection but does not include recondensation. A.

Berkeley Bresler et al[2-3]: Finite element, arbitrary shaped 2-D geometries (columns, slabs etc.), variable property, arbitrary heating rate. Does not include pyrolysis, recondensation or internal convection. A.

Pagni et al[4-6]: Quasi-analytic, finite difference, variable property, non-linear boundary conditions on rectangular or axisymmetric columns. Includes radiation and recondensation. A.

Cal Tech Zukoski Et Al[4]: Simple algebraic conduction model for transient response of finite thickness wall to a monotonically increasing heating rate. A.

Recommendations

1. Incorporate physics of recondensation into model and verify with gypsum board experiments.

2. Treat case of composite walls such as two gypsum panels separated by wood or metal studs.

3. Obtain better high temperature physical property data e.g. gypsum.

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4. M. S. Sahota and P. G. Pagni, "Temperature Fields in Structural Elements Subject to Fire", Journal of Heat Transfer 97C:4, 598-604, 1975.

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III I. REMOTE IGNITION (A. M. Kanury)

(i) General Review

Ignition models may be either predictive or descriptive. Predictive models generally rely on some ad-hoc engineering criteria associated with ignition. Typical criteria are: critical surface temperature, critical fuel mass transfer rate, critical pyrolysis depth, or some such related critical surface energy factor. Predictive models have been developed by: Martin (1), Simms (2), Akita (3), Weatherford (4), Welker (5), Fons (6), Bamford (7), Kanury (8), Steward (9), G. C. Williams (10), Sauer (11), etc. Predictive model correlations have proven effective for both piloted and spontaneous ignition, even though the detailed mechanisms that yield the employed criteria are not fully understood.

Descriptive models explain the ignition phenomena in terms of more detailed thermo-physical mechanisms. Typical mechanisms involve thermal, fuel concentration and/or convective boundary layers, global gas-phase Arrhenius kinetics, thermal explosion criteria, in-depth solid reactions, surface reactions, etc. Examples of such models are: Akita (3), Kashiwagi (12), Alvares and Kanury (13), Alvares and Martin (14), Emmons and Shivadev (15), Kindelan and F. A. Williams (24), plus extensive solid propellant literature (16-21). These models are more difficult to apply or even verify due to their inherent complexity and the absence of established chemical kinetic data.

Recommendations

1. Adopt a standard ignition test procedure which: (1) evaluates a material's (or product's) empirical resistance to piloted and spontaneous ignition, and (2) interpret results for application with general transient heating rates.

2. Collect all available data on ignition time measurements (there is a lot available!) and correlate them for use with engineering predictive models.

3. Study the mechanisms of: (1) smoldering ignition, (2) transition from smoldering to flaming, and (3) ignition of edges and corners.

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2. Simms, D.L., Comb. and Flame, 4, p. 293, (1960).

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IIIJ.NEXT ROOM PROBLEM (B. J. McCaffrey)

(i) General Review
NBS Quintiere[1]. C

(ii) Convection - The flow of smoke and hot combustion products between rooms.
NBS Benjamin et al[2]: General Review of Computational Methods, Practical Smoke Control Methods, and Experimental Data with Emphasis on U.S. Government Practices. B

Quintiere et al[3-4]: Smoke Visualization Techniques and Model Studies.

Japan Satoh[5]: Smoke Movement, Statification Effects, General Transient Theory and Experiments. A ?

Wamatsu[6]: Calculation Methods and Smoke Control Systems. A ?

Borehamwood Phillips[7]: Lateral Spread of Smoke in Shopping Malls. B

Karlsruhe Seeger[8]: Calculation Methods and Smoke Control Systems. B

Notre Dame Lloyd et al: Field Models for Room Corridor Geometries. C

(iii) Radiation - direct flame radiation through doorways (windows) as well as radiation from interior walls and ceilings as well as exiting flames and combustion products.

Borehamwood Thomas et al[9]: Radiation from Fully Developed Enclosure Fires. B

Sweden Fredlund et al[10]: Fire Spread. B

(iv) Related Studies

Japan Yokoi[11]: Fire and Smoke Plumes. B

Sweden Christensen et al[12]: Fire Spread. B

Recommendations

1. Perform experiments on the intermixing between hot and cold layers moving through room openings.

2. Develop more detailed models for flame reach from room openings in terms of flow and gas compositions at openings.

3. Interface existing multiroom smoke movement models with enclosure fire development models.

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IIIK. SMOKE AND TOXICITY (G. W. Mulholland)

i) Physical Properties of Smoke

Georgia Tech: Bankston, Powell, Cassanova, and Zinn,[1] Size distribution, optical density, and mass concentration of smoke from smoldering and flaming sources. C.

Utah: Seader and Ou,[2] The relationship between optical density and smoke concentration for smoldering and flaming smoke. B.

NBS: Lee and Mulholland,[3] Physical characteristics of smokes used in detector testing: lamp wick and heptane. C.

FMRC: Markstein,[4] Smoke absorption coefficients and mass concentration for large scale fires. C.

ii) Smoke Dynamics

Utah: Seader and Ou,[2] The effect of coagulation on the average particle size and light obscuration. B.

NBS: Mulholland, Lee and Baum,[5] A universal reduced size distribution for smoke undergoing coagulation. C.

Cal Tech: Friedlander,[6] A general equation for smoke dynamics including the effects of fluid flow, diffusion, coagulation, condensation/evaporation, and nucleation. B.

iii) Toxicity of Smoke

NBS: Birky,[7] Smoke inhalation hazard as related to human fatalities. B. C.

Utah: Seader and Einhorn,[8] General review of smoke and toxicity research. B.

Pittsburg; Alarie[9], Sensory irritation toxicity. B.

Recommendations

1. Measure and catalog the mass concentration, optical density, number concentration, and particle size per unit mass of smokes from real world fuels.

2. Develop a dynamic smoke model for predicting the mass concentration and number concentration as a function of space and time for coupling.

3. Determine (per unit mass of fuel consumed) the relative toxicity, smoke obscuration, and heat output for real world fuels. Compare these with the estimated relative human tolerance thresholds.

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MATHEMATICAL MODELING OF ENCLOSED FIRES
A REVIEW OF CURRENT U.S. RESEARCH

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University of Dayton Research Institute

ABSTRACT

This paper reports on the continuing development in the United States of mathematical models and computer simulations of fire growth in an enclosure. The emphasis is upon the status of the several comprehensive, computer implemented models which attempt to deterministically predict pre-flashover fire behavior. A companion paper will discuss the "submodels" - treatments of the individual mechanisms or parts of the enclosed fire problem - out of which the comprehensive models are constructed. The bulk of the work in the development of the comprehensive models has been concerned with fire in residential rooms and passenger aircraft cabins. After an initial development phase, most of the models are now being validated, refined, and extended by comparison to full scale fire tests. During this process a number of problem areas have been identified and a consensus is developing on which mechanisms in fire behavior are of critical importance and so should have the highest priority for future research. Identifying and improving our quantitative understanding of these critical mechanisms will not only better enable the mathematical models to help solve real world fire problems but will also suggest better fire tests of materials and furnishings.

INTRODUCTION

Fire researchers in the United States have established a goal of reducing the United States fire losses by 50% by the year 1995 [1]. An important factor in reaching this goal will be our progress in understanding the development of a fire within the enclosure of its origin, be it a residential room, an industrial or commercial interior, or a compartment in a transportation vehicle. We will need to understand what features of the compartment interior design and furnishings increase or lessen the potential for fire development. We want to be able to make sound engineering analyses, based upon trusted calculations, of just what type and quantity of materials are safe for use in a compartment. And we want to know, quantitatively, what the trade-off in safety will be if we introduce other, less safe materials. To achieve this type of understanding, analytic methods are required to deal with the fire safety of a room and its contents as a system.

Until very recently there were few organized efforts in the United States at developing such analytic methods. This situation, I am pleased to report, is changed. At the present time a number of investigators are working with mathematical models of enclosed fires. Models have been constructed for both pre-flashover and post-flashover behavior. The pre-flashover models deal with the period of fire development critical to human

survival and escape. Post-flashover models are concerned with the fire containment offered by the compartment to prevent spread to other parts of the structure. In this paper I shall review the current work on pre-flashover models, the models on which the majority of effort is now being focused. As I shall point out, the character of these models is often that they are constructed of more-or-less independent parts or sub-models of specific physical processes. I will attempt to describe the overall models and their current status while a companion paper by Dr. de Ris will deal with the sub-models in greater detail.

CONTROL VOLUME AND FIELD MODELS

Mathematical modeling of enclosed fires has taken two courses, differing primarily in the method of mathematical formulation. One approach has been to spatially lump the major physical processes to obtain separate, self-contained sub-models of each process. The sub-models are typically the fire flame and plume; the hot gas layer accumulating in the upper part of the enclosure; the lower layer of cool ambient air; the fuel bed; and the non-burning (or not yet burning) walls, floor, and ceiling. Because models of this type treat each of the zones as thermodynamic control volumes, they have come to be called "control volume" or "zone" models. In addition to isolating relatively large regions of space for individual analysis, the control volume models often separate the various heat and mass transfer mechanisms in individual sub-models of radiation, convection, flows through doors and windows, and the pyrolysis of

the fuel bed. The application of the model to a particular situation proceeds by a "network-type" numerical solution in which each sub-model acts as a "node". The system of nodes and flows must obey the overall conservation rules for the compartment. Control volume models may be steady-state or transient, the latter type involving systems of ordinary differential equations which are solved at successive times.

A second approach to constructing fire models has been to use a completely distributed formulation of the basic equations of fluid dynamics and heat transfer. Differential forms of the conservation equations are used to relate the major variables of the problem. This type of model, a "field" model, will consist of a set of partial differential equations which are solved numerically over a mesh of grid points within the enclosure space, normally by a finite difference technique. The field models take a more exact approach to the fluid mechanics and heat transfer mechanisms by avoiding the approximations of the control volume models. Field models address such difficult phenomena as turbulence and recirculating flows in two and three dimensions. The increased accuracy and generality of the field approach, however, exacts a price in terms of computational speed and in the geometry and thus the realism of the situations which can be handled. At present only very simple interior arrangements, e.g., a single fire and a two-dimensional flow field have been modeled. The future is likely to see dramatic improvement in the field models as basic knowledge and computer speed increase, but for the present the control volume models hold the most promise for immediate

application in fire safety analysis. I shall elaborate somewhat on the construction of control volume models below.

CONSTRUCTION OF A CONTROL VOLUME MODEL

Figure 1 shows the basic features of the control volume analysis of the enclosed fire. The figure is from one of the first of the models of this type which was constructed by Dr. Quintiere of NBS [2]. A flame and plume rise above a fuel bed on the compartment floor. The plume entrains air as it rises through the cool ambient air in the lower part of the room. The hot combustion products and entrained air then collect in the upper part of the compartment. The position interface between these upper and lower gas zones is called the thermal discontinuity position, X_d, as shown in the figure. This simple "two-fluid" model of the gas seems reasonable because the strong buoyancy of the hot upper gas inhibits mixing with the lower zone (except perhaps at the doorway). Hot gas leaves the compartment by buoyant flow out the door. The rate of outward flow is determined by the upper zone temperature and the door dimensions.

Quintiere analyzed this situation by considering control volumes enclosing the fuel, CVI in the figure, the plume, CVII, and the upper gas CVIII. By performing energy and mass balances in these regions and using sub-models of the fire plume and the flow through the door, he obtained a steady-state model of the compartment's "response" to different sized fires and doorways. He was able to judge the flashover potential of a certain room fire and doorway combination by calculating the radiant flux to

the floor and using simple, empirical flashover criteria based on upper zone temperature and flux level.

The modular character of the control volume models is reflected in the organization of the computer programs which implement the models. To be precise we should distinguish between the mathematical fire model and the computer program for solution of the model's equations, since it is the correctness of the model in which we are primarily interested. Because the two items are so closely related, this distinction is rarely made and I shall not hold to it - except to note that although the computer program is only a vehicle for using a model, it is important that the program be reliable and easy to use if the model is to gain wide acceptance.

Figure 2 shows the organization of the program of one particular control volume model, Computer Fire Code III, developed by Professor Emmons, Dr. Mitler, and their colleagues at Harvard and Factory Mutual Research Corporation [3]. CPC III is a fully transient model which integrates a set of ODE's to simulate the fire growth. The CPC III program places the individual sub-models in separate subroutines for the "physics" of the problem. A controlling subroutine interfaces the physics subroutines with the three alternative numerical procedures for solving the system. An overall control module, "FCRD" in the figure, selects the appropriate numerical method based on considerations of speed and convergence of the iterative solution. Other subroutines are added to write out the results, scale variables, aid the numerical solution, etc. The point I wish to

emphasize is that by designing a program in this way, a framework is provided to add, in an easy manner, new or improved sub-models as they are developed. Also, by adding the proper sub-models, we can imagine the program to be extended to multi-room situations.

SOME EXAMPLES OF MODELS AND THEIR RESULTS

Figure 3 presents four current mathematical fire models. I have elected to show results from these four since they are undergoing continuing development and improvement and have published documentation available.

RFIRES is a room fire model and code developed by Pape and Waterman [4] at the IIT Research Institute. It is a time dependent, control-volume type of model. RFIRES is distinguished by its treatment of radiation from the fire and hot gas layer which is used for the determination of remote ignition of new fires within the compartment. The model uses as input a specified burning rate of the initiating item obtained from full-scale tests on furniture. Multiple fires are considered and the gas dynamics model of Quintiere is used in a quasi-steady form for the fluid flow.

DACFIR is a model developed for simulating fire within an aircraft cabin by this author and coworkers at the University of Dayton Research Institute for the Federal Aviation Administration (FAA) [5]. The model uses a novel approach to representing the cabin interior geometry and the spread of burning over the interior surfaces. In addition, DACFIR uses materials fire test

data obtained from small scale tests. Current versions of the program can handle various cabin shapes and sizes and compute smoke, oxygen concentration, and toxic gas levels in addition to temperature of the cabin atmosphere.

Computer Fire Code III, mentioned above, is the third example of a time dependent control-volume model. This program has undergone considerable refinement and extension in the last two years. Highlights of the current version are the sophisticated numerics and fluid mechanics, calculation of the fuel pyrolysis rate from the flame heat feedback, and computation of the heating of the walls and a "target" combustible by the use of the non-steady heat conduction equation.

The fourth example is a field model which has received considerable development and attention. UNDSAFE is a product of the Fire Research Group at the University of Notre Dame [6]. The code uses the "physical variables" formulation to solve the transient fire and smoke spread problem. One-dimensional gas, soot, and wall radiation are included along with an algebraic turbulence model. Dynamic flow conditions are used to generate the turbulence so that the model can handle both laminar and turbulent flow as conditions dictate. The output from UNDSAFE has been processed into computer generated motion pictures which are a great aid in visualizing the flow fields. Some recent results with the model have been the simulation of a wave motion flow phenomenon which is observed in some fires and the calculation of some interesting flow effects at the door involving multiple inflow/outflow regions which have also been seen in tests.

Figures 4,5,6,7 and 8 show some sample results from each of these models. Without going into any detail, I wish to present them to suggest the level of achievement which we are now experiencing in simulating real tests. Figure 4 shows the comparison of RFIRES to the FMRC/HARVARD 1975 Bedroom Fire. Good agreement was obtained in predicting the hot layer temperature using the measured burning rate before and after flashover.

Figure 5 demonstrates the method of representation of burning area in DACFIR. The material surfaces, the major surfaces of a row of seats in this case, are divided into rectangular segments of about 15 cm X 15 cm. Each of these "elements" may exist in one of several states which represent the unburned condition, heating prior to ignition, burning, smoldering, or burned out. The progress of a fire on the material is simulated by computing the heat transfer to neighboring elements from a group of burning elements composing a single fire. This heat transfer, mainly radiant, is then used to select from the materials input data the proper values of flame spread velocity and heat, smoke, and gas release. Two results from calculations by DACFIR are given in Figure 6. The plots are comparisons of predicted and measured upper layer temperature in a small cabin mock-up fire test. In the upper figure, a set of relatively flammable furnishings were used. In the lower figure, the furnishings were a set of newer materials including an inert seat cushion material. DACFIR recognizes the improvement in safety, as evidenced by the gas temperature, that was observed in the tests.

Figure 7 shows calculations by Computer Fire Code III of the hot gas layer depth in the doorway and deep in the room for one of the 1977 FMRC/Harvard Fire tests compared to measurements of these quantities. Although the measured results fluctuate widely, on the average the program does well in predicting both depths.

Finally, Figure 8 shows the velocity field in a room and corridor computed by UNDSAFE at two time points. The fire is simulated by a hot spot on the floor in the smaller room at the left. The geometry and heat release rate chosen for this run correspond to certain full-scale corridor tests conducted at NBS. We see in the figure an upper level flow proceeding to the right out of the small room, down the corridor, and then out a second door at the right. A reverse flow of fresh air comes into the burn room along the corridor floor. This computed flow pattern duplicates to fair accuracy the observed flows in the NBS test.

Before leaving the subject of individual models, I would briefly like to note some current but not yet published work. Dr. L. Pietrzak and co-workers at Mission Research Corporation have recently developed a post-flashover compartment fire model with suppression by water sprays. The object is to calculate the water demand for extinguishment. The Department of Transportation is sponsoring additional aircraft cabin fire modeling by Mr. Ray Luoto and others at the Douglas Aircraft Company as part of a larger program concerning the combined fire hazards of cabin furnishing materials.

AN ORGANIZATION OF FIRE MODELERS AND MODEL USERS

A significant recent development in this country has been the establishment of the Ad Hoc Working Group on Mathematical Fire Modeling. This group, formed under the auspices of the Center for Fire Research, brings together the many investigators in this field. The Working Group's goals are to promote the exchange of ideas and information, to identify and coordinate research effort, and perhaps even exchange specific models and sub-models -- when their development has reached this point.

At its first meeting in January of 1977 the Working Group established the organization shown in Figure 9. Three major committees deal with, respectively, the comprehensive models and scenarios; (Professor Emmons, Chairman); the sub-models (Dr. de Ris, Chairman); and the computer implementation of the models and attendant problems (Dr. Rockett of NBS, Chairman). The committee on models and scenarios is divided into two subcommittees: one chaired by Dr. Quintiere, is composed of the developers of the comprehensive models, and the other, chaired by Mr. I. Benjamin of NBS, is formed of those interested in using the models to attack real world safety problems.

One of the first accomplishments of the Working Group was the conduct of a survey of the members to determine their opinions on the most pressing research needs. The results of this survey are shown in Figure 10. The topics listed, suggested by Emmons [7] were ranked in a manner that gives the lowest score to the item of highest priority. As we can see in the figure, understanding of the mass burning rate (under real fire conditions)

is first on our list. Other items judged critical to progress in mathematical modeling are flame spread rates, gas phase combustion (upper layer and flame), and the effect of radiation on spread and burning rate. As we move to the right, the present opinion is that those topics, while important, will not stand in the way of our analyses as much as the items on the left.

CONCLUSIONS

What benefits have we gained or do we expect to gain from developing and working with mathematical fire models? I think it is quite obvious that by setting ourselves this type of analytic problem -- the quantitative prediction of fire development -- we will better understand fire behavior and discover better methods to deal with it. More specifically, we can use the models as a method of extending the results of our full-scale tests to different conditions, reducing our dependence on this expensive procedure. As we develop and refine the models we discover areas in which our knowledge is lacking and research is needed. The models aid our design of small-scale tests in two ways. When test data is used for input to a model we determine the accuracy to which the test data is needed, and, indeed, whether a particular type of data is meaningful at all. In this light, the models help in solving one of the most difficult problems of fire research: how to relate small-scale test results to full-scale fire behavior.

ACKNOWLEDGEMENTS

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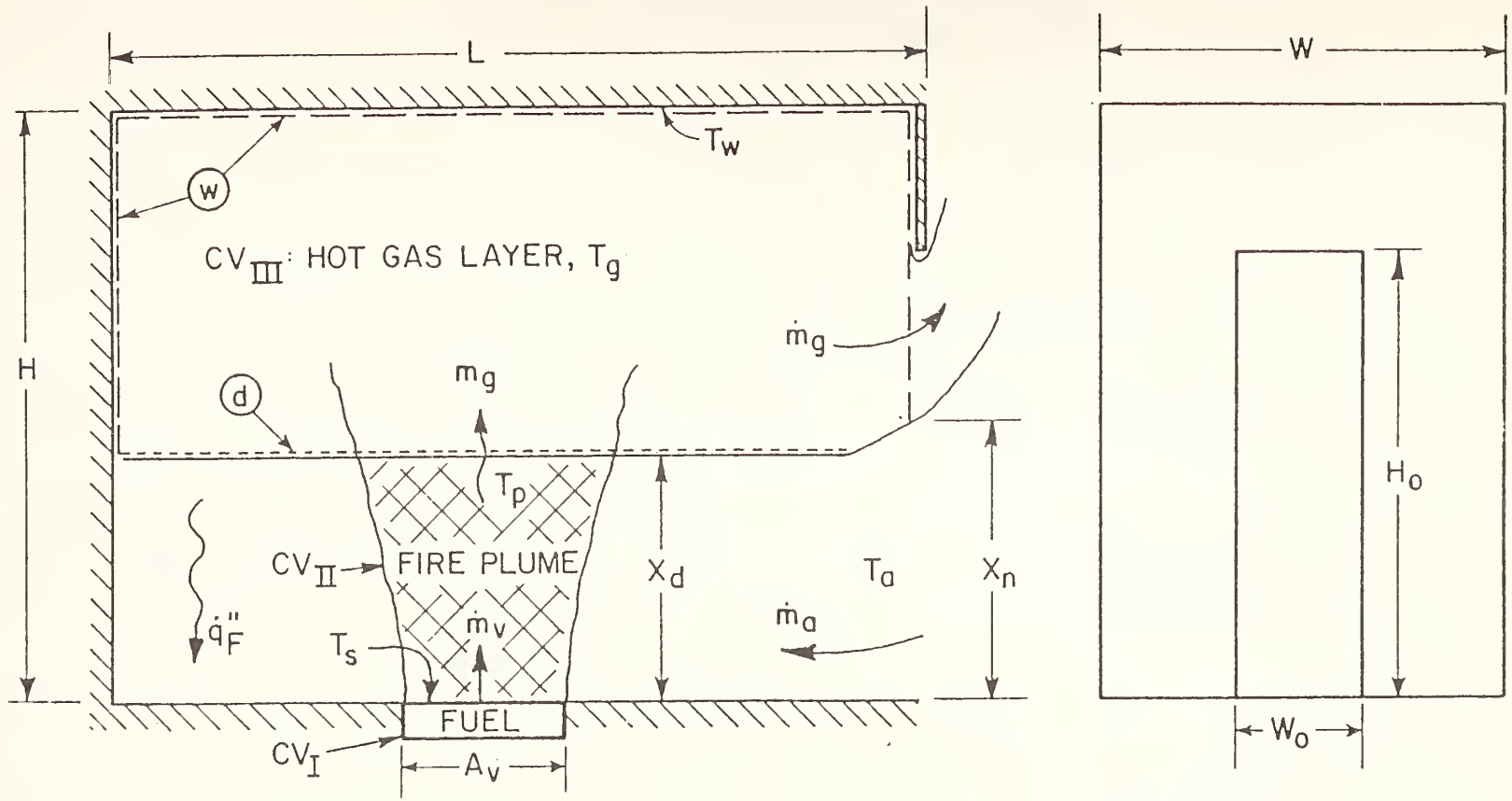
L
W
T_w
w
CV_{III}: HOT GAS LAYER, T_g
$\dot{m}_g$
H
d
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FIRE PLUME
X_d
T_a
X_n
H_o
$\dot{q}''_F$
$\dot{m}_v$
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T_s
FUEL
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A_v
W_o

FIGURE 1

PROGRAM ORGANIZATION - COMPUTER FIRE CODE III

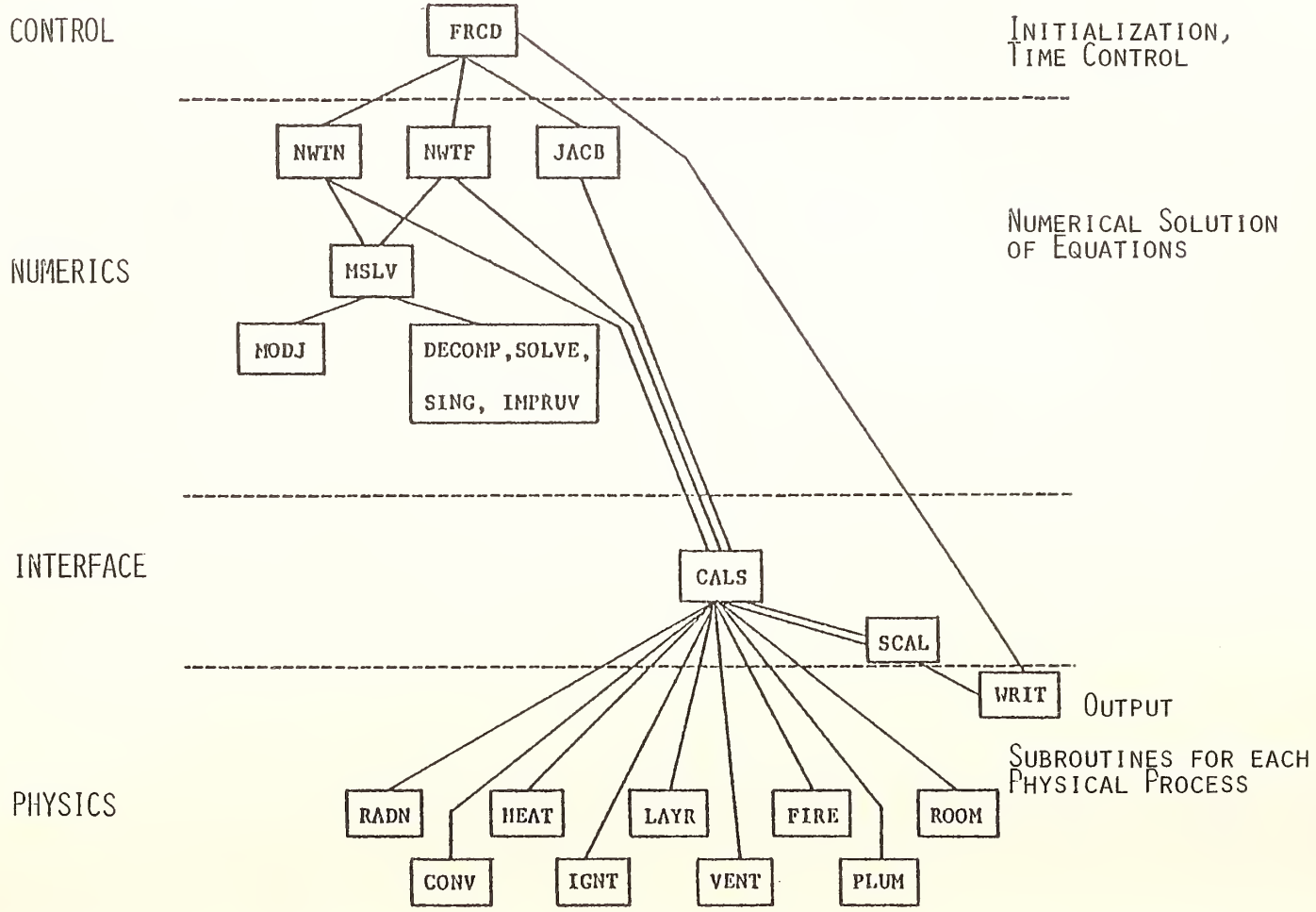

FIGURE 2

MATHEMATICAL MODELS - SOME EXAMPLES

NAME	AUTHOR	CHARACTERISTICS	SPECIAL FEATURES
RFIRES	Pape, Waterman IITRI	Time Dependent CV	Remote Radiative Ignition, Semi-Stochastic Burning Rates Input
DACFIR	MacArthur, Reeves University of Dayton Research Institute	Time Dependent CV	Aircraft Cabins, Flexible Geometry, Spread Details, Uses Materials Test Data
Computer Fire Code III	Emmons, Mitler Harvard/FMRC	Time Dependent CV	Sophisticated Numerics, Modular, Advanced Radiation and Fluid Dynamics
UNDSAFE	Ku, Doria, Lloyd University of Notre Dame	Field Model	Laminar/Turbulent Flows with Transition

FIGURE 3

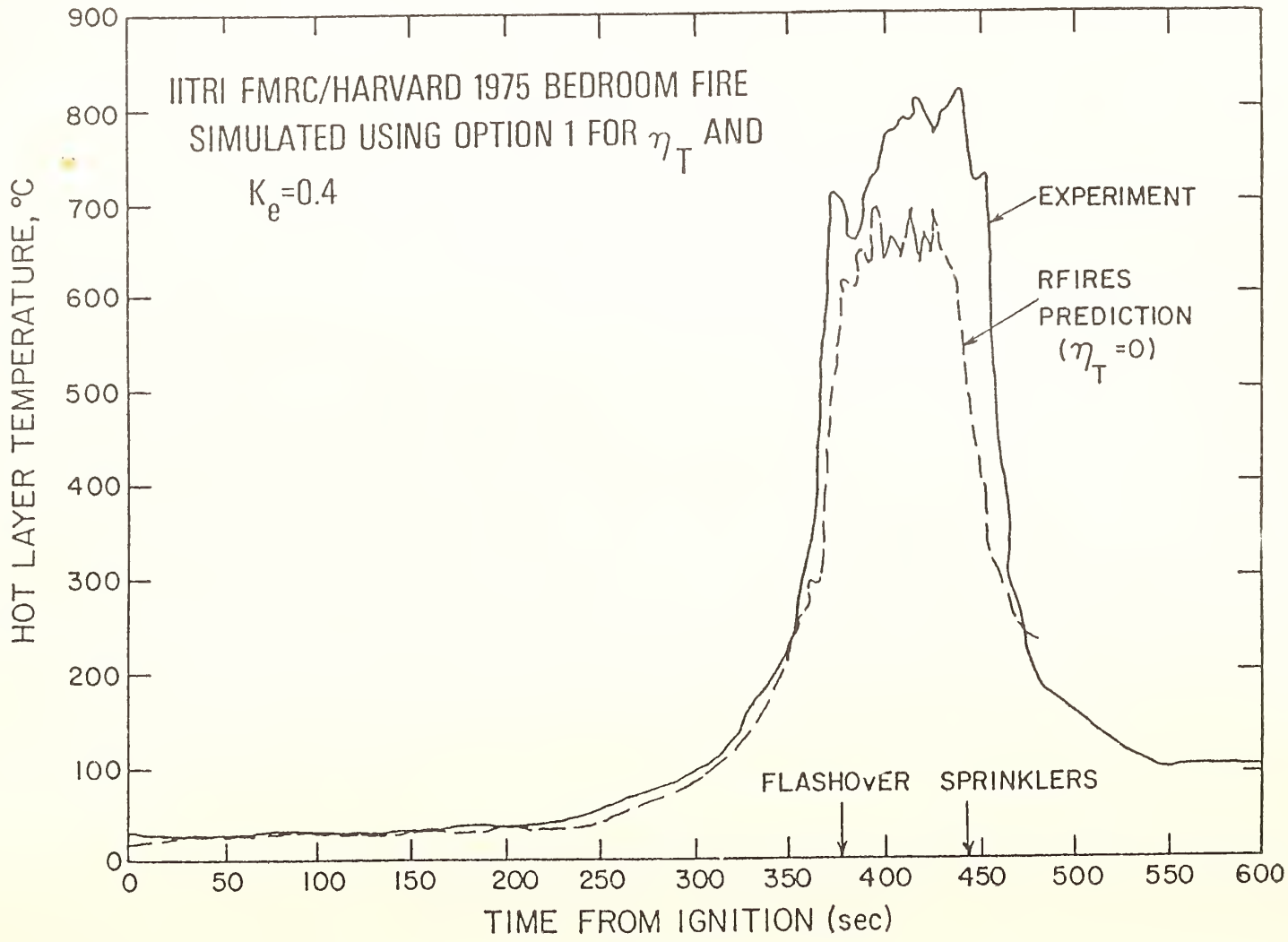
IITRI FMRC/HARVARD 1975 BEDROOM FIRE
SIMULATED USING OPTION 1 FOR η_T AND
K_e=0.4
EXPERIMENT
RFIRES
PREDICTION
(η_T=0)
FLASHOVER
SPRINKLERS
HOT LAYER TEMPERATURE, °C
TIME FROM IGNITION (sec)
0
100
200
300
400
500
600
700
800
900
0
50
100
150
200
250
300
350
400
450
500
550
600

FIGURE 4

FLAME SPREAD ON SEAT GROUP 1 AT 100 SECONDS

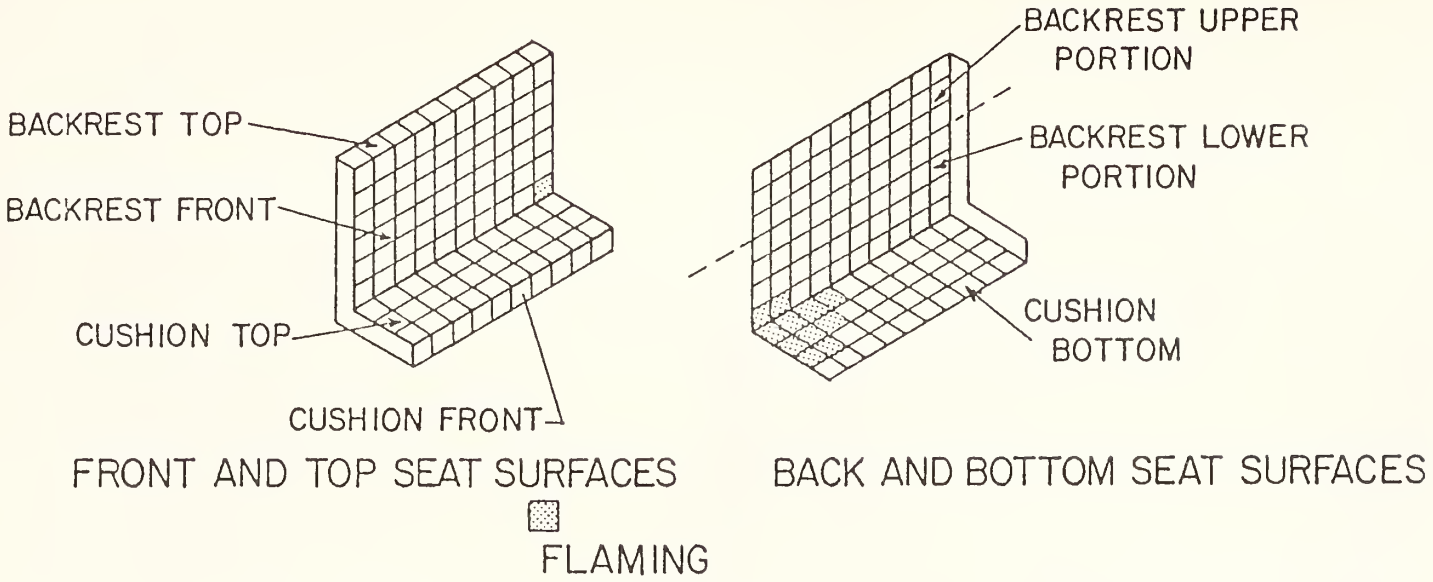

FIGURE 5

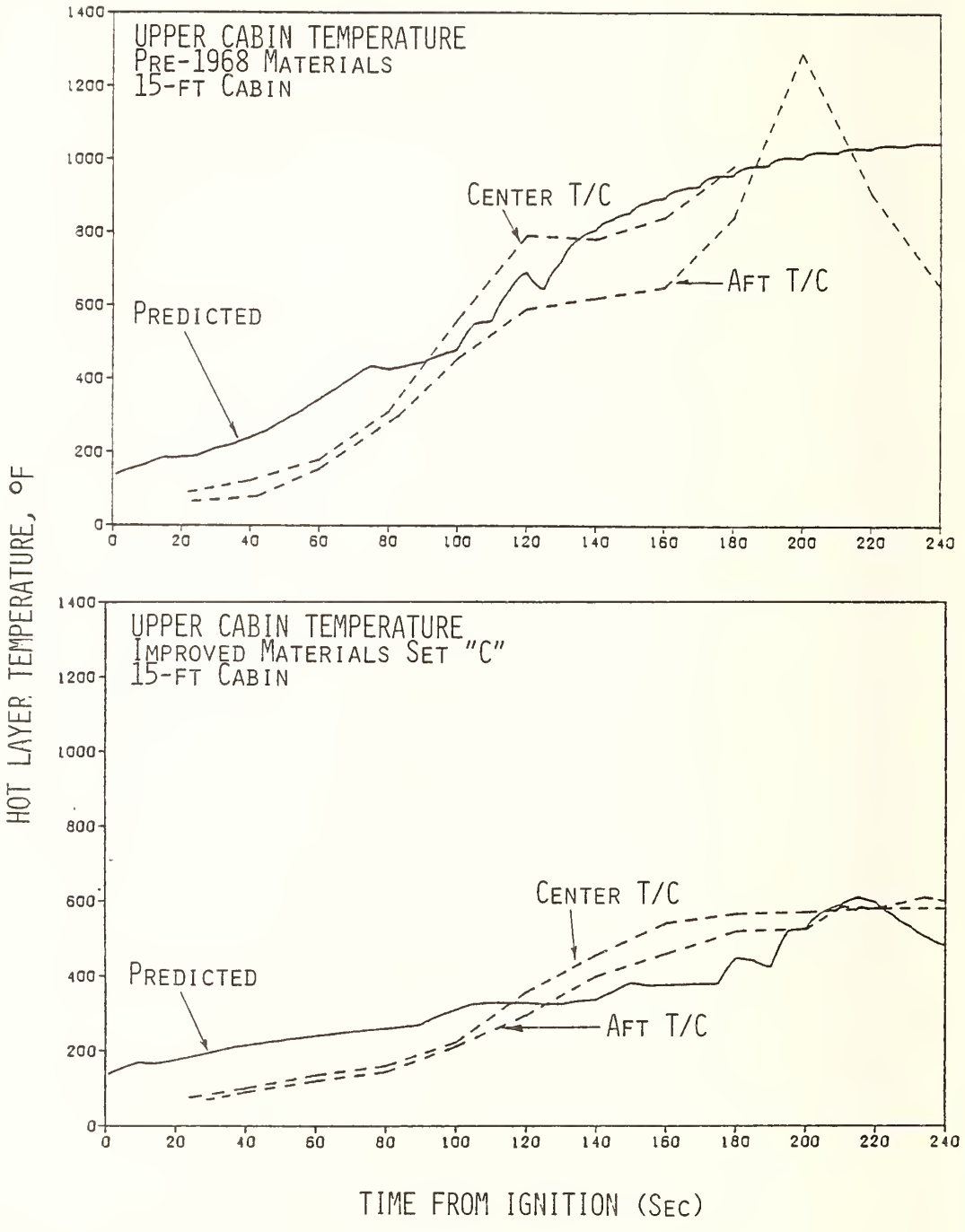
UPPER CABIN TEMPERATURE
PRE-1968 MATERIALS
15-FT CABIN
CENTER T/C
AFT T/C
PREDICTED
UPPER CABIN TEMPERATURE
IMPROVED MATERIALS SET "C"
15-FT CABIN
CENTER T/C
PREDICTED
AFT T/C
HOT LAYER TEMPERATURE, °F
TIME FROM IGNITION (SEC)
0
200
400
600
800
1000
1200
1400
0
20
40
60
80
100
120
140
160
180
200
220
240

FIGURE 6

HOT LAYER DEPTH IN ROOM AND IN DOORWAY

TEST: FMRC 6 JULY 1977 PROGRAM: CPC III (HARVARD)

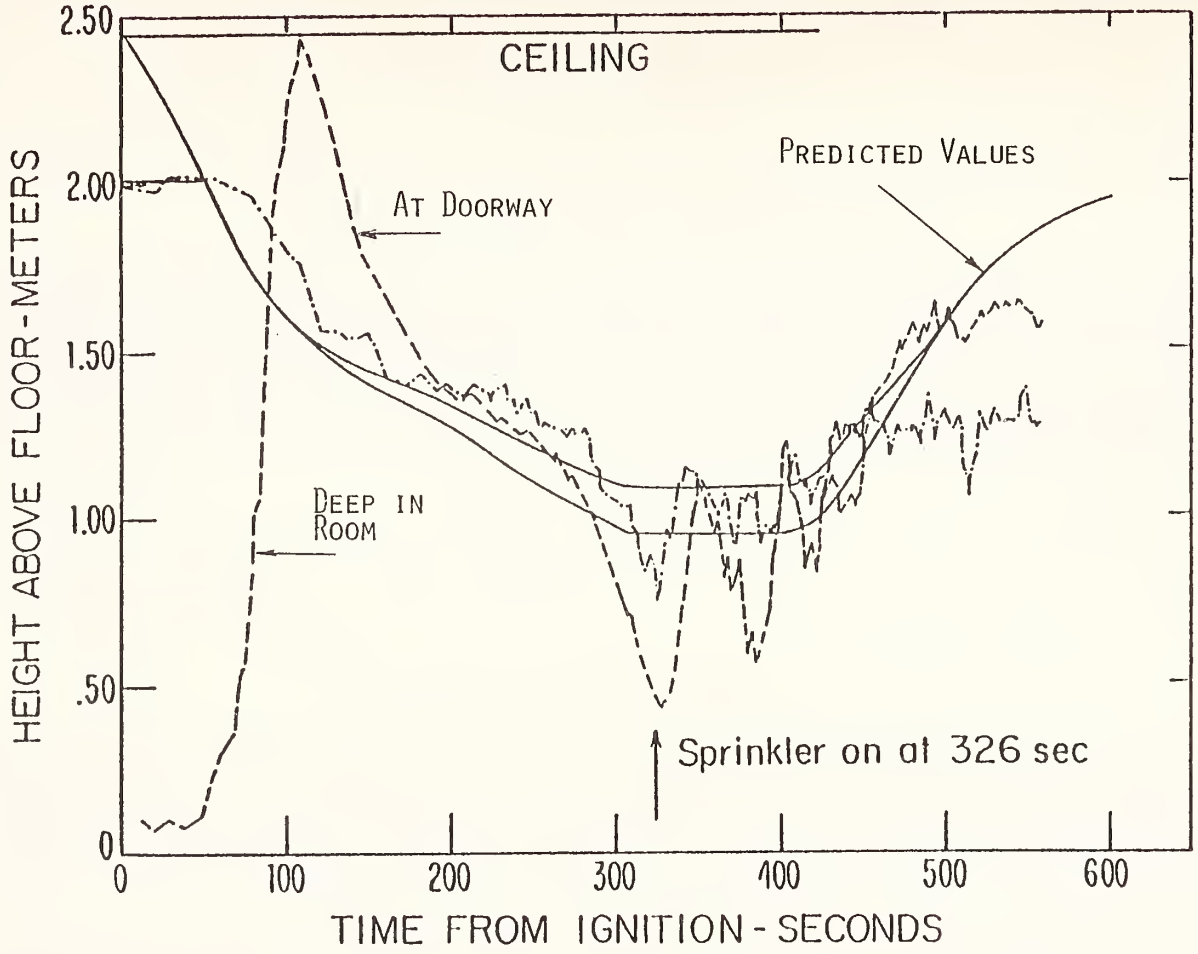

FIGURE 7

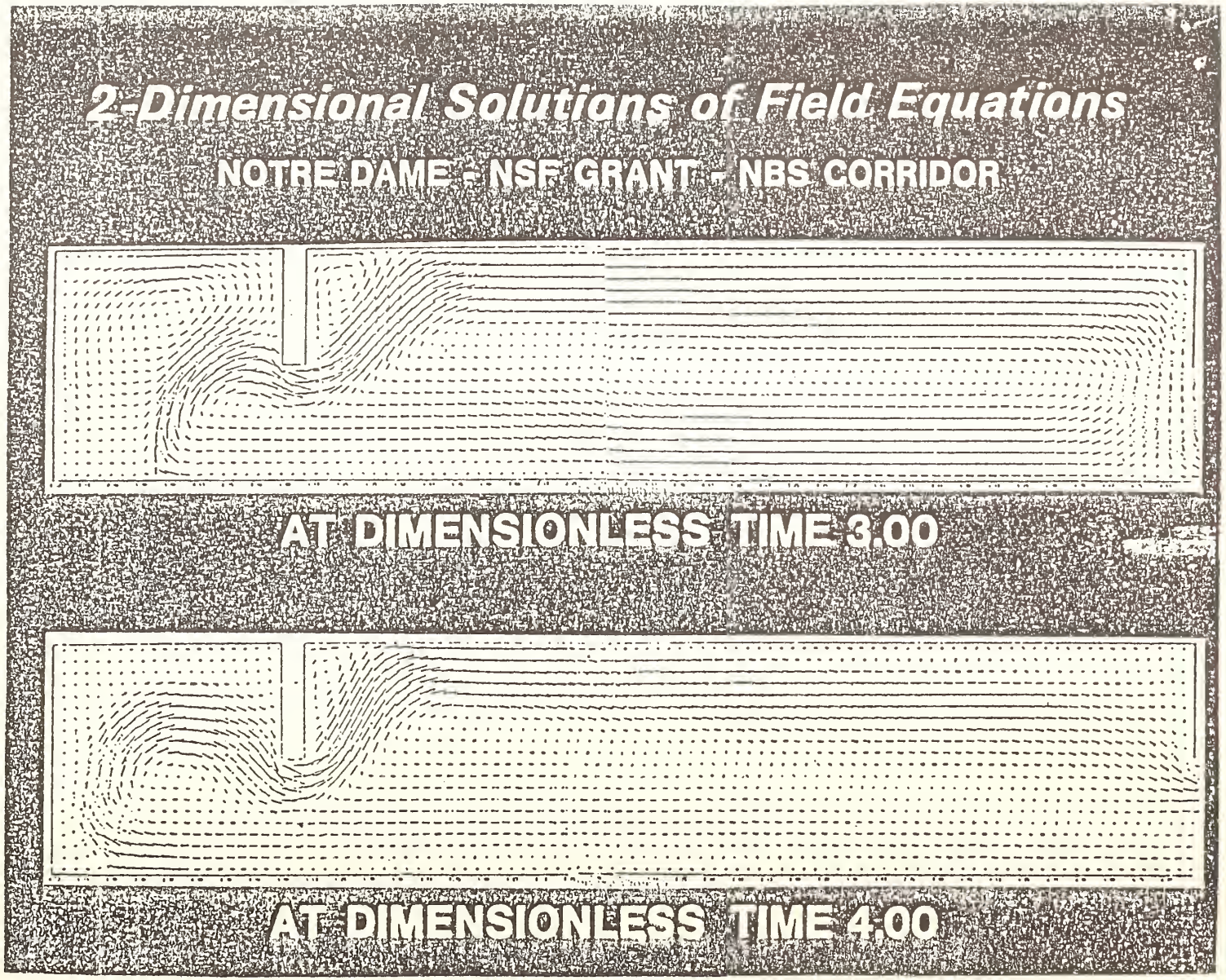
2-Dimensional Solutions of Field Equations
NOTRE DAME - NSF GRANT - NBS CORRIDOR
AT DIMENSIONLESS TIME 3.00
AT DIMENSIONLESS TIME 4.00

FIGURE 8

AD HOC WORKING GROUP ON MATHEMATICAL FIRE MODELING

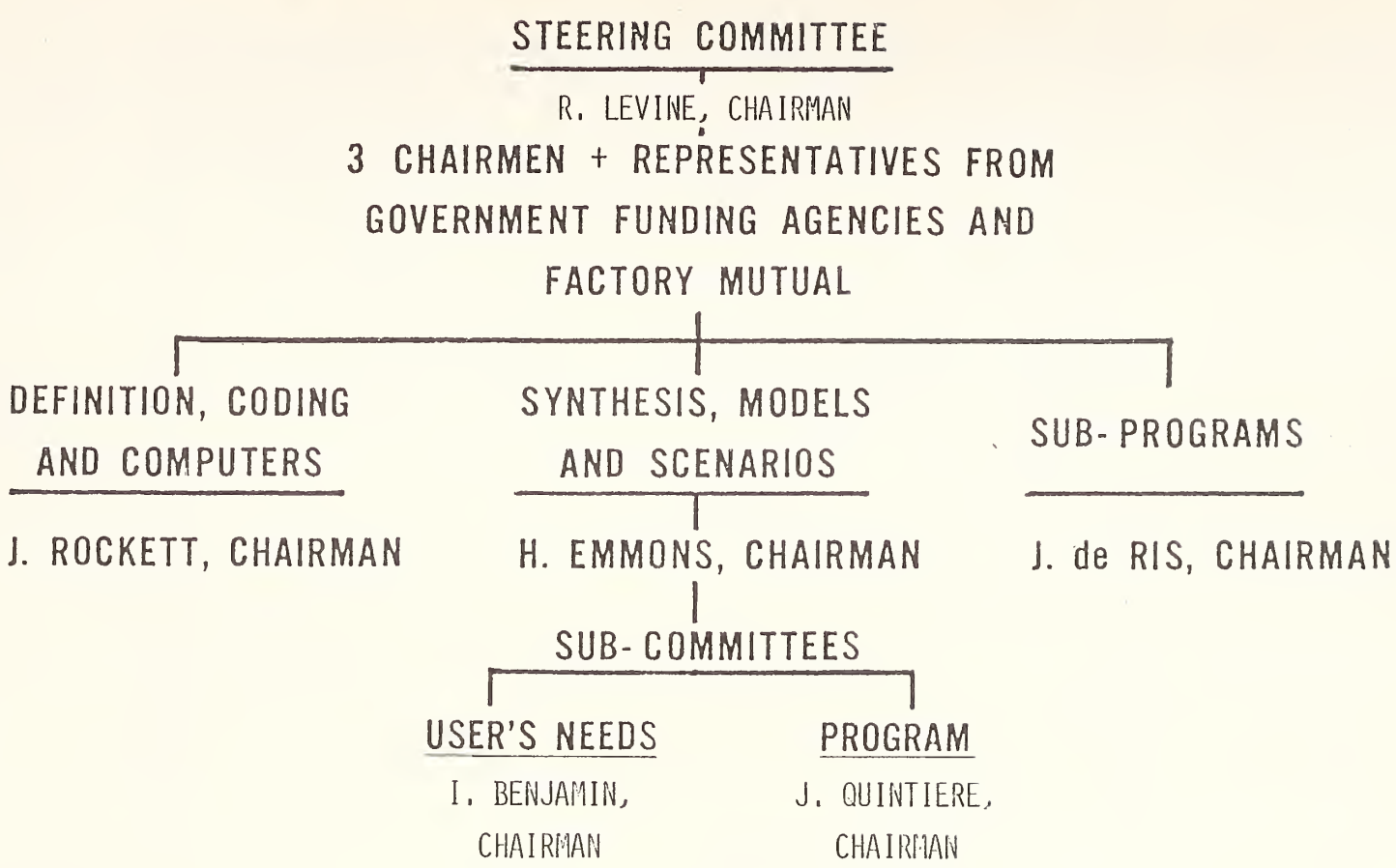

FIGURE 9

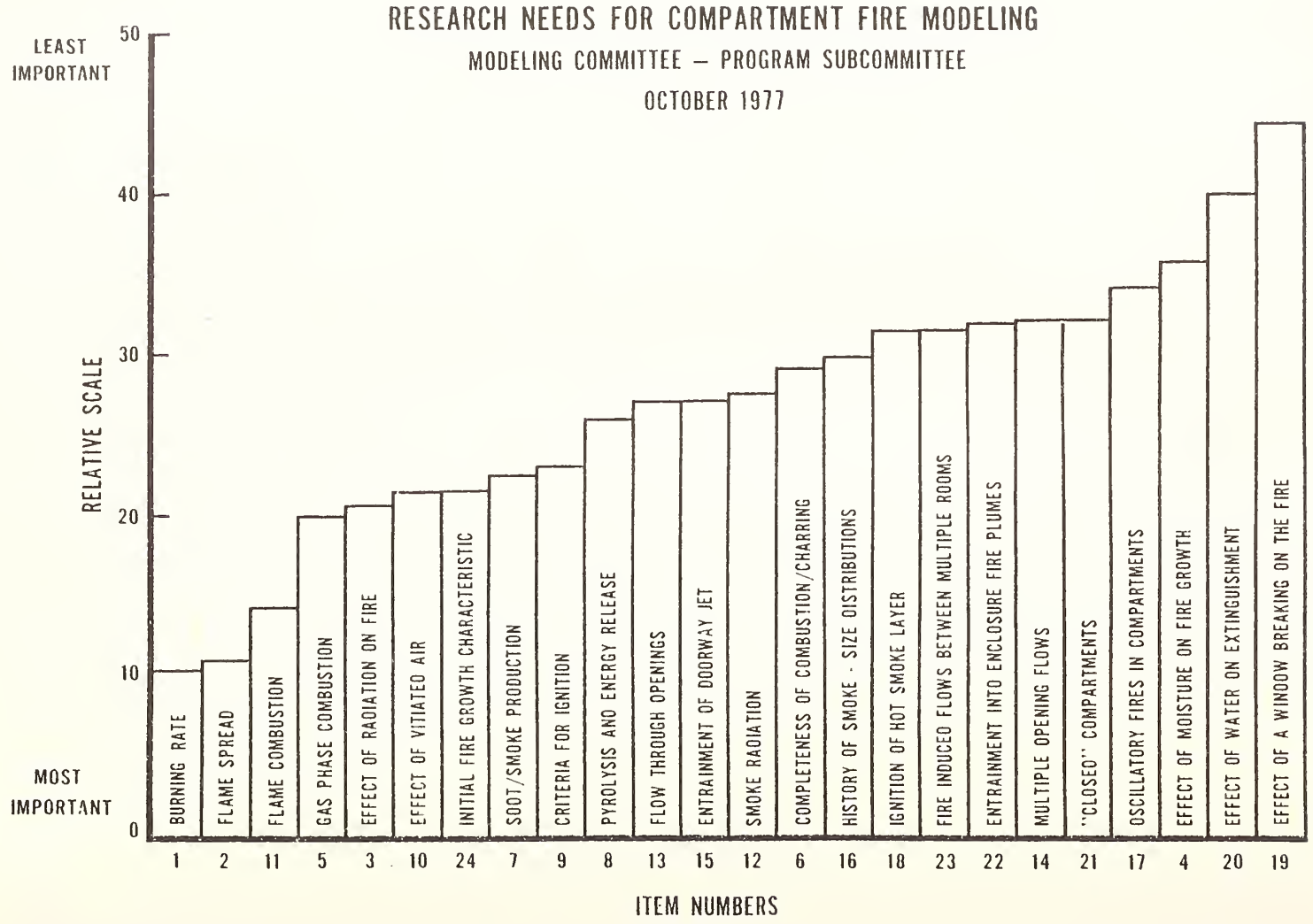
RESEARCH NEEDS FOR COMPARTMENT FIRE MODELING
MODELING COMMITTEE – PROGRAM SUBCOMMITTEE
OCTOBER 1977
LEAST IMPORTANT
MOST IMPORTANT
RELATIVE SCALE
50
40
30
20
10
0
BURNING RATE
FLAME SPREAD
FLAME COMBUSTION
GAS PHASE COMBUSTION
EFFECT OF RADIATION ON FIRE
EFFECT OF VITIATED AIR
INITIAL FIRE GROWTH CHARACTERISTIC
SOOT/SMOKE PRODUCTION
CRITERIA FOR IGNITION
PYROLYSIS AND ENERGY RELEASE
FLOW THROUGH OPENINGS
ENTRAINMENT OF DOORWAY JET
SMOKE RADIATION
COMPLETENESS OF COMBUSTION/CHARRING
HISTORY OF SMOKE - SIZE DISTRIBUTIONS
IGNITION OF HOT SMOKE LAYER
FIRE INDUCED FLOWS BETWEEN MULTIPLE ROOMS
ENTRAINMENT INTO ENCLOSURE FIRE PLUMES
MULTIPLE OPENING FLOWS
"CLOSED" COMPARTMENTS
OSCILLATORY FIRES IN COMPARTMENTS
EFFECT OF MOISTURE ON FIRE GROWTH
EFFECT OF WATER ON EXTINGUISHMENT
EFFECT OF A WINDOW BREAKING ON THE FIRE
1 2 11 5 3 10 24 7 9 8 13 15 12 6 16 18 23 22 14 21 17 4 20 19
ITEM NUMBERS

FIGURE 10

THEME
FIRE MODELING

BASIC PROBLEMS IN PHYSICAL UNDERSTANDING OF COMPARTMENT FIRE

by

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I. INTRODUCTION

This paper is concerned with the approach to understand the fire progress systematically. We know now that there are some patterns of this progress,and discontinuous development like flash-over may occur during a fire,but our knowledges on fire are generally so fragmentary that they can hardly be applied to a systematic planning of fire safety.

While it seems evident that fire modeling have a background of frank or tacit needs of many fields related to fire,concerns for fire phenomena will differ with standpoints or intentions of respective fields. For example,standard conditions of heating to be expected to occur during a fire will be a matter of great concern for the rational material test on combustibility,smoke generation or flame spread,whilst the qualitative forecast on patterns of fire progress and how a fire would be controled by architectural devices are the matters of interest to architects and building engineers. Conditions and specifications differ so much with buildings or maintenance conditions of them that a precise prediction of fire propagation may not be effective for a building planning and sometimes architects have only to know the critical conditions upon a fire development.

In the former case,the whole fire environment is the very thing to be grasped and the patterns of propagation may sometimes be out of concern,but the burning or combustible objects are watched in the latter case. It should be noted that there are some different ways or frames to grasp a process of fire according to the standpoints,even when it may be formulated physically in only one way.

The adequacy of fire modeling will be assessed on the authority of generality and quantitative precision. In this sense, most of the engineering level mathematical models now under studies[1,2,3] that correspond to the former case above introduced are "quantitatively precise" models,and the methods to grasp the context of fire progress called as "scenario" pay attention solely to the general rules of fire propagation.

As those methods should be used properly corresponding to concerns,it would be an urgent necessity to discuss both methods on a common ground not only to avoid the misunderstanding of extents where respective approaches are possible,but also to develop a more generalized model. To make the preparations of such a ground is one of the aims of this paper.

By the way,it seems that there remain still some basic problems in mathematical fire modeling and "scenario" methods. As to the mathematical modeling,there are now two approaches to it;Partial Differential Field type models[4,5,6,7] and Control Volume type models[1,2,3,8]. In the former approach,fire is supposed as a complicated but "inorganic" phenomenon,whilst the thought that regards a fire as an "organic system" composed of zones provided with peculiar functions seems to lie in the latter approach. So the latter approach takes on a new meaning; a frame to show the roles of the zones or contents in fire progress. Such a frame will offer us a guide to make rational tests on respective parts and contents in a compartment. Here,we discuss mainly the problems around the latter approach and ways to evolve it perspicuously. The "scenario" method is not enough systematized for the effective application to architectural plannings,and so should be refined from this viewpoint. We also propose a method to grasp the roles of combustible objects installed in a compartment as an example of the refinement of "scenario".

II. GENERAL FEATURES OF COMPARTMENT FIRES

Fire phenomena include some non-linear primary processes like radiation heat transfer or ignition,each of which behaves sometimes in much different manner on both sides of some diverging conditions related to it. Besides,discontinuities are observed in many sorts of conditions and specifications of compartment like opening conditions or combustibility of lining materials,and so even a linear phenomenon may behave discontinuously for a quantum change of the conditions. We must observe fire phenomena carefully and prepare a frame for modeling that does not include a qualitative oversight,not to be frustrated by fire that is so malicious.

In this Chapter,we discuss what physical problems should be considered or formulated in a modeling of fire. Of course,we can not expect a data gathering during a real fire,so we investigate here again the results of about 80 full-scale fire tests conducted in Japan up to 1976 to pick up the problems to be studied. To make studies perspicuous,the patterns and phases of fire progress are classified and some features of respective patterns and phases are picked out first,and then we discuss the problems concerning the zoning of fire space for a mathematical modeling of fire.

II-1. Global Features of Compartment Fires

Here,we classify the progress patterns of fire up to flashover,and then summarize the general features of fire progress for respective patterns.

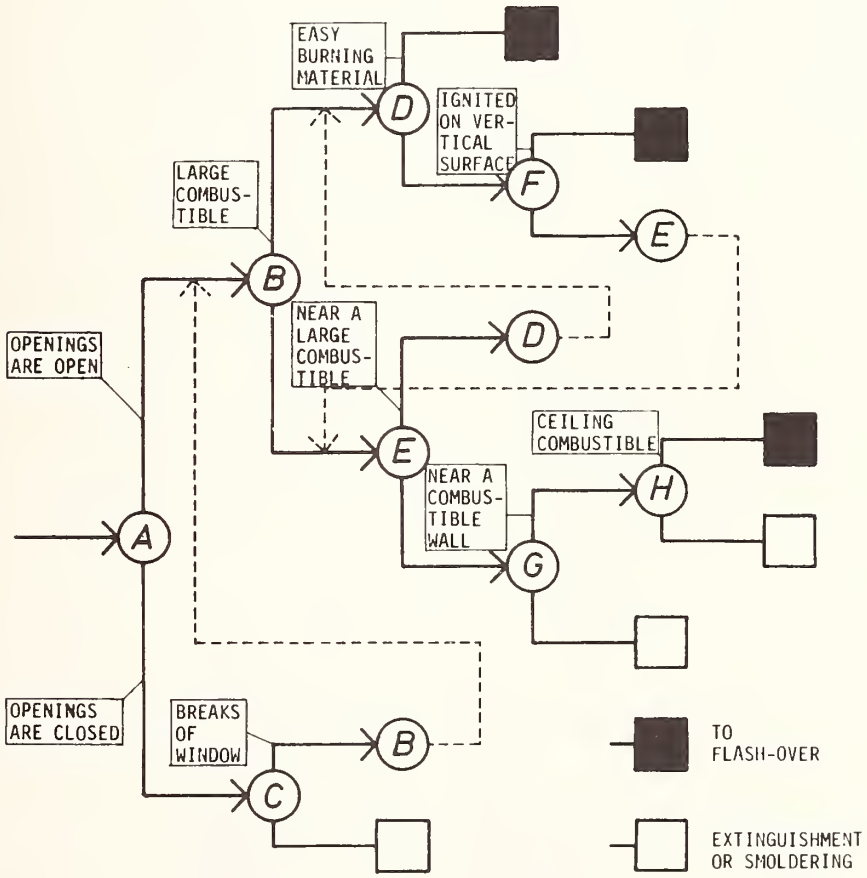
Generally,a fire would smolder or be extinguished during rather early stages in an entirely closed compartment. On the other hand,if enough ventilation is expected for a compartment, the behavior of fire in it seems to be characterized by the burning objects during respective stages of fire. The idea of "scenario" originates perhaps in this impression. After the results of full-scale tests,the conditions for a fire to come

to flash-over would be summarized in the way of event-tree as Fig.1,but the following conditions seem to be essential.

Type-1; stable ignition on a vertical surface of surrounding of compartment whose interior linings are wholly combustible.

Type-2; stable ignition on a flat combustible of easy burnable material.

Type-3; stable ignition on a large combustible.



CHARACTER OF DECISION GATES

A:opening condition
B:size of ignited matter
C:breaks of window during a fire
D:combustibility of ignited matter
E:geometrical relationship between other combustible components
F:position of ignition
G:position of ignited matter & combustiblity of wall
H:combustibility of ceiling

Fig.1

Most of fire progress patterns will be classified into one of 3 types or explained as "hybrids" among them. The visible differences among the patterns come from the types of "principal ignited objects". Among these patterns,the Type-1 progress pattern includes a lot of discontinuities. Thus,we classify a process of fire up to the fully-developed phase into 4 phases by referring the discontinuities of the characteristic process of Type-1 pattern,and summarize the physical features of each phase and safety-related problems in Tab.1. The phase-1 corresponds to a spot burning of the initially ignited object. While stable ignitions are realized in most full-scale experiments, the combustion during this phase seems to be most unstable in a real fire. If the fire compartment is entirely closed,a fire may never proceed to the next phase,but be extinguished or be followed by a smoldering fire. In the phase-2,fire spreads locally in the compartment and the combustion condition will become stable even in a real fire. In the phase-3,flame spreads entirely on a certain surface of the compartment and a strong heating on whole parts that precedes a flash-over will occur.

Discontinuities seen in Type-1 progress pattern come from the differences among the combustibilities and conditions of the burning objects in respective phases. But,does an ignition on a vertical wall bring always a flash-over in this pattern? Generally,a contact of good-extended flame with ceiling seems to be necessary for the ignition of a combustible ceiling. On the other hand,a significant horizontal flame spread does never occur during phase 2 of Type-1,whilst this phase is characterized by the significant vertical spread of flame on a vertical surrounding. So,if the flame of the burning object in the phase 1 is not so large,a flame that is enough large for the stable ignition of ceiling will not be formed on the wall nor above the burning object,and so a flash-over may never occur.

While a combustible ceiling has a role to spread a local burning on a part of wall horizontally,such a role can be per-

Tab.1 PATTERNS & PHASES OF FIRE PROGRESS IN COMPARTMENT

CLASSIFICATION OF PROGRESS PATTERNS	CLASSIFICATION BY THE INITIAL IGNITION CONDITIONS			PROGRESS PHASES	PHASE-1 (PRIMARY IGNITION)	PHASE-2 (DEVELOPMENT OF FIRE)	PHASE-3 (GROWTH OF FIRE)	PHASE-4 (FULLY DEVELOPED FIRE)
notations; The shadows in the following figures denote combustible parts of compartment.	CHARACTERISTIC IGNITION MATTER	EXAMPLES IN THE EXPERIMENTS	EXAMPLES IN THE REAL LIFE CONDITIONS	SAFETY RELATED PROBLEMS		SMOKE SPREAD TO OTHER SPACES SMOKE TOXICITY	SMOKE SPREAD TO OTHER SPACES HEATING OF HUMAN BODY CHOKE-DAMP SMOKE-TOXICITY FALL OF VISIBILITY	IN ADDITION TO THE PROBLEMS FOR PH.-3, EFFECTS TO STRUCTURES FIRE SPREAD TO OTHER SPACES
TYPE-1 : INTERIOR LINING FIRE 	SMALL COMBUSTIBLE MATTER NEAR A WALL	WOOD CRIB CHAIR	CHAIR DUST CAN ELECTRIC APPARATUS PILLOW "ZABUTON"	GENERAL DESCRIPTION & EPISODES	 *COMBUSTION OF IGNITED OBJECT.	 *COMBUSTION OF WALL, BUT ONLY THE PART NEAR THE IGNITED OBJECT *RAPID RISE OF TEMPERATURE OF UPPER PART	 *VIOLENT COMBUSTION NEAR THE CEILING *RAPID GENERATION OF BLACK SMOKE *RAPID RISE OF FLOOR TEMPERATURE *IGNITION ON FLOOR COVERINGS	 *FLAME EJECTION FROM OPENINGS
	FIRE RETARDED LARGE COMBUSTIBLE NEAR A WALL	"TATAMI"	"TATAMI" CARPET	CONDITION OF PHASE TRANSITION		IGNITION OF WALL	IGNITION OF CEILING	IGNITION OF OTHER PARTS OF COMPARTMENT
TYPE-2 : FLOOR FIRE (surroundings without shadow can be combustible) 	FLAT COMBUSTIBLE	WASTE LUMBERS	"KOTATSU" CARPET	GENERAL DESCRIPTION & EPISODES		 *RISE OF TEMPERATURE OF UPPER PART	 *RAPID FLAME SPREAD UNDER CEILING *RAPID RISE OF FLOOR TEMPERATURE *IGNITION ON FLOOR COVERINGS	
				CONDITION OF PHASE TRANSITION		TRANSITION FROM "1" TO "2" IS OBSCURE.	FLAME TOUCH AT CEILING	IGNITION OF ALL PARTS OF COMPARTMENT
TYPE-3 : MASS FIRE (surroundings without shadow can be combustible) 	LARGE COMBUSTIBLE	WASTE LUMBERS FURNITURES	LARGE FURNITURE GOODS IN WAREHOUSE	A) CASE WHERE IGNITION OCCURS AT THE UPPER PART OF LARGE COMBUSTIBLE		 *RISE OF TEMPERATURE OF UPPER PART	 *FLAME SPREAD UNDER CEILING	
				B) CASE WHERE IGNITION OCCURS AT THE LOWER PART				
				CONDITION OF PHASE TRANSITION		TRANSITIONS BETHEEN THE PHASES ARE ALMOST OBSCURE.		

formed in some degree by any downward combustible surfaces. For example,if the downward surface of a shelf fixed on a wall is ignited,a rapid horizontal spread of flame under the shelf will occur and bring a full burning of shelf that may be a cause of flash-over.[9]

There may not be an essential difference between Type-2 and Type-3 patterns,but different treatments may be inevitable for the modeling of the principal ignited object for respective patterns.

II-2. Local Features of Compartment Fires

There are now two approaches to the modeling of fire;one is called as Partial Differential Field type modeling and the another is Control Volume type modeling,as introduced in CH.I. In case that the physical structure is qualitatively known or well parameterized,a CV type model will give a good result that agrees with the general features of a real fire. In such a model,it is usual to characterize the distribution of a variable that describes the physical condition of each zone with one value,for instance the mean of the variable in the zone,but,for the non-linear processes may such a parameterization or averaging hurt the representation of phenomena.

Now,we suppose here a phenomenon basically described as $f\{\xi(s),\pi\}$,where $\xi(s)$ denotes the spatial distribution of the physical quantity ξ,and π is a parameter group. Then,if the following approximation is possible for the zone,the way of zoning will be regarded as adequate.

$$\frac{1}{Z}\int_Z f\{\xi(s),\pi\}ds \simeq F(\xi_Z,\pi) \quad , \quad \xi_Z \equiv \frac{1}{Z}\int_Z \xi(s)ds$$

F is the algebraic equation on "f" for all over Z. As F=f is valid for $f \propto \xi$,the spatial zoning for linear phenomena may not become a serious problem,but some problems will arise by a simple expression of a non-linear processes. So,the following

approaches are necessary for the proper expression of a non-linear phenomenon such as radiation or ignition that characterizes the fire progress.

1) Parameterization of the Distribution of Physical Variables in a Zone:

   This approach is to assume the form of the distribution of the physical property to be studied so that the process can be expressed properly by the form of $F(\xi_z)$. A modeling of plume in an ideal environment is a sort of this approach.

2) Parameterization of the Physical Structure of Zone:

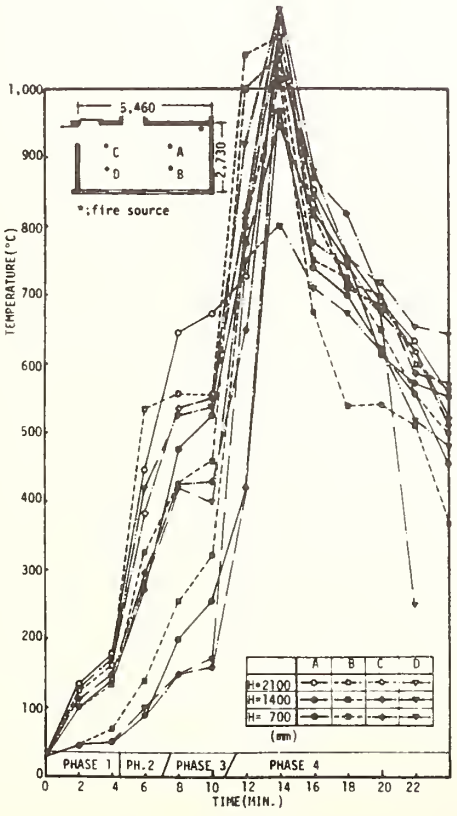
   Regressive or experimental expression of $F(\xi_z)$ will be inevitable for the temporary formulation of the phenomenon whose physical structure is too complicated to make a physical formulation on it. In fact,the furnitures settled in rooms and the lining materials are so various in shape, surface conditions or compositions that we must apply this approach for many subprograms of mathematical fire modeling whether we like it or not.

3) Precise Zoning:

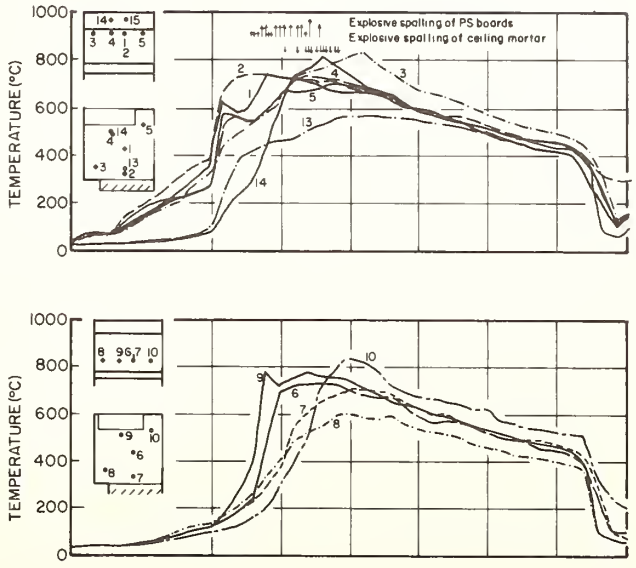
   A very precise zoning of the space to be studied will resolve many of the problems due to the distribution of physical properties in zones. However,this approach sacrifices the merits of CV type modeling like simplicity or perspicuity of the description.

Thus,the approaches 1 and 2 may sacrifice the generality for the physical description,whilst the approach 3 may sacrifice the simplicity for the generality. Once the way of zoning for CV type modeling is fixed upon,a series of experiments will be carried out for the experimental formulation of each primary process for each zone. However,an intuitive understanding of phenomenon is indispensable for these experiments. To balance the generality with the perspicuity of a modeling,it will be adequate to synthesize them so that the physical structure and

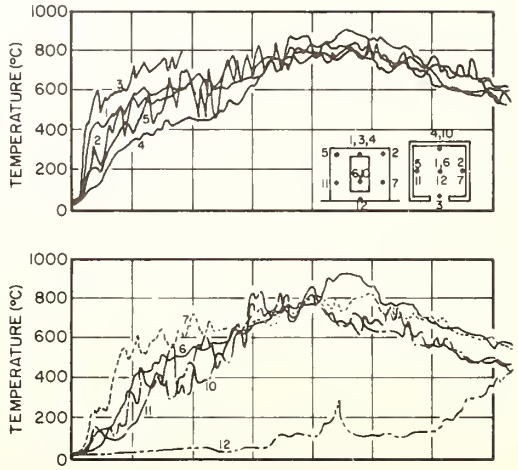
Figure 2. TYPICAL TIME HISTORIES OF TEMPERATURE DURING A FIRE



(A) TYPICAL TIME HISTORY OF TEMPERATURE FOR TYPE-1 [9]



(B) TYPICAL TIME HISTORY OF TEMPERATURE FOR TYPE-2 [11]



(C) TYPICAL TIME HISTORY OF TEMPERATURE FOR TYPE-3 [11]

the spatial distribution of physical properties in respective zones would be perspicuous.

In this sense,the way of zoning and the description of physical structure for each zone are "one body". Here we discuss the "local" features of fire progress as an approach to make an adequate zoning and physical description for them. The following ways of zoning and physical hypotheses are sometimes applied in CV type models proposed up to now.

1) Uniformity of Room Air Conditions[10]
2) Two Layer Model for Room Air[1,2,3,8].
3) Uniformity of Ceiling Temperature[1,2,3,8,10].

We discuss the adequacy of zoning and physical description on these hypotheses as clues by referring the results of full-scale tests. The main results to be referred are quated in Fig.2.

1) Uniformity of Room Air Conditions:

During the fully-developed phase,the distribution of room air temperature seems to be irregular that this hypothesis will be an adequate one. Of course,even in this case,the problem by what value of temperature one should characterize the room air temperature is not solved yet. However, the fact that this problem is not so serious for the practical application of the model for this phase was well shown by the modeling of Kawagoe-Sekine[10]. In contrast to this,the vertical gradient of temperature is much significant during the early stages of fire. So,the intense heating of ceiling preceding the ignition of upper part of compartment may not come out from this hypothesis.

2) Two Layer Model for Room Air:

It will be evident that this hypothesis on room air condition is more strict than 1. Especially during the early phases of a fire in the patterns of Type-1 and Type-2,one can observe a significant difference between the tempera-

tures near the ceiling and near the floor. We discuss two cases on this hypothesis.

2-a) Uniformity of the Hot Gas Layer Conditions:
The temperature distribution in a hot gas layer seems to be described as a function of distance from ceiling or height during the phases before the ignition of ceiling occurs. As the form of this function is not determined yet,it may be inevitable to adopt this hypothesis,but the danger that the preheating of ceiling might be underestimated lurks again in this case.

2-b) Characteristic Temperature of Lower Layer≡Ambient Temperature:
It may be evident that this assumption would be valid only in the phase-1.

3) Uniformity of Ceiling Temperature:
The hypothesis that an ignition of ceiling occurs when the ceiling temperature reaches at a certain threshold value is adopted in many cases for the ignition condition of ceiling or hot layer. This hypothesis would look apparently good,because the temperature distribution near a ceiling is represented as a function of height or distance from ceiling for respective cases of experiment,but when a ceiling burns in an experiment,the ignition occurs at a small spot that is heated most strongly by the flame of fire source,and then flame spreads all over the ceiling. Such a phenomenon may not come out from this hypothesis. We should consider the same problem for the case that the vertical surroundings are made of combustible materials. Provided that the fire source is located enough near a combustible wall,the ignition of a part of wall can be caused easily by the "blow-down" of flame due to Coanda effect or the radiation heat transfer from the flame. If the radiation heat transfer from the heat source to wall is simply for-

mulated under the image of the radiation between an object and a plane simulating the wall,the process of the ignition of the limited part of wall whose geometrical factor to see the flame is extremely large may not come out.

As the full-scale tests that we referred to here are not so special ones,we should note that some basic features of fire that generate evidently in a real fire may not generate in a mathematical simulation. A precise zoning may be a way to resolve this problem,but a precise zoning would be essentially required for only certain limited parts that take part in the combution history during fire. So as to make such an effective zoning for combustible objects and interior linings,a method to search the spots that may be ignited by the combustion of a certain zone or object. The important cases of new ignition in real fires seem to be the following two cases.

1) Ignition due to the Touch of Flame
2) Ignition due to the Radiation from Flame and Burning Object

In both cases,the area of the part that is ignited at the same time is at most the projected area of flame on the plane that includes it. Thus,the following three parts of compartment should be regarded as different zones.

1) Fire Element: Complex of Burning Part & the Flame above it.
2) Flamed Hot Spot: the Part that Contacts with the Flame of a Fire Element.
3) Radiated Hot Spot: the Part that is Radiated Strongly by the Flame of a Fire Element.

The fuel volatilization and ignition processes should be modeled for the "hot spots". Once an ignition occurs in compartment,"hot spots" dependent to the ignited part,that is a "fire

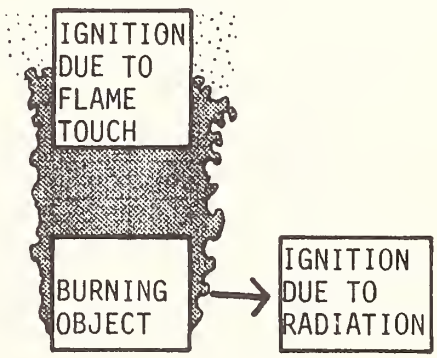
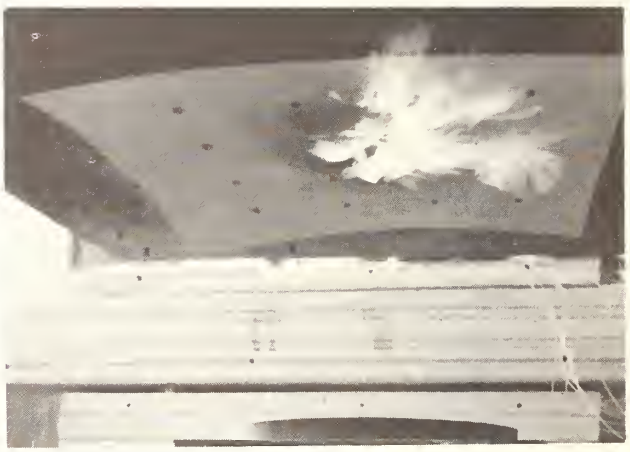


Fig.3 Typical Cases of New Ignition

(A) BEFORE IGNITION

PYROLYSIS ABOVE FIRE SOURCE

(B) IGNITION



(C) AFTER IGNITION

FLAME SPREAD BENEATH CEILING

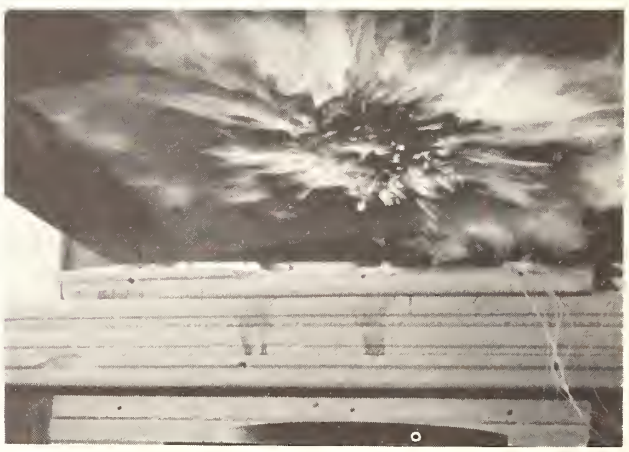


PHOTO.1 IGNITION OF CEILING (PREPARATORY EXPERIMENT FOR CEILING TESTS)

element,should be searched following certain standards that specify the possibility of intense volatilization and ignition. These standards on ignition are the common bases to the generality of mathematical fire modeling and the basic rules of fire propagation for "scenario" method,but most of them are left for future studies.

III. PROGRAMS FOR MATHEMATICAL MODELING AND SCENARIO OF FIRE

If the results of mathematical models of fire would be rearranged into a type of representation as "scenario",the role o each combustible object in the fire progress could be clarified and this would lead to a rational fire provision planning. However,the present state of "scenario",for instance a type of description as shown in Fig.1,permits an arbitrary choice of way at each gate,it is still in a common sense for a building planning or designing. Besides,a model that treats only burning objects at respective phases like "scenario" method may overlook the effects of non-combustible zones like air layers or unignited surroundings. Thus,a reinforcement of "scenario" with mathematical modeling is indispensable for the improvement of our overall grasping of the context of fire progress,but it should be noted that there remains still a gap between "grasping" of fire and "prediction" or "simulation" of fire. A confusion around such a problem must maze the rational understanding and provision of fire.

As it is not always necessary to grasp and predict a fire by only one way,we shall here redefine the mathematical fire modeling as an approach to predict a fire and the "scenario" as an approach to grasp a fire. The generality and quantitative precision are the very things that are expected to the former approach,whilst the intuitive perspicuity is the central problem in the latter approach. The research programs for respective approaches should be determined on the consideration of these peculiar purposes,and here will be discussed the basic problems concerning the mathematical fire modeling and proposed a way of rearrangement of prediction results for an architectural application. It should be mentioned first that our interest in this paper is only concerning the programs for the approaches to understanding of fire and progresses of subprograms or simulation methods are not included.

III-1. Diagram for Control Volume Type Modeling

The procedure to evolve a CV type mathematical modeling is divided into two steps;the formulation of the processes for a temporary frame diagram of model and the verification of the adequacy of the temporary frame diagram. Of course,a frame that may explain the general features of fire should be proposed preceding these works. As a confusion of these two steps will maze the program for the fire modeling,the frame of model had better be described in a systematic diagram. A systematic diagram of fire,which may seem high handled,permits us to know the positions and roles of respective submodels more distinctly and to evaluate the temporary state of modeling more clearly. Here, we show an attempt to systematize the physical structure of fire and then discuss the approach to evolve a CV type methematical modeling perspicaciously.

As discussed in CH.II,the adequacy of fire modeling depends essentially upon the way of the set of space zoning and physical description for them. From the studies in the former parts of the paper,we make a zoning of compartment in the way as shown in Tab.2. Each zone is provided with some peculiar functions,as if

Tab.2 MAJOR FUNCTIONS OF ZONES FOR FIRE MODELING

NAME OF ZONES	DEFINITION OR COMPOSITION	MAJOR FUNCTIONS
1) FIRE ELEMENT	COMPLEX OF BURNING PART & ITS FLAME	*GENERATION OF HEAT *CHEMICAL REACTION *FUEL VOLATILIZATION
2) FLAMED HOT SPOT	PART OF COMBUSTIBLE OBJECT FLAMED BY A FIRE ELEMENT	*FUEL VOLATILIZATION
3) RADIATED HOT SPOT	PART OF COMBUSTIBLE OBJECT STRONGLY RADIATED BY A FIRE ELEMENT	*FUEL VOLATILIZATION
4) SURROUNDING OBJECT	UNIGNITED PART EXCEPT FOR HOT SPOTS	*SKIN OF FIRE ENVIRONMENT
5) HOT LAYER		*HEATING OF CEILING *GAS EXHAUSTION
6) LOWER COLD LAYER		*FRESH AIR SUPPLY
7) PLUME	UPWARD CURRENT ABOVE A FIRE ELEMENT	*PUMPING OF HEAT & GAS FROM FIRE ELEMENT & COLD LAYER
8) EXTERIOR		

it were an organ of a "body of fire".

By the way, some simplifications or controls on some processes in zones will be necessary for the studies of subprograms. So, we should grasp the major relationships and interactions among the zones, to make effective controls and not to give a serious influence on the process to be studied by such simplifications. Tab.3 shows the major relationships among the

Tab.3 MAJOR RELATIONSHIPS AND INTERACTIONS AMONG THE ZONES

	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8
1) FIRE ELEMENT	x/x	x	x	o/x*[1]	x	x	o	x
2) FLAMED HOT SPOT	x	x/x	x	x	x	x	x	x
3) RADIATED HOT SPOT	x	x	x/x	x	x	x	x	x
4) SURROUNDING OBJECT	x	x	x	x/x	x	x	x	x
5) HOT LAYER	x	o	o	x		x	o	o
6) LOWER COLD LAYER	x	o	o	x	x		o	o
7) PLUME	o	x	x	x	o	o	x/x	x
8) EXTERIOR	x	x	x	x	o	x	x	

TRANSFER OF MASS EXCEPT FOR FUEL GAS

TRANSFER OF FUEL GAS

*[1]; o corresponds to the fire spread over an object.

	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8
1) FIRE ELEMENT	x/o/x*	x	x	o	x	x	o	o
2) FLAMED HOT SPOT	o	x/x	x	o	o	o	o	o
3) RADIATED HOT SPOT	o	x	x/o/x*[2]	o	o	o	x	o
4) SURROUNDING OBJECT	o	o	o	x/o	o	o	x	o
5) HOT LAYER	o/x*[1]	o/x*[1]	o/x*[1]	o		o	o	o
6) LOWER COLD LAYER	x	x	x	x	x		o	x
7) PLUME	o/x*[1]	o/x*[1]	o/x*[1]	o/x*[1]	o/x*[1]	x	x/x	x
8) EXTERIOR	o	x	x	o/x*[2]	o/x*[1]	x	x	

CONVECTION & CONDUCTION HEAT TRANSFER

RADIATION HEAT TRANSFER

*[1]; o or x depends on the smoke concentration of hot layer or plume.

*[2]; o or x depends on the geometrical relationship between the zones.

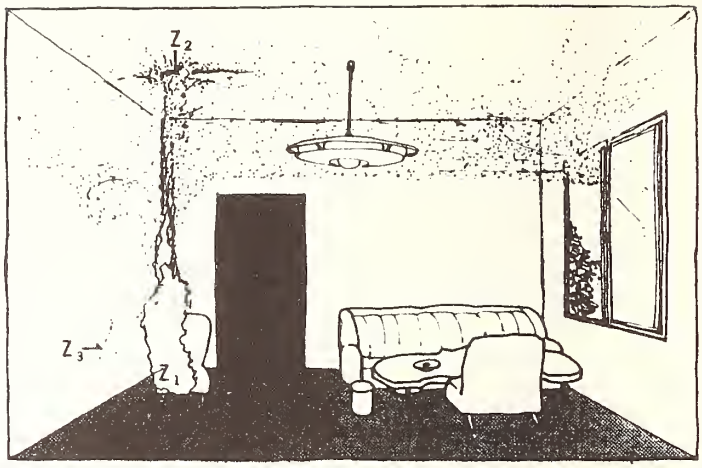
zones on some processes,which are estimated from the qualitative impressions on the results of full scale tests. Of course,this attempt will have to be corrected temporarily by an advancement of the knowledge on fire,but the items shown here should at least be considered for the explanation of the results of past experiments. A schematic diagram for any phase of fire progress is diagramed almost automatically by the assemblage of the sets of zone and its input/output arrows as shown in Fig.4. The problem whether such a diagram represents a real fire well or not corresponds to the latter step of the evolution procedure of a modeling. Here we discuss the approaches to study subprograms and to systematize them into a full system of CV type modeling, independently of this problem.

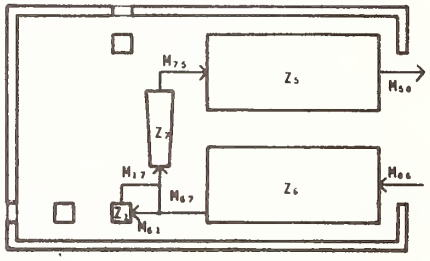
The estimation of the parameters and the parameterization for physical processes are the central problems of the step for the formulations for a temporary diagram. But fire is still a complicated system,even if it is classified for the convenience of modeling or rearranged into a discrete system composed of some spatial zones and processes as above described. Zones are now settled discretely,to be sure,but it is sometimes difficult to produce only one zone in a laboratory. Besides,even if one succeed in separating zones in experiment or PDF type simulation, the synthesis of them will not be always an easy task. As interactions are just the problems that cause particular phenomena like flash-over,the formulations without considering them would lead to a modeling of "fake world". The circumstance that the formulation on a certain zone requires the separation of zones but this may lead to a false simulation shows that the studies on subprograms may enter a maze. A systematic program should be prepared.

A "trial and error" approach would be inevitable to break through such an endless maze,but this approach shall be converged. We consider this problem in a block diagram. So as to know

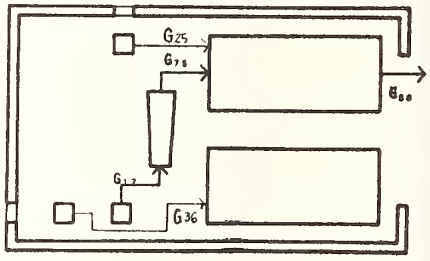
Fig.4 DIAGRAM OF FIRE ENVIRONMENT

(A) FIRE ROOM CONDITION

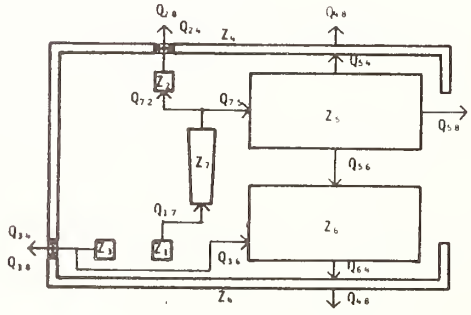




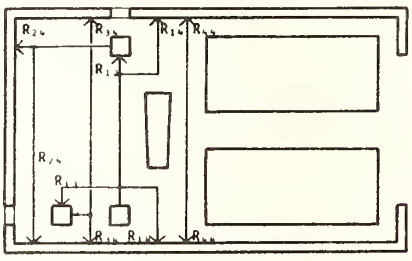
(B) DIAGRAM FOR MASS FLUX



(C) DIAGRAM FOR FUEL GAS FLUX



(D) DIAGRAM FOR CONDUCTIVE OR CONVECTIVE HEAT FLUX



(E) DIAGRAM FOR RADIATIVE HEAT FLUX

the flux represented by the thick arrow in the unsteady system shown in Fig.5,the fluxes represented by broken arrows and conditions of the blocks A and B should be controled,measured or computed by known methods,unless the thick arrow flux is formulated with known parameters or can be measured directly. If even only one of the broken arrows and conditions of A and B is not grasped,authentic quantity of the thick arrow flux can never be obtained. We must start with rough impressions on the whole features of the system to be studied.

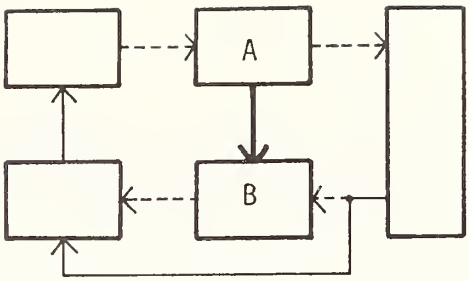


Fig.5 A BLOCK DIAGRAM

Thus,also for fire-related processes,we must recognize before everything what can be controled,what can be measured and what can be computed with known parameters. From this viewpoint,we classify the processes according to the "intimacy" levels.

Tab.4 INTIMACY LEVELS OF PROCESSES

LEVELS	CONTROL	MEASUREMENT	COMPUTATION WITH KNOWN DATA	FORMULATION WITH UNKNOWNS
1	o			
2	x	o	o	
3	x	x	o	
4	x	o	x	o
5	x	x	x	o
6	x	o	x	x
7	x	x	x	x
	←EXPERIMENT RELATED ITEMS→			
		←SIMULATION RELATED ITEMS→		

*o: possible
x: impossible or almost impossible in a fire experiment

The level 1 processes can be controled by some way. Improvements in experiment techniques have significantly expanded the range of measurement,whilst the appearance of EDPS has enabled us to expand the effective extent of the computational approach. Thus, the level 1~3 processes are already in our hands. The level 4 processes will also fall into our hands by physically "justified" ways. The other level processes are now out of our hands and may not be easily measured directly or are not formulated because of the complexity of the physical structure.

A systematic approach as Fig.5 would enable us to obtain rough estimates for the level 5 and level 6 processes;the temporary estimation of parameters for level 5 processes and the regressive formulation for level 6 processes,although this approach may sometimes be lacking in the backing of physical meanings. Some heigher level processes that are basically formulated like fluid mechanics may be simulated by the partial application of PDF type modeling. Thus,the heigher level processes will be classified again as Tab.5. To adopt the systematic approach as Fig.5,one should arrange experiment conditions so that only one process to be studied could be involved. But,fire involves so

Tab.5 APPROACHES TO ANALYZE THE HEIGHER LEVEL PROCESSES

<table>
<tr><td>INTIMACY LEVELS</td><td>2∿4</td><td colspan="4">5∿7</td></tr>
<tr><td>BASIC FORMULATION</td><td>o</td><td colspan="2">o</td><td colspan="2">x</td></tr>
<tr><td>CLOSED EXPERIMENT</td><td></td><td>x</td><td>o</td><td>o</td><td>x</td></tr>
<tr><td>POSSIBLE APPROACHES</td><td>TRADITIONAL WAYS</td><td colspan="2">PARTIAL DIFFERENCIAL FIELD TYPE ANALYSIS</td><td colspan="2"></td></tr>
<tr><td></td><td></td><td></td><td colspan="2">PARAMETERIZATION OF PHYSICAL STRUCTURE</td><td></td></tr>
</table>

Tab.6 INTIMACY LEVELS OF FIRE-RELATED PROCESSES

ZONES	ROLES OF ZONES		INTIMACY LEVELS							
			Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8
1) FIRE ELEMENT	HEAT SOURCE	1	x	x	x	5,7*	x	x	7*	x
	CHEMICAL REACTION	5,7*	x x							
	FUEL GAS SUPPLY	1,6	7*	x	x	x	x	x	7*	x
2) FLAMED HOT SPOT	FUEL VOLATILIZATION	5~7*	x	x	x	x	x	x	x	x
				x x						
			6*	x	x	x	5*	5*	x	x
3) RADIATED HOT SPOT	FUEL VOLATILIZATION	5~7*	x	x	x	x	x	x	x	x
					x x					
			6*	x	3	x	5*	5*	x	x
4) SURROUNDING OBJECT	HEAT STORAGE	3	5	3	3	x	x	x	x	x
						x x				
			6*	3	3	3	x	x	x	x
5) HOT LAYER			x	5*	5*	5*		x	3	3
			6,7*	6,7*	6,7*	6,7*		x	3	3
6) LOWER COLD LAYER			x	5*	5*	5*	5		3	3
			x	x	x	x	x		3	x
7) PLUME			7*	7*	x	x	3,5	3,5	x	x
									x x	
					x	7*	7*	x	x	x
8) EXTERIOR			5*	3	3	3	3	x	x	
			5*	x	x	5*	7*	x	x	

MASS TRANSFER EXCEPT FOR FUEL GAS
FUEL GAS TRANSFER
RADIATION HEAT TRANSFER
CONVECTIVE & CONDUCTIVE HEAT TRANSFER

Tab.7 POSSIBILITY OF PRIMITIVE CONTROLS & ESTIMATIONS ON HEIGHER LEVEL PROCESSES

ZONES	ROLES OF ZONES	WAYS OF SIMPLIFICATION							
		Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8
1) FIRE ELEMENT		13 1 2	1		2			2	
2) FLAMED HOT SPOT	FUEL VOLATILIZATION	4	1			4	4		
3) RADIATED HOT SPOT	FUEL VOLATILIZATION	4	1			4	4		
4) SURROUNDING OBJECT			1						
5) HOT LAYER			6	6	6				
			5	5	5				
6) LOWER COLD LAYER			6	6	6				
7) PLUME			6			5	7		
			5	5	5	5			
8) EXTERIOR			2						
			2,5		5	5			

REMARKS

1 HEAT PLATE, FIXED HEAT SOURCE	2 CONTROLABLE FUEL	3 GAS SUPPLY	4 NON-COMBUSTIBLE LINING
5 CLEAN HEAT SOURCE, CLEAN FUEL	6 CONTROL OR CALCULATION OF CONDUCTION	7 OTHER WAYS	

* 1⊂2, 1⊂5

many heigher level processes for such approaches as shown in Tab.6 that we must make simplifications on experiment conditions or perform partial experiments simulating limited features of real fires in order to reduce the number of heigher level processes and realize a "closed" experiment for the process to be studied. The symbol * in Tab.6 denotes that one can produce the experiment conditions or environments where the processes with * do not have important roles or can be estimated indirectly under some practical assumptions as shown in Tab.7. Though a "closed" experiment is essential to a quantitative experiment,what features are conserved and what are sacrificed should be always discussed upon the comparison of the diagram representing the real fire like Fig.4 and the one for the experiment conditions. In case that a systematic approach is adopted,the sensitivity of the estimated result should always be discussed,because the result may not be more than a practical estimate.

For a level 6 process,we can obtain at best input/output relationships under some specific conditions,though the combustion processes of the most of combustible objects usually settled in rooms are classified in this type. For such a process, regressive expression of the output by the input to it is inevitable,but even in this case,an accurate measurement is essential to a reliable formulation of the output/input relationship for this level process. This procedure is sometimes difficult to do, but the estimation of this relationship is at least indispensable to locate the process clearly in the whole system of fire phenomena. For example,to study such processes as fuel volatilization of furnitures,we should at least measure the mass loss rate of the object under studies and estimate the thermal environment that heats the burning object in terms of heating rate. In such a case,a partial application of simulation techniques based on the mathematical modeling would be effective. If the general features of the simulation results agree well with the results of the experiment including such a nondescript,

we may expect that the conditions of the environment that heats the nondescript might be clarified.

On the other hand,the estimation of parameters is the central problems on the level 5 processes,and this can be formally performed by a systematic approach,provided that the experiment is "closed" for the process under studies. It may be lacking in the backing of physical structure,but there is no other authentic way to grasp a rough range of it. However,one should note that a "closed" experiment is not always realized. One can not obtain even a rough estimate for such a case. An innovation in experiment techniques or partial differential field modeling is indispensable to formulate a process that can never be grasped even by a systematic way.

The level 7 processes are now far from our practical or macroscopic understanding. As they have complicated structures and intense distributions,there would be a limit in macroscopic approaches like macroscopic experiments or systematic ways. Though some of them may be grasped by partial differential field type modeling or experiments as shown in Tab.5,our understanding on those processes will be still in a qualitative impression for some time.

III-2. Diagram for Evaluation of Fire Progress

For architectural fire provisions,it is a matter of importance to grasp the role of room components or objects settled in compartment during a fire progress. However,the sorts,conditions and arrangements of these objects are generally so various that the application of a prediction method to a prototyped condition itself is not enough for the fire provision of respective compartment. Of course,to predict the fire progress for many cases to be supposed for the building under the planning of an architect must be a fairly expensive and hard task,and a "scenario" method like Fig.1 has a weakness in this point. The way that is expected for such a purpose is one that permits us to understand intuitively the overall patterns of fire progress and to grasp the main points for the fire provisions,even if the precision of physical description may be sacrificed to some extent compared with mathematical fire modeling* Here,we propose the concept of "Ignition Graph" as an example of the refinement of "scenario",but whose details are almost rest for future studies.

We symbolize that an object "B" would be ignited by the combustion of the object "A" by (A)→(B),and if (A)→(B) and (A)←(B) are both satisfied,we symbolize it by (A)←→(B). To grasp clearly the position of an object in a fire progress,some rational rules and definitions are adopted.

1) Grouping of Objects

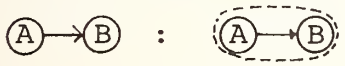
If the relationship (A)←→(B) is satisfied,the objects A and B are regarded as "one body". Thus,the group AB is defined as follows.

(A)←→(B) : (AB)

*Generally,a danger-side hypothesis is adopted to a safety planning of a system with unknown or uncertain parts. So it is assumed here that an object would burn if an ignition occurs on it.

2) Territory of Object

If (A)→(B) is satisfied,but (A)←(B) is not satisfied,B will be regarded to be dependent to A. Thus,the territory of A is defined as

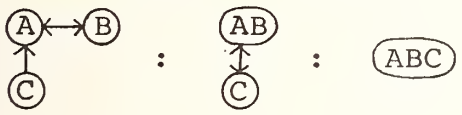


3) Combustion of Two Objects

That A and B burn at the same time is symbolized in the same way as 1).

4) Growth of Group

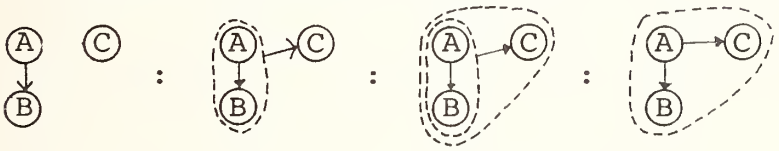
Even when neither (A)→(C) nor (B)→(C) are satisfied, (AB)→(C) may be satisfied. Thus,when those three relationships, (A)↔(B) and (C)→(A) or (C)→(B) are satisfied,the group AB grows to ABC as



It indicates that if one of A,B and C is ignited stably, all of them would burn some time.

5) Expansion of Territory

If (A)→(B) and (AB)→(C),the territory of A becomes



By continuing these procedures for all combustibles in a compartment,one can grasp what object will have an important role during a fire. While the ignition conditions are important in this method,the estimation of them for the objects usually settled in rooms is left for future works.

Fig.6 shows the result of an example of the application of this approach under the arbitorarily determined conditions of

ignition. Fig.6(c) corresponds to the condition of Phase-2 in a fire progress,and Fig.6(d),(e) correspond to Phase-3. The result shows that an stable ignition on only one of F,G,H,K,L, M,Q,R,S,T,U,V,W,X,Y and Z may cause a full room involvement of fire,whilst an ignition on the other objects will lead to a partial development of fire.

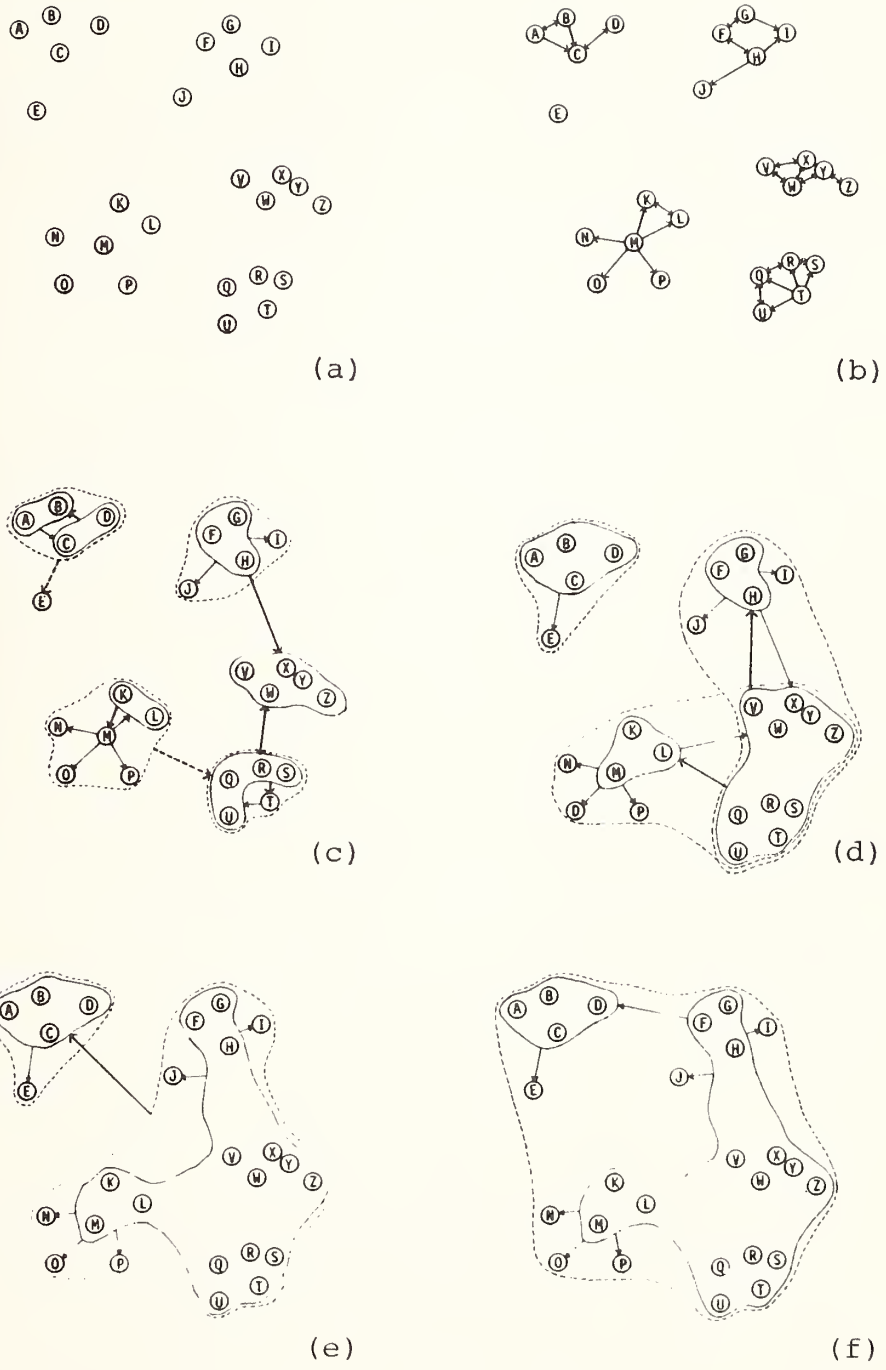


Fig.6 AN EXAMPLE OF "IGNITION GRAPH"

IV. CONCLUSIONS

After the discussions in the former parts of this paper, the mathematical fire modeling involves so many "bugs" that the practical computer prediction of the whole history of a fire might become realized in a far future. But,this does not mean the incompetenty of the fire modeling or the systematic approach to fire phenomena. We should recognize where the problem lie.

Though there may be some overlooks in our recognition on the state of the arts of fire modeling arranged in Tab.2 7,it would be roughly summarized as follows. A numerical prediction of the state of the environment generated by combustion does not seem to be so difficult with known subprograms[2,8,10] and those that are almost in our hands in the sense mentioned in CH.III-1, whereas the experiments on it will be perhaps considerably expensive and require many hands. In contrast with this,an experiment on the combustion of combustible contents or lining materials under some heating conditions is not so difficult with the present technical level in the face of the difficulty in the physical formulation for it. A regressive formulation for the combustion related processes will differ with the sorts of furnitures or lining materials,but this circumstance would be almost same in a physical formulation for them.

Perhaps,we must accept such a dissolution for some time whether we like it or not. Such a hybrid approach may be inevitable to understand complicated phenomena or systems like fire, to be sure,but "bridges" that connect the respective elementary approaches are indispensable to converge the frame to understand the whole system. After the results of current CV type mathematical models[2,8],the bridge from "combustion" to "environment" has been constructed to some extent,but even a design is not performed yet for the one from "environment" to "combustion". As discussed in CH.III-1,it seems to be a merit of simulation approach that the result of a numerical simulation will contribute us a prospect to such a bridge and the recognition on the gap between a real fire and the state of our understanding of fire.

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* References with the symbol * are written in Japanese.

Theme
FIRE MODELING

A MODEL ON FIRE SPREAD IN SMALL SCALE BUILDING

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Third Joint Meeting
U.S. Japan Panel on Fire Research and Safety
UJNR, Washington, D.C., March 13 - 17, 1978

SUMMARY

This paper describes the theory and some results of sample computer simulations on a model which is devised in order to predict the behavior of the hot gas generated by a fire source combustion when a fire bereaks out in a small scale building.

This model is to compute the temperatures and depths of the hot gas layers in arbitrary rooms in a fire starting building on the basis of fundamental assumption that the hot gas layers are formed and kept near the ceilings in any rooms into which the hot gas flows in.

The author hopes that this model can be used to investigate the role that the hot gas plays on the fire spread from one room to another in small scale buildings such as Japanese dwelling houses. The application of the model to one or two floor buildings seems comparatively well.

1. INTRODUCTION

It is the inevitable way of a fire spread that it follows the spread of the heat generated by the combustion of the fire itself, and it is all the same as to building fires. Therefore, to investigate a fire spread in a building. We must begin it with the investigation of the spread of the heat.

As a mechanism of spread of combustion heat, heat transport by hot gas generated by fire source combustion must be as important as thermal radiation, eapecially, in the case of room-to-room fire spread, the former is expected to play an extremely important part. A fire spread in a building such as a dwelling house is usually treated in many fire protective activities, at least in Japan, regarding that the fire progresses in a typical order such as ignition -- initial spread in a fire room -- flashover -- fully developed stage of a room fire -- a fire spread to another room.

However, for the buildins that room compartmentation is not firm such as Japanese usual dwelling houses, the risk of fire spread by hot gas flow through internal openings is expected so serious that we cannot be entirely free from the worry that only a burning of a large size furniture such as a bed, sofa and cabinet in the fire room might bring fire spread to other rooms.

On the other hand, there are not many studies on such a room-to-room fire spread by hot gas flow through internal openings as yet. In the following we briefly mention some concerning works: Quintiere introduced an idea of hot gas layer and presented a stationary state model on it for a single compartment [1], the author presented a time dependent model also for hot gas layer in a single compartment [2], and Wakamatsu has been engaged in the calculation of Smoke Flow in Buildings [3]. The author proposes the present model on the basis of these works.

2. THEORY

2.1 General Description of the Model

Let's consider the case that a fire source appears on the floor of a room in a building and continues to generate heat as shown in fig. 1. Above the fire source, a fire plume is formed and hot gas warmed and rendered buoyancy by the fire source combustion rises up through the plume entraining surrounding air. The hot gas which rise up through the plume is accumulated under the ceiling of the room and forms a hot gas layer which is also a smoke layer involving a large amount of smoke particles.

If the condition allows the burning of the fire source is maintained, the hot gas layer gains its depth and sooner or later begins to flow out into the next rooms and there, forms hot gas layers again. On the other hand, air at room temperature flows into the fire room from the next rooms and is entrained into the fire plume to be hot gas and again mix into the hot gas

layer of the fire room.

The heat transported to each room is transferred to the ceiling, floor, walls and live combustible in the room and raise their temperature, and put them in danger of ignition when they are made of combustible materials. On the other hand, a hot gas layer gradually drops its temperature according to the distance from the fire room by transferring heat to surroundings, so the farther a room is from the fire room, the smaller the danger of the direct fire spread from the fire room becomes.

2.2 Assumption for the Model Formulation

For the convenience of formulating the model described above, we adopt several assumptions as follows:

(i) the combustion at the fire source is completed on its surface, therefore the plume does not involve any combustion;

(ii) The thermal radiation heat loss from the fire plume is neglected, therefore all the heat produced by the combustion on a fire source surface is given to the hot has layer through the fire plume;

(iii) a hot gas layer at upper part of a room and an air layer at lower part of a room are separated by a definite discontinuity surface and never mix each other except through the fire plume;

(iv) temperature of a hot gas layer in any room is uniform everywhere in the layer for it is fully disturbed;

(v) any hot gas layer is completely opaque for the smoke involved, and therefore it is a complete medium for thermal radiation and absorption;

(vi) any air layer at lower part of a room is perfectly perspective, and therefore absorbs no thermal radiation;

(vii) convective heat transfer from a heated floor and wall to

an air layer in any room is neglected;

(viii) hot gas flowing through an opening flows into a hot gas layer and air flows into an air layer respectively, and therefore the two layer is not mixed each other by the flows at openings.

(ix) the heat evolution of the heat source is independent of the flow rates of air into the fire room and the thermal condition of the fire room.

Assumptions (i) and (ii) are to some extent apart from an actual fire, because a fire plume due to burning of furniture or oil usually involves a lot of flames and flares brilliantly. These assumptions are to apply a Yokoi's Work to the fire plume and they are more or less unavoidable treatments for we have few theory conveniently available when a fire plume involves combustion. As a result of these assumptions, the fire plume model introduced here becomes a thermal plume rather than a fire plume. Adding this, assumption (ii) brings about the overestimation of the heat given to the hot gas layer by the heat source, however the error due to the assumption may be partially compensated for several reasons as follows: the first reason is that the part of the plume exposed to the air layer becomes smaller according to the growth of the hot gas layer in the fire room; the second reason is that about a half of the heat emitted by an actual fire plume is expected to be emitted to the hot gas layer; and the other reason is the heat emitted directly to the floor or walls from the plume is expected to reduce the heat loss from the hot has layer by raising the surface temperature of the internal wall slabs.

Assumptions (iii) and (iv) have been supported by some papers [1], [4], and these might be valid so far as the heat input by the fire source is sufficiently large compared with the building size and therefore the temperature of hot layers are kept high enough.

Assumption (v) is not necessarily essential but only for simplification of the heat transfer computation. If we do not assume hot layers black, we must estimate smoke density of the layers which might depend on kinds of heat sources, burning condition of them and etc., so cannot be determined without a lot of difficulties. This assmuption might be almost valid in actual fires because they usually produce a large amount of smoke.

Assumptions (vi) and (vii) make the energy conservation equations for air layers useless, because the temperatures are kept constant at anytime. The absorption of emission by air layers may be negligible but the convective heat transfer from floors and walls might not be so if their temperatures becomes very high. The validity of assumption (vii) should be examined by some future experiments.

Assmuption (viii) is in the extension of assumption (iii) and plays a main role to sustain the model together with assumption (iii).

Assmuption (ix) might be unavoidable in this model, because at present state, our knowledge on fire plumes that involve combustion is not so rich that we can not calculate various values quantitatively on such plumes.

2.3 Formulation

2.3.1 BASIC GOVERNING EQUATIONS

Considering about phenomena in any room in a building, including the fire room, we can obtain several useful relationships as follows (refer to Fig. 1).

1) Mass Conservation of Hot Gas Layer

Into the hot gas layer in an arbitrary room i in the building that a fire occurs, hot gas is being supplied at the rate of $M_{s,i}$ per unit time, though $M_{s,i} = 0$ except the fire room. The hot gas layer is exchanging hot gas with the hot gas layer in an arbitrary room j which is connected with room i through some openings. Let's regard the symbol $\sum_k$ denotes to sum up the hot gas flows for all the openings between room i and j and the symbol $\sum_j$ denotes to sum up the flows for all the rooms connected with room i , so the mass conservation of the hot has layer in room i is described as follows:

$$\frac{d}{dt}(\rho_{s,i} A_{R,i} Z_{s,i}) = \sum_j \sum_k (SS_{ji} + SA_{ji} - SS_{ij} - SA_{ij})_k + M_{s,i} \quad (i = 1, n) \qquad (1)$$

where n is the total number of rooms in the building, SS and SA are both mass rates of hot gas flow which will be defined later in section 2.3.5, and subscripts ij and ji denote that gas flows from i to j and j to i respectively.

2) Mass Conservation of Air Layer

In an arbitrary room i , the air layer supplies air to the fire plume at the rate of $M_{e,i}$ and exchanges air with next rooms through openings. So neglecting the volume of the fire plume, the mass conservation of the air layer becomes as follows:

$$\frac{d}{dt}(\rho_a A_{R,i} Z_{a,i}) = \sum_j \sum_k (AS_{ji} + AA_{ji} - AS_{ij} - AA_{ij})_k - M_{e,i} \quad (i = 1, n) \qquad (2)$$

where AS and AA are the mass rates of air flows through openings which will be defined later too.

3) Energy Conservation of Hot Gas Layer

The hot gas layer in an arbitrary room i receives heat from

the fire source through the fire plume, transfers heat to the internal walls by radiation and exchanges heat with the hot layers of the next rooms by the hot gas flow through openings. Because the radiative heat loss from the plume is neglected, the heat that the hot gas layer receives from the fire source is completely equal to the heat generated by the fire source. As to the heat transferred to the internal walls, we take only about the radiative heat transfer into consideration neglecting convective heat transfer. Regarding that the specific heat of the hot gas is constant for any temperature, energy conservation of the hot gas layer is described as follows:

$$\frac{d}{dt}\{C_p \rho_{s,i} A_{R,i} Z_{s,i}(\theta_{s,i}-\theta_a)\}$$

$$= \dot{Q}_{c,i} - \dot{Q}_{r,i} + \sum_j \sum_k \{C_p(SS_{ji}+SA_{ji})(\theta_{s,j}-\theta_a) - C_p(SS_{ij}+SA_{ij})(\theta_{s,i}-\theta_a)\}_k$$

$$(i = 1, n) \qquad (3)$$

where $\dot{Q}_{c,i}$ and $\dot{Q}_{r,i}$ are the heat produced by the fire source and the radiative heat transferred to the internal walls of the room respectively.

4) State of Gas

Strictly speaking, state of gas depends on its comportnents and pressure as well as temperature. However it is obvious that such a strict treatment is not significant in this model, so we adopt the following equation as the equation of state.

$$\rho_{s,i}\theta_{s,i} = \rho_a\theta_a \qquad (i = 1, n) \qquad (4)$$

5) Identical Equations

The following two are definite identical equations:

$$Z_{s,i} + Z_{a,i} = H_{R,i} \qquad (i = 1, n) \qquad (5)$$

$$M_{p,i} + M_{e,i} = M_{s,i} \qquad (i = 1, n) \qquad (6)$$

where $Z_{s,i}$, $Z_{a,i}$ and $H_{R,i}$ are the depth of the hot layer, the depth of the air layer and the height of ceiling of the room i respectively. (As to $M_{p,i}$, $M_{e,i}$ and $M_{s,i}$, see Fig. 1)

Though the Eqs. (1) - (6) are regarded the most fundamental equations to govern the behaviors of hot gas layers in a building, it is obvious that they involve some terms that need further modelling.

2.3.2. FIRE PLUME

Because we have assumed that combustion is completed on the surface of the fire source and is not involved in the fire plume, the "fire plume" we call here is rather a thermal plume than a fire plume. Admitting the above sophistication for the fire plume, it is still difficult to deal with when its area is large. Therefore as shown in Fig. 1 we assume a virtual point heat source at $Z = 1.5\sqrt{A_f}$ below the fire source of area A_f .

As regards the thermal plume above a point heat source, the wellknown works has been done by Yih and Yokoi. Yih obtained an empirical expression for temperature profile along the axis of the plume [5]. This is as follows:

$$\frac{\Delta\theta}{\theta_o} = \frac{11}{g^{1/3}}\left(\frac{Q}{c_p \rho_o \theta_o}\right)^{2/3} Z^{-5/3} \qquad (7)$$

where g : acceleration due to gravity (m/sec^2)
θ_o : temperature of surrounding air (°K)
ρ_o : density of surrounding air (kg/m^3)

C_p : specific heat of surrounding air (kcal/kg °K)

Q : heat evaluation of the heat source (kcal/sec)

$\Delta\theta(z)$: temperature difference between plume axis and surrounding air (°K)

z : height from the point heat source (m)

And Yokoi, as to the same problem, obtained theoretically the following expression [6] which is essentially the same as Eq. (7),

$$\frac{\Delta\theta}{\theta_0} = 0.4321\, C^{-8/9} \frac{1}{g^{1/3}} \left(\frac{Q}{C_p \rho_m \theta_0} \right)^{2/3} z^{-5/3} \qquad (8)$$

where c is said as a parameter to express turbulent intensity and is determined by experiments. If we specify this as $c^{2/3} = 0.1$ as Yokoi did, it follows that $0.4321 C^{-8/9} \fallingdotseq 9.2$, therefore coefficients of Eqs.(7) and (8) becomes nearly equal.

However according to the Yokoi's theory, ρ_m in Eq. (8) is average density of plume gas. The reason why in the almost equal two expressions, one uses surrounding air density and the other uses average density of plume gas, may be that the two equations are available only within the limit that the temperature of a plume does not extraordinary exceeds the temperature of the surrounding air.

We use, however, Eq.(8) for any density of plume gas stretching the meaning for the convenience of application. Yokoi, starting from the same theory as above, also obtained the following expression for flow rate of plume gas [7].

$$M = 0.244 \left(\frac{\rho_m^2 Q g}{C_p \theta_0} \right)^{1/3} z^{5/3} \qquad (9)$$

If we try to apply Eq.(9) to this model, the average gas density in Eq.(9) must be determined. If we can introduce the average temperature of the plume θ_m , ρ_m becomes as follows:

$$\rho_m = \frac{\rho_0 \theta_0}{\theta_m}$$

On the other hand, considering further as $\theta_m = \theta_o + \Delta\theta_m = \theta_o + m\Delta\theta$ where $\Delta\theta_m$ and m are defined as $\Delta\theta_m = \theta_m - \theta_o$ and $m = \Delta\theta_m/\Delta\theta_o$ respectively. then,

$$\frac{1}{\rho_m} = \frac{\theta_m}{\rho_o\theta_o} = \frac{\theta_o + \Delta\theta_m}{\rho_o\theta_o} = \frac{1 + \frac{\Delta\theta_m}{\theta_o}}{\rho_o} = \frac{1 + m\frac{\Delta\theta}{\theta_o}}{\rho_o} \tag{10}$$

Substituting Eq.(10) into Eq.(8) yields

$$\frac{\Delta\theta}{\theta_o} = \frac{9.2}{g^{1/3}}\left(\frac{Q}{c_p\rho_o\theta_o}\right)^{2/3} Z^{-5/3}\left(1 + m\frac{\Delta\theta}{\theta_o}\right)^{2/3} \tag{8'}$$

Therefore Eq.(8') involves $\Delta\theta/\theta_o$ in both sides. Although we can obtain a cubic equation for $\Delta\theta/\theta_o$ by multiplying each side twice itself, for the convenience sake we had better adopt the approximation as follows:

$$\left(1 + m\frac{\Delta\theta}{\theta_o}\right)^{2/3} \fallingdotseq 1 + \frac{2}{3}\left(m\frac{\Delta\theta}{\theta_o}\right) - \frac{1}{9}\left(m\frac{\Delta\theta}{\theta_o}\right)^2 \tag{11}$$

Substituting Eq.(11) into Eq.(12) yields a quadratic equation for $\Delta\theta/\theta_o$, so we can solve it as

$$\frac{\Delta\theta}{\theta_o} = 6k\left\{1 - 3\beta k + \sqrt{(1 - 3\beta k)^2 + 1}\right\} \tag{12}$$

where, $k = 1/2m$

$$\beta = \frac{g^{1/3}}{9.2}\left(\frac{Q}{c_p\rho_o\theta_o}\right)^{-2/3} Z^{5/3}$$

Accordingly the rate of gas flow rising through a thermal plume at any height Z can be estimated as follows, using Eqs.(9) and (12):

$$M_Z = 0.244\left(\frac{\rho_o^2 Q g}{c_p\theta_o}\right)^{1/3} Z^{5/3}\left(1 + m\frac{\Delta\theta}{\theta_o}\right)^{-2/3} \tag{13}$$

Then $M_{p,i}$ and $M_{s,i}$ in Fig. 1 become as

$$M_{p,i} = 0.244 \left(\frac{\rho_0^2 Q g}{c_p \theta_0} \right)^{1/3} z_0^{5/3} \left(1 + \frac{\Delta\theta}{\theta_0}\Big|_{z_0} \right)^{-2/3} \tag{14}$$

$$M_{s,i} = 0.244 \left(\frac{\rho_0^2 Q g}{c_p \theta_0} \right)^{1/3} (z_0 + z_a)^{5/3} \left(1 + \frac{\Delta\theta}{\theta_0}\Big|_{z_0+z_a} \right)^{-2/3} \tag{15}$$

respectively.

It is needless to say that the above deling with a fire plume is very sophisticated one, because in actual fires, though mass is given to fire plume together with heat, $M_{p,i}$ that is calculated from heat evolution of a fire source alone does not meet the actual mass input.

2.3.3 RADIATIVE HEAT TRANSFER FROM HOT GAS LAYER

The hot gas layers near ceilings transfer heat to ceilings, floors, walls and furniture etc. in the rooms and raise their temperature. The final aim of the model is to predict the risk of their ignition by estimating the heat transfer rates and their temperature rise. When we are going to deal with ignition problems, we would have to deal heat transfer to target objects exactly enough, however, as in this case when we are at first going to estimate the temperature and depth of the hot layers over the building, strict treatments on heat transfer are almost impossible. Therefore it might be practically useful to consider such strict treatments independently with the energy conservation of the hot layers, after the temperatures and the deptns of the hot layers are obtained by use of approximation on heat transfer.

Then, with regard to the heat transfer for each room we introduce the following assumptions:

(i) convective heat transfer is negligible;

(ii) heat emitted to other rooms from the hot layer in a room through openings is negligible;

(iii) the temperature of the part of the wall soaked in the hot layer in a room is equal to the ceiling temperature of the room and the temperature of the other part of the wall which is exposed to air layer is equal to the floor temperature of the room;

(iv) the ceilings, floors and walls of a building completely absorb emission.

The main reason that we make assumption (i) is we have few good means to calculate the convective heat transfer as to hot layers, however this might be approximately justified because while a hot layer temperature is low, radiative and convective heat transfers are both negligible and when the temperature becomes high radiative heat transfer becomes dominant.

The heat transfer from a hot layer to a wall is related to the surface temperature of the wall as well as the temperature of the layer, therefore we have to calculate the wall temperature in order to obtain the heat transfer. Although we can regard that a ceiling is always in a hot layer and a floor is always in an air layer, on the other hand, as to a vertical wall we cannot deal with it in the same way because a part of the wall that is out of a hot layer is possibly soaked in it in a while according to the growth of the hot layer. Because there is a difference in heat transfer rate between in and out of a hot layer, a wall must have vertical temperature gradient according to its history. However, to take such a fact into consideration is obviously very troublesome, therefore we intend to avoid the trouble by assumption (iii).

The possible error derived from assumption (iv) is expected sufficiently small because absorptivities of usual building materials and furniture are mostly larger than 0.8, and additionally

in actual fires adhesion of smoke particles to them increases their absorptivities.

By the aid of these assumptions, we can estimate the radiative heat transfer as follows:

1) Heat Transfer to Ceiling

A ceiling we call here includes the part of walls that is soaked in a hot layer. A ceiling is entirely covered with a completely opaque hot gas layer, therefore heat flux to a ceiling $\dot{q}''_{sc}$ (kcal/m^2·sec) is

$$\dot{q}''_{sc} = \sigma (\theta_s^4 - \theta_{c,s}^4) \tag{16}$$

where $\theta_{c,s}$ is the surface temperature of the ceiling (°K). And the total heat transfer rate to the ceiling $\dot{Q}_{sc}$ is

$$\dot{Q}_{sc} = \dot{q}''_{sc} A_c = \sigma (\theta_s^4 - \theta_{c,s}^4) A_c \tag{17}$$

where $A_c = 2 \times (B_R + D_R) Z_S + A_R$ is the total area of the ceiling and the part of the wall in the hot layer.

2) Heat Transfer to Floor

A Floor here also includes the part of walls below a hot layer. As shown in Fig. 2, the system composed of a bottom of a hot layer and a floor is closed, therefore as regards their configulation factors, the following relationships are generally satisfied:

$$F_{ss} + F_{sw} = 1 \tag{18}$$

$$F_{ws} + F_{ww} = 1 \tag{19}$$

$$A_s F_{sw} = A_w F_{ws} \tag{20}$$

where $A_w = 2 \times (B_R + D_R) Z_a + A_R$ is the total area of a floor and the part of walls below a hot layer, and A_S is the area of the bottom of the hot layer and is equal to the room area, that is $A_S = A_R$.

Paying attention to the fact that the bottom of a hot layer is flat, we can specify F_{ss} as follows:

$$F_{ss} = 0$$

Making use of this and Eqs.(18) - (20), we can obtain all the configulation factors as

$$F_{sw} = 1 \ , \ F_{ws} = A_s / A_w \ , \ F_{ww} = 1 - A_s / A_w$$

Accordingly, the total heat transfer rate to the floor becomes as follows:

$$\dot{Q}_{sw} = \sigma (\theta_s^{*4} - \theta_{w,s}^{*4}) A_s F_{sw} = \sigma (\theta_s^{*4} - \theta_{w,s}^{*4}) A_s \qquad (21)$$

where $\theta_{w,s}$ is the surface temperature of the floor. Besides the heat flux per unit area $\dot{q}''_{sw}$ becomes.

$$\dot{q}''_{sw} = \frac{\dot{Q}_{sw}}{A_w} = \sigma (\theta_s^{*4} - \theta_{w,s}^{*4}) \frac{A_s}{A_w} \qquad (22)$$

According to the above consideration, the total radiation heat transfer rate from a hot layer, that is $\dot{Q}_{r,i}$ in Equs.(3) is as follows:

$$\dot{Q}_{r,i} = \dot{Q}_{sc,i} + \dot{Q}_{sw,i} \qquad (23)$$

2.3.4 THERMAL CONDUCTION WITHIN SLAB

As clearly shown in Eqs.(17) and (21), heat transfer rates to ceilings and floors are related to their surface temperatures, however because the temperatures varies successively due to the incident heat flux, we have to obtain the temperatures by solving

an equation of thermal conduction within the internal slabs such as ceilings and floors.

Here we solve the thermal conduction equation in one dimension along the axis that is vertical to the surface of the internal slabs, for it is evident from the previous discussions that a treatment in more than one dimension has no meaning. Additionally, we don't take the effects due to variation of thermal properties, water vaporization, thermal decomposition of the heated slabs into consideration because our knowledges about the problems are insufficient as yet.

Accepting the simplification as above, the fundamental equation of thermal conduction and the boundary conditions are described as follows:

fundamental equation

$$\frac{\partial \theta}{\partial t} = \left(\frac{k}{c\rho}\right)\frac{\partial^2 \theta}{\partial x^2} \tag{23}$$

boundary conditions

$$-k\frac{\partial \theta}{\partial x}\Big|_{x=0} = \dot{q}''_{in}$$
$$-k\frac{\partial \theta}{\partial x}\Big|_{x=\ell} = \dot{q}''_{out} \tag{24}$$

where k : thermal conductivity of the slab (kcal/m.sec.°K)
c : specific heat of the slab (kcal/kg.°K)
ρ : density of the slab (kg/m^3)
ℓ : thickness of the slab (m)
$\dot{q}''_{in}$: net incident heat flux to the slab surface ($kcal/m^2.sec$)
$\dot{q}''_{out}$: net heat loss flux from the back of the slab ($kcal/m^2.sec$)

In the case when the slab is a ceiling, $\dot{q}''_{in}$ is equal to $\dot{q}''_{sc}$ by Eq.(16) and when the slab is a floor, $\dot{q}''_{in}$ is equal to $\dot{q}''_{sw}$

by Eq.(22), however $\dot{q}''_{out}$ must be properly formulated according to the actual thermal condition of the back of the slab, for example, when it is thermally insulated, we can do as $\dot{q}''_{out} = 0$, and when it face to a heat sink which has a constant temperature θ_0 we might do as $\dot{q}''_{out} = \sigma(\theta_\ell^4 - \theta_0^4)$.

In usual cases that the heat flux varies successively according to time, it is impossible to solve Eqs.(23) and (24) analytically, therefore we use a finite difference method to solve them. Crank-Nicolson type finite differentiation of Eq.(23) yields:

$$\frac{\theta_{i,j+1} - \theta_{i,j}}{\Delta t} = \frac{1}{2}\left(\frac{k}{c\rho}\right)\left\{\frac{\theta_{i+1,j+1} - 2\theta_{i,j+1} + \theta_{i-1,j+1}}{\Delta x^2} + \frac{\theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j}}{\Delta x^2}\right\} \quad (25)$$

where i denotes an arbitrary spatial differntiated grid point and j denotes an arbitrary time step. Rewriting the above equation yields:

$$\theta_{i,j+1} = \frac{1}{2}\gamma(\theta_{i+1,j+1} - 2\theta_{i,j+1} + \theta_{i-1,j+1}) + b_{i,j} \quad (26)$$

where

$$\gamma = \frac{\Delta t}{\Delta x^2}\left(\frac{k}{c\rho}\right)$$

$$b_{i,j} = \theta_{i,j} + \frac{1}{2}\gamma(\theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j})$$

Eq.(26) is the equation for the temperature at a usual spatial point. In order to obtain the equations for the boundary temperatures, applying Eq.(26) to the points where i = 0 and i = N, we obtain,

$$\theta_{0,j+1} = \frac{1}{2}\gamma(\theta_{1,j+1} - 2\theta_{0,j+1} + \theta_{-1,j+1}) + b_{0,j} \quad (27)$$

where

$$b_{0,j} = \theta_{0,j} + \frac{1}{2}\gamma(\theta_{1,j} - 2\theta_{0,j} + \theta_{-1,j})$$

and,

$$\theta_{N,j+1} = \frac{1}{2} r \left(\theta_{N+1,j+1} - 2\theta_{N,j+1} + \theta_{N-1,j+1} \right) + b_{N,j} \tag{28}$$

where $$b_{N,j} = \theta_{N,j} + \frac{1}{2} r \left(\theta_{N+1,j} - 2\theta_{N,j} + \theta_{N-1,j} \right)$$

respectively. On the other hand, applying centered differentiation to the boundary conditions yields

$$-k \frac{\theta_{1,j} - \theta_{-1,j}}{2\Delta x} = \dot{q}''_{in}$$

$$-k \frac{\theta_{N+1,j} - \theta_{N-1,j}}{2\Delta x} = \dot{q}''_{out}$$

Rewriting these equations as,

$$\theta_{-1,j} = \theta_{1,j} + \frac{2\Delta x}{k} \dot{q}''_{in} \tag{29}$$

$$\theta_{N+1,j} = \theta_{N-1,j} - \frac{2\Delta x}{k} \dot{q}''_{out} \tag{30}$$

and substituting Eqs.(29) and (30) to eliminate the temperatures of the virtual grid points θ_{-1} and θ_{N+1}, we obtain

$$\theta_{0,j+1} = r \left(\theta_{-1,j+1} - \theta_{0,j+1} + \frac{\Delta x}{k} \dot{q}''_{in} \right) + b_{0,j} \tag{31}$$

where $$b_{0,j} = \theta_{0,j} + r \left(\theta_{1,j} - \theta_{0,j} + \frac{\Delta x}{k} \dot{q}''_{in} \right)$$

$$\theta_{N,j+1} = r \left(\theta_{N-1,j+1} - \theta_{N,j+1} - \frac{\Delta x}{k} \dot{q}''_{out} \right) + b_{N,j} \tag{32}$$

where $$b_{N,j} = \theta_{N,j} + \gamma\left(\theta_{N-1,j} - \theta_{N,j} - \frac{\Delta x}{k}\dot{q}''_{out}\right)$$

By the use of Eqs.(26), (31) and (32), the temperatures at all grid points can be computed. Here we compute these equations by Gauss-Seidel iteration method. Application of this method to Eq.(28) yields:

$$\theta^{n+1}_{i,j+1} = \frac{1}{2}\gamma\left(\theta^{n}_{i+1,j+1} - 2\theta^{n+1}_{i,j+1} + \theta^{n+1}_{i-1,j+1}\right) + b_{i,j} \tag{33}$$

where n denotes the number of iteration. Rewriting Eq.(33) yields:

$$\theta^{n+1}_{i,j+1} = \frac{\gamma}{2(1+\gamma)}\left(\theta^{n}_{i+1,j+1} + \theta^{n+1}_{i-1,j+1}\right) + \frac{b_{i,j}}{1+\gamma} \tag{34}$$

In the same way, we obtain the equations for boundary temperatures as,

$$\theta^{n+1}_{0,j+1} = \frac{\gamma}{1+\gamma}\left(\theta^{n}_{1,j+1} + \frac{\Delta x}{k}\dot{q}''_{in}\right) + \frac{b_{0,j}}{1+\gamma} \tag{35}$$

$$\theta^{n+1}_{N,j+1} = \frac{\gamma}{1+\gamma}\left(\theta^{n+1}_{N-1,j+1} - \frac{\Delta x}{k}\dot{q}''_{out}\right) + \frac{b_{N,j}}{1+\gamma} \tag{36}$$

respectively.

Accordingly we can compute all the temperatures at time point $j+1$ by successive substitution of θ_i $(i = 1, n)$ into Eqs.(34) - (36) starting from the temperatures at time point j.

By the way, it might be needless to say that θ_o means the surface temperature of a ceiling or a floor, that is $\theta_{c,s}$ or $\theta_{w,s}$.

2.3.5 FLOW THROUGH OPENING

The fluid flow between a room i and another room j can be calculated using Bernoulli's theorem if the static pressure difference between room i and j at arbitrary height $\Delta P_{ij}(Z)$ has been known, that is, if fluid flows from i to j through the opening of the width B_w, the mass flow rate between the heights Z_1, and Z_2, R_{ij} is

$$R_{ij} = \alpha B_w \int_{Z_1}^{Z_2} \rho_i V_z \, dZ = \alpha B_w \int_{Z_1}^{Z_2} \sqrt{2 \rho_i \Delta P_{ij}(Z)} \, dZ \tag{37}$$

where α is coefficient of discharge and is assumed here approximately constant at any height.

On the other hand, $\Delta P_{ij}(Z)$ is obtained as follows:

$$\begin{aligned} \Delta P_{ij}(Z) &= \left(P_i - \int_0^Z \rho_i(Z) g \, dZ\right) - \left(P_j - \int_0^Z \rho_j(Z) g \, dZ\right) \\ &= P_i - P_j - \int_0^Z (\rho_i - \rho_j) g \, dZ \end{aligned} \tag{38}$$

where P_i, P_j : static pressure of room i and j at a standard level respectively (P_a)

ρ_i, ρ_j : fluid density of room i and room j respectively (kg/m^3)

But generally in the calculation of flow rate, we don't need absolute pressure but need pressure difference between two spaces, so we take P_i, P_j as relative pressures to the static pressure of outdoor air at some standard level such as ground level.

When the temperatures of room i and room j are equal to each other, the static pressure difference at standard level is kept at any height, that is always $\Delta P_{ij}(Z) = P_i - P_j$ therefore, in this case R_{ij} is as follows:

$$K_{ij} = \alpha B_w \sqrt{2\rho_i |p_i - p_j|}\,(z_2 - z_1) \tag{39}$$

The other case in which we are interested concerning with the present model is when each ρ_i and ρ_j are independent of z but $\rho_i \neq \rho_j$. In this case it follows that

$$\Delta p_{ij}(z) = p_i - p_j - (\rho_i - \rho_j) g z \tag{40}$$

therefore at the height of $z = (p_i - p_j)/(\rho_i - \rho_j) g$, $\Delta p_{ij}(z)$ becomes zero, in other words, the static pressures of both rooms become equal and no fluid flows. The plane at this height is wellknown as a neutral plane. In such a case, flow rate calculation becomes easy by regarding the height of the neutral plane as the standard level, that is, introducing new height z' as follows:

$$z' = z - \frac{p_i - p_j}{(\rho_i - \rho_j) g}$$

and substituting this into Eq.(40) yield,

$$\Delta p_{ij}(z) = -(\rho_i - \rho_j) g z' \tag{41}$$

Rewriting z_1 and z_2 in Eq.(37) as z_1' and z_2' respectively based on the height of the neutral plane, K_{ij} becomes,

$$K_{ij} = \alpha B_w \int_{z_1'}^{z_2'} \sqrt{2 g \rho_i |\rho_i - \rho_j|}\; z'^{1/2}\, dz'$$

$$= \frac{2}{3} \alpha B_w \sqrt{2 g \rho_i |\rho_i - \rho_j|}\,(z_2'^{3/2} - z_1'^{3/2}) \tag{42}$$

In the following, it follows that by the aid of Eqs.(39) and (42), we calculated the flow rates in the case when hot layers exist

near ceilings of rooms.

Before calculating the flow rates let's study the static pressure profile in room i . Although a static pressure generally decreases according to height z , the decrease rate above the bottom of a hot layer is smaller than that below it, because density of hot gas is smaller than that of air at room temperature. Accordingly, as shown in Fig.4 the line to express the static pressure decrease bends at the height of discontinuity $Z_{a,i}$. The situation is almost the same as to room j , but the height that the line bends and the decrease rate of static pressure above the height $Z_{a,j}$ differs each other, because the depth and the temperature of the hot gas layer of room j is generally different from those of room i .

The next thing we must study is the profile of the pressure difference between room i and j : $\Delta P_{ij}(Z)$. Here, we assume for a while that the hot layer of room i is deeper than that of room j . So by the aid of Fig.4, we can see that $\Delta P_{ij}(Z)$ varies as follows according to z : i) where $Z \leq Z_{a,i}$, $\Delta P_{ij}(Z)$ is constant; ii) where $Z_{a,i} < Z \leq Z_{a,j}$, $\Delta P_{ij}(Z)$ varies in proportion to $\rho_a - \rho_i$, and iii) where $Z_{a,j} < Z$, $\Delta P_{ij}(Z)$ varies in proportion to $\rho_i - \rho_j$. This means that case i) has no neutral plane and therefore flow rate is calculated by Eq.(39) and that the cases ii) and iii) have different neutral planes each other.

The height of the neutral plane in case ii): X_{nas} and that in case iii): X_{nss} can be obtained as follows: At first writing down the static pressures of room i and room j at an arbitrary height z as,

$$P_i(Z) = \begin{cases} P_i - \rho_a g Z & (Z \leq Z_{a,i}) \quad (43a) \\ P_i - \rho_a g Z_{a,i} - \rho_{s,i}(Z - Z_{a,i}) & (Z > Z_{a,i}) \quad (43b) \end{cases}$$

$$\Delta P_{i,j}(Z) = \begin{cases} P_j - \rho_a g Z & (Z \le Z_{a,j}) \quad (44a) \\ P_j - \rho_a g Z_{a,j} - \rho_{s,j}(Z - Z_{a,j}) & (Z > Z_{a,j}) \quad (44b) \end{cases}$$

and equating Eq.(43b) and Eq.(44a) yield X_{nas} as

$$X_{nas} = \frac{P_j - P_i}{(\rho_a - \rho_i)g} + Z_{a,i} \qquad (45)$$

In the same way, equating Eq.(43b) and Eq.(44b) yields X_{nss} as,

$$X_{nss} = \frac{P_j - P_i}{(\rho_{s,j} - \rho_{s,i})g} + \frac{\rho_a - \rho_{s,i}}{\rho_{s,j} - \rho_{s,i}} Z_{a,i} + \frac{\rho_{s,j} - \rho_a}{\rho_{s,j} - \rho_{s,i}} Z_{a,j} \qquad (46)$$

The profile of the pressure difference between room i and room j possibly take various figures because the hot layer densities $\rho_{s,i}$ and $\rho_{s,j}$ and the static pressures P_i and P_j vary successively according to the growth of fire. Therefore, next let's examine the typical profile that the static pressure difference $\Delta P_{i,j}(Z)$ is possible to take. At first, we begin the study with separating the cases into the case when $\rho_{s,i} \le \rho_{s,j}$ and the case when $\rho_{s,i} > \rho_{s,j}$. For we have assumed that the hot layer in room i is deeper than that of room j, the latter case seems somewhat unrealistic, because it is more or less difficult to suppose that the temperature of the superior layer is lower than that of the inferior one. However, taking the cases when some change take place in conditions of openings or heat transfer and when some trivial errors occur in numerical procedure into account, we had better include these cases in the model.

The pressure difference profile can be classified typically as follows with the aid of X_{nas} (see Fig.5):

A) in the case when $\rho_{s,i} \le \rho_{s,j}$:

a) when $X_{nas} \leq Z_{a,i}$, the static pressure of room j is lower than that of room i at any height, therefore air flows where $Z \leq Z_{a,i}$ and hot gas flows where $Z > Z_{a,i}$ both from room i to room j ;

b) when $Z_{a,i} < X_{nas} \leq Z_{a,j}$, the static pressure of j is higher than that of i where $Z \leq X_{nas}$ and is reverse where $Z > X_{nas}$, therefore air flows from j to i where $Z \leq X_{nas}$ and hot gas flows from i to j where $Z > X_{nas}$;

c) when $Z_{a,j} < X_{nas}$, the static pressure of j is higher than that of i where $Z \leq X_{nss}$ and is reverse where $Z > X_{nss}$, therefore air flows where $Z \leq Z_{a,j}$ and gas flows where $Z_{a,j} \leq Z < X_{nss}$ both from j to i and hot gas flows from i to j where $Z > X_{nss}$

B) in the case when $P_{s,i} > P_{s,j}$:

a) when $X_{nas} \leq Z_{a,i}$, the static pressure of room j is lower than that of i where $Z > X_{nss}$ and is reverse where $Z \leq X_{nss}$. therefore air flows where $Z \leq Z_{a,i}$ and hot gas flows where $Z_{a,i} \leq Z < X_{nss}$ both from i to j and hot gas flows from j to i where $Z > X_{nss}$;

b) when $Z_{a,i} < X_{nas} < Z_{a,j}$. the static pressure of room j is higher than that of i where $Z > X_{nss}$ and $Z \leq X_{nas}$ and is reverse where $X_{nas} < Z \leq X_{nss}$, therefore air flows where $Z \leq X_{nas}$ and hot gas flows where $Z > X_{nss}$ both from j to i . and hot gas flows from i to j where $X_{nas} < Z \leq X_{nss}$

c) when $Z_{a,j} < X_{nas}$, the static pressure of room j is higher than that of i at any height, therefore air flows where $Z \leq Z_{a,j}$ and hot gas flows where $Z > Z_{a,j}$ both from j to i .

What is shown above is merely the flow which is possible from the viewpoint of the profile of the static pressure difference between room i and j . It is clear that actual flows are realized in relation to opening conditions as well as the static pressure difference profile, for example, when a threshold of an opening is higher than $Z_{a,j}$, it follows that there is not any flow of air. Accordingly formulae for the flow rates should be obtained, taking the various cases of openings into consideration. The results are shown in Tab. 1. In the Table 1, hot gas flows where $Z > Z_{a,j}$, hot gas flows where $Z_{a,i} < Z \leq Z_{a,j}$, air flows where $Z_{a,i} < Z \leq Z_{a,j}$ and air flows where $Z \leq Z_{a,i}$ are indicated as SS, SA, AS and AA respectively for simplicity of expression and subscripts ij denotes that fluid flows from room i to room j .

In the above discussions, we have assumed that the hot layer of room i is deeper than that of room j , however it must be needless to say that the assumption is merely a matter of notation, if necessary we can exchange i and j at any time.

2.4 Computation Procedure

2.4.1 COUPLING EQUATIONS FOR HOT LAYER TEMPERATURE AND DEPTH

Although Eqs.(1) - (6) given in section 2.3.1 are regarded as the fundamental equations that govern the phenomena in any room including the fire room, they have not as yet given the temperatures and depths of the hot layers explicitly which are what we want to know directly. Then, in the following we try to obtain more convenient expressions.

1) Differential Equations for the Temperature of Hot Layer

Expanding the left-hand side of the energy conservation equation of hot layers Eq.(3) as,

$$\frac{d}{dt}\{c_p \rho_{s,i} A_{R,i} Z_{s,i}(\theta_{s,i}-\theta_a)\}$$

$$= c_p(\theta_{s,i}-\theta_a)\frac{d}{dt}(\rho_{s,i} A_{R,i} Z_{s,i}) + \rho_{s,i} A_{R,i} Z_{s,i}\frac{d}{dt}\{c_p(\theta_{s,i}-\theta_a)\} \quad (47)$$

and substituting the mass conservation equation Eq.(1) to the first term of it we can rewrite Eq.(3) as follows:

$$c_p(\theta_{s,i}-\theta_a)\{\sum_j\sum_k (SS_{ji}-SA_{ji}-SS_{ij}-SA_{ij})_{,k}+M_{s,i}\}+\rho_{s,i}A_{R,i}Z_{s,i}\frac{d}{dt}\{c_p(\theta_{s,i}-\theta_a)\}$$

$$= \dot{Q}_{c,i}-\dot{Q}_{r,i}+c_p\sum_j\sum_k\{(SS_{ji}+SA_{ji})(\theta_{s,j}-\theta_a)-(SS_{ij}+SA_{ij})(\theta_{s,i}-\theta_a)\}_{,k}$$

therefore

$$c_p \rho_{s,i} A_{R,i} Z_{s,i}\frac{d\theta_{s,i}}{dt} = \dot{Q}_{c,i}-\dot{Q}_{r,i}-c_p M_{s,i}(\theta_{s,i}-\theta_a)$$

$$-c_p\sum_j\sum_k\{(SS_{ji}+SA_{ji})(\theta_{s,j}-\theta_a)-(SS_{ij}+SA_{ij})(\theta_{s,i}-\theta_a)\}_{,k}$$

$$-c_p\sum_j\sum_k\{(SS_{ji}+SA_{ji}-SS_{ji}-SA_{ij})(\theta_{s,i}-\theta_a)\}_{,k}$$

$$= \dot{Q}_{c,i}-\dot{Q}_{r,i}$$

$$+c_p\sum_j\sum_k\{(SS_{ji}+SA_{ji})(\theta_{s,j}-\theta_{s,i})\}_{,k}-c_p M_{s,i}(\theta_{s,i}-\theta_a)$$

Rearranging this equation by substituting the equation of gas state Eq.(4) to eliminate $\rho_{s,i}$, we obtain the final equation for the temperature of the hot gas layer in an arbitrary room i as follows:

$$\frac{d\theta_{s,i}}{dt} = \frac{\theta_{s,i}}{c_p \rho_a \theta_a A_{R,i} Z_{s,i}} (\dot{Q}_{c,i} - \dot{Q}_{r,i}) + \frac{\theta_{s,i}}{\rho_a \theta_a A_{R,i} Z_{s,i}} \left[\sum_j \sum_k \left\{ (SS_{ji} + SA_{ji})(\theta_{s,j} - \theta_{s,i}) \right\}_{,k} - M_{s,i}(\theta_{s,i} - \theta_a) \right] \quad (48)$$

2) Differential Equations for the Depth of a Hot Layer

Expanding the left-hand side of the mass conservation of equation of hot layers,

$$\frac{d}{dt}(\rho_{s,i} A_{R,i} Z_{s,i}) = A_{R,i}\left(\rho_{s,i} \frac{dZ_{s,i}}{dt} + Z_{s,i} \frac{d\rho_{s,i}}{dt}\right) \quad (49)$$

and substituting the following relation,

$$\frac{d\rho_{s,i}}{dt} = -\frac{\rho_a \theta_a}{\theta_{s,i}^2} \cdot \frac{d\theta_{s,i}}{dt} \quad (50)$$

which can be obtained from Eq.(4), Eq.(1) becomes as follows:

$$\rho_{s,i} \frac{dZ_{s,i}}{dt} - Z_{s,i} \frac{\rho_a \theta_a}{\theta_{s,i}^2} \cdot \frac{d\theta_{s,i}}{dt} = \frac{1}{A_{R,i}} \left\{ \sum_j \sum_k (SS_{ji} + SA_{ji} - SS_{ij} - SA_{ij})_{,k} + M_{s,i} \right\}$$

Using again Eq.(4), this becomes as follows:

$$\frac{dZ_{s,i}}{dt} = \frac{Z_{s,i}}{\theta_{s,i}} \cdot \frac{d\theta_{s,i}}{dt} + \frac{\theta_{s,i}}{\rho_a \theta_a A_{R,i}} \left\{ \sum_j \sum_k (SS_{ji} + SA_{ji} - SS_{ij} - SA_{ij})_{,k} + M_{s,i} \right\}$$

And furthermore substituting Eq.(48) for the temperature of the hot gas layer into the second term of the right-hand side of this equation, this becomes as follows:

$$\frac{dZ_{s,i}}{dt} = \frac{Z_{s,i}}{\theta_{s,i}}\left[\frac{\theta_{s,i}(\dot{Q}_{c,i}-\dot{Q}_{r,i})}{c_p\rho_a\theta_a A_{R,i}Z_{s,i}} + \frac{\theta_{s,i}}{\rho_a\theta_a A_{R,i}Z_{s,i}}\sum_j\sum_k\left\{(SS_{ji}+SA_{ji})(\theta_{s,j}-\theta_{s,i})\right\}_{,k} - \frac{\theta_{s,i}M_{s,i}(\theta_{s,i}-\theta_a)}{\rho_a\theta_a A_{R,i}Z_{s,i}}\right]$$

$$+\frac{\theta_{s,i}}{\rho_a\theta_a A_{R,i}}\left\{\sum_j\sum_k(SS_{ji}+SA_{ji}-SS_{ij}-SA_{ij})_{,k}+M_{s,i}\right\}$$

$$= \frac{\dot{Q}_{c,i}-\dot{Q}_{r,i}}{c_p\rho_a\theta_a A_{R,i}} + \frac{-M_{s,i}(\theta_{s,i}-\theta_a)}{\rho_a\theta_a A_{R,i}} + \frac{\theta_{s,i}M_{s,i}}{\rho_a\theta_a A_{R,i}}$$

$$-\frac{1}{\rho_a\theta_a A_{R,i}}\left[\sum_j\sum_k\left\{(SS_{ji}+SA_{ji})(\theta_{s,j}-\theta_{s,i})\right\}_{,k}+\sum_j\sum_k(SS_{ji}+SA_{ji}-SS_{ij}-SA_{ij})\theta_{s,i}\right\}_{,k}\right]$$

Therefore, we obtain the final expression for the depth of the hot layer in any room as follows:

$$\frac{dZ_{s,i}}{dt} = \frac{\dot{Q}_{c,i}-\dot{Q}_{r,i}}{c_p\rho_a\theta_a A_{R,i}} + \frac{M_{s,i}}{\rho_a A_{R,i}} + \frac{1}{\rho_a\theta_a A_{R,i}}\left[\sum_j\sum_k\left\{(SS_{ji}+SA_{ji})\theta_{s,j}-(SS_{ij}+SA_{ij})\theta_{s,i}\right\}_{,k}\right] \quad (i=1,n) \tag{51}$$

The 2n equations expressed by Eqs.(48) and (51) are the coupling ordinary differential equations for the temperatures and depths of the hot layers in n rooms in a fire building.

Accordingly integrating them starting from the ignition, we can predict the behavior of the hot layers. However, when $Z_{s,i} = 0$. it is evidently impossible to integrate Eq.(48), therefore we need some sophistication to avoid this difficulty.

2.4.2. COMPUTATION OF MULTI-ROOM PRESSURE

The coupling differential Eqs.(48) and (51) involves many terms concerning the rates of the hot gas flow which are very important because they connect the phenomena of each other rooms mutually. On the other hand, as shown in Tab. 1 each flow rate is expressed using the static pressures of corresponding rooms at ground level as parameters, therefore in actual computations it is necessary for us to manage to obtain the pressures. So in the following we treat this problem:

1) Equation of Flow Condition

Generally speaking, an equation of gas state usually contains pressure, however because we have adopted Eq.(4) as the equation of state excluding pressure, we cannot calculate the pressure and therefore flows by the use of the equation of state. But even if we adopted an equation which includes pressure in place of Eq.(4), it would be almost impossible to compute the flow rates exactly enough by the use of the pressure. The reason is as follows: The change of temperatures or densities obtained by numerical integration of Eq.(48) or so might be considerably large even if the time interval is taken small enough, for instance as 1 sec. If we assume that the degree of the change of the temperature is about 1%, the degree of the change of pressure calculated from an equation of state would be about $10^5 \times 0.01 = 10^3 P_a$ which would be recognized as a very big value because the degree of the wind pressure of the flows that we are usually concern with respect to fires in small scale buildings may be 10 P_a or so.

Accordingly, it is obvious that we need another method to determined the pressures. What is adopted here is a hypothesis that flow rates are determined to satisfy the mass conservation of the air layer in each room. Because the flow rates are described using the static pressures of the rooms at ground level, we can use the expression "the pressures are determined" in stead of the expression "flow rates are determined". By the way, we can use another hypothesis that the pressures are determined to satisfy the total mass conservation of any room instead of the above hypothesis because the mass conservation of hot layer in arbitrary room have been also satisfied.

Because the above hypothesis means that flows follow the other changes in rooms, it might be difficult to apply the hypothesis to the case when the changes in some rooms are very quick compared with the flow rates. However, at least in such a case as here when multi-room fire spread is put into consideration, we can suppose that the vents are so large as to supply enough air to the

dominant burning in the fire room.

From Eq.(5) we can obtain the flowing relationship:

$$\frac{dZ_{a,i}}{dt} = -\frac{dZ_{s,i}}{dt}$$

Substituting this into mass conservation equation of air layer Eq.(2), we obtain Eq.(52')

$$\rho_a A_{R,i} \frac{dZ_{s,i}}{dt} + \sum_j \sum_k (AS_{ji} + AA_{ji} - AS_{ij} - AA_{ij})_{,k} - M_{e,i} = 0 \qquad (52')$$

Rearranging Eq.(52') by substituting Eq.(51) yields

$$\frac{\dot{Q}_{c,i} - \dot{Q}_{r,i}}{c_p \theta_a} + \frac{1}{\theta_a}\left[\sum_j \sum_k \left\{(SS_{ji} + SA_{ji})\theta_{s,j} - (SS_{ij} + SA_{ij})\theta_{s,i}\right\}_{,k}\right]$$

$$+ \sum_j \sum_k (AS_{ji} + AA_{ji} - AS_{ij} - AA_{ij})_{,k} + M_{s,i} - M_{e,i} = 0 \qquad (i = 1, n) \qquad (52)$$

This equation describes the condition that the pressures must satisfy.

By the way, that starting from the total mass conservation gives the same result can be shown as follows: At first, writing down the total mass conservation equation as,

$$\frac{d}{dt}(\rho_a A_{R,i} Z_{a,i} + \rho_{s,i} A_{R,i} Z_{s,i})$$

$$= \sum_j \sum_k (SS_{ji} + SA_{ji} + AS_{ji} + AA_{ji} - SS_{ij} - SA_{ij} - AS_{ij} - AA_{ij})_{,k} + M_{p,i}$$

and substituting the mass conservation equation of hot gas layer Eq.(1) into this yield Eq.(52').

To investigate the physical meaning of Eq.(52), let's rewrite Eq.(52) as follows:

$$\sum_j \sum_k \left\{ (SS_{ji} + SA_{ji}) \frac{\theta_{s,j}}{\theta_a} \right\}_{,k} - \sum_j \sum_k \left\{ (SS_{ij} + SA_{ij}) \frac{\theta_{s,i}}{\theta_a} \right\}_{,k}$$

$$+ \sum_j \sum_k (AS_{ji} + AA_{ji})_{,k} - \sum_j \sum_k (AS_{ij} + AA_{ij})_{,k} + \frac{\dot{Q}_{c,i}}{C_p \theta_a} - \frac{\dot{Q}_{r,i}}{C_p \theta_a} + M_{p,i} = 0 \qquad (53)$$

In more plain expression, this becomes,

$$\begin{pmatrix}\text{mass flow rate of}\\ \text{hot gas into } i\end{pmatrix} \times \frac{\begin{pmatrix}\text{temperature of}\\ \text{hot gas into } i\end{pmatrix}}{\theta_a} - \begin{pmatrix}\text{mass flow rate of}\\ \text{hot gas out of } i\end{pmatrix} \times \frac{\begin{pmatrix}\text{temperature of}\\ \text{hot gas of } i\end{pmatrix}}{\theta_a}$$

$$\begin{pmatrix}\text{mass flow rate}\\ \text{of air into } i\end{pmatrix} - \begin{pmatrix}\text{mass flow rate}\\ \text{of air out of } i\end{pmatrix} + \begin{pmatrix}\text{rate of}\\ \text{heat input}\end{pmatrix} \times \frac{1}{C_p \theta_a} - \begin{pmatrix}\text{rate of}\\ \text{heat loss}\end{pmatrix} \times \frac{1}{C_p \theta_a}$$

$$+ \begin{pmatrix}\text{mass input}\\ \text{by fire source}\end{pmatrix} = 0$$

The reason why hot gas flows are more effective to the flow condition equation than air flows is understood by the fact that hot gas has larger bulk than the air of equal mass, and the reason why heat have influence on the condition equation is recognized as heat input increase the bulk of hot gas and inversely heat loss decrease it. However, it seems that mass input from fire source is independent of the temperature in spite of its high temperature but the question is solved if we take care of the fact that $\dot{Q}_{c,i}$ is transported by $M_{s,i}$ and $M_{p,i}$, that is,

$$\dot{Q}_{c,i} = C_p M_{s,i} (\theta_{s,i} - \theta_a) = C_p M_{p,i} (\theta_{p,i} - \theta_a) \qquad (54)$$

where $\theta_{s,i}$ and $\theta_{p,i}$ are average plume temperatures at corresponding height respectively.

2) Computation of Multi-Room Pressure

It has been known that the condition the pressure of any room must satisfy is Eq.(52). However they contain flow rate terms

SS, SA, AS and AA any of which is related to the pressures of the both sides of the opening, therefore generally speaking, any one of Eq.(52) is possible to be related to the pressure of any room, that is Eq.(52) is coupling equations for n unknowns $P_1 \cdots\cdots, P_n$. Furthermore they are nonlinear for the pressures, because SS, SA AS and AA are all made applying Bernoulli's theorem.

In the following, we try to solve the simultaneous nonlinear equations described by Eq.(52). Let's express Eq.(52) as follows for the simplicity of treatment,

$$f_i(P_1, P_2, \cdots\cdots\cdots, P_n) = 0 \qquad (i = 1, n) \tag{55}$$

Taking care that the concrete form of each f_i is

$$f_i \equiv \begin{pmatrix} \text{flow rates of hot gas} \\ \text{and air into room i} \end{pmatrix} - \begin{pmatrix} \text{flow rates of hot gas} \\ \text{and air into room i} \end{pmatrix} + \begin{pmatrix} \text{heat} \\ \text{etc.} \end{pmatrix}$$

where the former two terms depend on the pressures and the third does not depend on them. Generally speaking, if the pressure of room i becomes lower than those of the surroundings, the rates of hot gas and air flow into room i increase and the flow rates out of i decrease and on the contrary if the pressure of room i becomes higher than those of surroundings, the flow rates into i decrease and the flow rates out of i increase, that is, if the pressures of the surroundings are constant f_i always decreases according to the increase of P_i as shown schematically in Fig.6. And it follows that Eq.(55) requires every P_i to be determined as the value when the curve of f_i crosses the abscissa.

The main difficulty of the problem lies on the fact that n nonlinear equations in Eq.(55) must be satisfied simultaneously, but we begin the study with the case of n = 1 for the simplicity of comprehension, that is

$$f_1(P_1) = 0 \tag{56}$$

We can regard the case as a single compartment fire. Although Eq.(56) is nonlinear, it is not simultaneous but a single equation for a single unknown P_1, therefore we can solve it using Newton-Raphson method or Regula-Falsi method etc.

What we use here is a method which is made by adding some devises to Regula-Falsi method[8]. But before explaining the method, we briefly relate to Regula-Falsi method for the convenience of explanation. Let's omit subscritp 1 for a while for the simplicity sake.

In Regula-Falsi method, we calculate f(p) giving a proper initial value to p. Then, if f(p) is positive, we make new p adding a proper positive gain Δp to p, on the other hand, if f(p) is negative, we subtract Δp from p, because f(p) is known as a function that decreases monotonously according to the increase of p. Subsequently we calculate f(p) till the sign of f(p) changes, successively altering p with new value as above, and as soon as the sign changes, we calculate a new p in turn as,

$$p = \frac{p_+ f_- - p_- f_+}{f_- - f_+} \tag{57}$$

and calculate f(p) using this $f(p)$ where f_+ and f_- are the positive f and negative f before and after the sign changed respectively and p_+ and p_- are corresponding static pressure. We repeat this procedure until enough accuracy is obtained using the newest positive and negative values of f as f_+ and f_- respectively (Fig. 7).

Regula-Falsi method may be valid for the case when the range of p can be prospected, but may be not necessarily valid for the other case, because if we take Δp small, a large number of computations is necessary before the sign change of f(p) if we take Δp large, we need them after the sign change. The following method that we adopt here may compensate the defect partially.

(i) at first, we calculate $f_o \equiv f(p_o)$ for proper initial value p_o

(ii) examining the sign of f_o, if $f_o > 0$ we make p_1 as $p_1 = p_o + \Delta p$ and if $f_o < 0$, we make p_1 as $p_1 = p_o - \Delta p$ and then calculate $f_1 \equiv f(p_1)$

(iii) compare the signs of f_o and f_1

(iv) if the signs of f_o and f_1 are equal, make new p as

$$p = \frac{p_1 f_o^2 - p_o f_1^2}{f_o^2 - f_1^2} \tag{58}$$

and considering this p as initial value, repeat calculation from (i)

(v) if the signs of f_o and f_1 are different, we calculate new p using Eq.(57) and repeat calculations until satisfactory accuracy is obtained (Fig. 8).

In the procedure shown above, Eq.(58) is an equation that is obtained assuming that $f \propto p^{1/2}$. (See Fig.8) Because we have applied Bernoulli's theorem to obtain flow rates, function f which is principally composed of the flow rates, is almost proportional to $p^{1/2}$ where p is largely separated from the solution. In this method, because we can bring p near the solution at a stretch when p is very far from the solution, we can take Δp considerably small.

The method described above is essentially taken as a trial and error method even if there might be many devises to gain adequate values quickly, so we describe the procedure schematically as in Fig. (9).

Next, we consider on the case when $n = 2$, that is, the problem to obtain p_1 and p_2 that simultaneously satisfy the following equations:

$$f_1(P_1, P_2) = 0 \tag{59a}$$

$$f_2(P_1, P_2) = 0 \tag{59b}$$

Here, let's consider that p_1 can be obtained as a function of p_2 from Eq.(59a) as,

$$P_1 = f_1^*(P_2) \tag{60}$$

then, substituting Eq.(60) into (59b) yields;

$$f_2(f_1^*(P_2), P_2) = 0 \tag{61}$$

this is a single function for a single unknown p_2, therefore it is essentially the same as Eq.(56) and can be solved numerically by a trial and error method. It is true that we cannot obtain Eq.(60) analytically for Eq.(59a) is nonlinear, but because the meaning of Eq.(60) can be interpreted as we can always obtain p_1 for an arbitrary p_2, so it is sufficient to calculate p_1 at every time when p_2 changes. It is also possible for us to calculate p_1 using Eq.(59a) because it is an equation for a single unknown when p_2 is specified. Then it is clear that the procedure to solve Eqs.(50a) and (59b) can be shown as in Fig.10.

Let's advance to the case when n = n, that is the case when we solve the following equations:

$$\left.\begin{aligned} f_1(P_1, P_2, \cdots\cdots, P_n) &= 0 \\ f_2(P_1, P_2, \cdots\cdots, P_n) &= 0 \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots & \\ f_n(P_1, P_2, \cdots\cdots, P_n) &= 0 \end{aligned}\right\} \tag{62}$$

In this case, at first we solve p_1 as a function of $p_2 \cdots\cdots, p_n$ as follows, using the first equation of Eqs.(62)

$$P_1 = f_1^*(P_2, P_3, \cdots\cdots, P_n) \tag{63}$$

and then substituting into the other equations of Eqs.(62) yields,

$$\left.\begin{array}{l} f_2(f_1^*(p_2, p_3, \cdots\cdots, p_n), p_2, p_3, \cdots\cdots, p_n) = 0 \\ f_3(f_1^*(p_2, p_3, \cdots\cdots, p_n), p_2, p_3, \cdots\cdots, p_n) = 0 \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ f_n(f_1^*(p_2, p_3, \cdots\cdots, p_n), p_2, p_3, \cdots\cdots, p_n) = 0 \end{array}\right\} \qquad (64)$$

Eqs.(64) are $n - 1$ simultaneous equations for $n - 1$ unknowns p_2, p_3, ..., p_n. So furthermore we solve p_2 as a function of p_3, ..., p_n using the first equation of Eqs.(64) as,

$$p_2 = f_2^*(p_3, p_4, \cdots\cdots, p_n) \qquad (65)$$

and again substituting Eq.(65) into the other equations of Eqs.(64) yield $n - 2$ equations for $n - 2$ unknowns p_3, ..., p_n. In the same way, eliminating p_3, p_4, ..., p_{n-1} one after another we can finally obtain one function for only one unknown p_n, therefore we can solve the equation. And then the meaning of Eq.(63) is also that we can always calculate p_2 whenever even one of p_2, p_3, ..., p_n changes, and it is similar as to Eq.(65). So it is clear that the procedure to solve Eqs.(62) using a trial and error method becomes as shown in Fig.11.[9]

Up to now, we have considered as a general discussion that f_i is related to the pressures of all rooms p_1, ..., p_n. But actually, such a case is really unusual, because rooms in a building have some rules in mutual connection according to their use. And consideration on the rule makes pressures computation much easier. For example, in a building shown in Fig.12, because it has four rooms in general discussion it follows that we must solve the equations as follows:

$$f_i(p_1, p_2, p_3, p_4) = 0 \qquad (i = 1, n) \qquad (66)$$

This procedure becomes as shown in Fig.13. But if we take care of the fact that there is no openings between room 1, 2 and 3 and therefore there is no exchange of flows, it follows that it is sufficient for us to solve the following equations:

$$\begin{aligned} f_1(P_1, P_4) &= 0 \\ f_2(P_2, P_4) &= 0 \\ f_3(P_3, P_4) &= 0 \\ f_4(P_1, P_2, P_3, P_4) &= 0 \end{aligned} \tag{67}$$

Eqs.(67) suggestes that by making use of the former three equations, p_1, p_2 and p_3 are all given as functions of only one variable p_4, in other words, it is sufficient for us to calculate p_1, p_2 and p_3 only when p_4 changes during the exection of the calculation. Accordingly, the procedure for Eqs.(67) becomes as shown in Fig.14 and becomes much simpler comparing that shown in Fig.14.

In actual problems, such simplification as stated above is almost always possible and is useful to make omputation time short.

2.4.3 FLOW CHART OF COMPUTATION PROCEDURE

The model outline of which is shown above can calculate the temperatures and depths of the hot layers, the flow rates of hot gas and air, the temperatures of ceilings and floors, and the incident heat flux to ceilings and floors, if the parameter values on the dimensions, thermal properties, opening conditions and connecting relations of the rooms in the object building and the location, area and heat evolution rate of the fire source are specified.

It might be said that the core of the computation procedure of the model is to integrate the coupling ordinary differential Eqs.(48) and (51) by use of Runge-Kutta Gill method. The flow chart shown in Fig.15 is the outline of the computation procedure of the Model.

3. SAMPLE COMPUTATIONS AND DISCUSSION

In the following we show some sample computations to investigate the validity of the model.

3.1 Specification of Parameter

3.1.1. DIMENSIONS OF SAMPLE BUILDING

Two buildings are adopted here as the objects of the sample computations.

One is, as shown in Fig.16, a single floor building which has five equal rooms. This sample building which is very simple for the convenience of the results exhibition suit the aim of the present model, because the model has been devised to apply to the problems on fire spread in Japanese dwelling houses.

The other is, as shown in Fig.17, a three-floor building which has nine rooms and one stairwell. To tell the truth, I think it is not very suitable to apply the model to such a tall building because the model as yet neglect the entrainment when hot gas rises up in a tall space such a stairwell. In Japan, it is seldom that a dwelling house has such a large scale as this sample, so to apply the model to such a building is practically not important in Japan. The reason why we dare to adopt this sample is to investigate the degree of the validity of the model.

With regard to the dimensions of the principal parts of the two buildings, we show them in Figs.(16) and (17). Additionally we show an example of pressure calculation loops for each case in Figs.(18) and (19), however some alternative loops are possible.

3.1.2 FIRE SOURCE CONDITIONS

The parameters we use here to characterize the conditions of

a fire source are location, area and heat evolution rate of a fire. Those parameter values for each sample are exhibited in Table 3.

3.1.3 THERMAL PROPERTIES OF BUILDING

As the thermal properties, we take the same values for all the rooms in the sample buildings which are shown in Tab. 2. and besides we make as $\dot{q}''_{out} = 0$ in Eq.(24). These specification might be in some extent unrealistic, because it is almost as good as each room in a building is entirely enclosed by 10 cm thick concrete slabs, nevertheless we adopt them to simplify the thermal conditions.

3.2. Sample Computations and Discussion

1) Sample 1

This is a case when a fire source which has 1 square meter area appears and continue to generate heat at the rate of 40 kcal/sec. This heat evolution may roughly correspond to the burning rate 10 g/sec when the fuel is wood.

The transitions of the temperatures and depths are shown in Fig.21-a and Fig.21-b respectively, and the states in the buildings at some elapsed times are shown in Fig.21-c.

In Fig.21-c, a white number near ceilings without an arrow indicate the temperatures of hot layers θ_s (°K) and a white numbers with a white arrow and a black number with a black arrow indicate a mass flow rate of hot gas SS + SA (kg/sec) and air AS + AA (kg/sec) respectively.

In this sample, the depth of the hot layer in the fire room becomes stable in a minute, but about seven minutes are required until all the hot layers become stable. The temperature rise to 380 °K

in fire room, but this is regarded as such a low temperature that the fire spread to the other rooms is entirely impossible.

2) Sample 2

The conditions of this sample are the same as those of sample 1 except the heat generation rate which is 80 kcal/sec in this case.

The general tendency of the results shown in Figs. (22-a), (22-b) and (22-c) are similar with sample 1. It is true that the time required for all the hot layers to be stable becomes shorter and the temperatures become higher. But the danger of the fire spread to out of the fire foom is also small.

3) Sample 3

In this case, the heat generation rate is 120 kcal/sec, but the other conditions are the same as the preceding samples. The tendency of the results are also similar with the previous samples, though the temperatures and spread velocity of the hot gas becomes larger.

4) Sample 4

In any of the previous samples 1 - 3, a constant heat evolution rate was given from the begining, however we cannot continue to increase the heat evolution rate in this manner because the larger the rate becomes, the steeper the changes of the temperatures and depths of the hot layers at initial time point and therefore the more difficult the pursuit of the change becomes. So, in this sample, the heat evolution rate is given in the manner shown in Fig.24-a, that is, the heat evolution rate increases gradually to 400 kcal/sec which might correspond to the burning rate when a large scale furniture such as a bed, a sofa, a chest of drawers is entirely involved in fire.

In this case, the temperature of the hot layer in fire room rise to about 700 °K and that of a next room rise to about 500°K but even in this sample the danger of the fire spread out of the fire room may not yet be so serious.

5) Sample 5

This is a case when a fire breaks out in a room on the first floor of the sample building that was shown in Fig.17. As stated before, to apply the model to such a building is not very suitable for the model as yet neglect entrainment of gas rising up in a tall space, in other words, availability of the model will be improved if a treatment of the entrainment is introduced. In the result, it is hard to believe that the temperatures of room 1 and stairwell are almost equal .

6) Sample 6

In this sample, the windows of Rooms (7) and (9) are closed and the fire source area and the width of the door between the fire room and the stairwell are both made twice those of sample 5 so that the rooms on the 3rd floor are filled with hot gas.

In this case, the second cause why it is difficult to apply the model to tall buildings appears, that is, the air that is pressed out from the rooms on the third floor by the hot gas flowing into the rooms, flows into the hot layer in the stairwell. Although this fact is contradictory to the assumption that hot gas flows into a hot layer and air flows into an air layer, it follows that the assumption insist on that the air pressed out from the rooms on the third floors flows down through the hot layer in the stairwell without mixing and flows into the air layer. However if we can submit to this error, the results are interesting enough.

4. CONCLUDING REMARKS

In this paper, we can show only a few sample computations. However it seems comparatively suitable to apply the present model to low buildings such as Japanese usual dwelling houses, though its application to tall buildings contains some difficulties as yet.

In future, we intend to try to improve the model to be able to apply to all buildings and to fully developed fire. Additionally, some experiments and further simulations would be also required for the verification of the model.

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NOMENCLATURE

Symbols

B_R	:	frontage of room (m)
D_R	:	depth of room (m)
H_R	:	height of room (m)
A_R	:	area of room (m^2)
B_W	:	width of opening (m)
H_h	:	height of upper edge of opening (m)
H_e	:	height of lower edge of opening (m)
z	:	height (m)
z_s	:	depth of hot gas layer (m)
z_a	:	depth of air layer (m)
M	:	mass flow rate of plume gas (kg/sec)
M_P	:	mass rate of gas input from heat source to plume (kg/sec)
M_S	:	mass rate of gas input from plume to hot layer (kg/sec)
M_e	:	mass rate of air entrainment to plume (kg/sec)
SS,SA	:	mass rate of hot gas flow through opening (kg/sec)
AS,AA	:	mass rate of air flow through opening (kg/sec)
ρ	:	density of gas, slab (kg/m^3)
θ	:	temparature of gas, slab (°K)
$\Delta\theta$	:	temparature difference (°K)
C_P	:	specific heat of gas (kcal/kg.°K)
σ	:	Stefan-Boltzmaun Constant ($kcal/m^2 \cdot sec \cdot °K^4$)
g	:	acceleration due to gravity (m/sec^2)
$\dot{q}''$	:	heat flux ($kcal/m^2 \cdot sec$)

$\dot{Q}, \dot{Q}_c$: heat evolution rate of heat source (kcal/sec)

$\dot{Q}_r$: rate of radiative heat transfer (kcal/sec)

F : configuration factor

t : time (sec)

Δt : time gain (sec)

κ : thermal conductivity of slab (kcal/m·sec·°K)

c : specific heat of slab (kcal/kg·°K)

ℓ : thickness of slab (m)

p : static pressure (P_a)

Δp : static pressure difference (P_a)

X_{nas}, X_{nss}: height of neutral plane of static pressure (m)

α : coefficient of discharge

R : rate of fluid flow (kg/sec)

f : function of flow condition

n : total number of rooms

Subscripts

i : denotes i-th room

k : denotes k-th opening

s : denotes hot layer, surface

f : denotes fire

a : denotes air

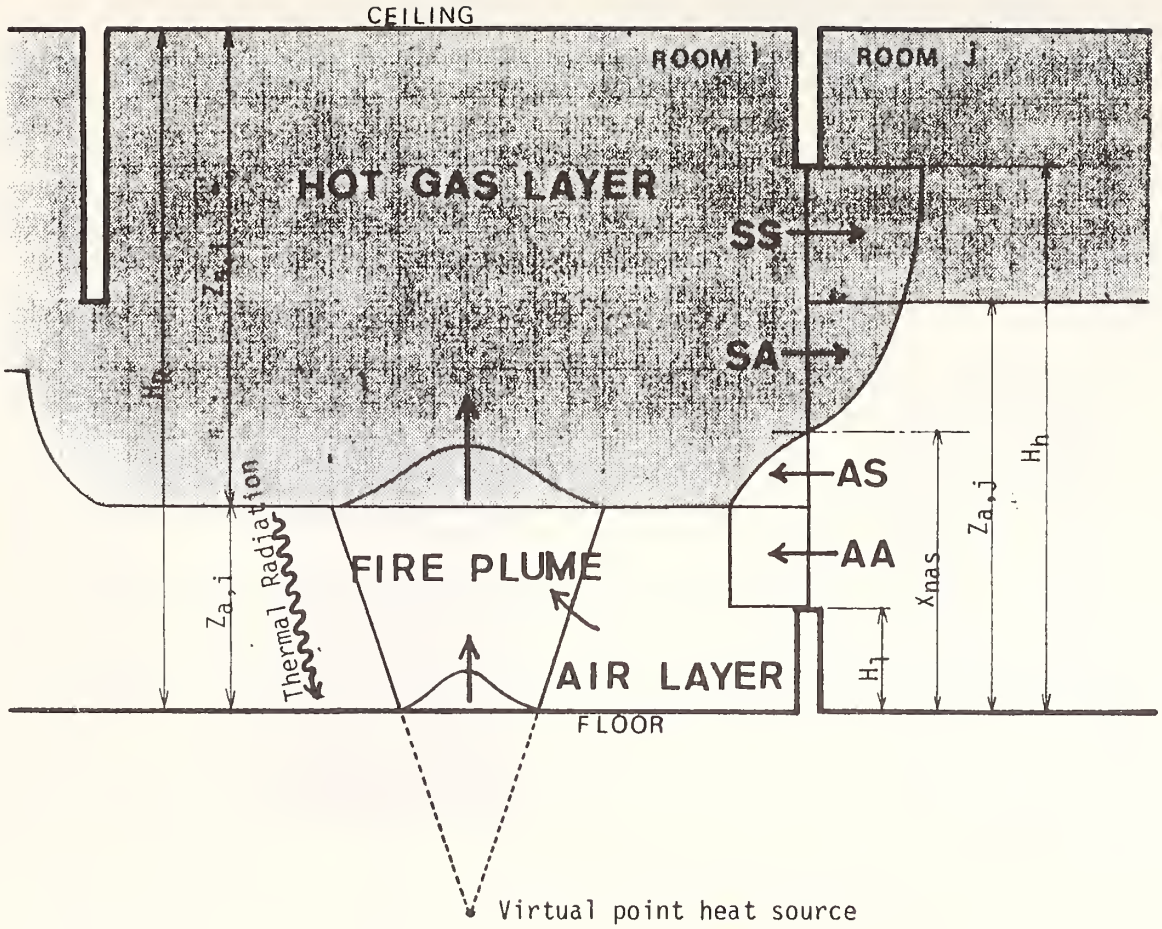
R : denotes room

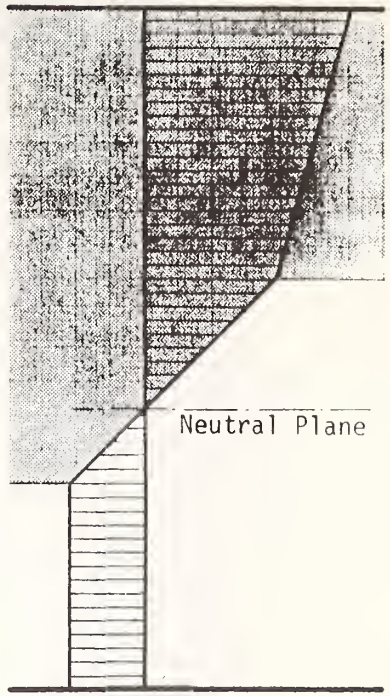
c : denotes ceiling, combustion

w : denotes floor

r : denotes thermal radiation

ij : denotes room i to room j





PRESSURE DIFFERENCE PROFILE
BETWEEN ROOM i AND ROOM j

Fig. 1 Outline of The Model

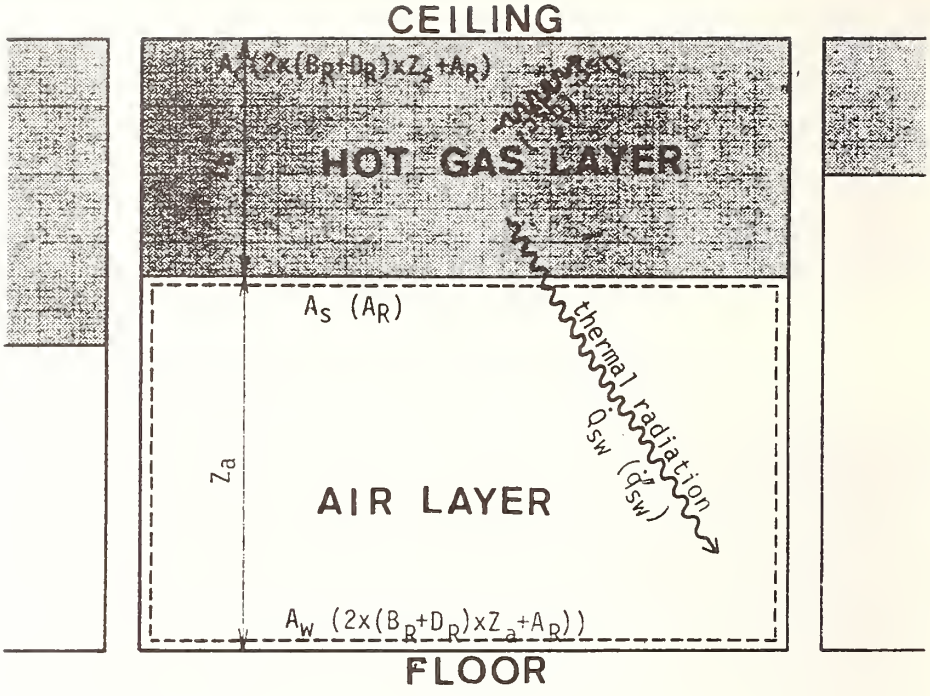


Fig. 2 Thermal Radiation Heat Transfer

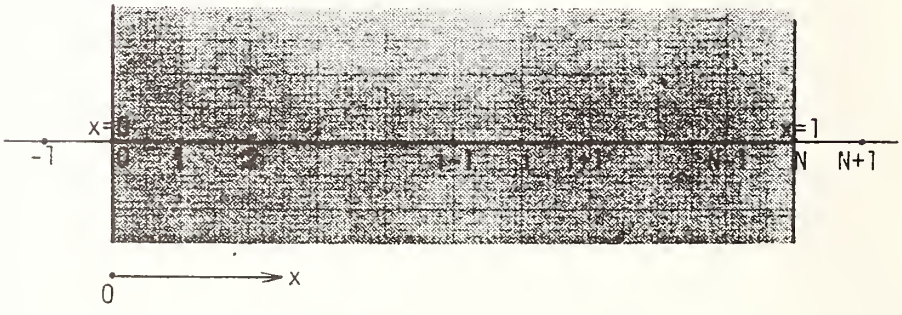
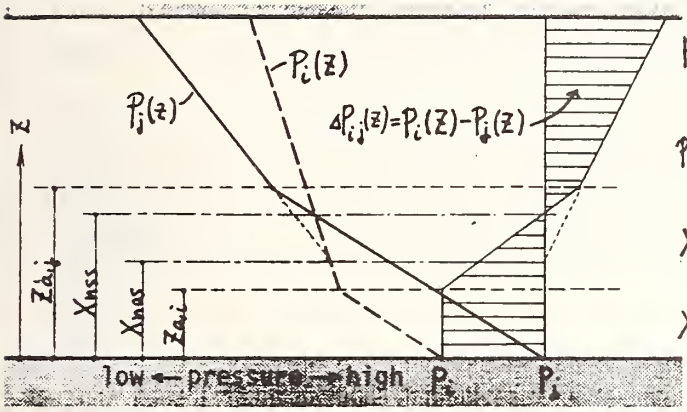


Fig. 3 Grid Points for Finite Differentiation



$$P_i(z)=\begin{cases} P_i-\rho_a g z & (z\le Z_{a,i}) \\ P_i-\rho_a g Z_{a,i}-\rho_{s,i}(z-Z_{a,i}) & (z>Z_{a,i}) \end{cases}$$

$$P_j(z)=\begin{cases} P_j-\rho_a g z & (z\le Z_{a,j}) \\ P_j-\rho_a g Z_{a,j}-\rho_{s,j}(z-Z_{a,j}) & (z>Z_{a,j}) \end{cases}$$

$$X_{nas}=\frac{P_j-P_i}{(\rho_a-\rho_i)g}+Z_{a,i}$$

$$X_{nss}=\frac{P_j-P_i}{(\rho_{s,j}-\rho_{s,i})g}+\frac{\rho_a-\rho_{s,i}}{\rho_{s,j}-\rho_{s,i}}Z_{a,i}+\frac{\rho_{s,i}-\rho_a}{\rho_{s,j}-\rho_{s,i}}Z_{a,j}$$

Fig. 4 Profile of Pressure Decrease & Difference

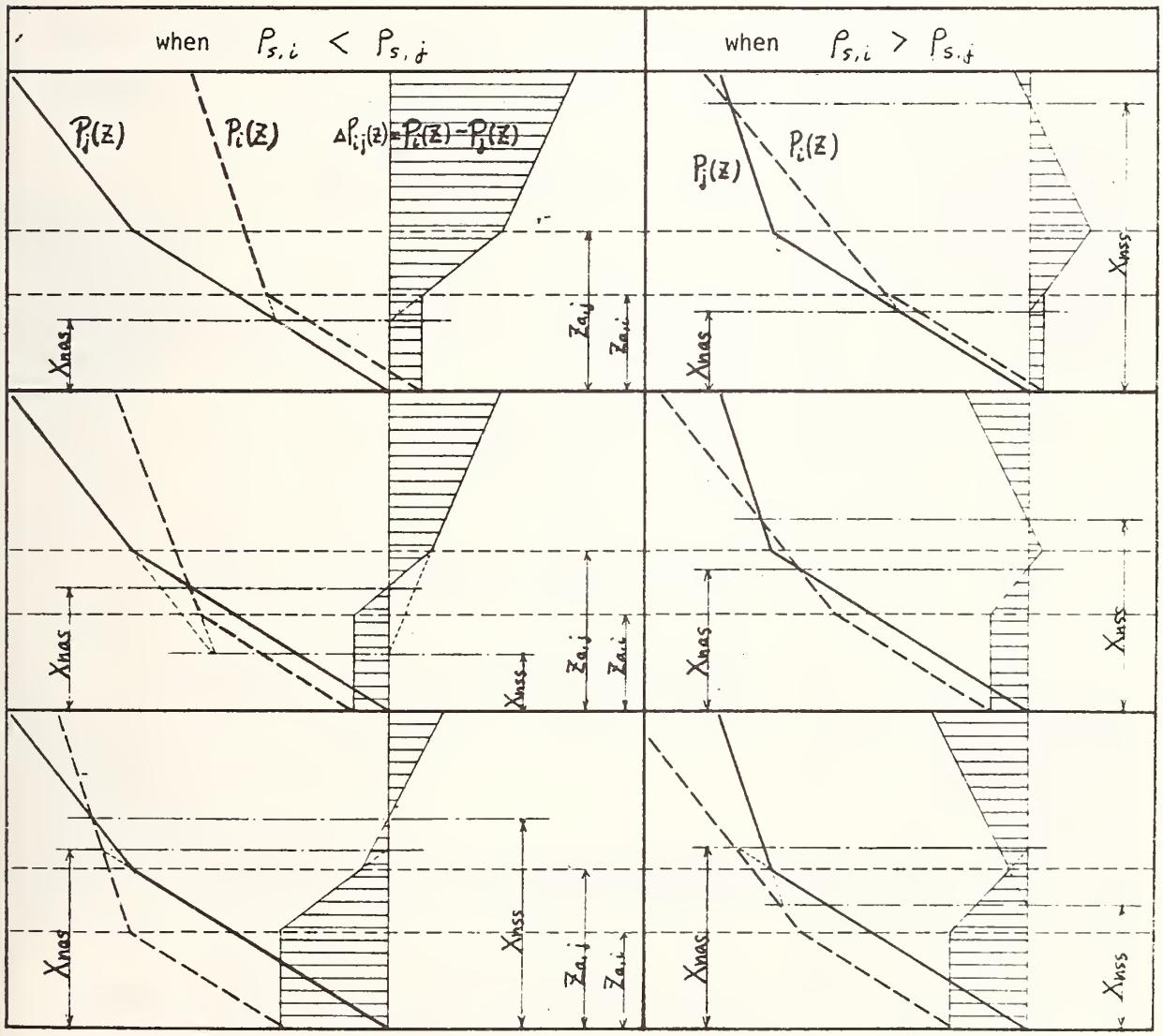


Fig. 5 Typical Pattern of Pressure Difference Profile

Tab. 1-a Flow Rate of Hot Gas & Air ($\rho_{s,i} < \rho_{s,j}$)

$X_{nas} \le Z_{a,i}$

$$SS_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_{s,j}|}\left\{(H_h - X_{nss})^{3/2} - (\max(H_e, Z_{a,j}) - X_{nss})^{3/2}\right\} & (H_h > Z_{a,j}) \\ 0. & (H_h \le Z_{a,j}) \end{cases}$$

$$SS_{ji} = 0.$$

$$SA_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_a|}\left\{(\min(H_h, Z_{a,j}) - X_{nas})^{3/2} - (\max(H_e, Z_{a,i}) - X_{nas})^{3/2}\right\} & (H_e > Z_{a,i} \,\&\, H_e < Z_{a,j}) \\ 0. & (H_e \le Z_{a,i} \text{ or } H_e \ge Z_{a,j}) \end{cases}$$

$$SA_{ji} = 0.$$

$$AS_{ij} = AS_{ji} = 0.$$

$$AA_{ij} = \begin{cases} \alpha' B_w \{\min(H_h, Z_{a,i}) - H_e\}\sqrt{2\rho_a|\rho_i - \rho_j|} & (H_e < Z_{a,i}) \\ 0. & (H_e \ge Z_{a,i}) \end{cases}$$

$$AA_{ji} = 0.$$

$Z_{a,i} < X_{nas} \le Z_{a,j}$

$$SS_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_{s,j}|}\left\{(H_h - X_{nss})^{3/2} - (\max(H_e, Z_{a,j}) - X_{nss})^{3/2}\right\} & (H_e > Z_{a,j}) \\ 0. & (H_e \le Z_{a,j}) \end{cases}$$

$$SS_{ji} = 0.$$

$$SA_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_a|}\left\{(\min(H_h, Z_{a,j}) - X_{nas})^{3/2} - (\max(H_e, X_{nas}) - X_{nas})^{3/2}\right\} & (H_e > X_{nas} \,\&\, H_e < Z_{a,j}) \\ 0. & (H_e \le X_{nas} \text{ or } H_e \ge Z_{a,j}) \end{cases}$$

$$SA_{ji} = 0.$$

$$AS_{ij} = 0.$$

$$AS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_a|\rho_a - \rho_{s,i}|}\left\{(X_{nas} - \max(Z_{a,i}, H_e))^{3/2} - (X_{nas} - \min(H_h, X_{nas}))^{3/2}\right\} & (H_e > Z_{a,i} \,\&\, H_e < X_{nas}) \\ 0. & (H_e \le Z_{a,i} \text{ or } H_e \ge X_{nas}) \end{cases}$$

$$AA_{ij} = 0.$$

$$AA_{ji} = \begin{cases} \alpha' B_w \{\min(H_h, Z_{a,i}) - H_e\}\sqrt{2\rho_a|\rho_j - \rho_i|} & (H_e < Z_{a,i}) \\ 0 & (H_e \ge Z_{a,i}) \end{cases}$$

$Z_{a,j} < X_{nas}$

$$SS_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_{s,j}|}\left\{(H_h - X_{nss})^{3/2} - (\max(H_e, X_{nss}) - X_{nss})^{3/2}\right\} & (H_e > X_{nss}) \\ 0. & (H_h \le X_{nss}) \end{cases}$$

$$SS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,j}-\rho_{s,i}|}\left\{(X_{nss} - \max(H_e, Z_{a,j}))^{3/2} - (X_{nss} - \min(H_h, X_{nss}))^{3/2}\right\} & (H_e > Z_{a,j} \,\&\, H_e < X_{nss}) \\ 0. & (H_e \le Z_{a,j} \text{ or } H_e \ge X_{nss}) \end{cases}$$

$$SA_{ij} = SA_{ji} = 0.$$

$$AS_{ij} = 0.$$

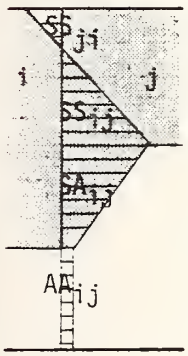
$$AS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_a|\rho_a - \rho_{s,i}|}\left\{(X_{nas} - \max(H_e, Z_{a,i}))^{3/2} - (X_{nas} - \min(H_h, Z_{a,j}))^{3/2}\right\} & (H_e > Z_{a,i} \,\&\, H_e < Z_{a,j}) \\ 0. & (H_e \le Z_{a,i} \text{ or } H_e \ge Z_{a,j}) \end{cases}$$

$$AA_{ij} = 0.$$

$$AA_{ji} = \begin{cases} \alpha' B_w (\min(H_h, Z_{a,i}) - H_e)\sqrt{2\rho_a|\rho_j - \rho_i|} & (H_e < Z_{a,i}) \\ 0. & (H_e \ge Z_{a,i}) \end{cases}$$

Tab. 1-b Flow Rate of Hot Gas & Air ($\rho_{s,i} > \rho_{s,j}$)

$X_{nas} \le Z_{a,i}$



$$SS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,j}|\rho_{s,j}-\rho_{s,i}|}\left\{(H_e - X_{nss})^{3/2} - (\max(H_e, X_{nss}) - X_{nss})^{3/2}\right\} & (H_e > X_{nss}) \\ 0. & (H_e \le X_{nss}) \end{cases}$$

$$SS_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_{s,j}|}\left\{(X_{nss} - \max(H_e, Z_{a,j}))^{3/2} - (X_{nss} - \min(H_e, X_{nss}))^{3/2}\right\} & (H_e > Z_{a,j} \ \&\ H_e < X_{nss}) \\ 0. & (H_e \le Z_{a,j} \text{ or } H_e \ge X_{nss}) \end{cases}$$

$$SA_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_a|}\left\{(\min(H_e, Z_{a,j}) - X_{nas})^{3/2} - (\max(H_e, Z_{a,i}) - X_{nas})^{3/2}\right\} & (H_e > Z_{a,i} \ \&\ H_e < Z_{a,j}) \\ 0. & (H_e \le Z_{a,i} \text{ or } H_e \ge Z_{a,j}) \end{cases}$$

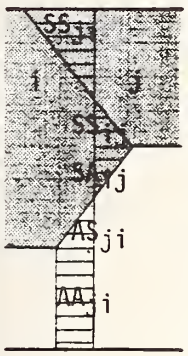
$$SA_{ji} = 0.$$

$$AS_{ij} = AS_{ji} = 0.$$

$$AA_{ij} = \begin{cases} \alpha' B_w \{\min(H_e, Z_{a,i}) - H_e\}\sqrt{2\rho_a|\rho_i - \rho_j|} & (H_e < Z_{a,i}) \\ 0. & (H_e \ge Z_{a,i}) \end{cases}$$

$$AA_{ji} = 0.$$

$Z_{a,i} < X_{nas} < Z_{a,j}$



$$SS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,j}|\rho_{s,j}-\rho_{s,i}|}\left\{(H_e - X_{nss})^{3/2} - (\max(H_e, X_{nss}) - X_{nss})^{3/2}\right\} & (H_e > X_{nss}) \\ 0. & (H_e \le X_{nss}) \end{cases}$$

$$SS_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_{s,j}|}\left\{(X_{nss} - \max(H_e, Z_{a,j}))^{3/2} - (X_{nss} - \min(H_e, X_{nss}))^{3/2}\right\} & (H_e > Z_{a,j} \ \&\ H_e < X_{nss}) \\ 0. & (H_e \le Z_{a,i} \text{ or } H_e \ge X_{nss}) \end{cases}$$

$$SA_{ij} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,i}|\rho_{s,i}-\rho_a|}\left\{(\min(H_e, Z_{a,j}) - X_{nas})^{3/2} - (\max(H_e, X_{nas}) - X_{nas})^{3/2}\right\} & (H_e > X_{nas} \ \&\ H_e < Z_{a,j}) \\ 0 & (H_e \le X_{nas} \text{ or } H_e \ge Z_{a,j}) \end{cases}$$

$$SA_{ji} = 0$$

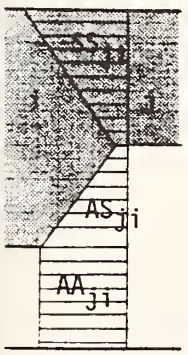
$$AS_{ij} = 0.$$

$$AS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_a|\rho_a - \rho_{s,i}|}\left\{(X_{nas} - \max(H_e, Z_{a,j}))^{3/2} - (X_{nas} - \min(H_e, X_{nas}))^{3/2}\right\} & (H_e > Z_{a,i} \ \&\ H_e < X_{nas}) \\ 0. & (H_e \le Z_{a,i} \text{ or } H_e \ge X_{nas}) \end{cases}$$

$$AA_{ij} = 0.$$

$$AA_{ji} = \begin{cases} \alpha' B_w \{\min(H_e, Z_{a,i}) - H_e\}\sqrt{2\rho_a|\rho_j - \rho_i|} & (H_e < Z_{a,j}) \\ 0. & (H_e \ge Z_{a,i}) \end{cases}$$

$Z_{a,j} < X_{nss}$



$$SS_{ij} = 0.$$

$$SS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_{s,j}|\rho_{s,j}-\rho_{s,i}|}\left\{(H_e - X_{nss})^{3/2} - (\max(H_e, Z_{a,j}) - X_{nss})^{3/2}\right\} & (H_e > Z_{a,j}) \\ 0. & (H_e \le Z_{a,j}) \end{cases}$$

$$SA_{ij} = SA_{ji} = 0.$$

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$$AS_{ji} = \begin{cases} \frac{2}{3}\alpha B_w \sqrt{2g\rho_a|\rho_a - \rho_{s,i}|}\left\{(X_{nas} - \max(H_e, Z_{a,j}))^{3/2} - (X_{nas} - \min(H_e, Z_{a,j}))^{3/2}\right\} & (H_e > Z_{a,i} \ \&\ H_e < Z_{a,j}) \\ 0 & (H_e \le Z_{a,i} \text{ or } H_e \ge Z_{a,j}) \end{cases}$$

$$AA_{ij} = 0.$$

$$AA_{ji} = \begin{cases} \alpha' B_w \{\min(H_e, Z_{a,i}) - H_e\}\sqrt{2\rho_a|\rho_j - \rho_i|} & (H_e < Z_{a,i}) \\ 0. & (H_e \ge Z_{a,i}) \end{cases}$$

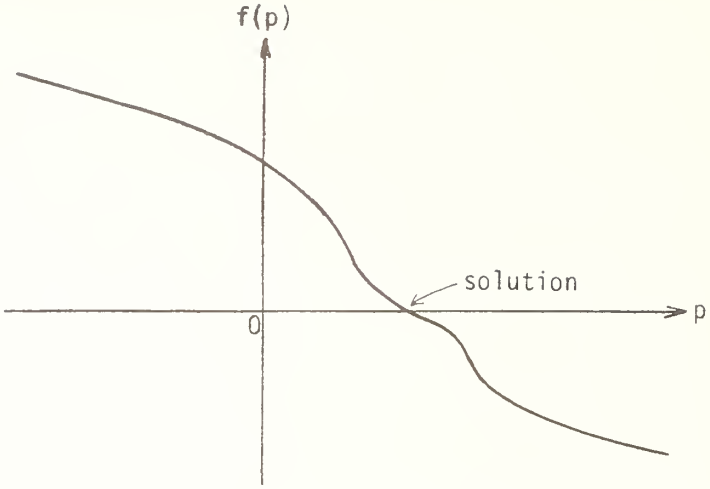


Fig. 6 Diagram of p-f(p) Relation

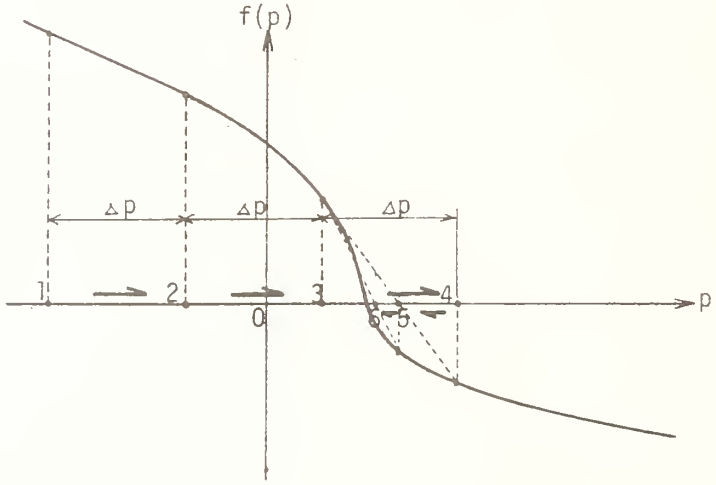


Fig. 7 Regula-Falsi Method

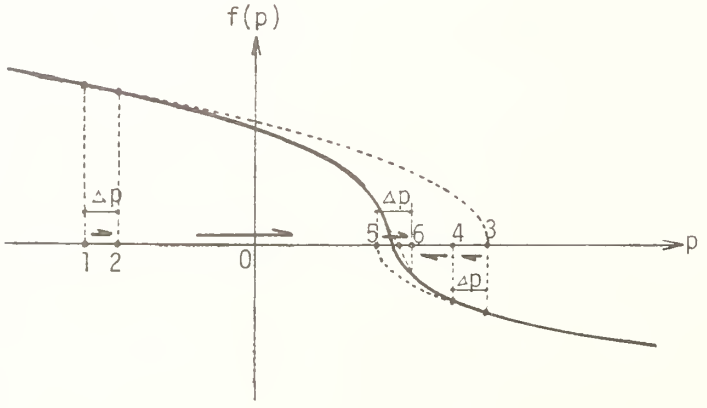


Fig. 8 Modified Regula-Falsi Method

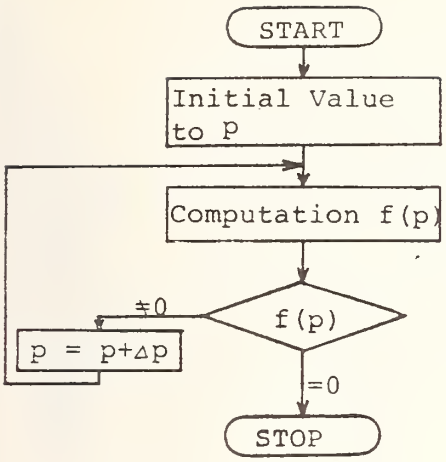


Fig. 9 Computation Procedure by Trial and Error Method

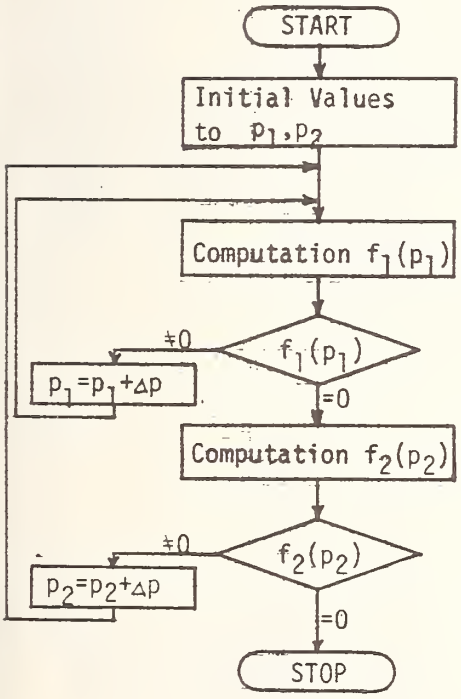


Fig. 10 Pressure Computation of 2 Rooms

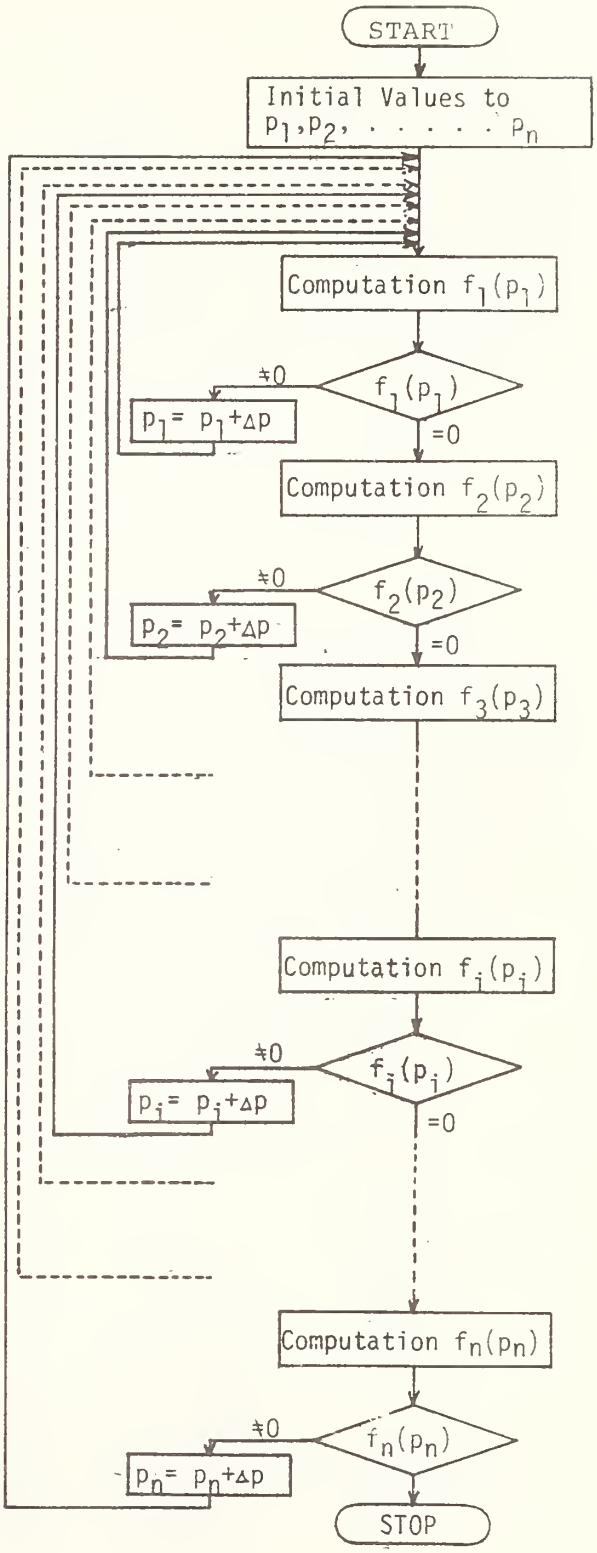


Fig. 11 Pressure Computation of n Rooms

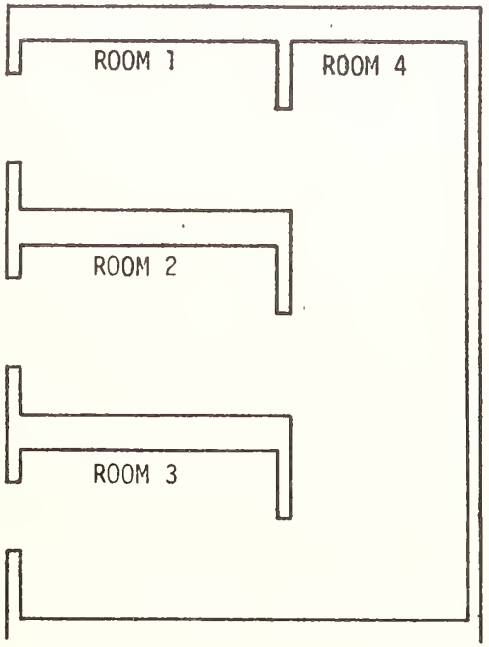


Fig. 12 A Model of 4-Rooms Building

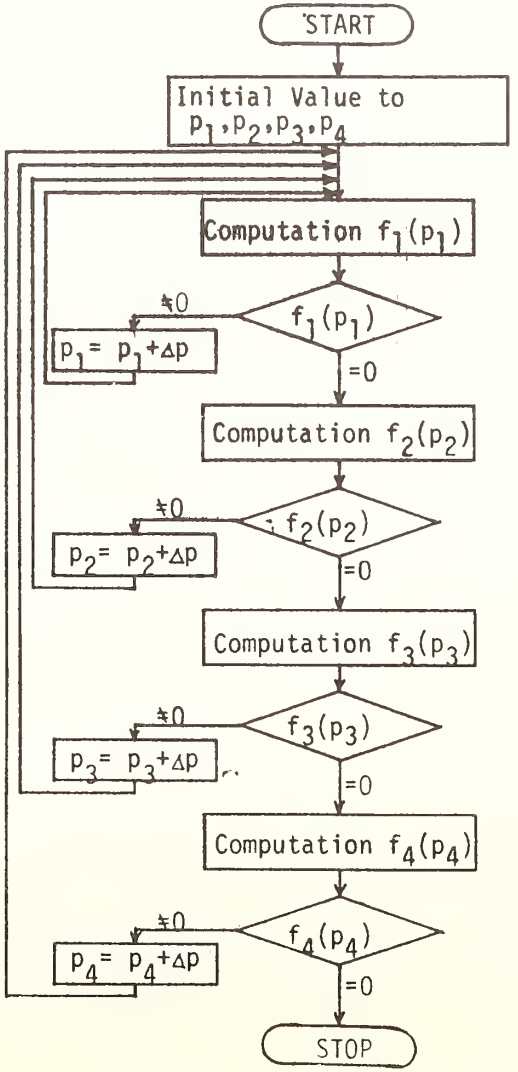


Fig. 13 Pressure Computation of 4-Rooms (General manner)

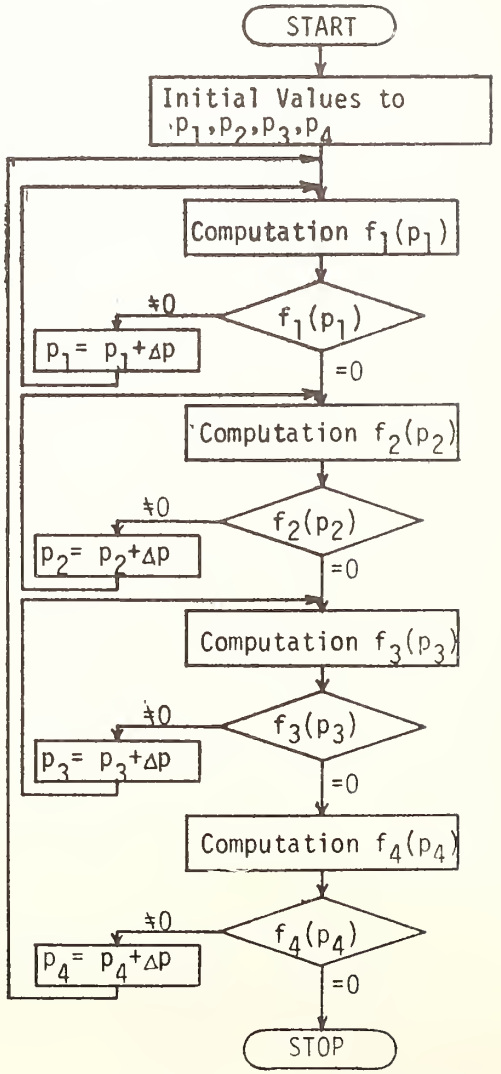


Fig. 14 Pressure Computation of 4- Rooms (Simplified manner)

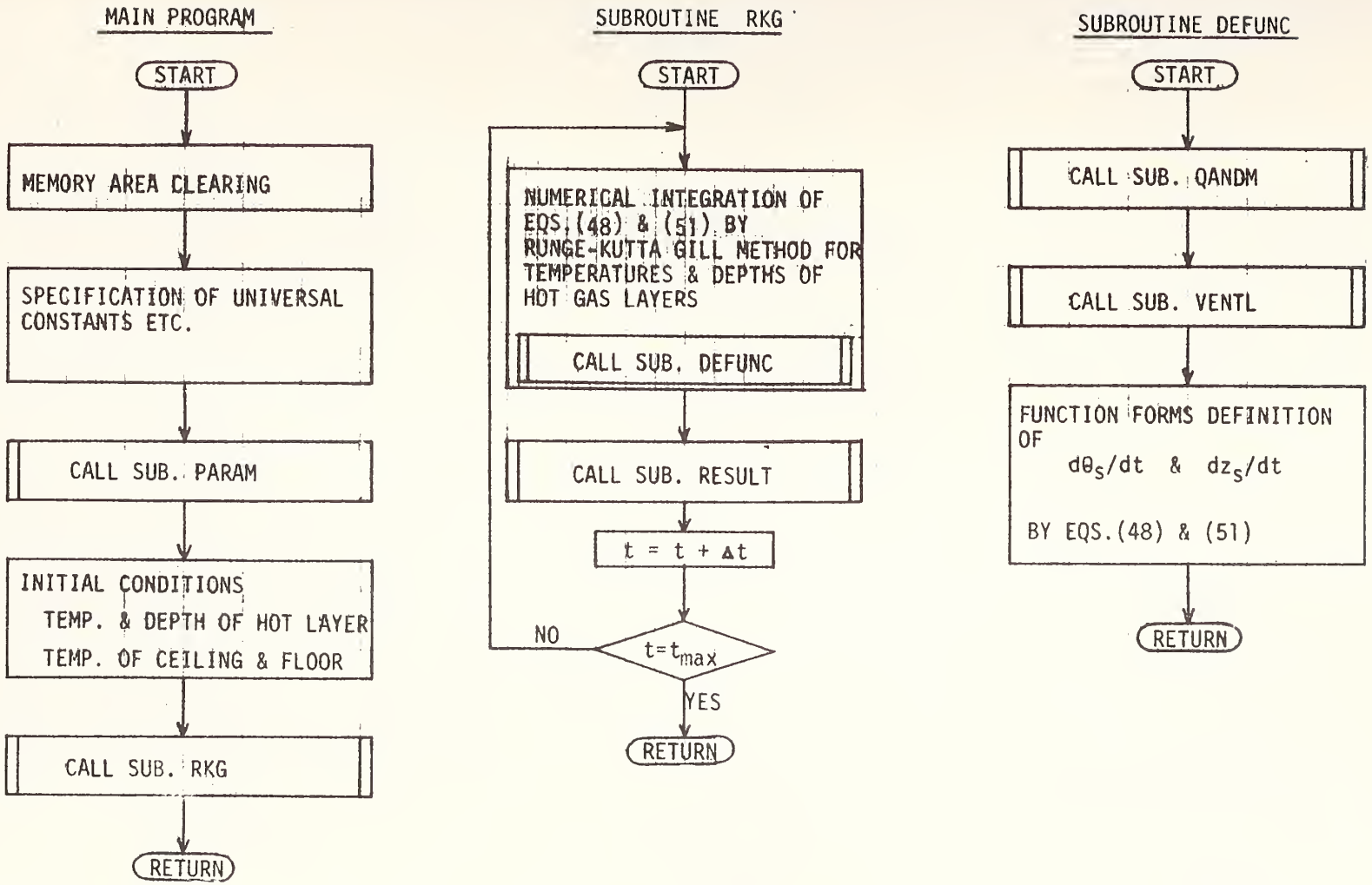
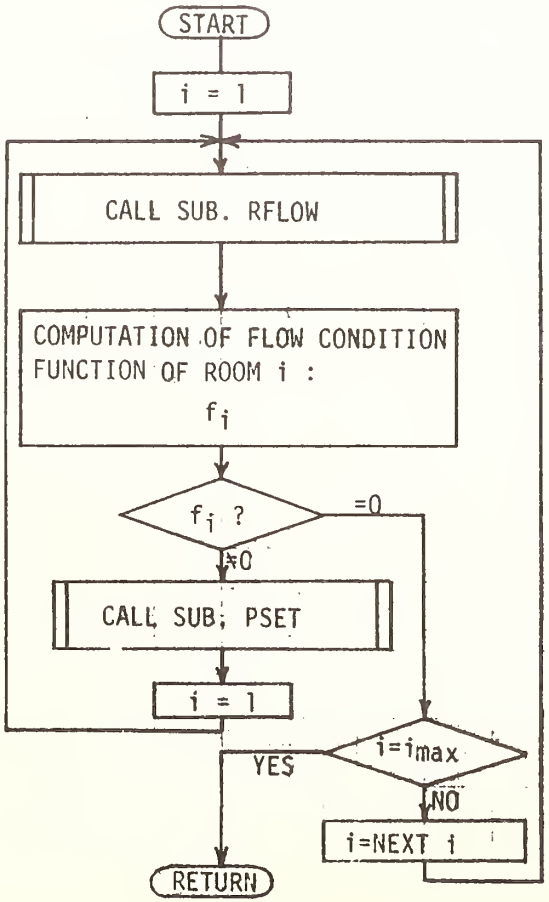
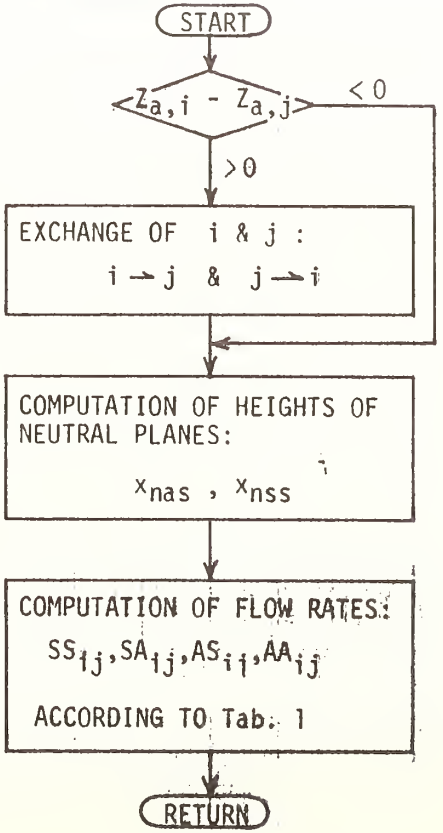


Fig. 15 Flow Chart of Computation Procedure

SUBROUTINE VENTL



SUBROUTINE RFLOW



SUBROUTINE PSET

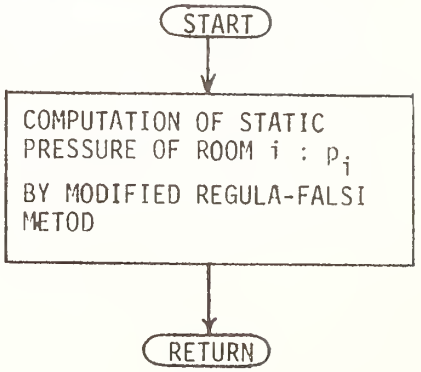
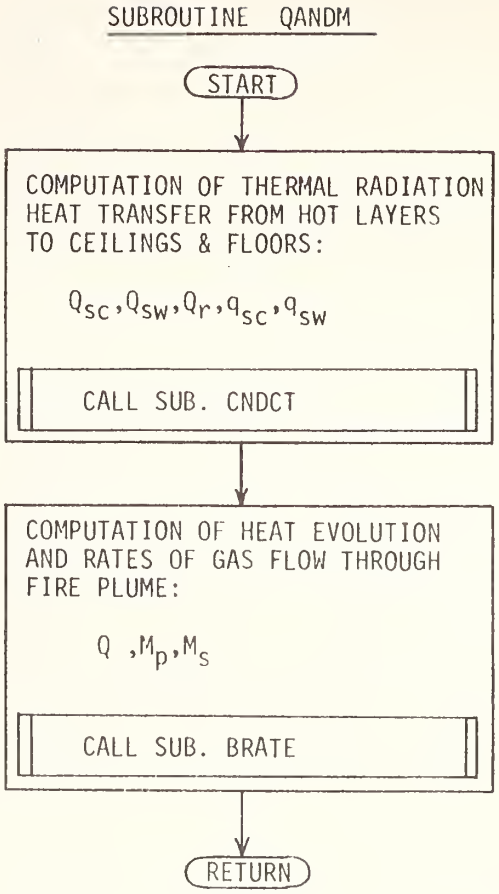
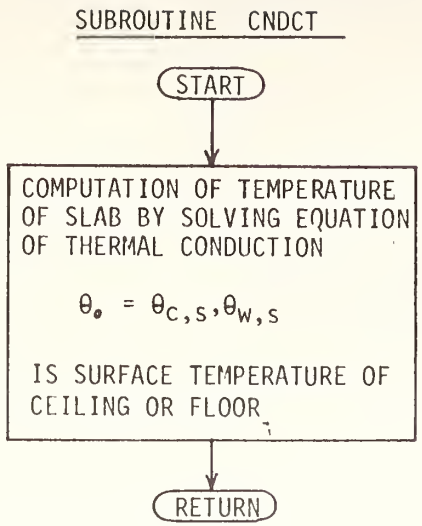


Fig. 15 (2)


SUBROUTINE QANDM
START
COMPUTATION OF THERMAL RADIATION HEAT TRANSFER FROM HOT LAYERS TO CEILINGS & FLOORS:
$Q_{sc}, Q_{sw}, Q_r, q_{sc}, q_{sw}$
CALL SUB. CNDCT
COMPUTATION OF HEAT EVOLUTION AND RATES OF GAS FLOW THROUGH FIRE PLUME:
Q , M_p, M_s
CALL SUB. BRATE
RETURN


SUBROUTINE CNDCT
START
COMPUTATION OF TEMPERATURE OF SLAB BY SOLVING EQUATION OF THERMAL CONDUCTION
$\theta_* = \theta_{c,s}, \theta_{w,s}$
IS SURFACE TEMPERATURE OF CEILING OR FLOOR
RETURN

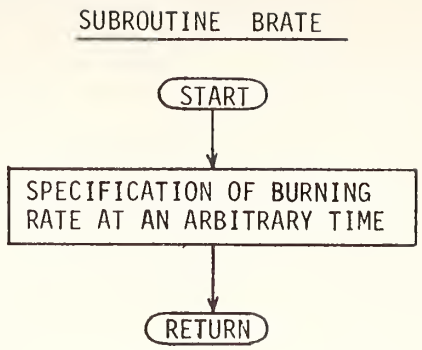

SUBROUTINE BRATE
START
SPECIFICATION OF BURNING RATE AT AN ARBITRARY TIME
RETURN

Fig. 15 (3)

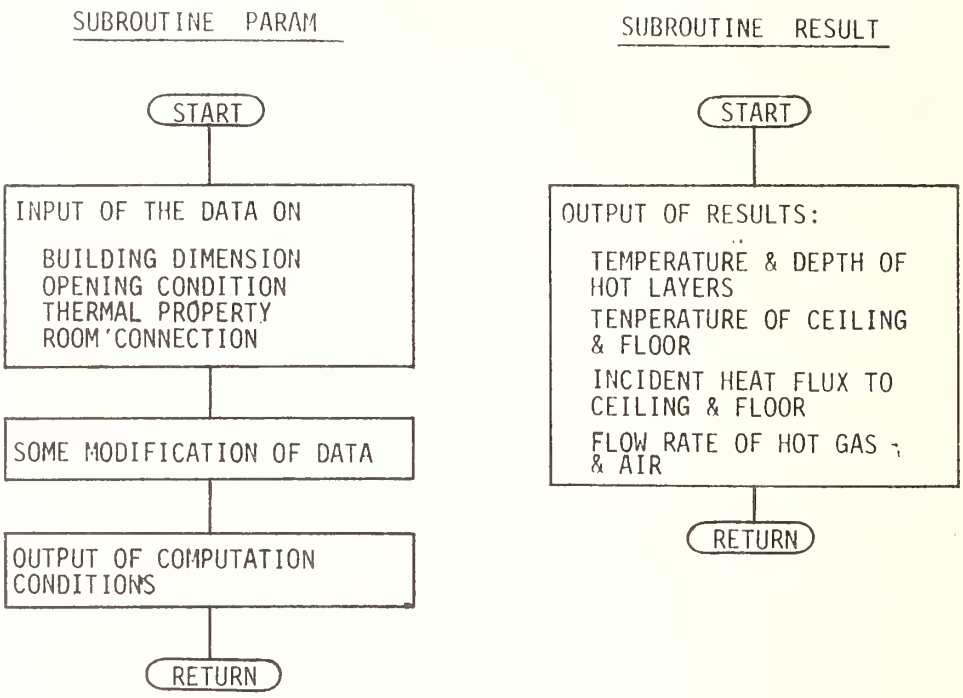

SUBROUTINE PARAM
START
INPUT OF THE DATA ON
BUILDING DIMENSION
OPENING CONDITION
THERMAL PROPERTY
ROOM CONNECTION
SOME MODIFICATION OF DATA
OUTPUT OF COMPUTATION CONDITIONS
RETURN
SUBROUTINE RESULT
START
OUTPUT OF RESULTS:
TEMPERATURE & DEPTH OF HOT LAYERS
TENPERATURE OF CEILING & FLOOR
INCIDENT HEAT FLUX TO CEILING & FLOOR
FLOW RATE OF HOT GAS & AIR
RETURN

Fig. 15 (4)

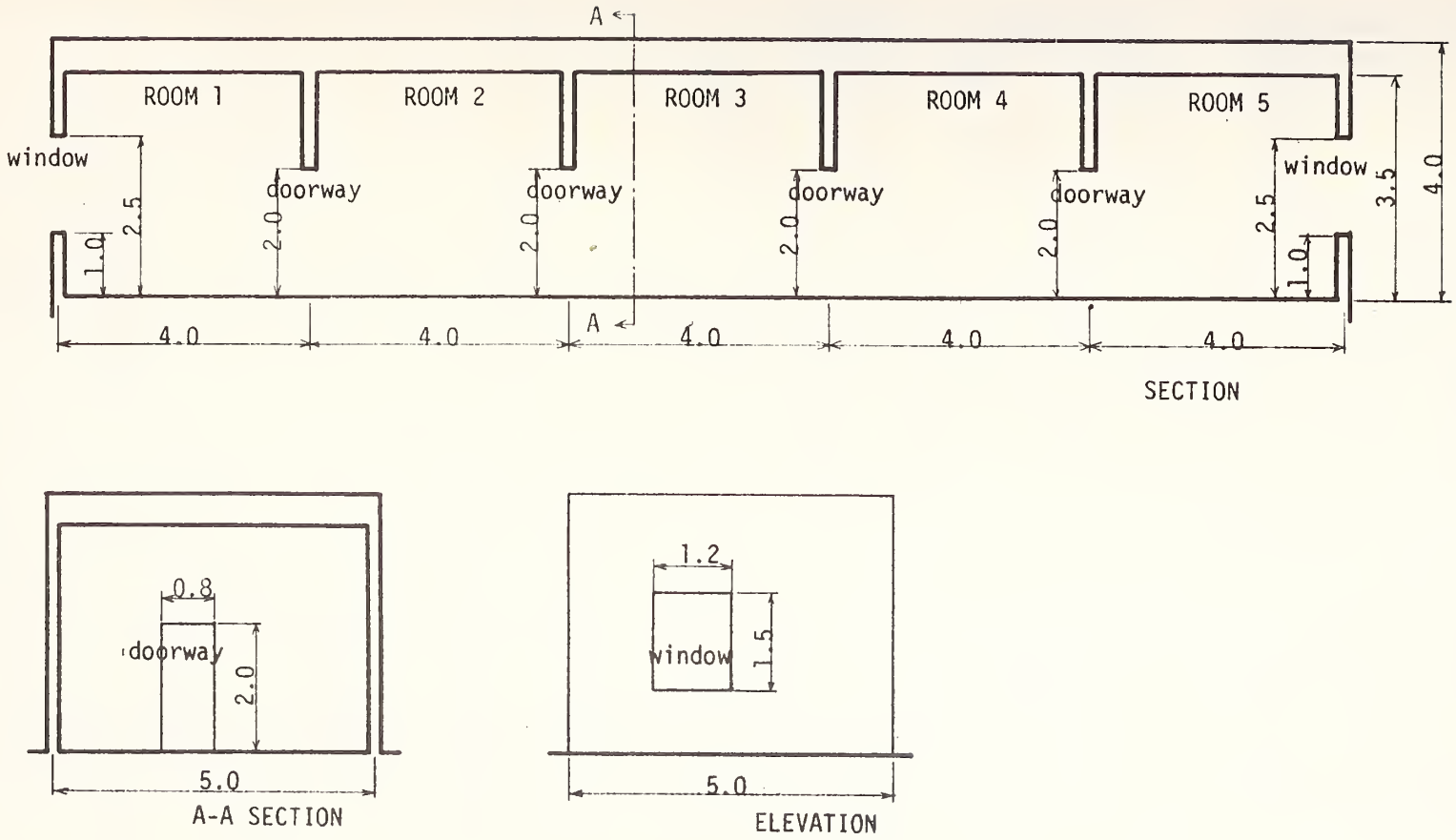
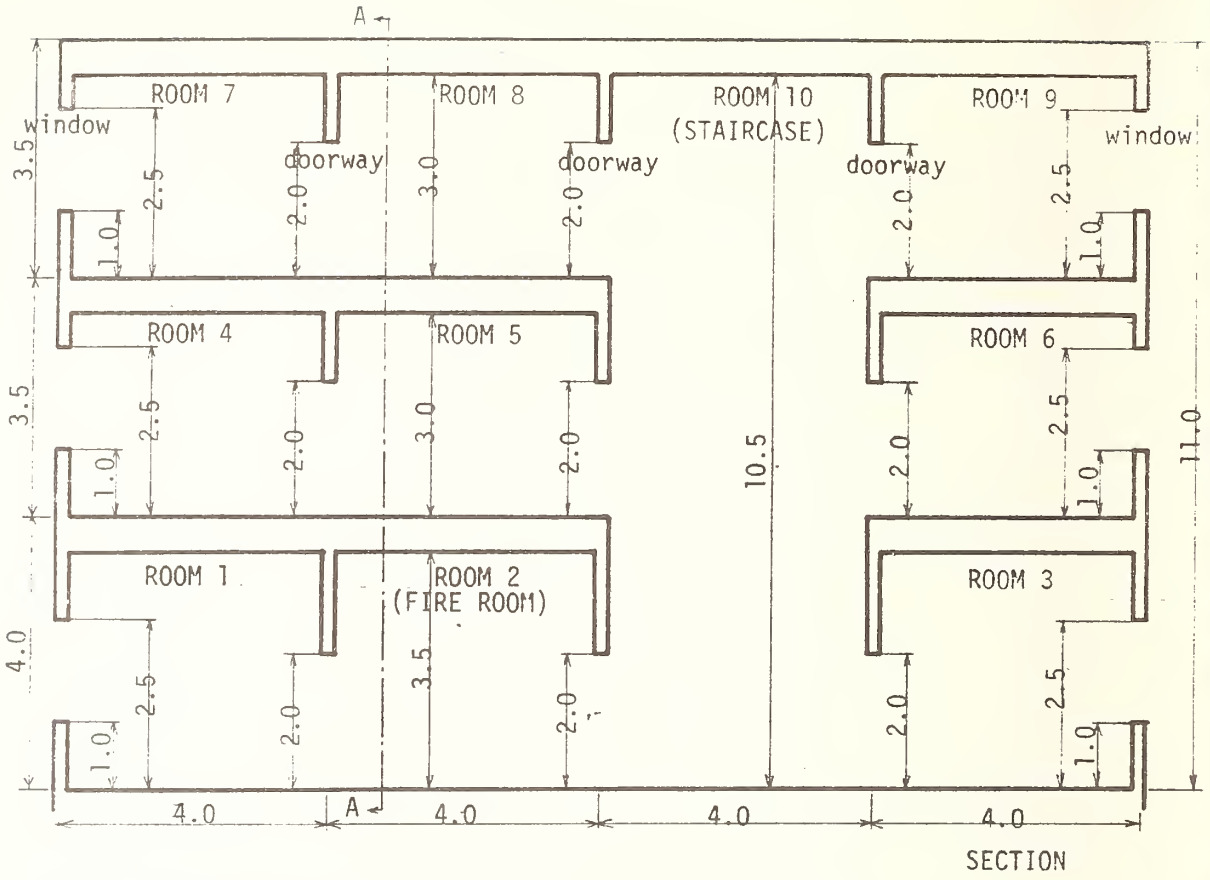
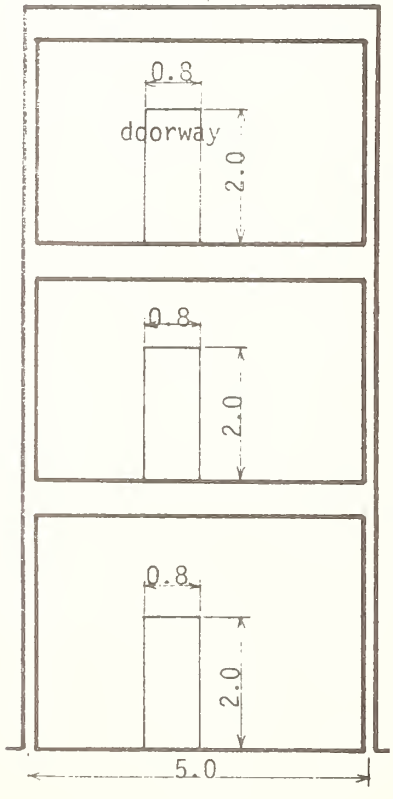


Fig. 16 Dimensions of 1-Floor Building
(unit:m)





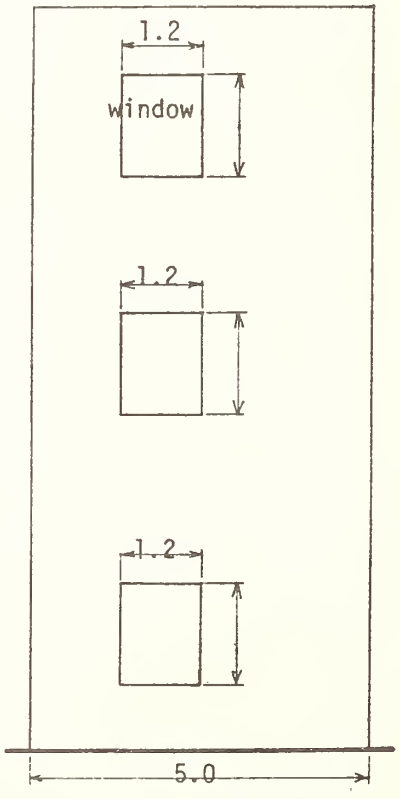


Fig. 17
Dimensions of
3-Floor Building
(unit:m)

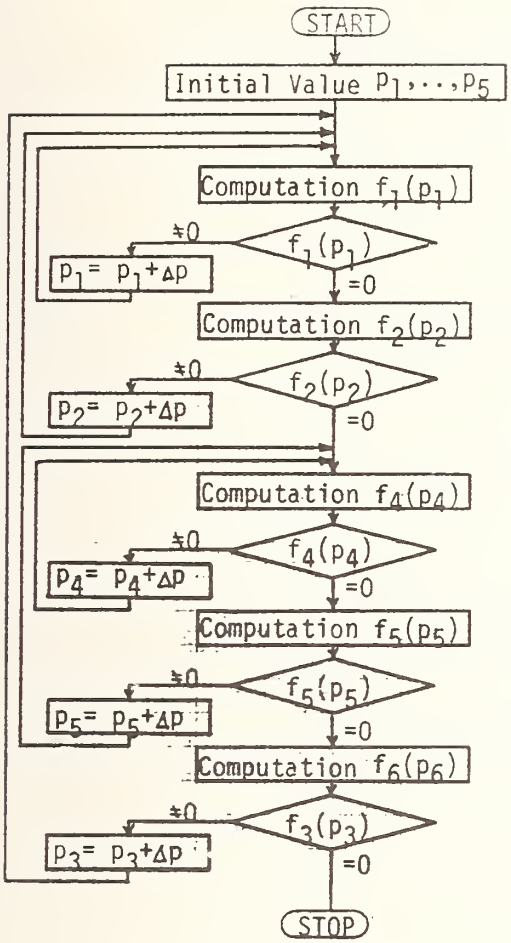


Fig. 18 Pressure Computation of 1-Floor Building

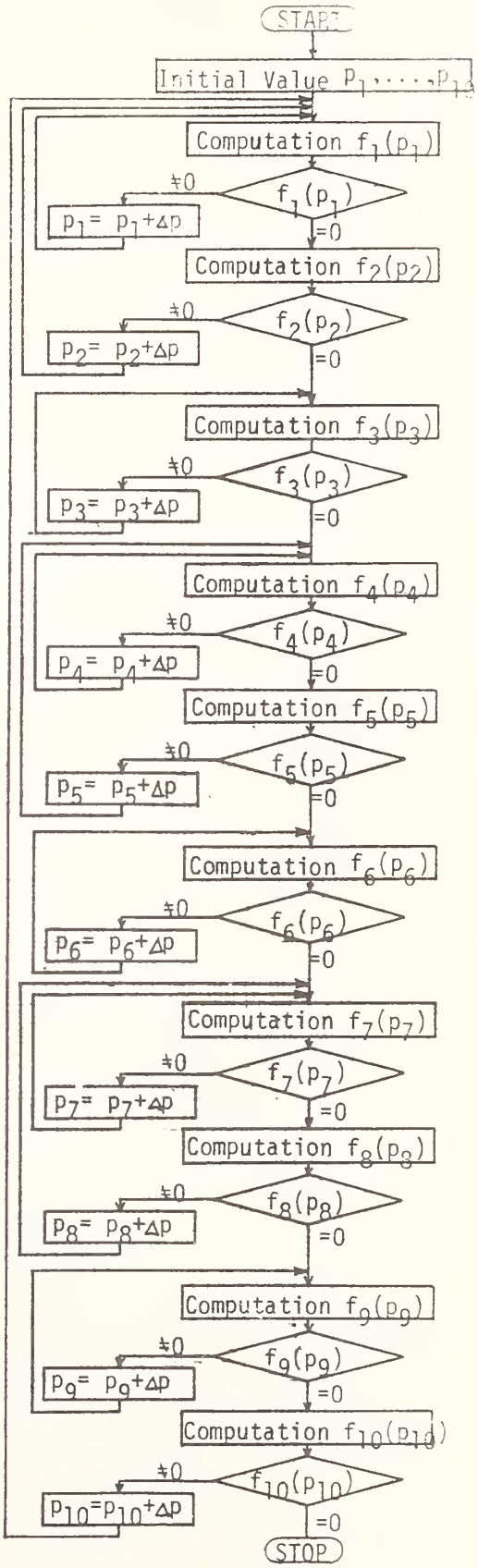


Fig. 19 Pressure Computation of 3-Floor Building

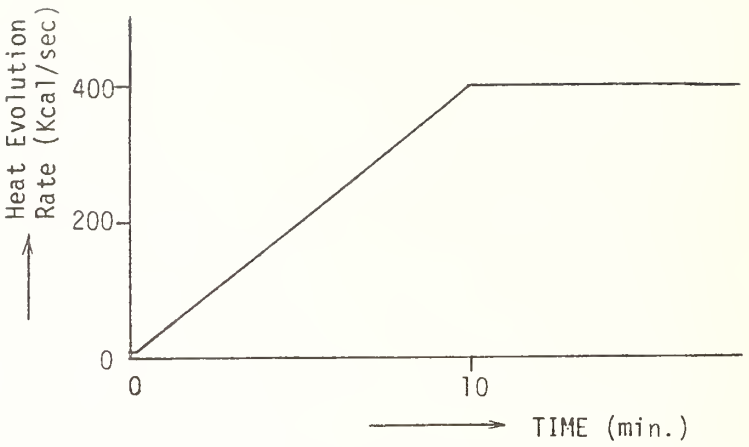


Fig. 20 Heat Evolution Rate in Samples(4)-(6)

Tab. 2 Thermal Properties of Wall Slab(common to all walls)

thermal conductivity	2.78×10^{-4}	(Kcal/m.sec.°K)
specific heat	2.00×10^{-1}	(Kcal/Kg.°K)
density	2.00×10^{3}	(Kg/m^3)
thickness	1.00×10^{-1}	(m)

Tab. 3 Conditions for Sample Computation

SAMPLE NO.	AREA OF FIRE SOURCE (m^2)	HEAT EVOLUTION RATE	FIGURES FOR RESULT
1	1	40 (Kcal/sec)	Figs.21-a,b,c
2	1	80 (Kcal/sec)	Figs.22-a,b,c
3	1	120 (Kcal/sec)	Figs.23-a,b,c
4	1	rate shown in Fig. 20	Figs.24-a,b,c,d,e
5	1	rate shown in Fig. 20	Figs.25-a,b,c
6	2	rate shown in Fig. 20	Figs.26-a,b,c
	the windows of the rooms on the 3-rd floor are closed the width of the doorway between the fire room and the staircase is twice the former i.e. 1.6 m		

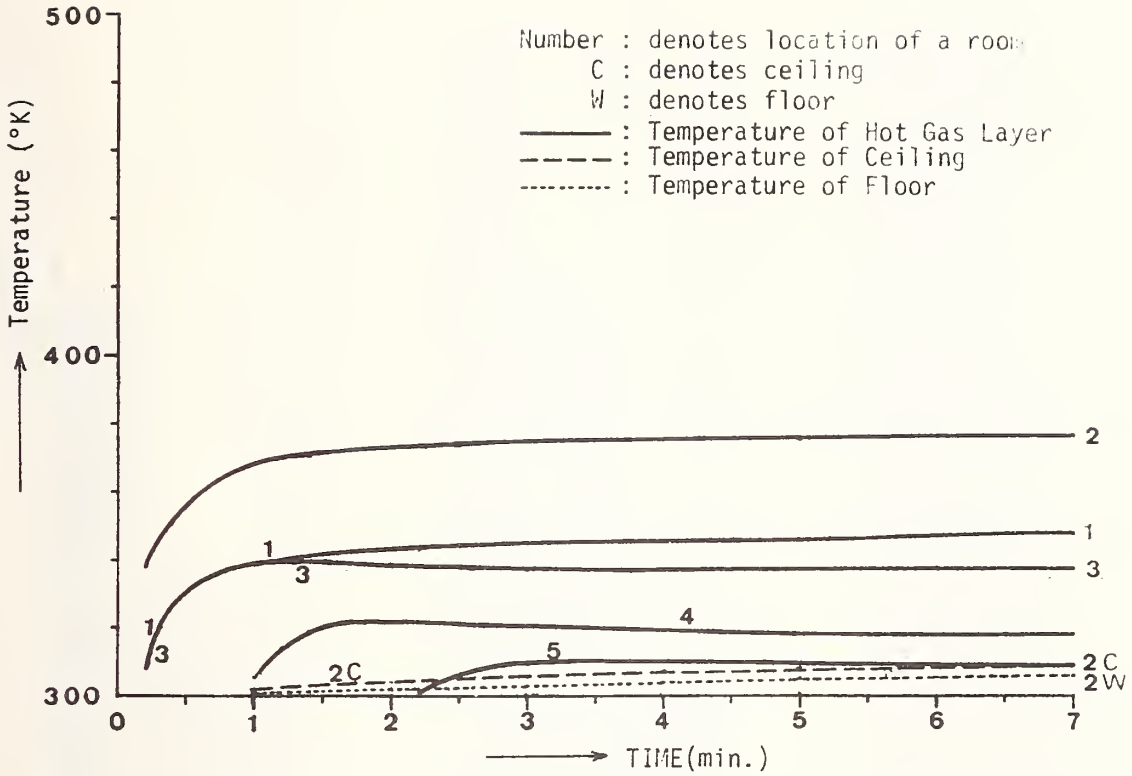


Fig. 21-a Temperature of Hot Layer & Ceiling (Sample 1)

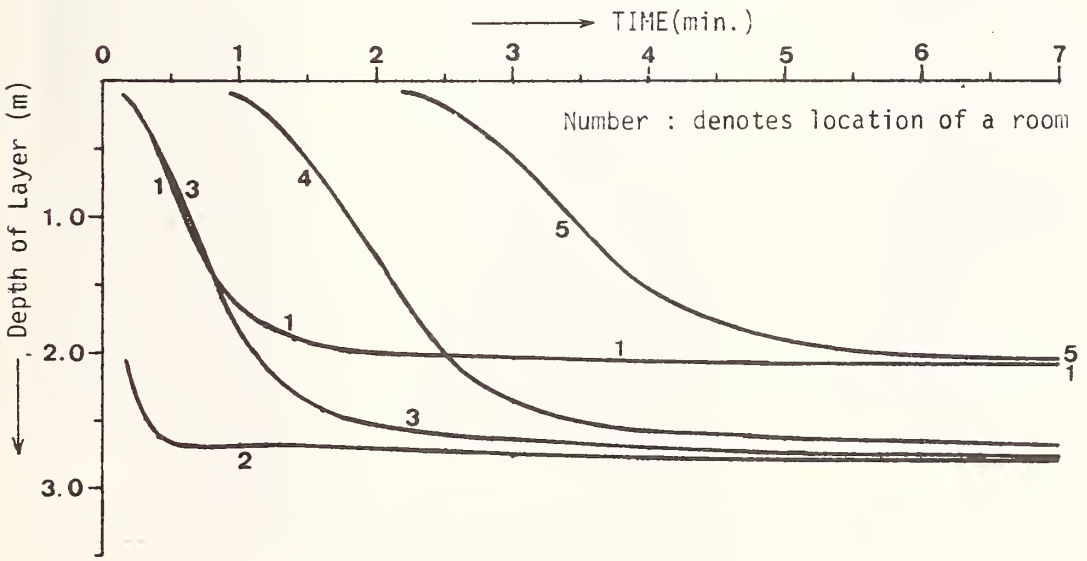


Fig. 21-b Depth of Hot Layer (Sample 1)

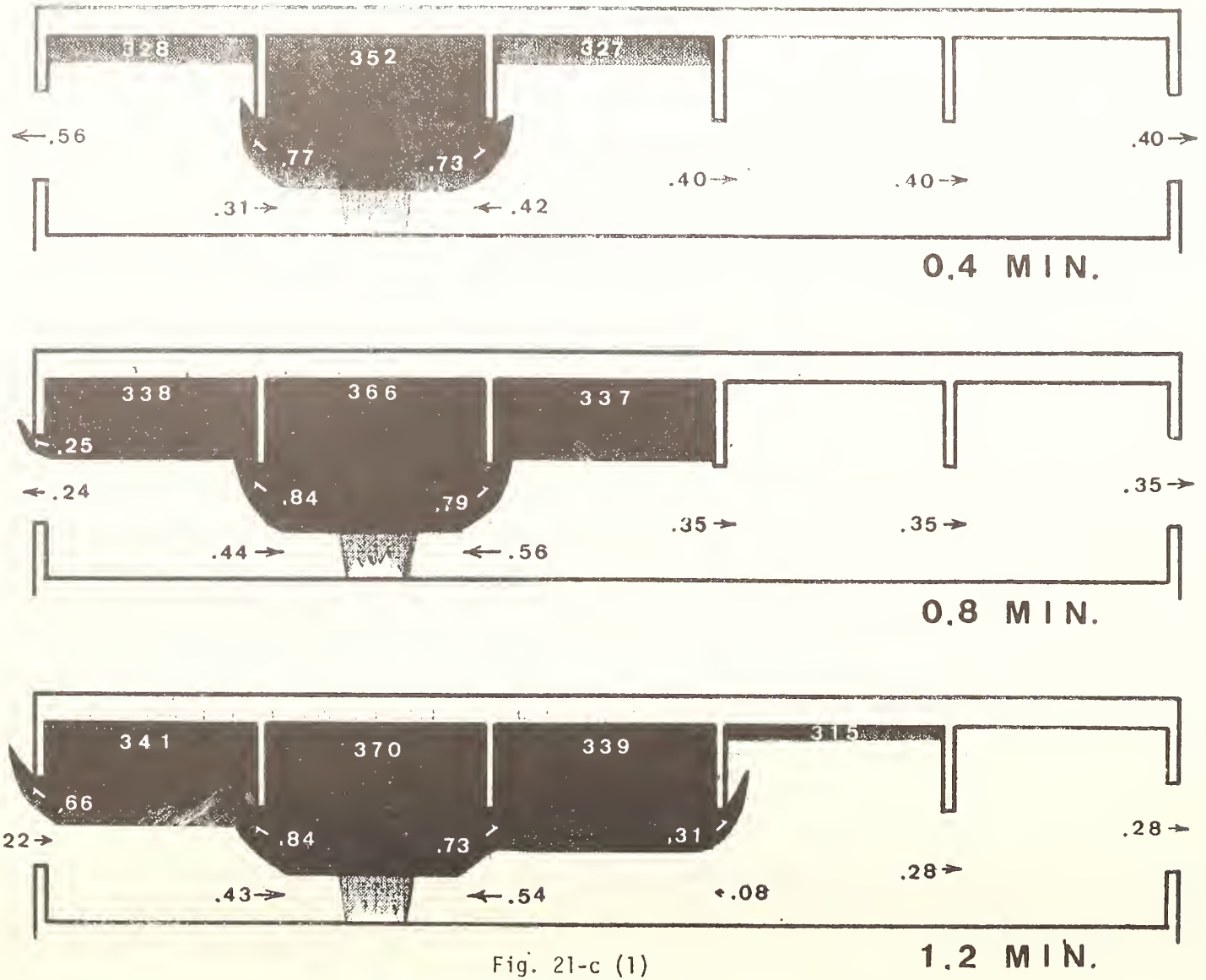


Fig. 21-c (1)
Behavior of Hot Layer (Sample 1)

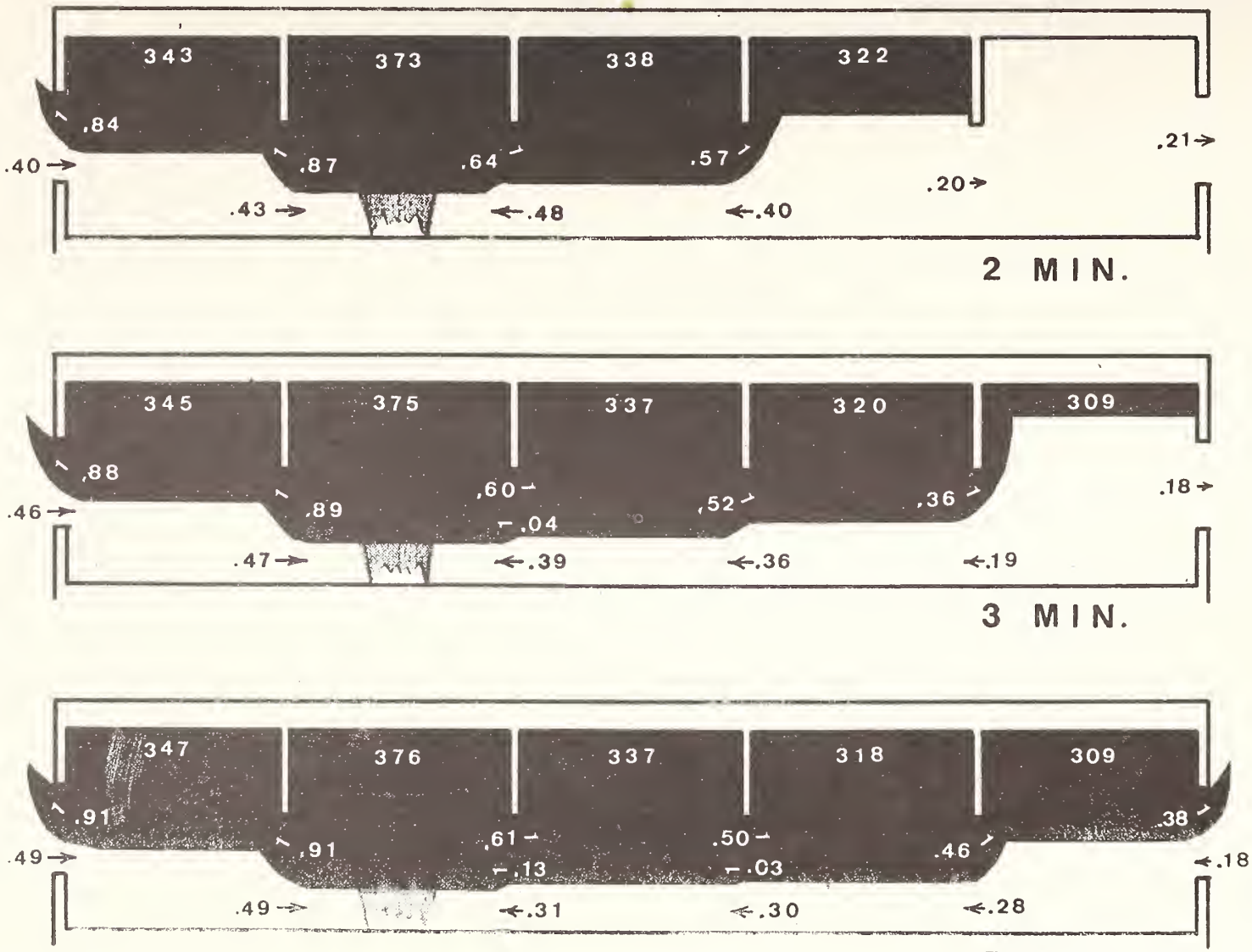

343
373
338
322
.84
.87
.64
.57
.40
.21
.20
.43
.48
.40
2 MIN.
345
375
337
320
309
.88
.89
.60
.04
.52
.36
.46
.18
.47
.39
.36
.19
3 MIN.
347
376
337
318
309
.91
.91
.61
.13
.50
.03
.46
.38
.49
.18
.49
.31
.30
.28
5 MIN.

Fig. 21-c (2)

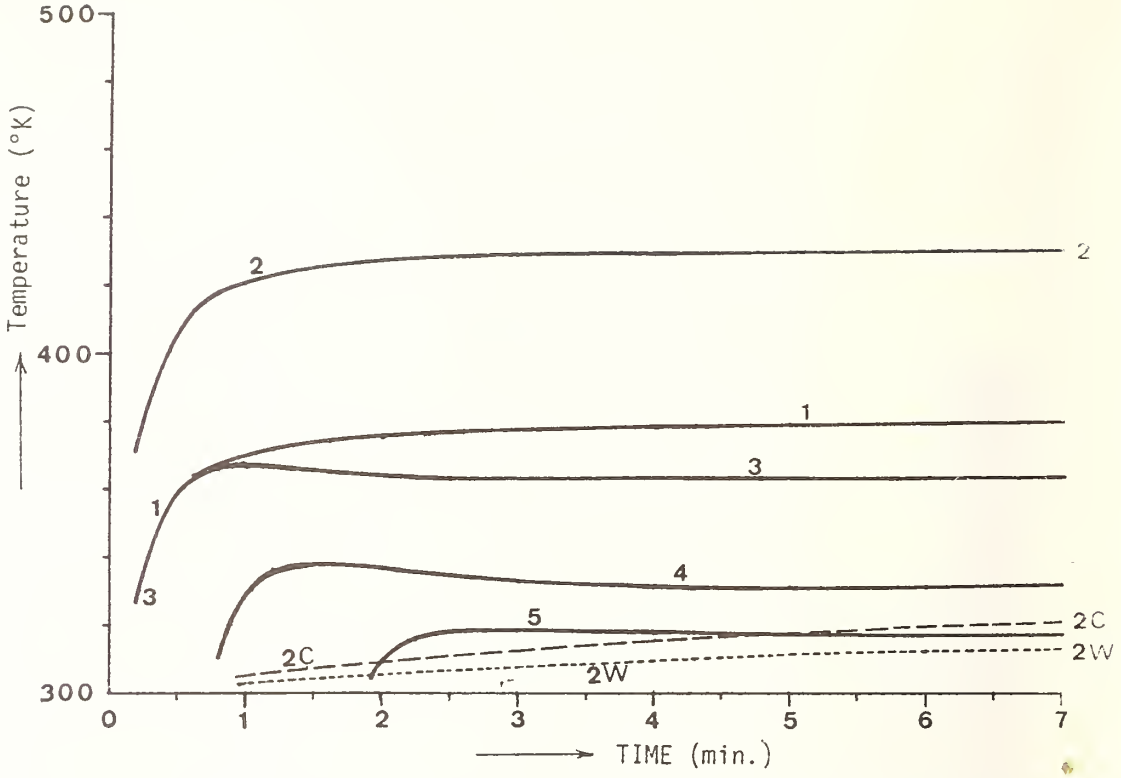


Fig. 22-a Temperature of Hot Layer & Ceiling etc. (Sample 2)

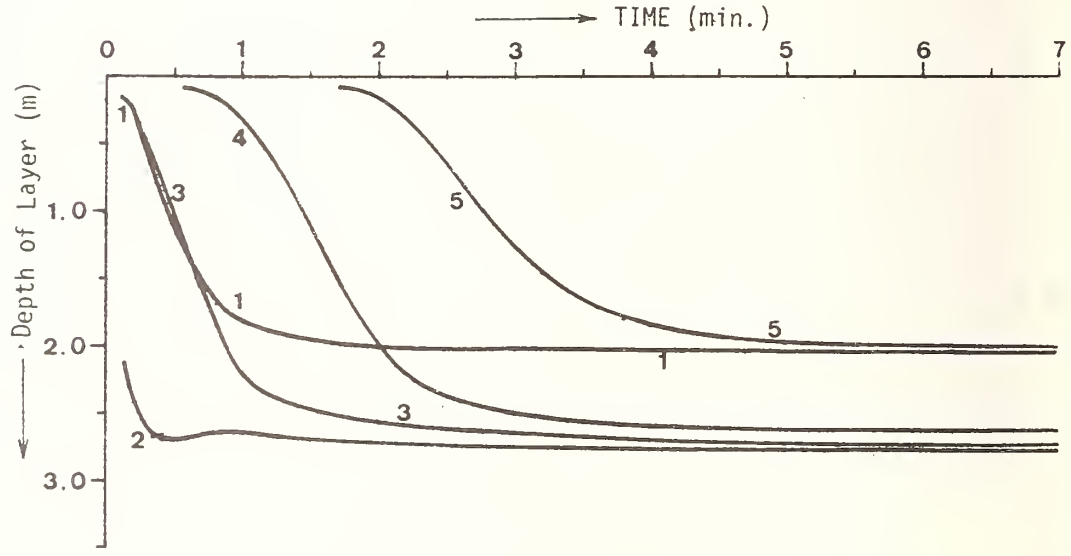


Fig. 22-b Depth of Hot Layer (Sample 2)

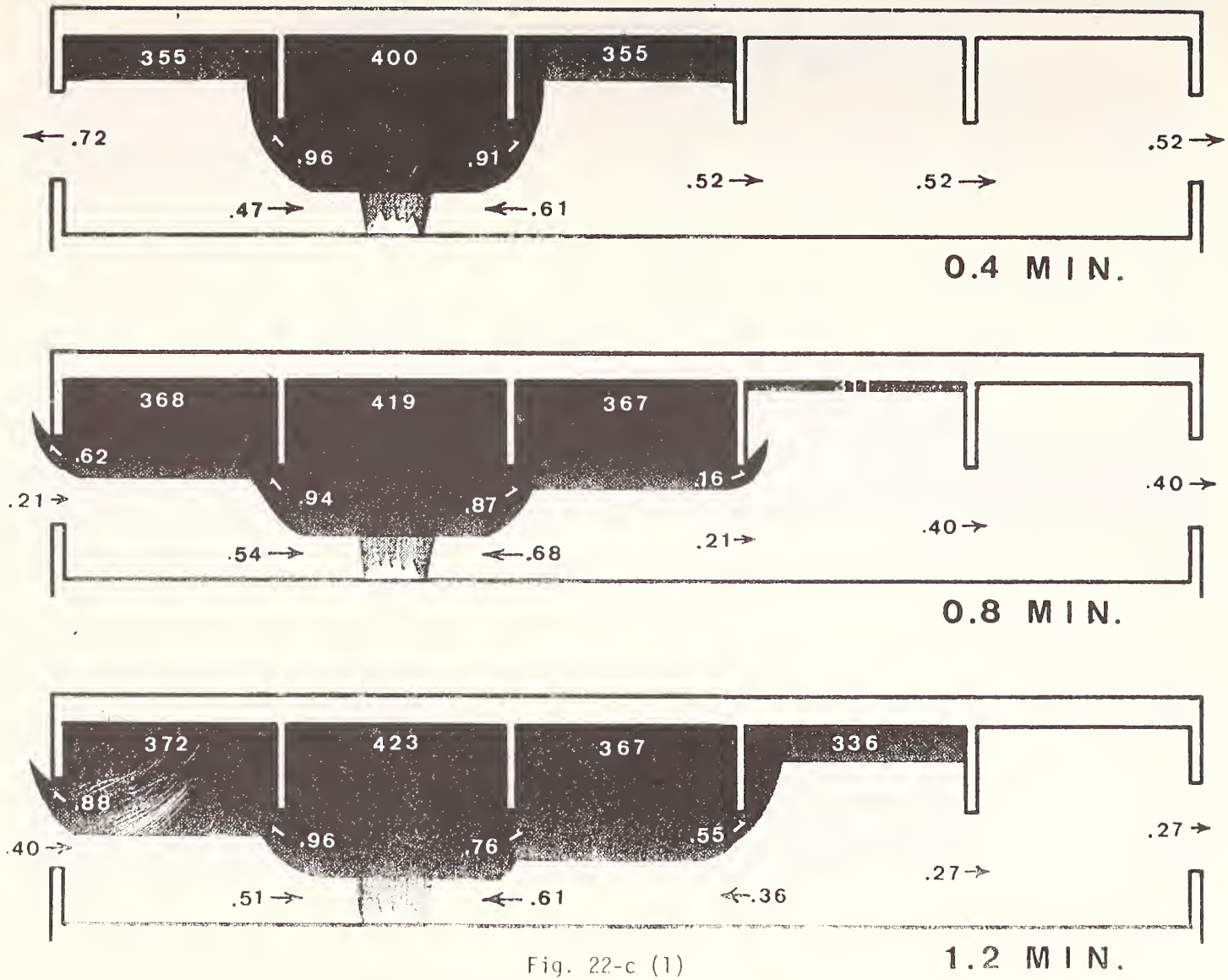


Fig. 22-c (1)
Behavior of Hot Layer (Sample 2)

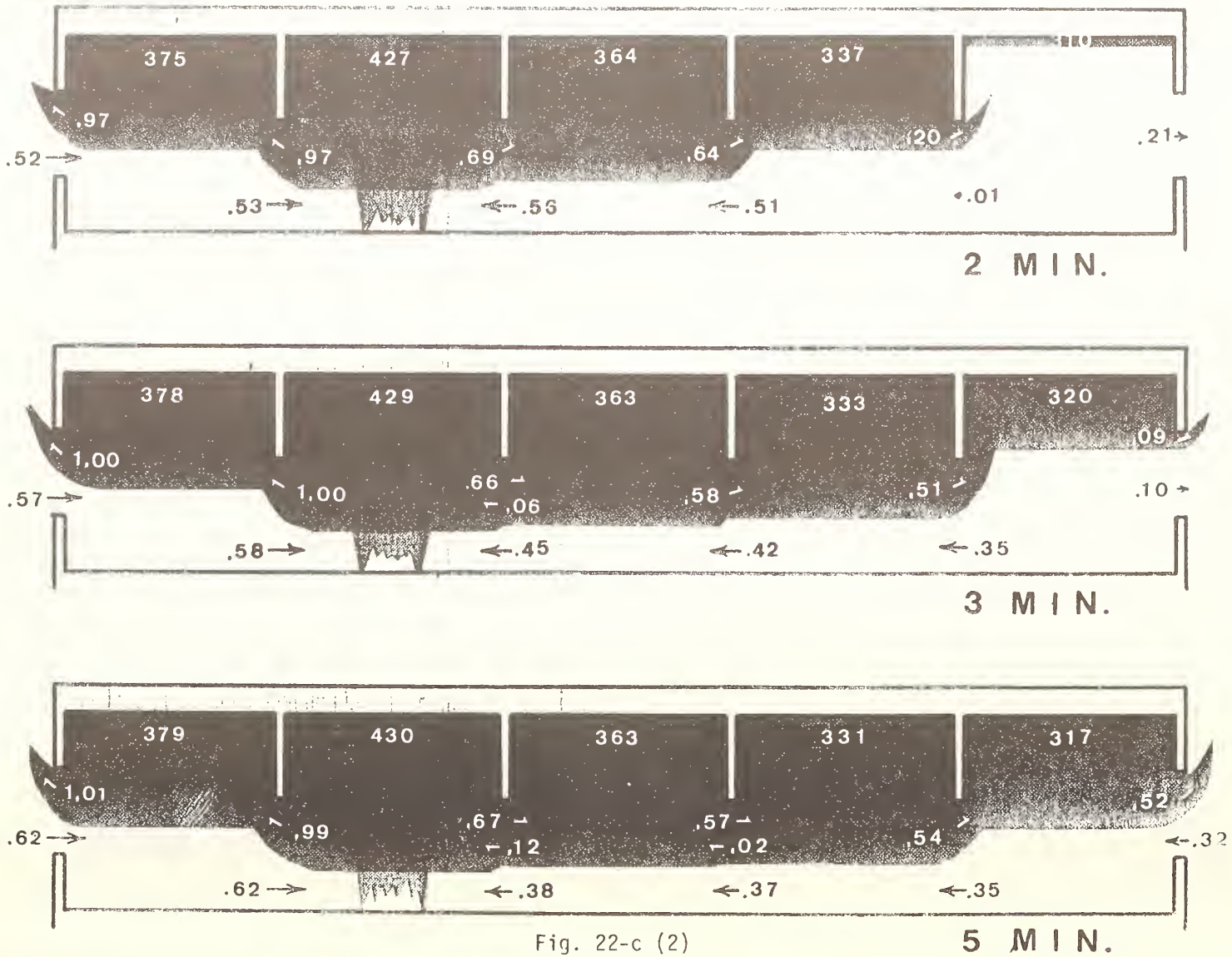

375
427
364
337
.97
.97
.69
.64
.20
.52
.21
.53
.56
.51
.01
2 MIN.
378
429
363
333
320
1.00
1.00
.66
.06
.09
.57
.58
.51
.10
.58
.45
.42
.35
3 MIN.
379
430
363
331
317
1.01
.99
.67
.12
.57
.02
.54
.52
.62
.32
.62
.38
.37
.35
5 MIN.

Fig. 22-c (2)

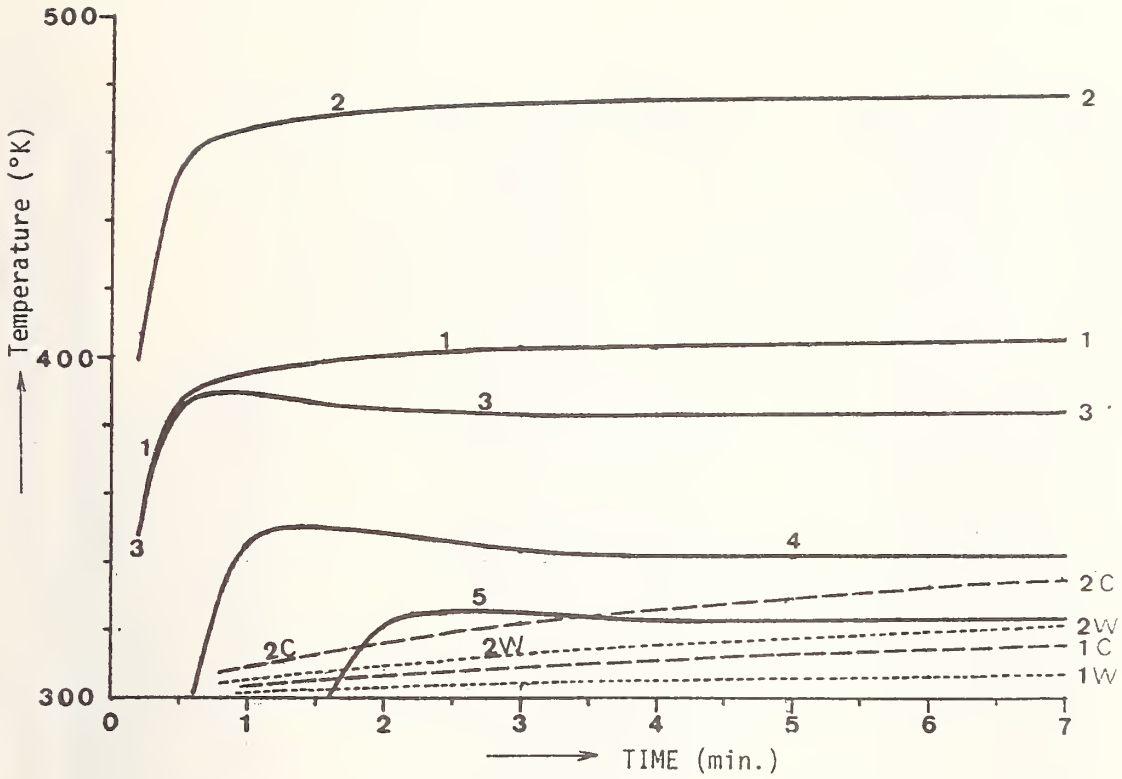


Fig. 23-a Temperature of Hot Layer & Ceiling etc. (Sample 3)

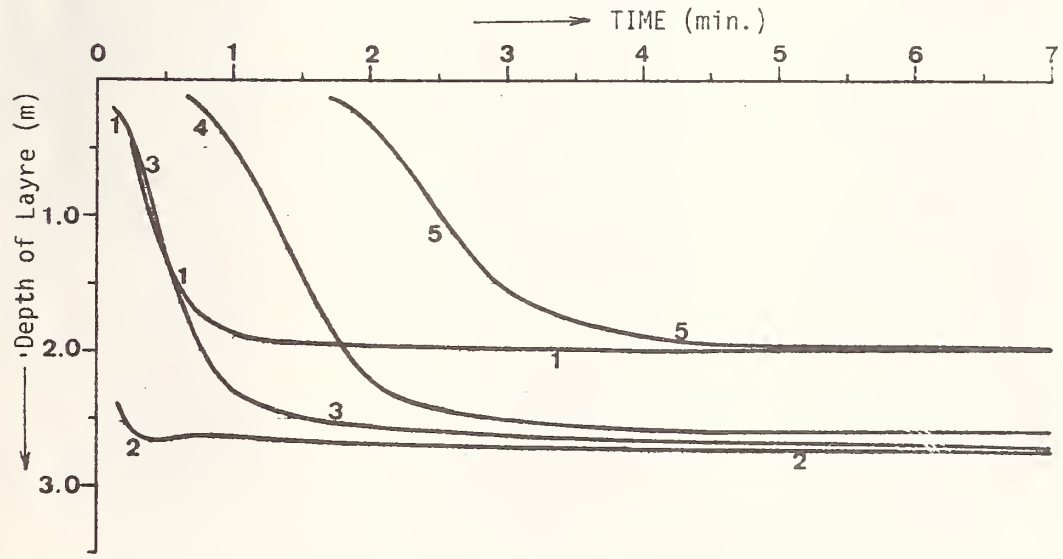


Fig 23-b Depth of Hot Layer (Sample 3)

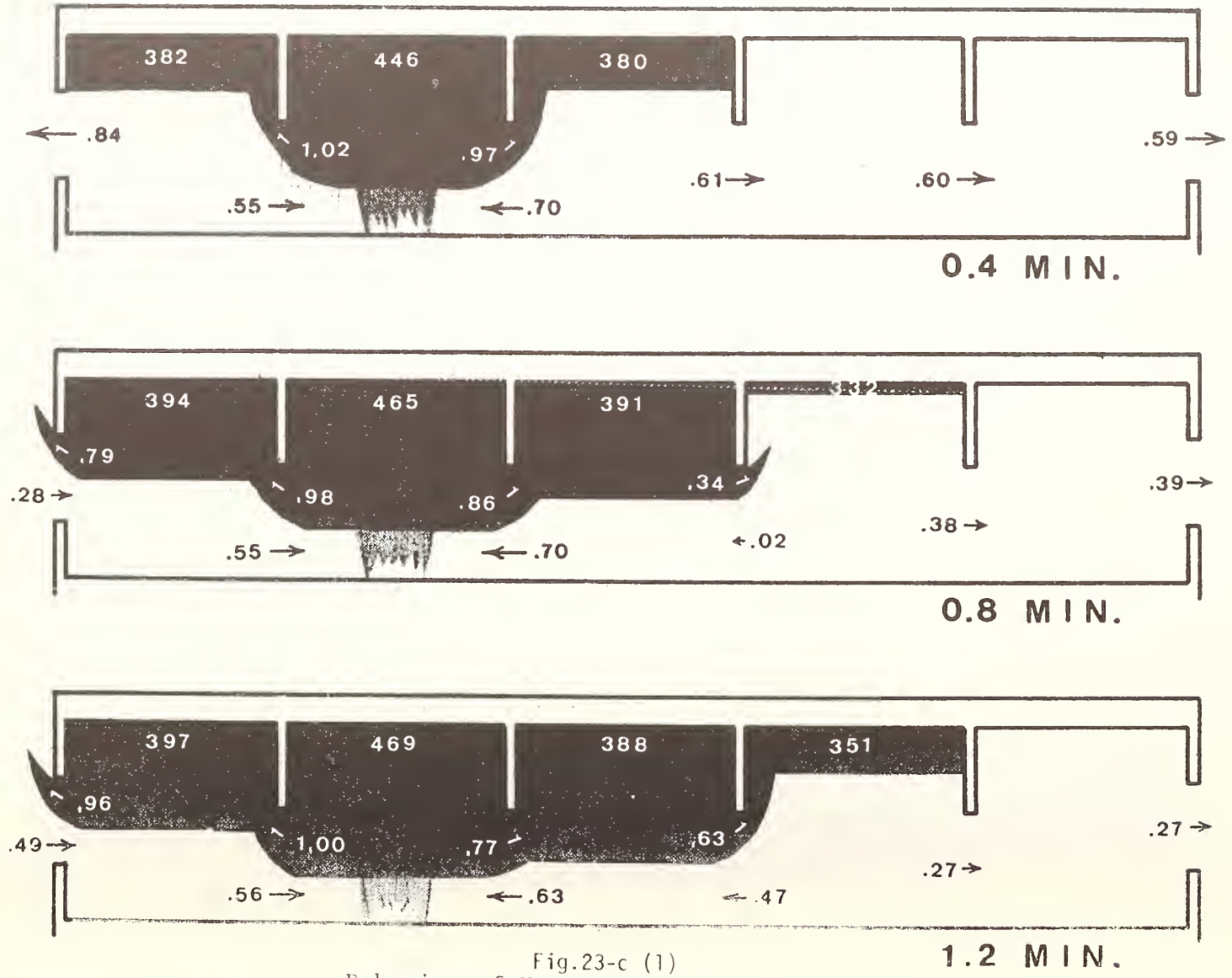


Fig.23-c (1)
Behavior of Hot Layer (Sample 3)

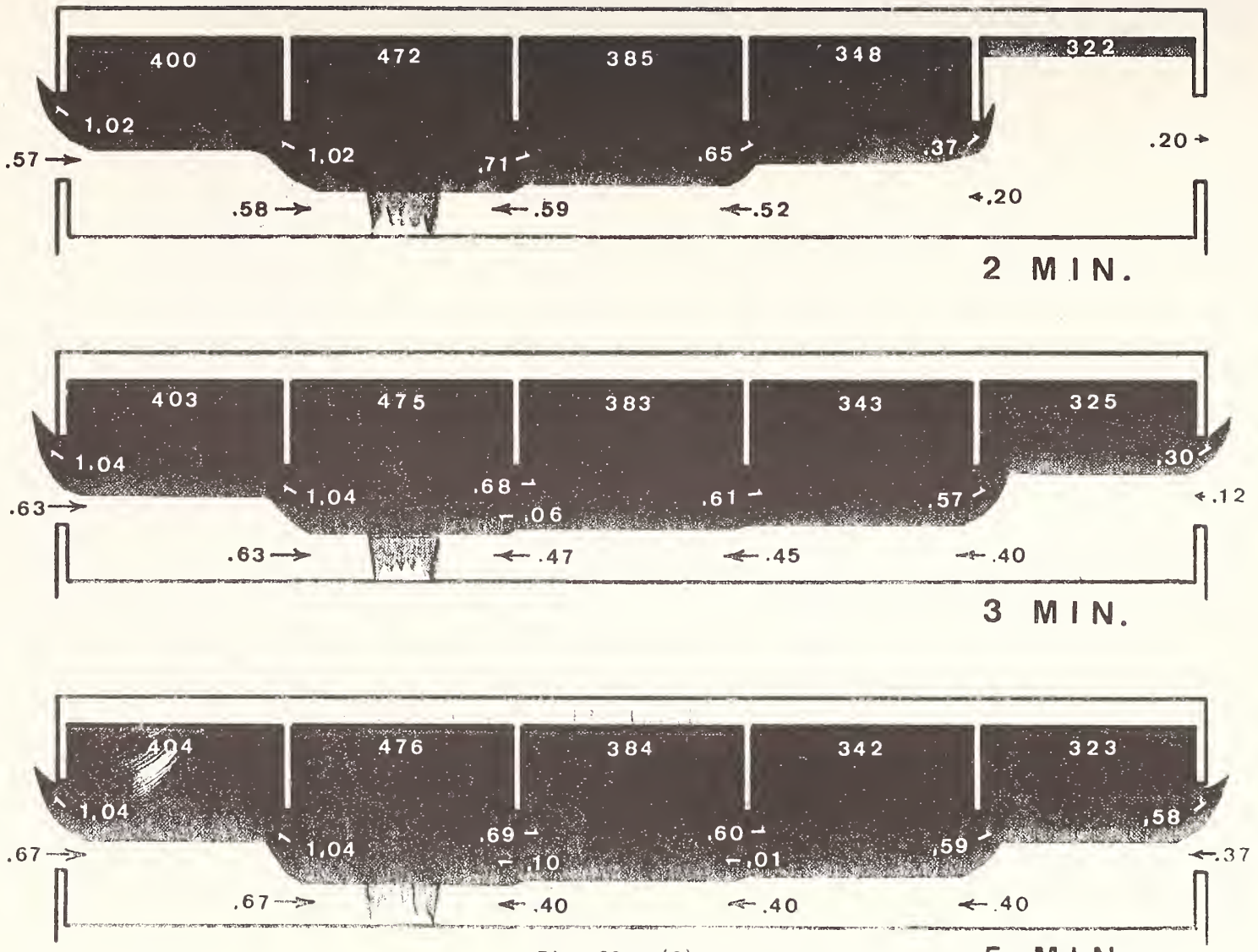

400
472
385
348
322
1.02
1.02
.57
.71
.65
.37
.20
.58
.59
.52
.20
2 MIN.
403
475
383
343
325
1.04
1.04
.68
.06
.61
.57
.30
.63
.12
.63
.47
.45
.40
3 MIN.
404
476
384
342
323
1.04
1.04
.69
.10
.60
.01
.59
.58
.67
.37
.67
.40
.40
.40
5 MIN.

Fig. 23-c (2)

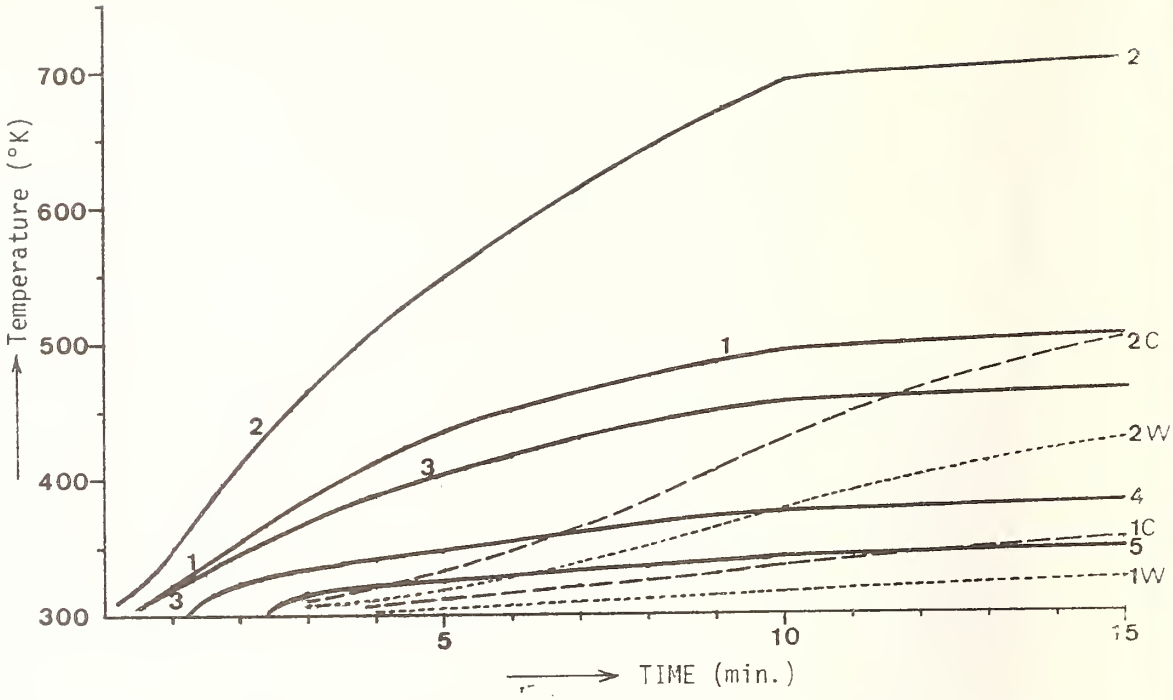


Fig. 24-a Temperature of Hot Layer & Ceiling etc. (Sample 4)

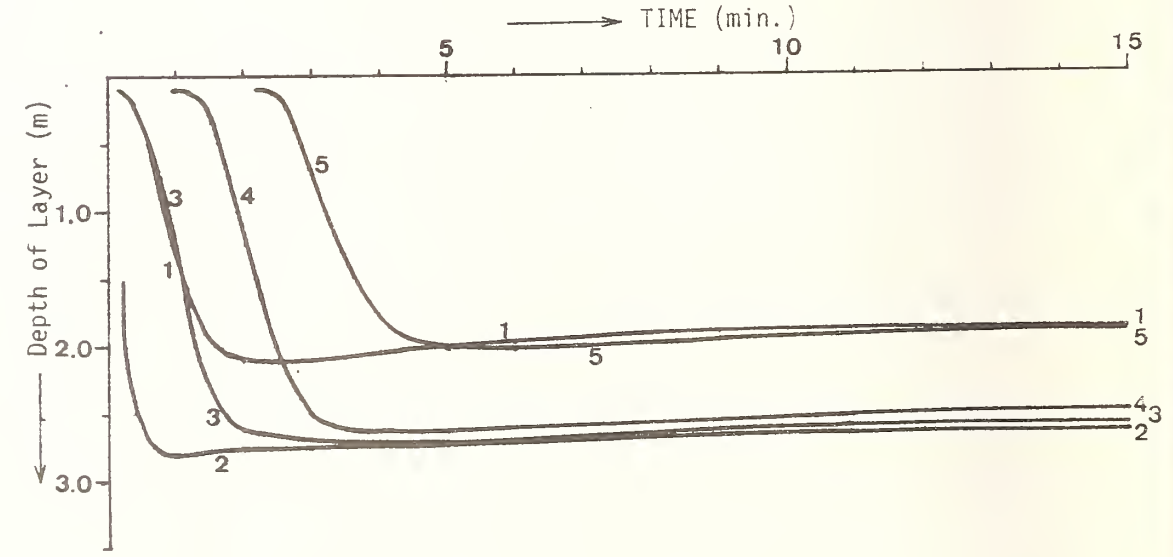


Fig. 24-b Depth of Hot Layer (Sample 4)

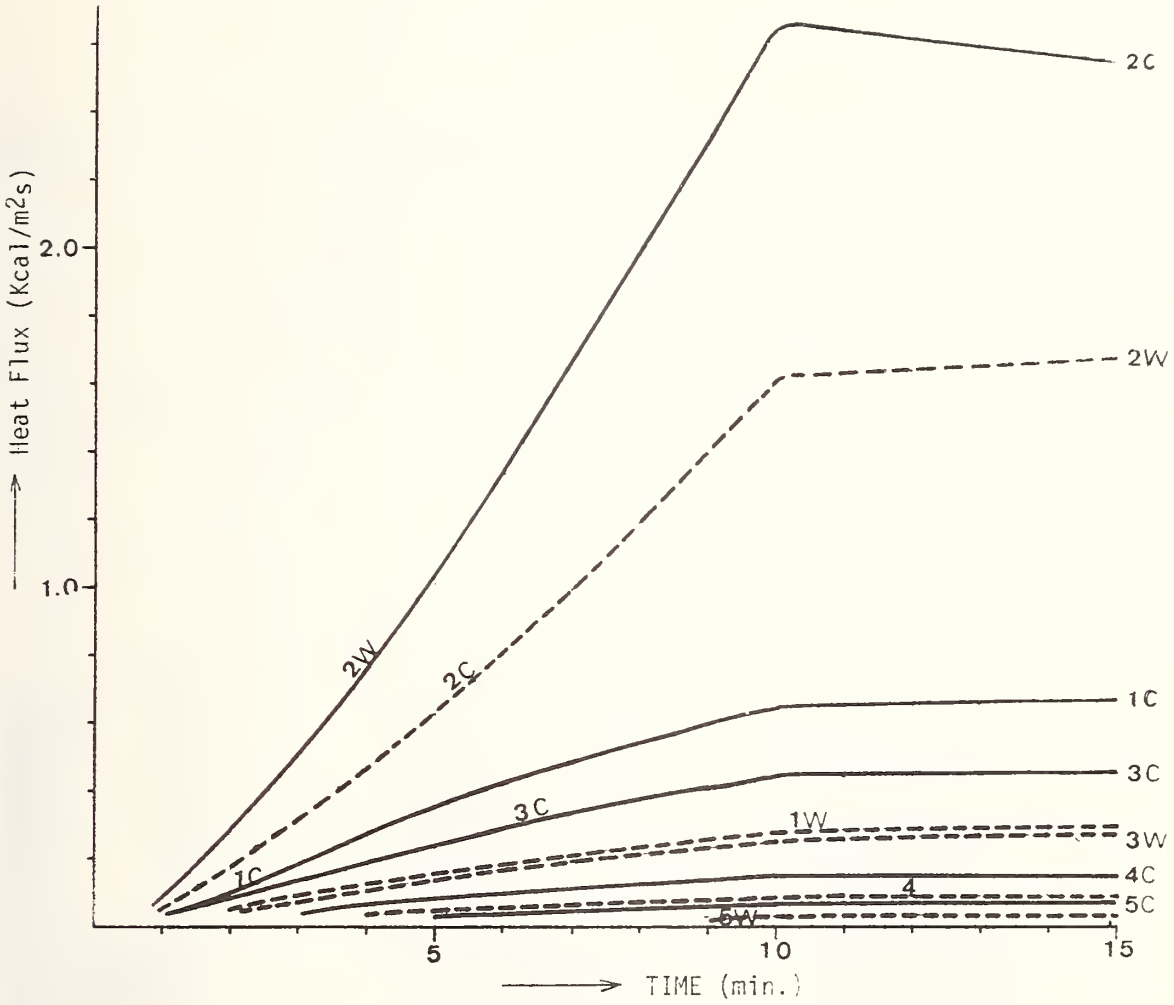


Fig. 24-c Incident Heat Flux to Ceiling & Floor (Sample 4)

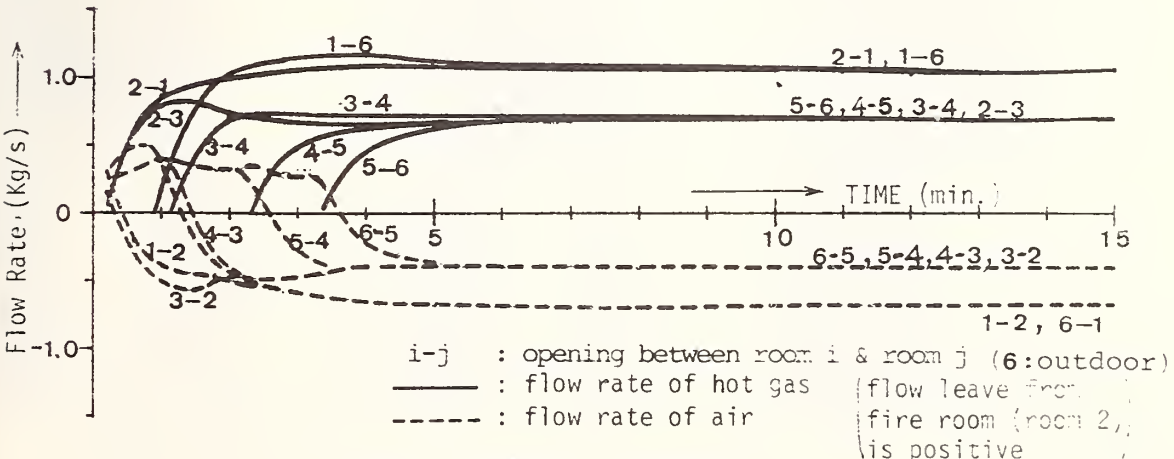


Fig. 24-d Flow Rate of Hot Gas & Air (Sample 4)

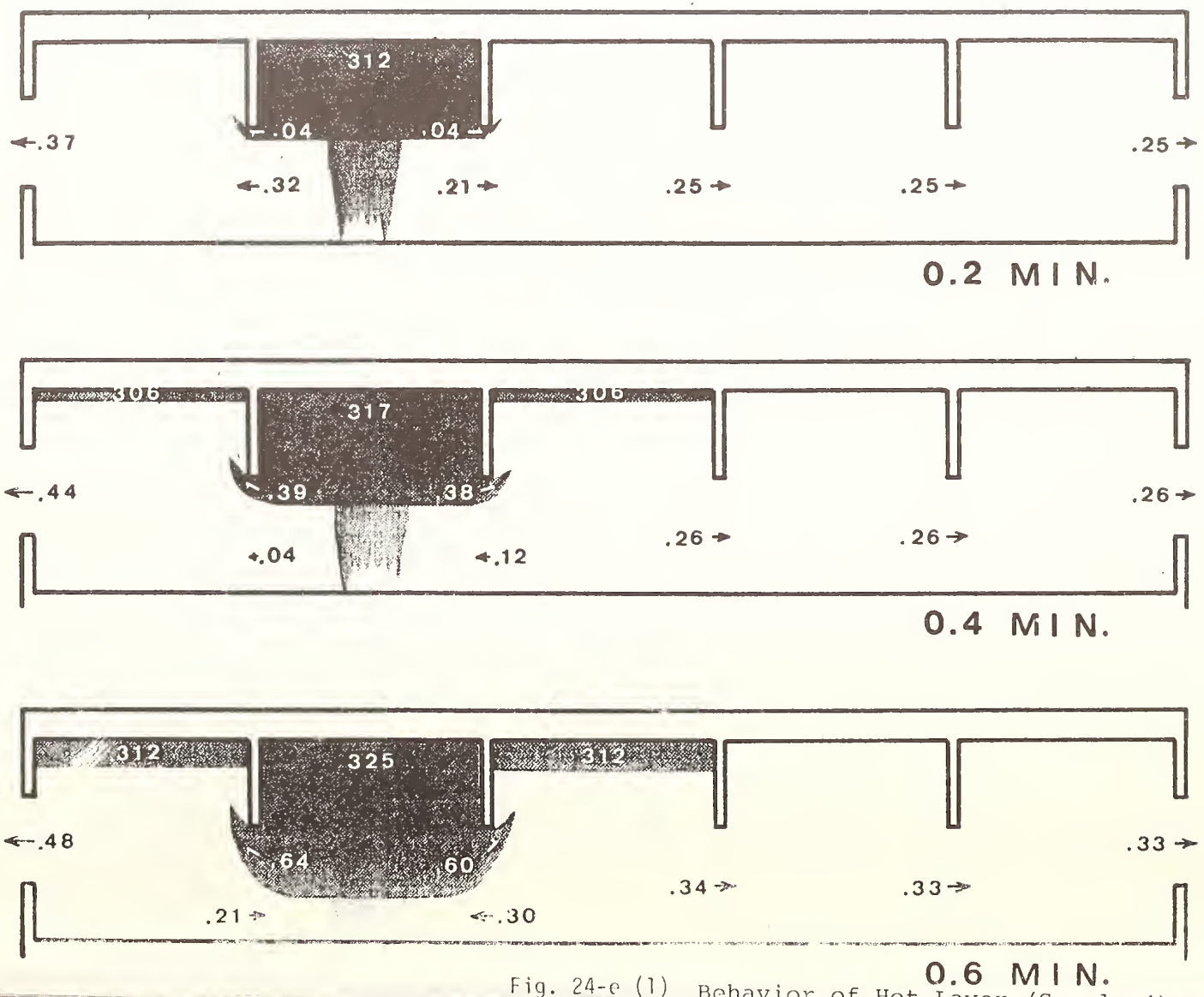


Fig. 24-e (1) Behavior of Hot Layer (Sample 4)

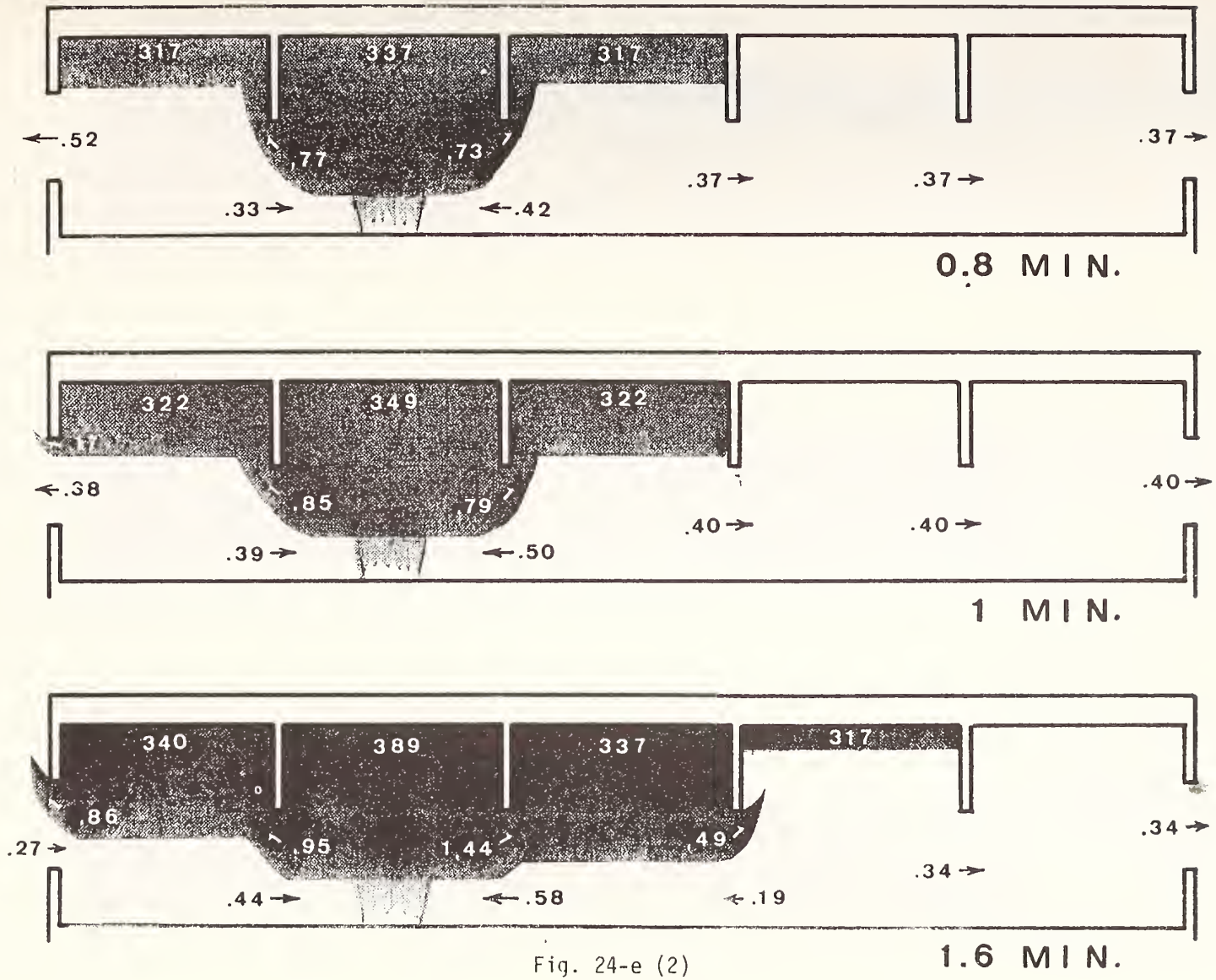

317
337
317
.52
.77
.73
.37
.37
.37
.33
.42
0.8 MIN.
322
349
322
.38
.85
.79
.40
.40
.40
.39
.50
1 MIN.
340
389
337
317
.86
.95
1.44
.49
.34
.27
.34
.44
.58
.19
1.6 MIN.

Fig. 24-e (2)

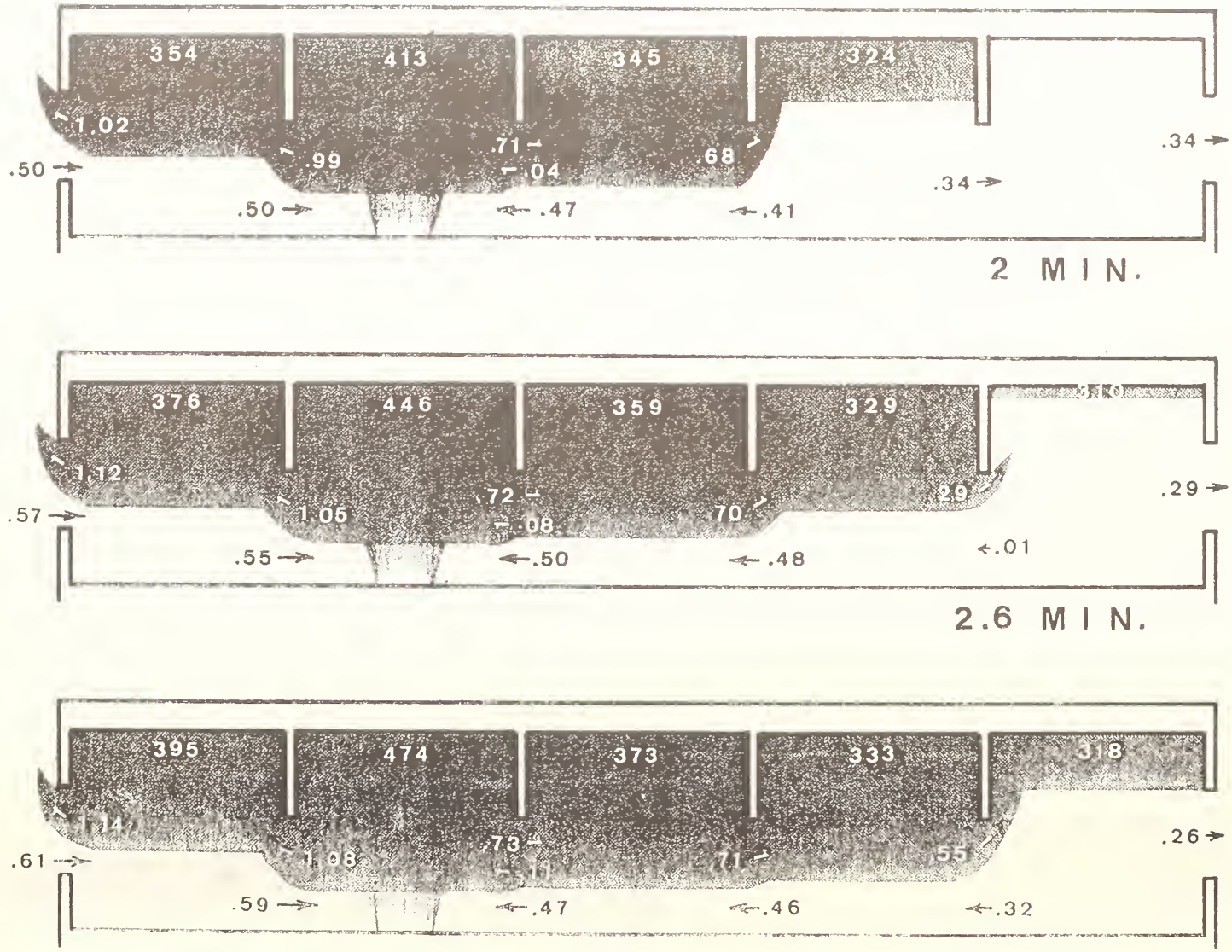

354
413
345
324
1.02
.99
.71
1.04
.68
.34
.50
.34
.50
.47
.41
2 MIN.
376
446
359
329
1.12
1.05
.72
1.08
.70
.29
.57
.29
.55
.50
.48
.01
2.6 MIN.
395
474
373
333
318
1.14
1.08
.73
1.11
.71
.55
.61
.26
.59
.47
.46
.32
3.2 MIN.

Fig. 24-e (3)

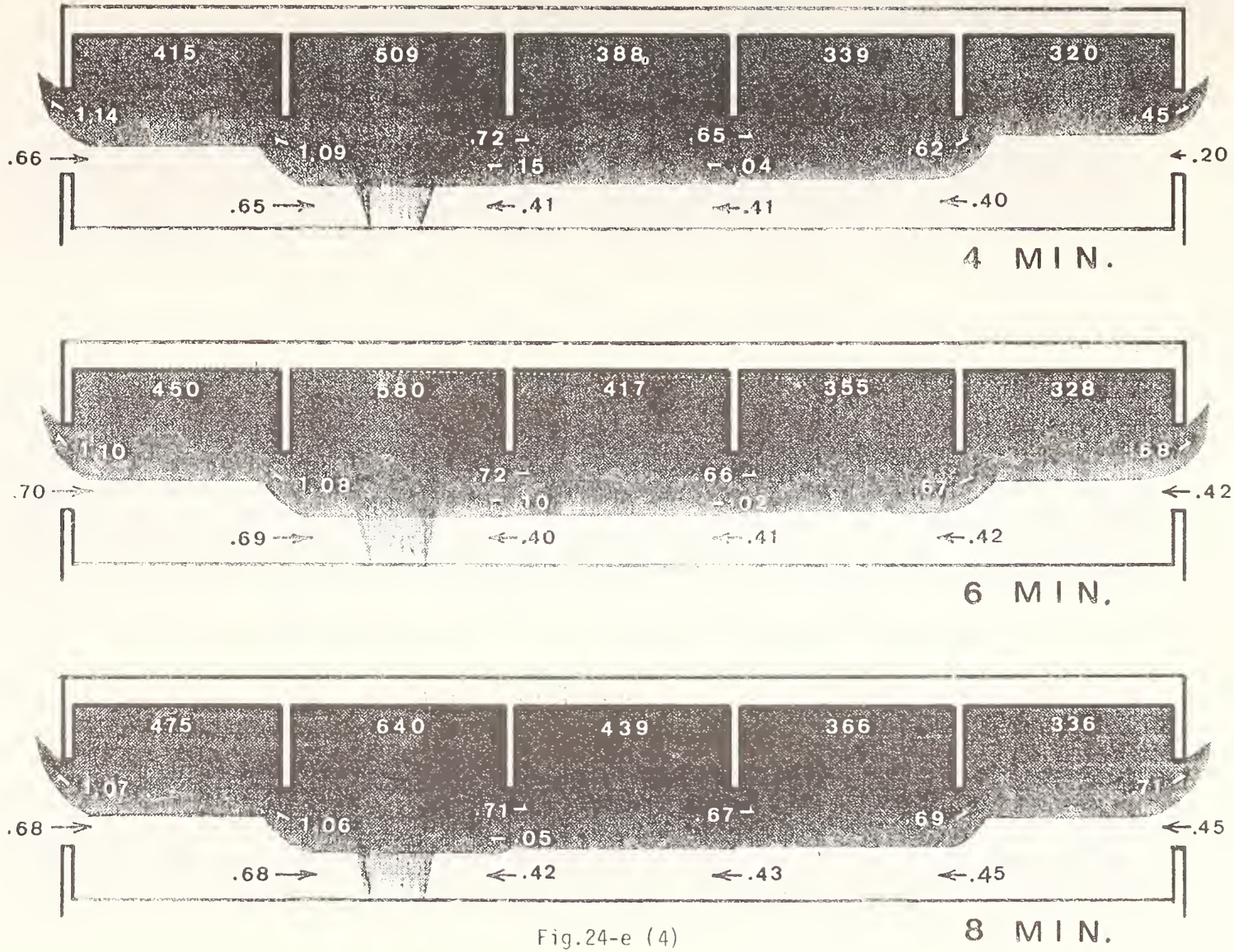

415
509
388
339
320
1.14
1.09
.72
.65
.45
.66
.15
.04
.62
.20
.65
.41
.41
.40
4 MIN.
450
580
417
355
328
1.10
1.08
.72
.66
.68
.70
.10
.02
.67
.42
.69
.40
.41
.42
6 MIN.
475
640
439
366
336
1.07
1.06
.71
.67
.71
.68
.05
.69
.45
.68
.42
.43
.45
8 MIN.

Fig.24-e (4)

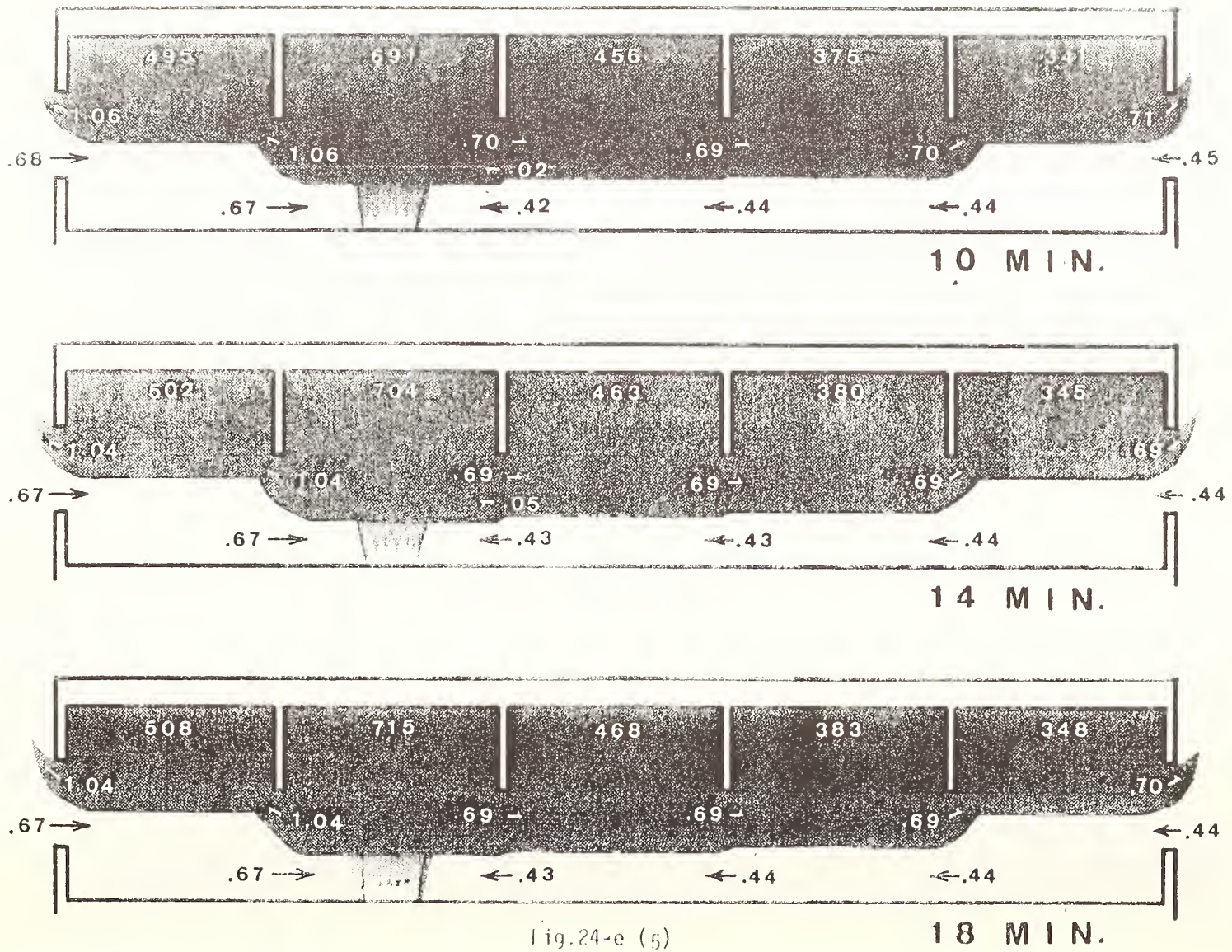

495
691
456
375
341
1.06
1.06
.70
.69
.70
.71
.68
.45
.02
.67
.42
.44
.44
10 MIN.
502
704
463
380
345
1.04
1.04
.69
.69
.69
.67
.44
.05
.67
.43
.43
.44
14 MIN.
508
715
468
383
348
1.04
1.04
.69
.69
.69
.70
.67
.44
.67
.43
.44
.44
18 MIN.

Fig.24-e (5)

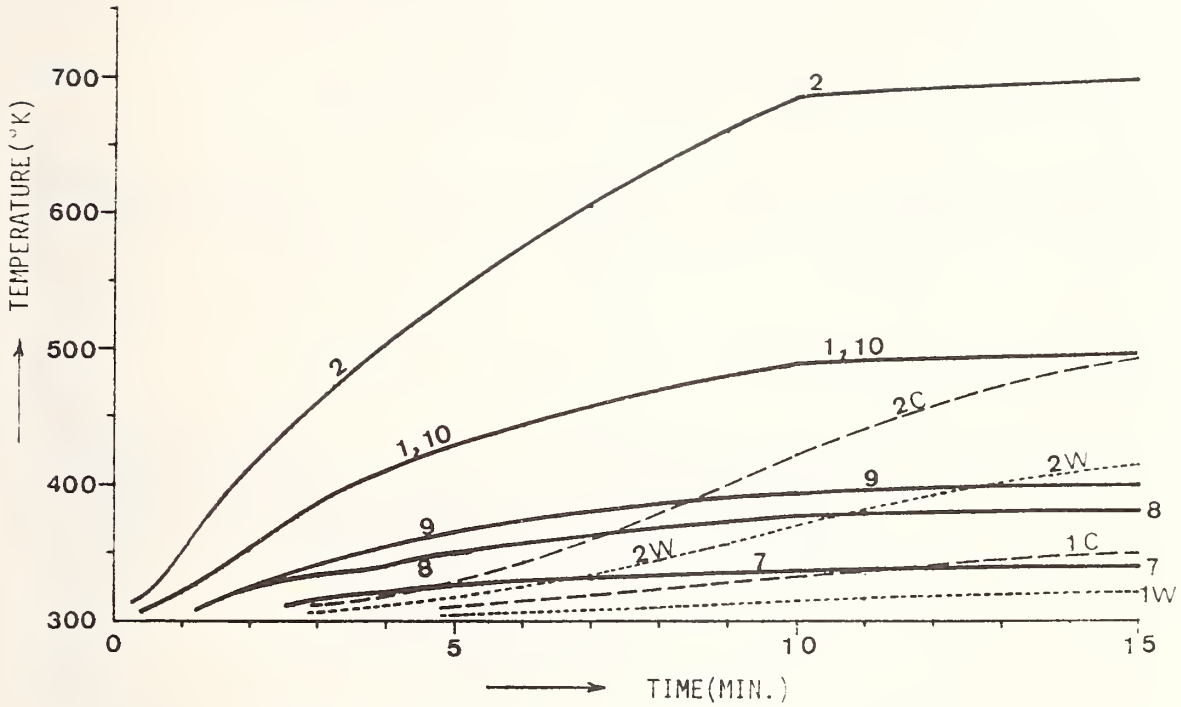


Fig. 25-a Temperature of Hot Layer & Ceiling etc. (Sample 5)

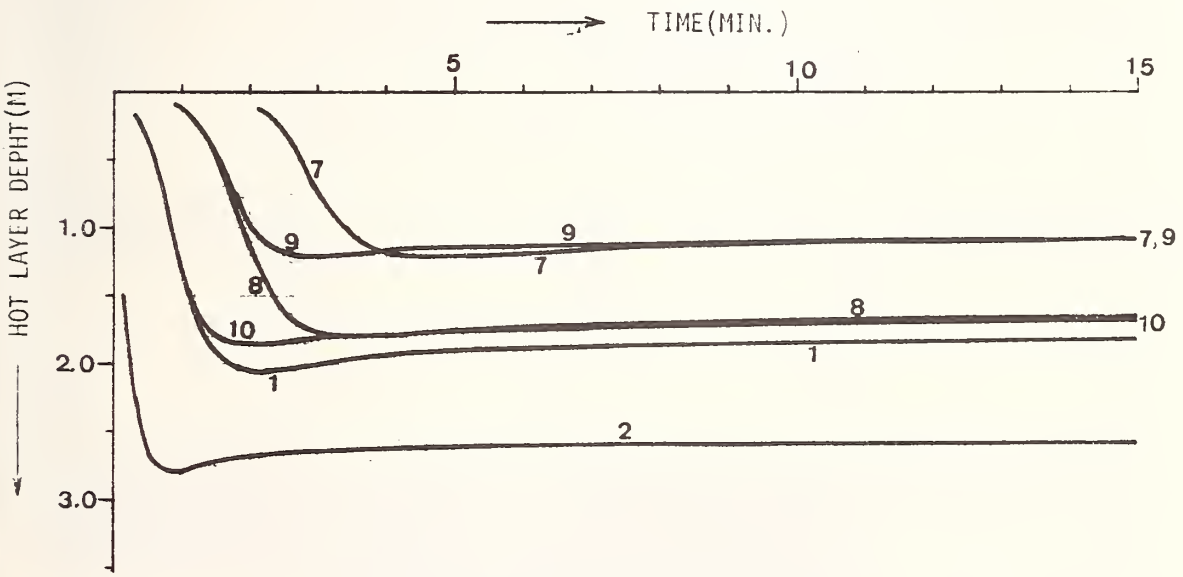
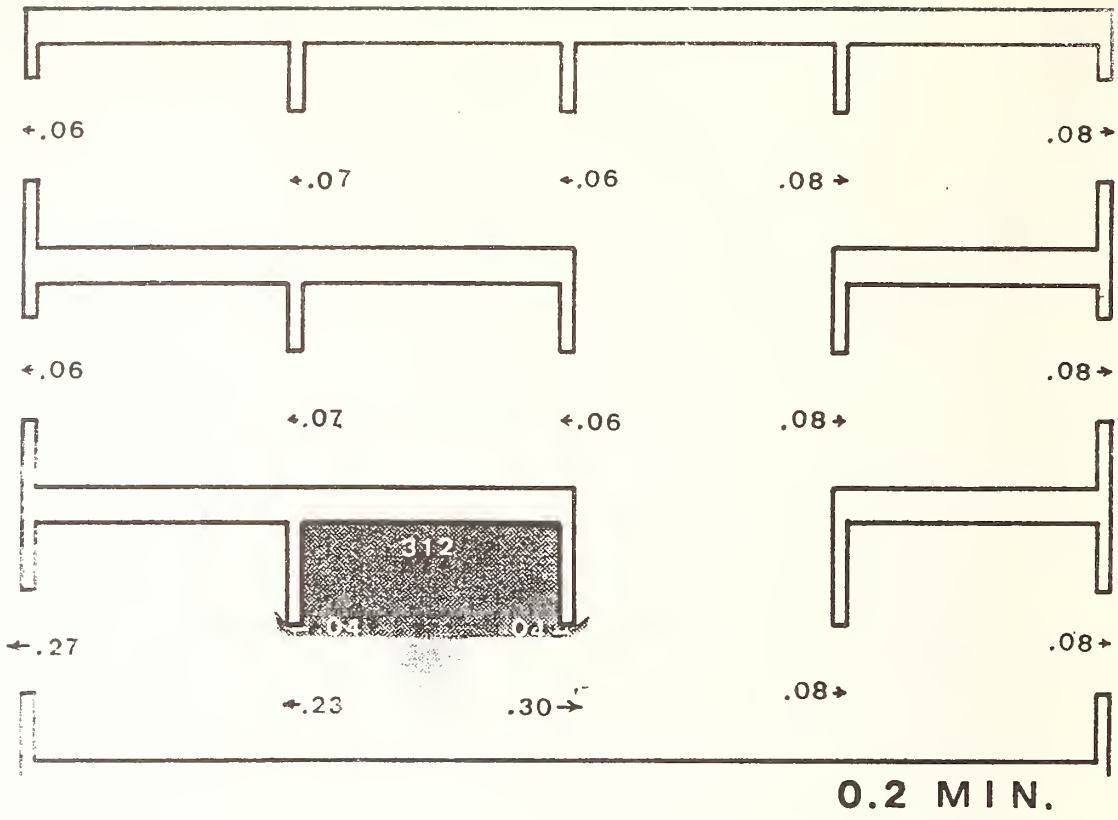


Fig. 25-b Depth of Hot Layer (Sample 5)



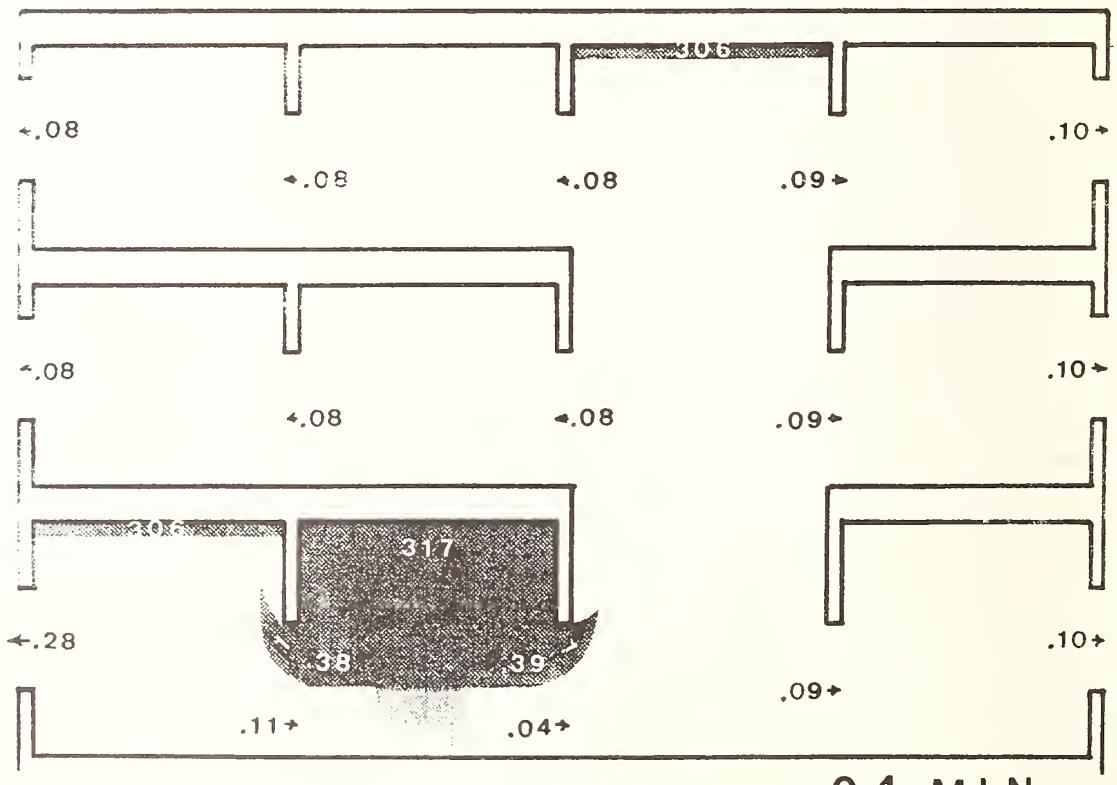
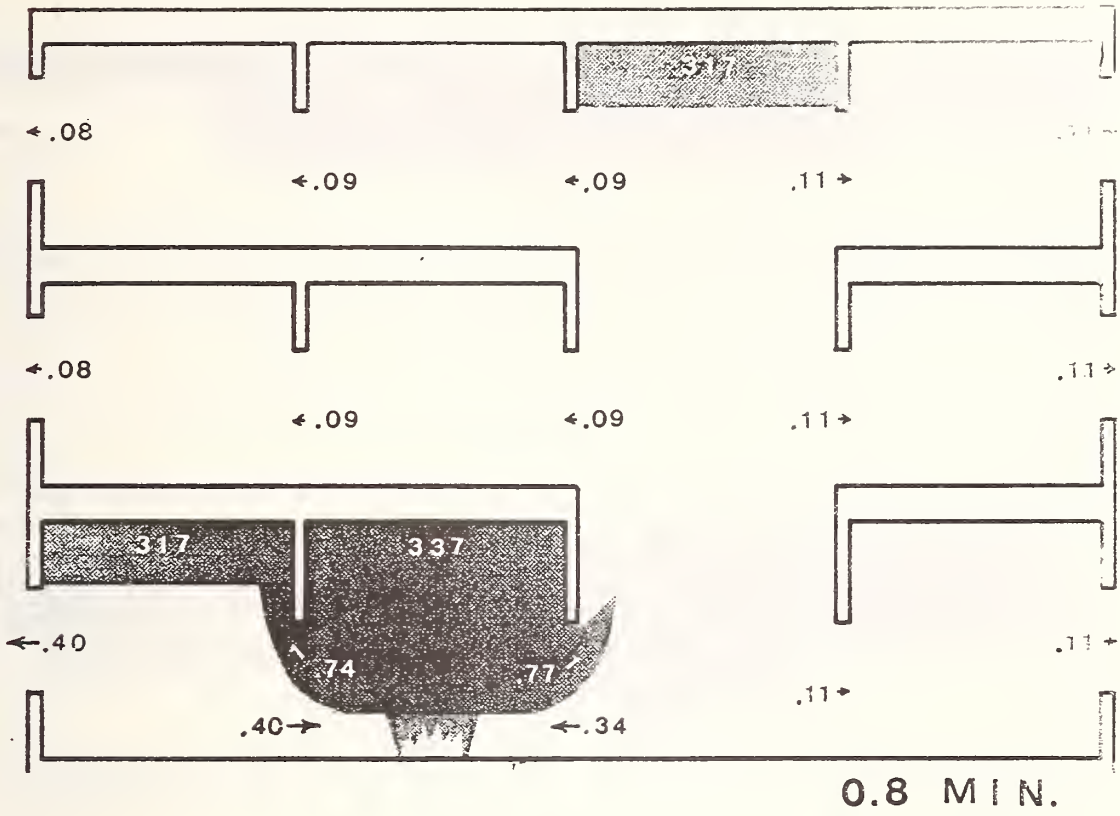


Fig. 25-c (1) Behavior of Hot Layer (Sample 5)


.08
.09
.09
.11
.08
.11
.09
.09
.11
317
337
.40
.74
.77
.11
.40
.34
0.8 MIN.

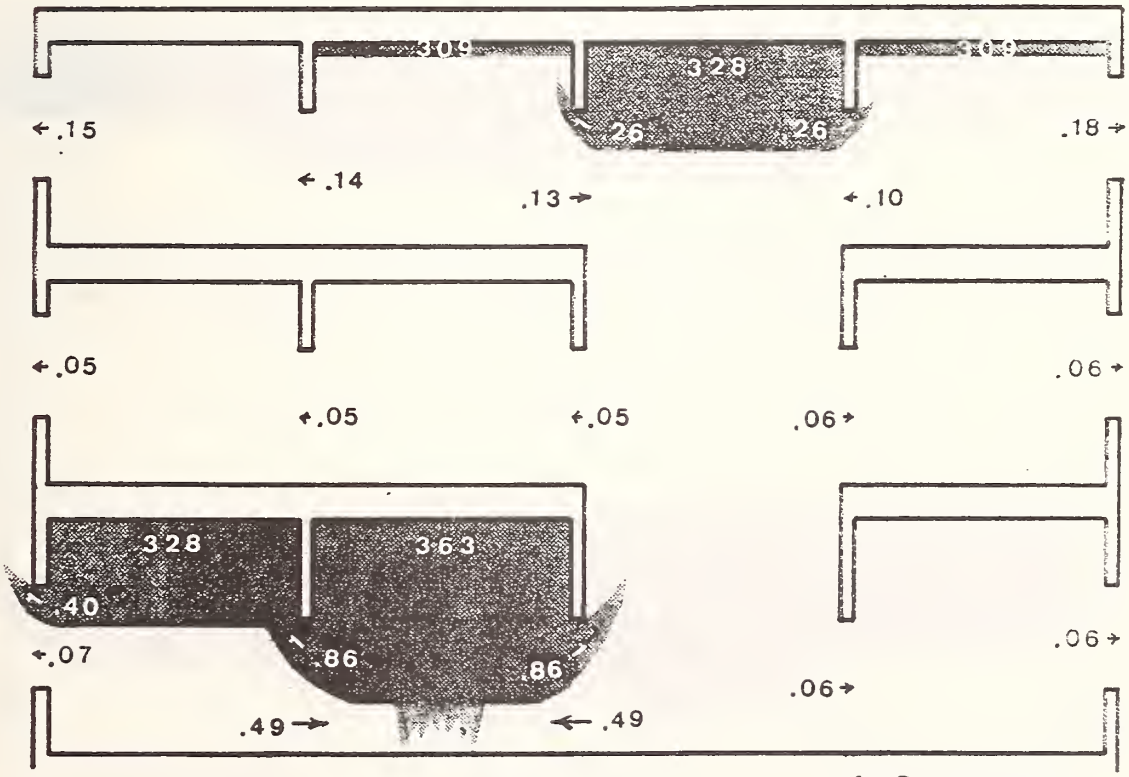
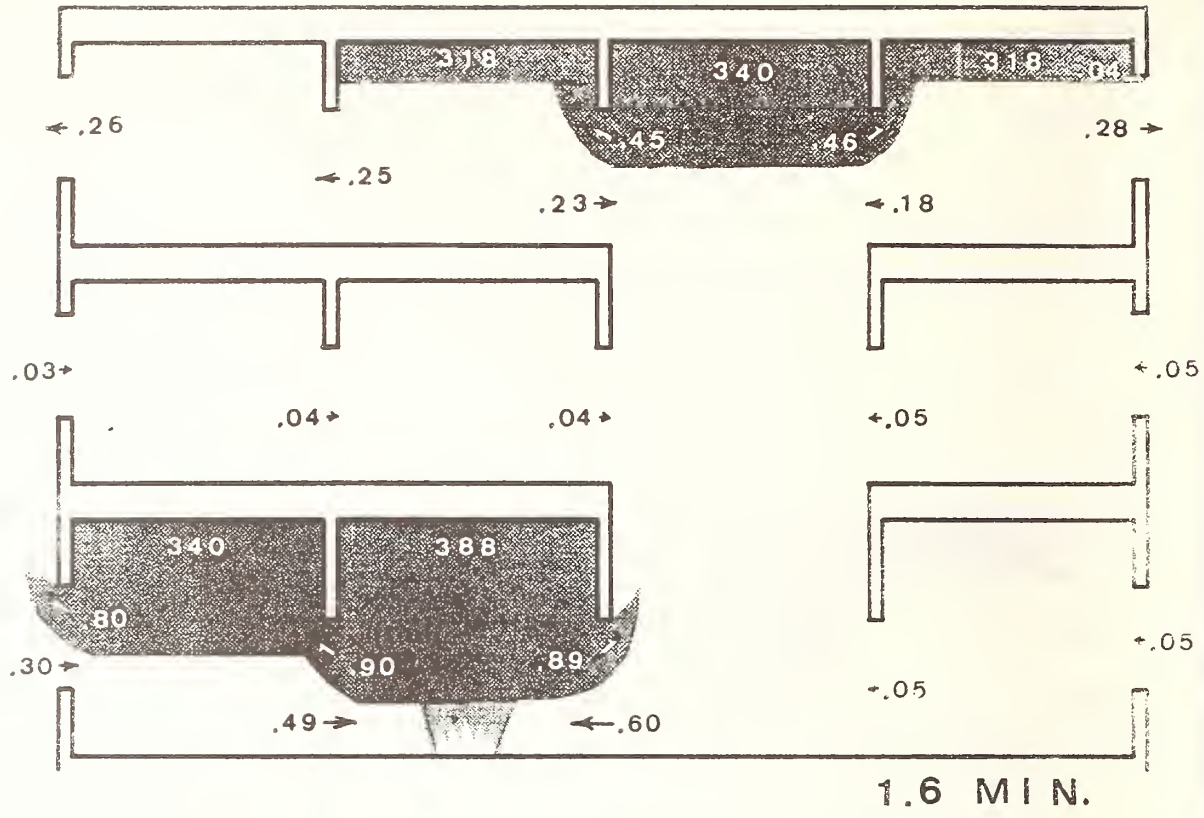

.15
.14
.13
.10
.18
.05
.05
.05
.06
.06
328
363
.40
.07
.86
.86
.06
.06
.49
.49
1.2 MIN.

Fig. 25-c (2)


318
340
318
.26
.28
.45
.46
.25
.23
.18
.03
.05
.04
.04
.05
340
388
.80
.05
.30
.90
.89
.05
.49
.60
1.6 MIN.

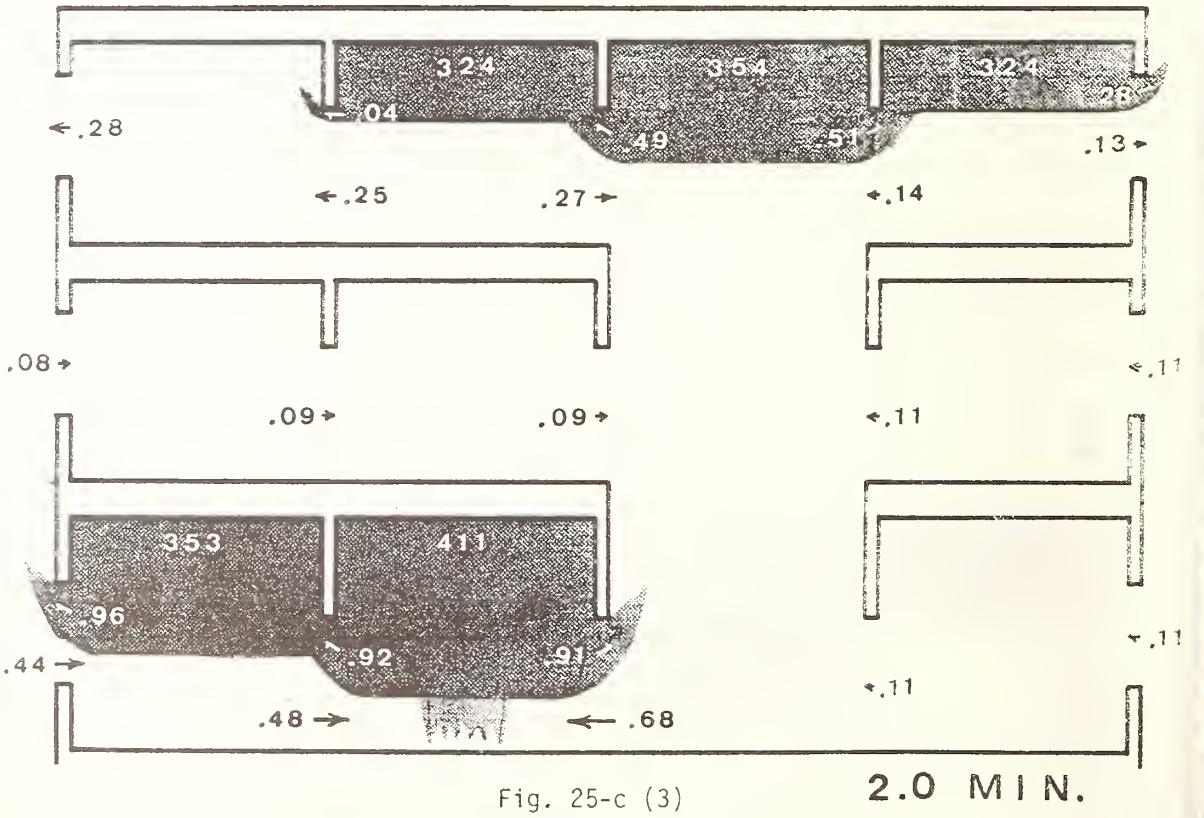
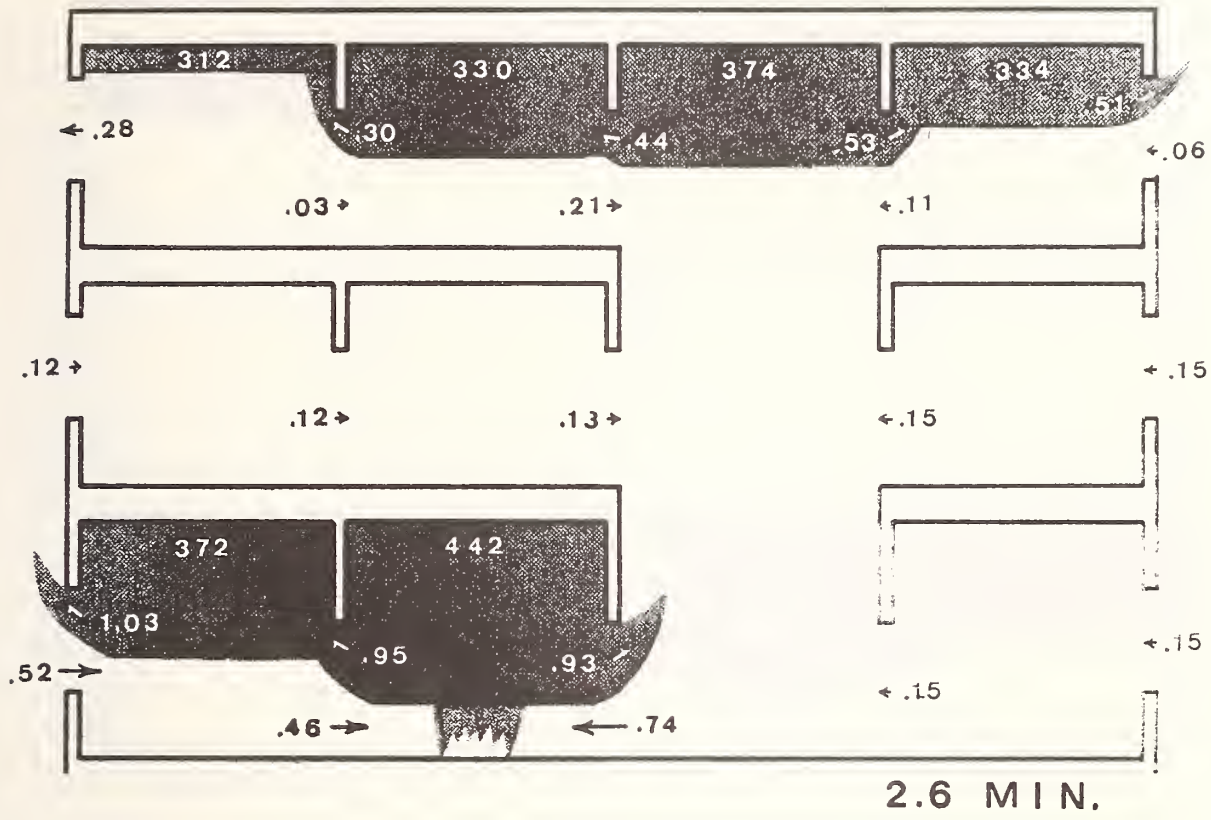

324
354
324
.28
.04
.49
.51
.13
.28
.25
.27
.14
.08
.11
.09
.09
.11
353
411
.96
.11
.92
.91
.44
.11
.48
.68
2.0 MIN.

Fig. 25-c (3)


312
330
374
334
.28
.30
.44
.53
.51
.06
.03
.21
.11
.12
.15
.12
.13
.15
372
442
1.03
.95
.93
.52
.15
.15
.46
.74
2.6 MIN.

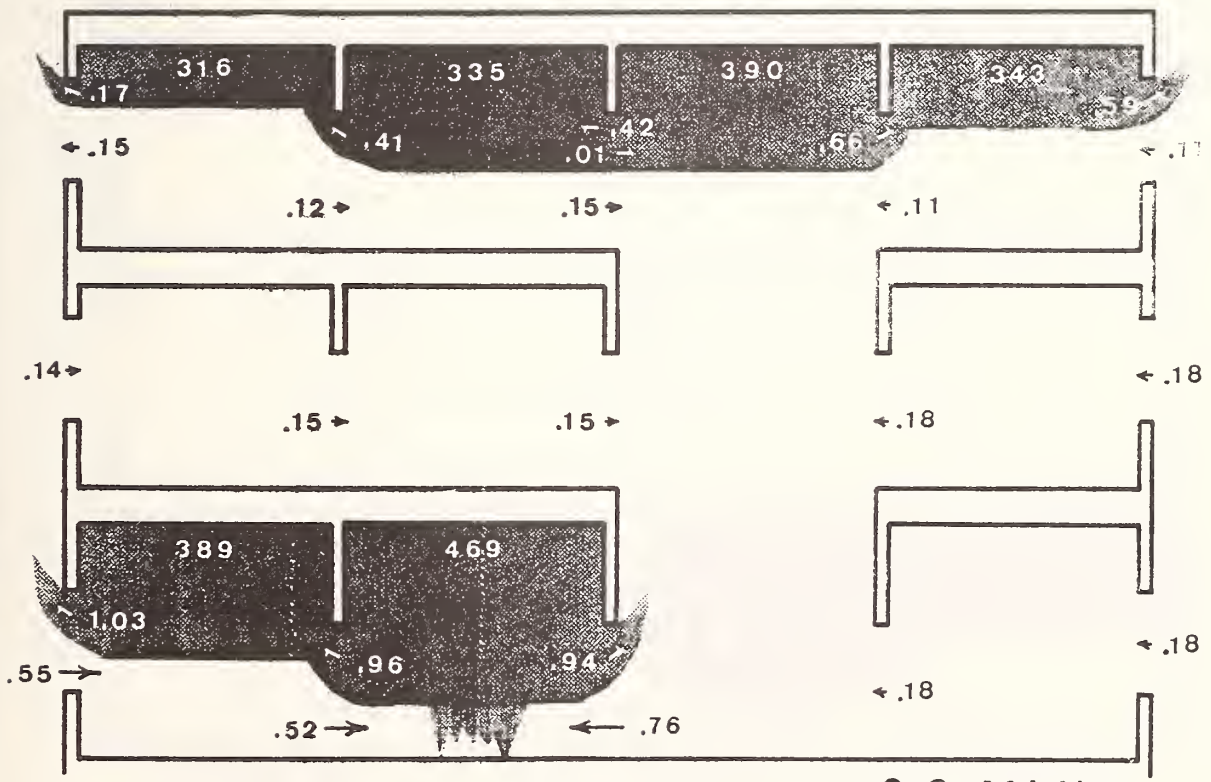
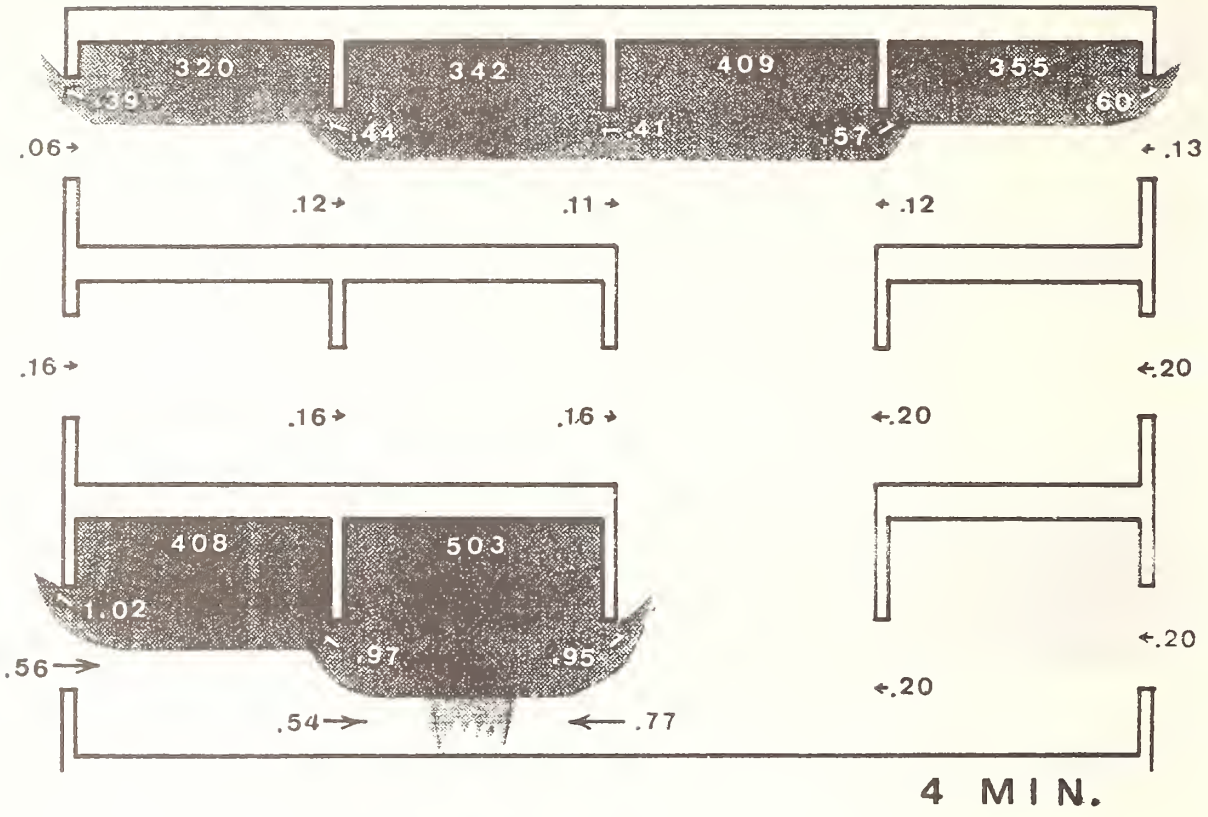

316
335
390
343
.17
.41
.42
.01
.66
.59
.15
.12
.15
.11
.14
.18
.15
.15
.18
389
469
1.03
.96
.94
.55
.18
.52
.76
3.2 MIN.

Fig. 25-c (4)


320
342
409
355
.39
.44
.41
.57
.60
.06
.13
.12
.11
.12
.16
.20
.16
.16
.20
408
503
1.02
.97
.95
.56
.20
.54
.77
4 MIN.

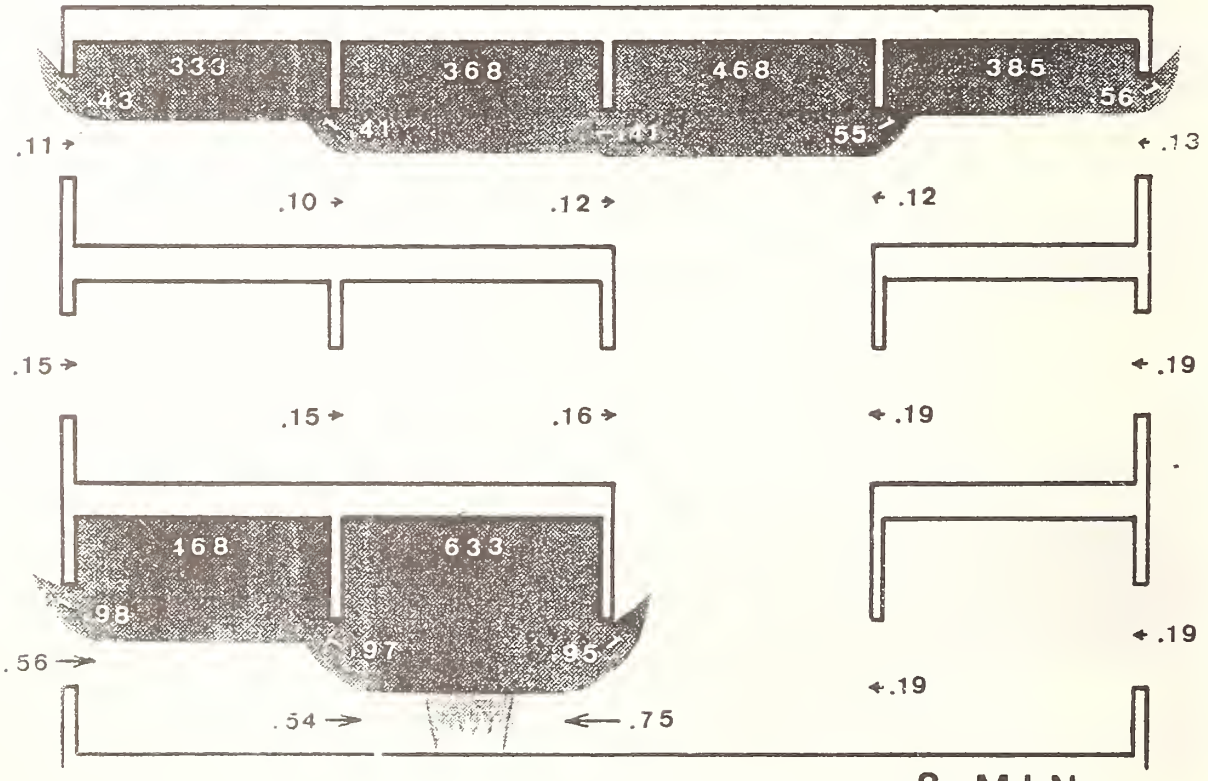
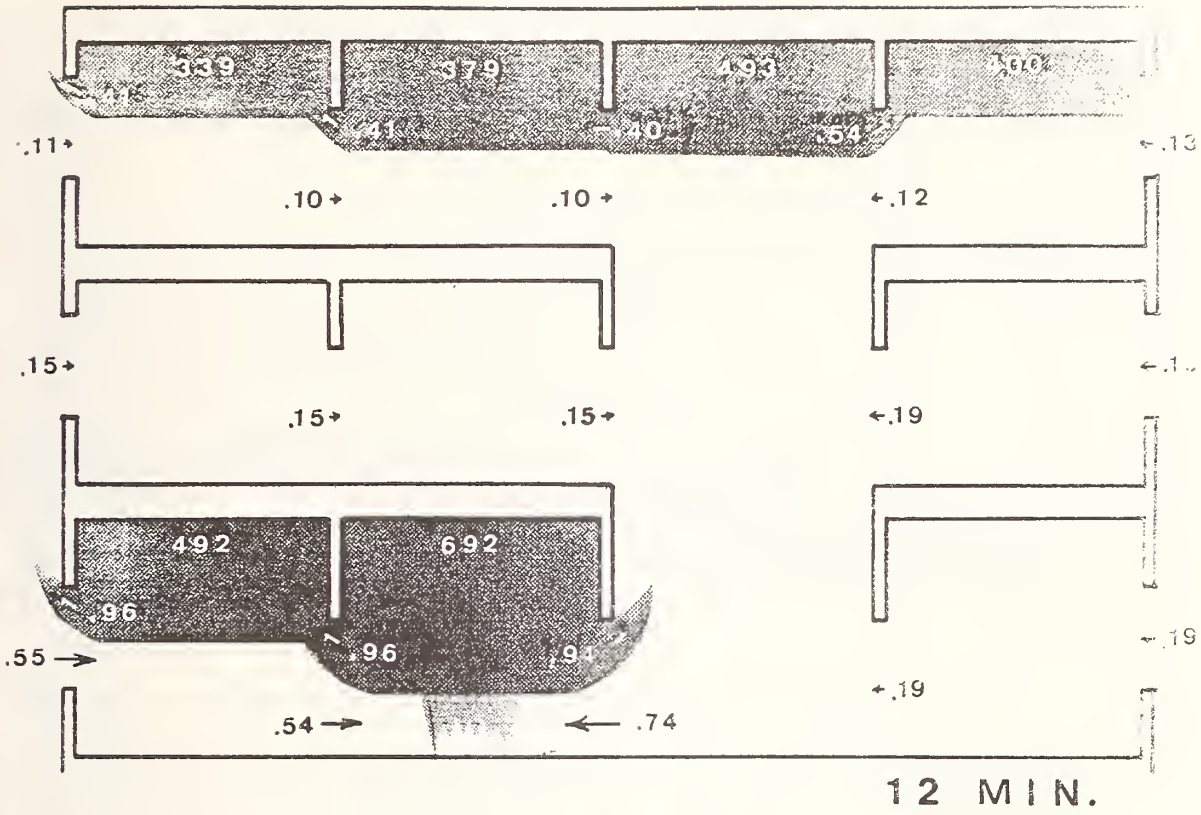

333
368
468
385
.43
.41
.41
.55
.56
.11
.13
.10
.12
.12
.15
.19
.15
.16
.19
468
633
98
.97
.95
.56
.19
.54
.75
8 MIN.

Fig. 25-c (5)


439
379
493
.41
.40
.54
.11
.13
.10
.10
.12
.15
.15
.15
.19
492
692
.96
.96
.94
.55
.19
.54
.74
12 MIN.

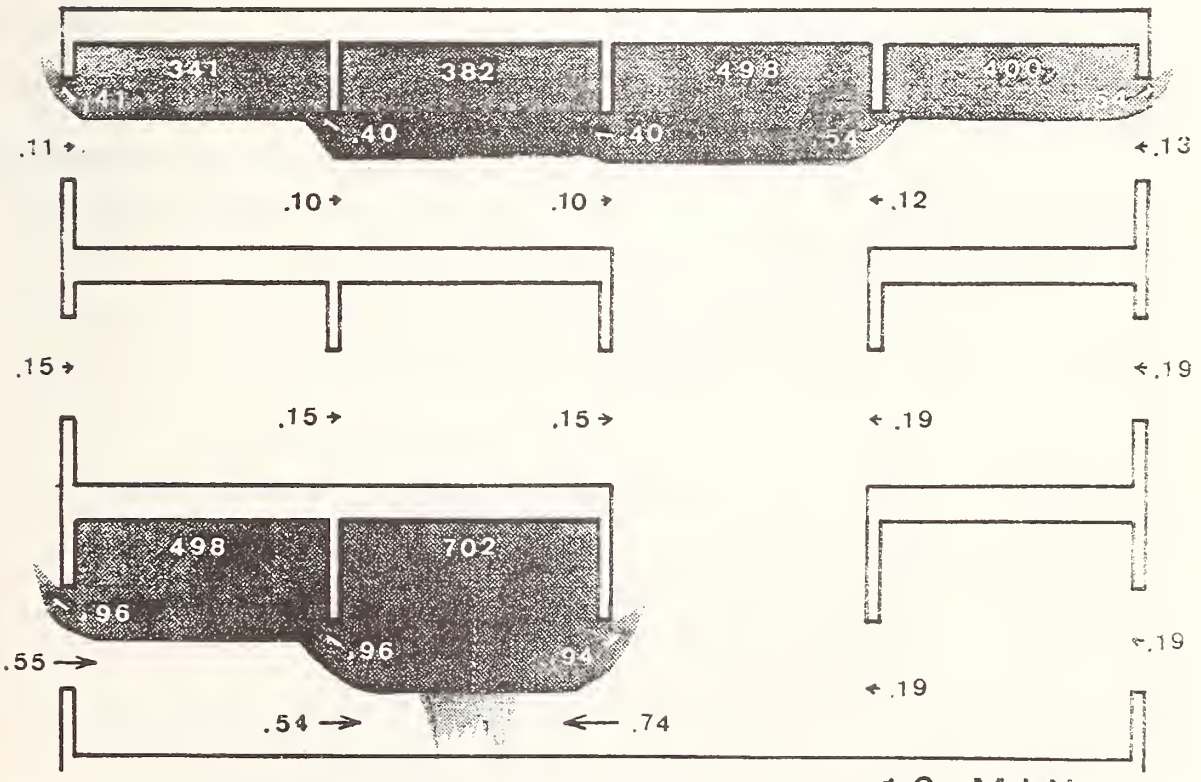

341
382
498
.41
.40
.40
.54
.11
.13
.10
.10
.12
.15
.19
.15
.15
.19
498
702
.96
.96
.94
.55
.19
.54
.74
16 MIN.

Fig. 25-c (6)

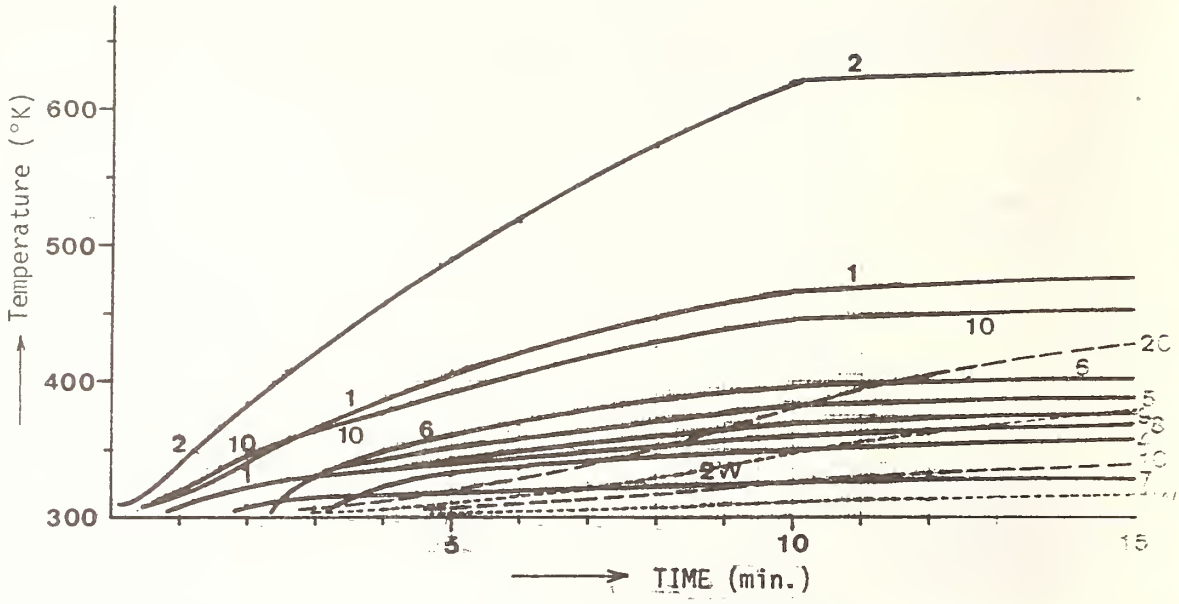


Fig. 26-a Temperature of Hot Gas Layer & Ceiling etc. (Sample 6)

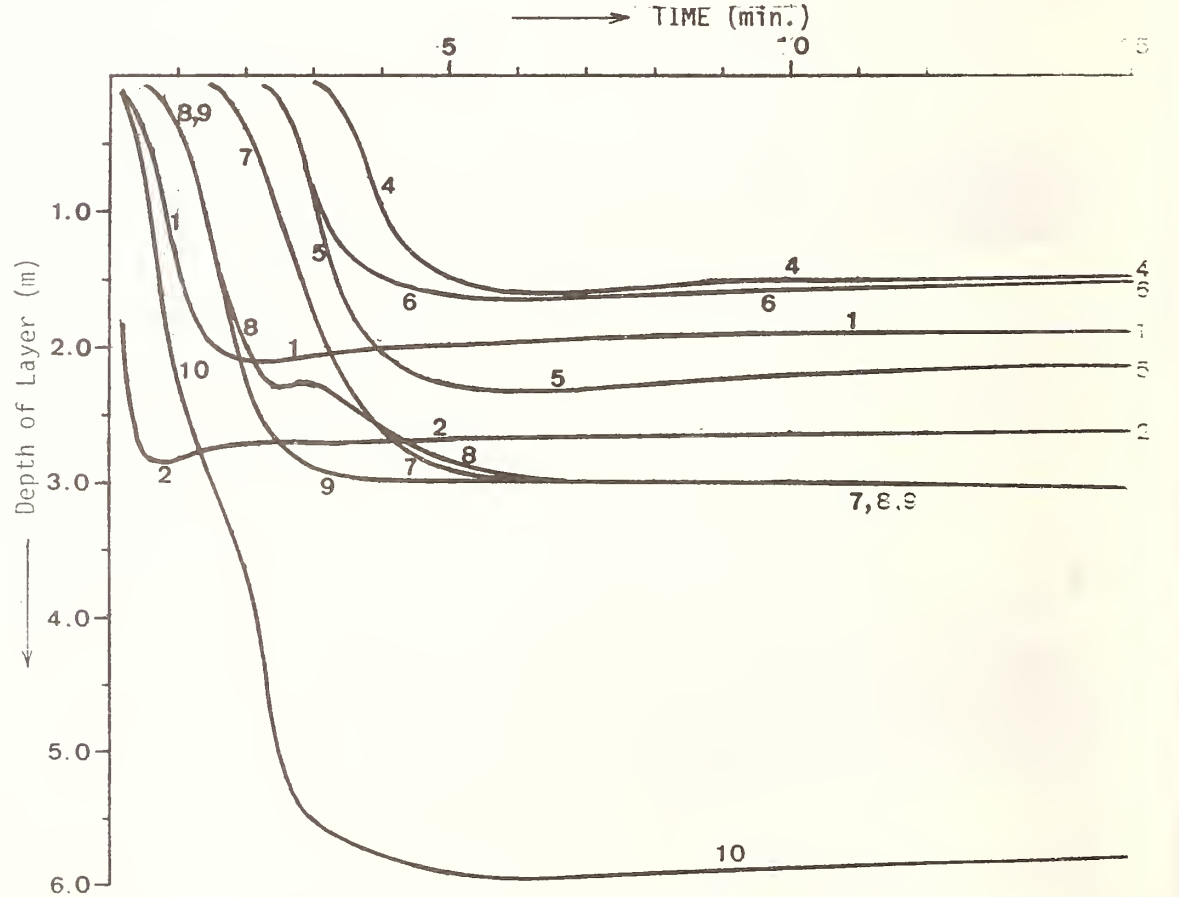


Fig. 26-b Depth of Hot Layer (Sample 6)

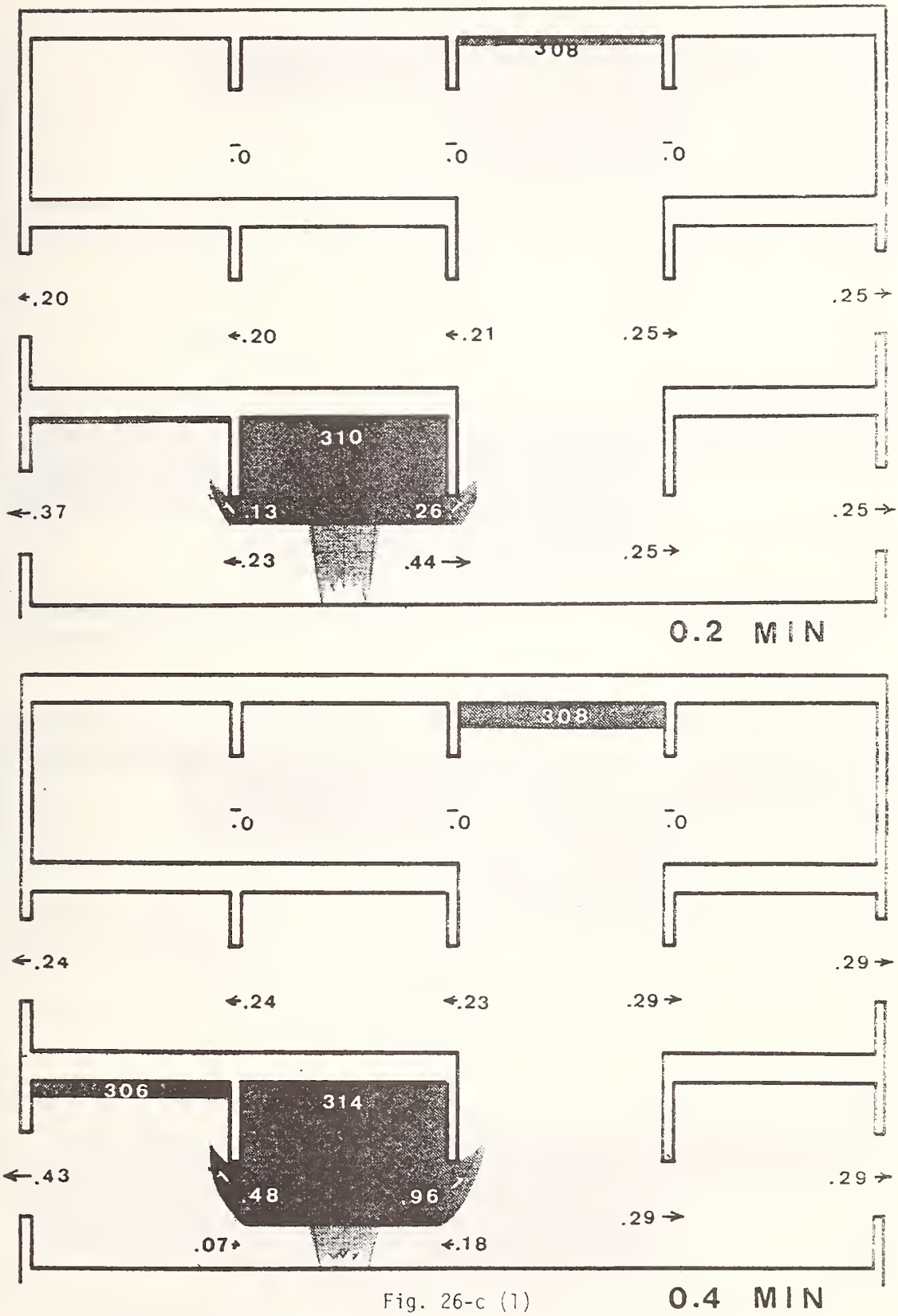
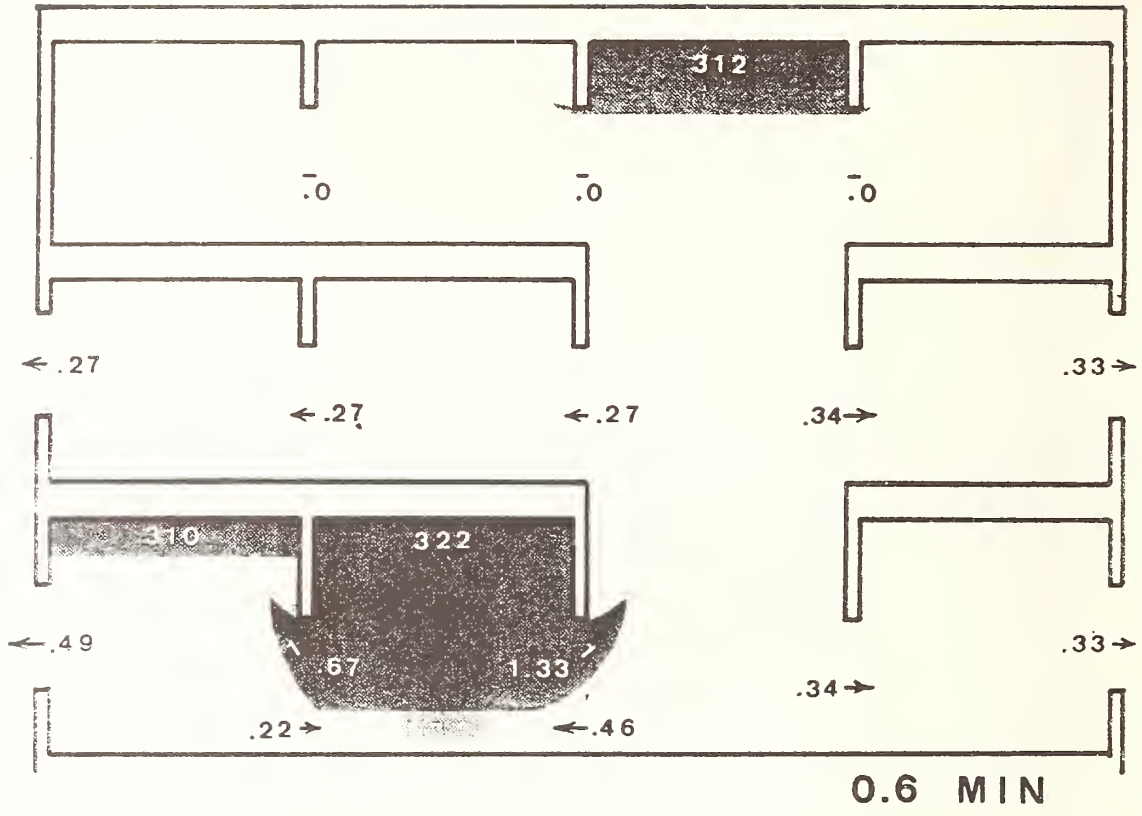


Fig. 26-c (1)
Behavior of Hot Layer (Sample 6)


312
.0
.0
.0
.27
.33
.27
.27
.34
310
322
.49
.33
67
1.33
.34
.22
.46
0.6 MIN

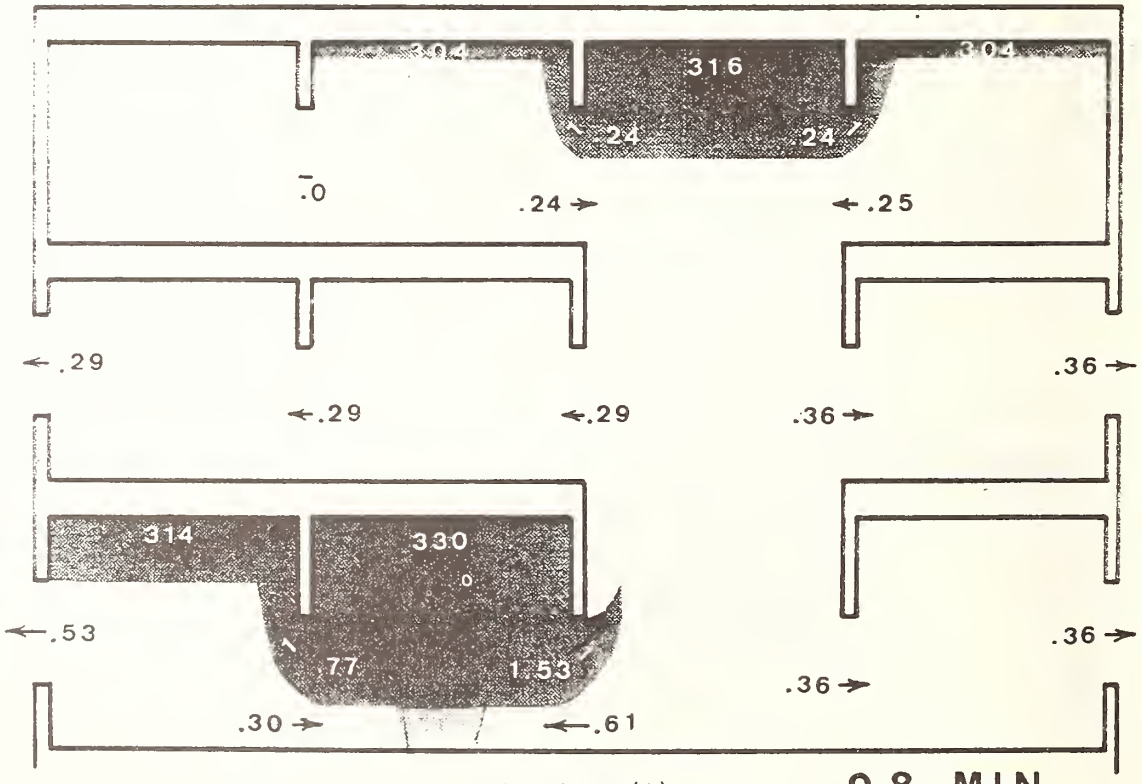
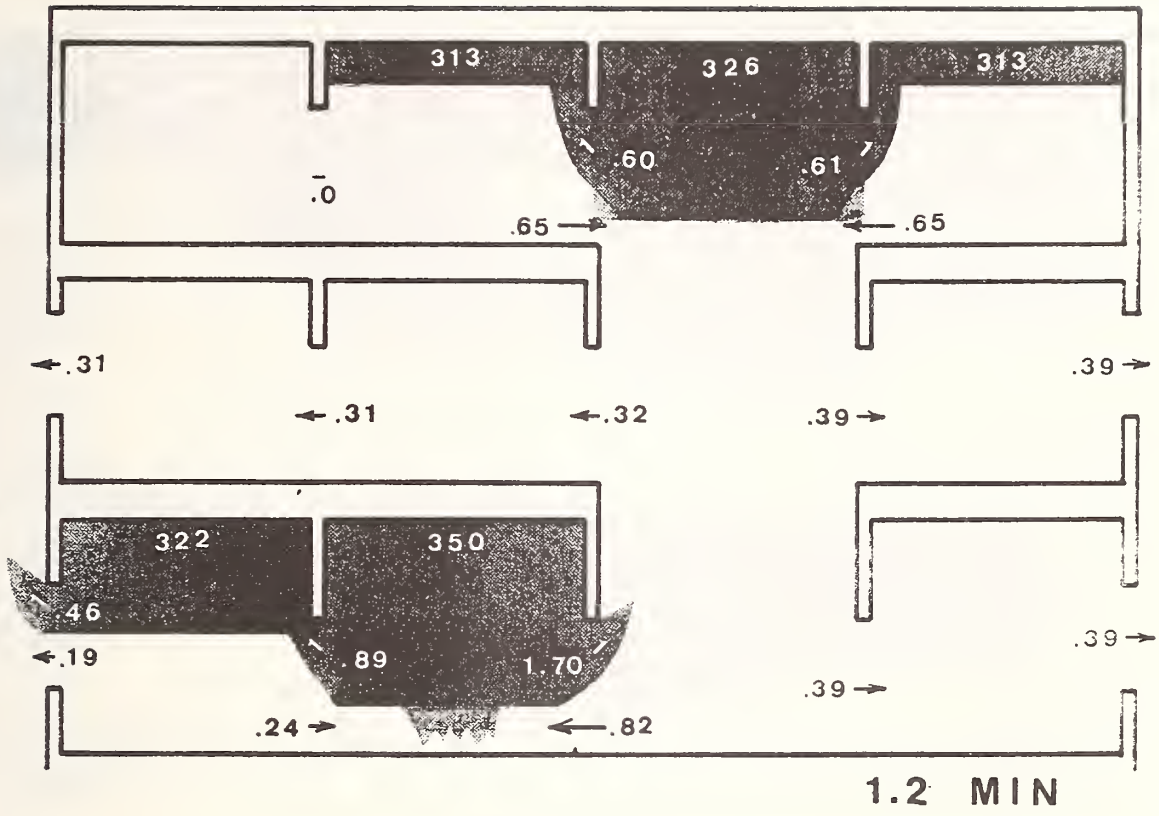

304
316
304
.24
.24
.0
.24
.25
.29
.36
.29
.29
.36
314
330
.53
.36
77
1.53
.36
.30
.61
0.8 MIN

Fig. 26-c (2)


313
326
313
.60
.61
.0
.65
.65
.31
.39
.31
.32
.39
322
350
.46
.19
.89
1.70
.39
.24
.82
1.2 MIN

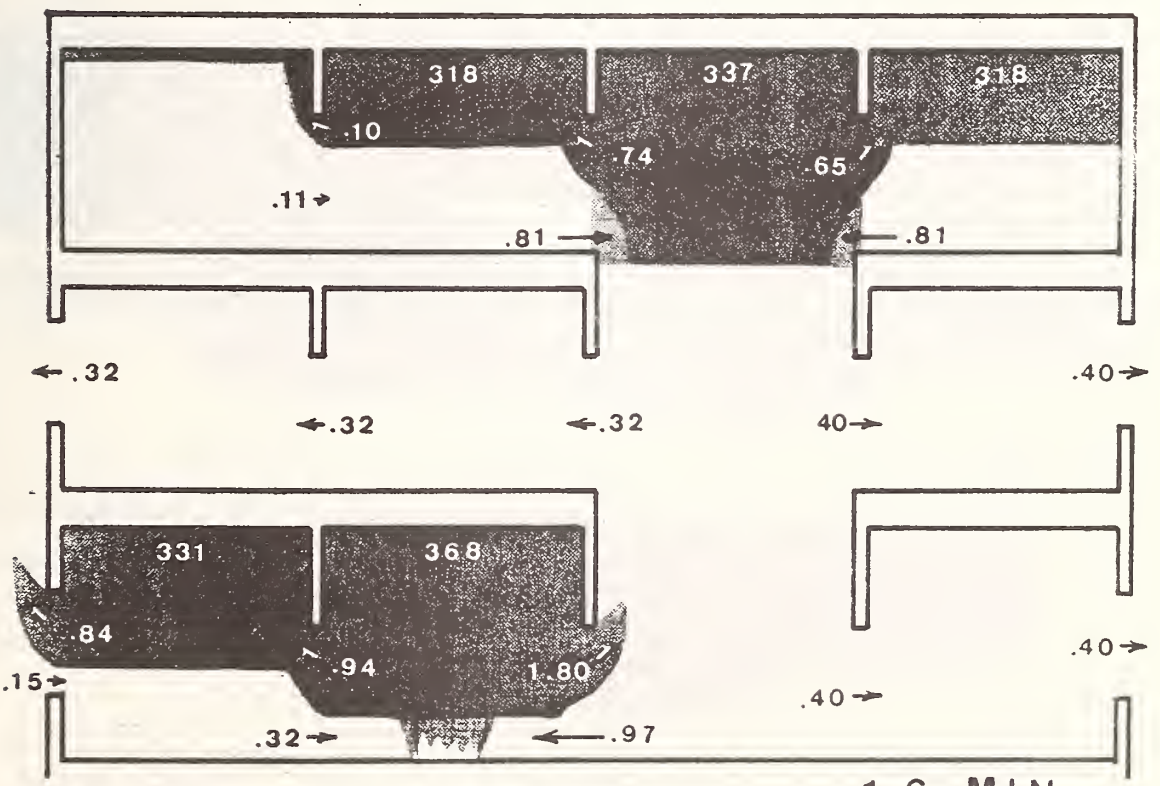
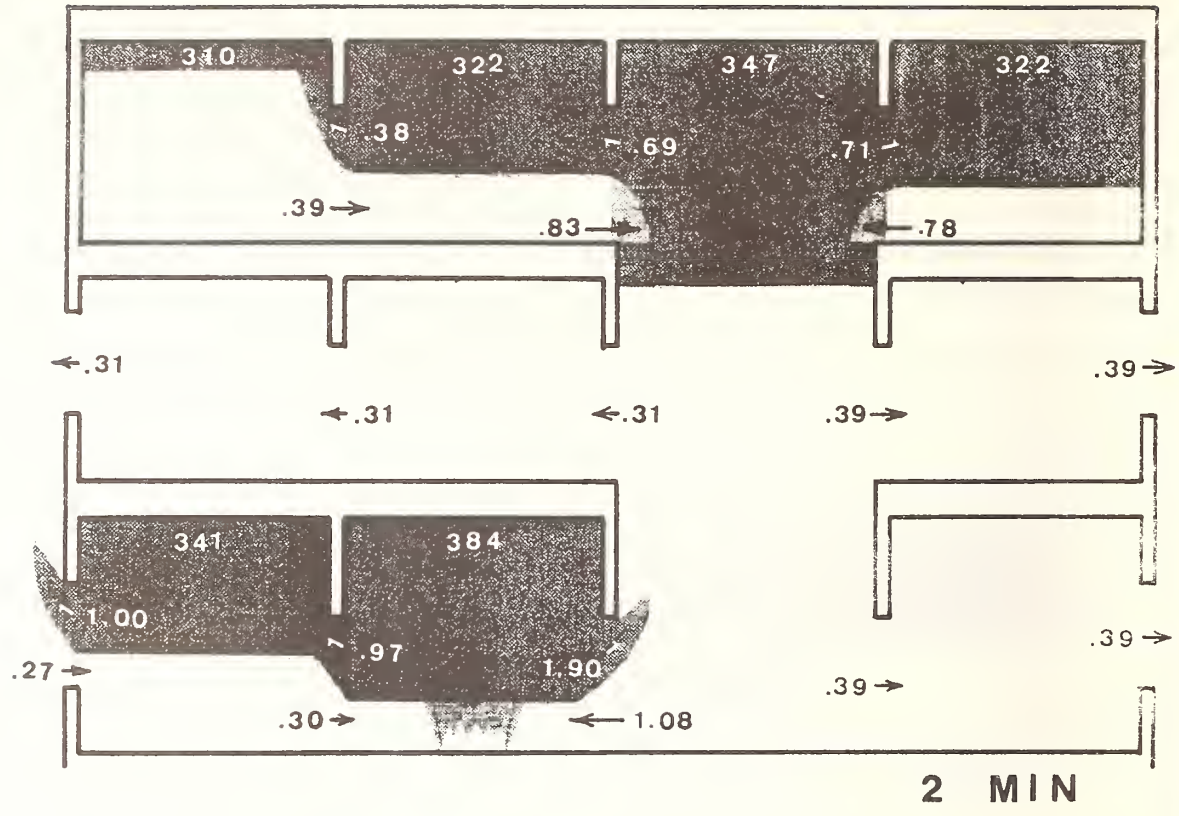

318
337
318
.10
.74
.65
.11
.81
.81
.32
.40
.32
.32
40
331
368
.84
.94
1.80
.15
.40
.40
.32
.97
1.6 MIN

Fig. 26-c (3)


340
322
347
322
.38
.69
.71
.39
.83
.78
.31
.39
.31
.31
.39
341
384
1.00
.97
1.90
.27
.39
.30
1.08
2 MIN

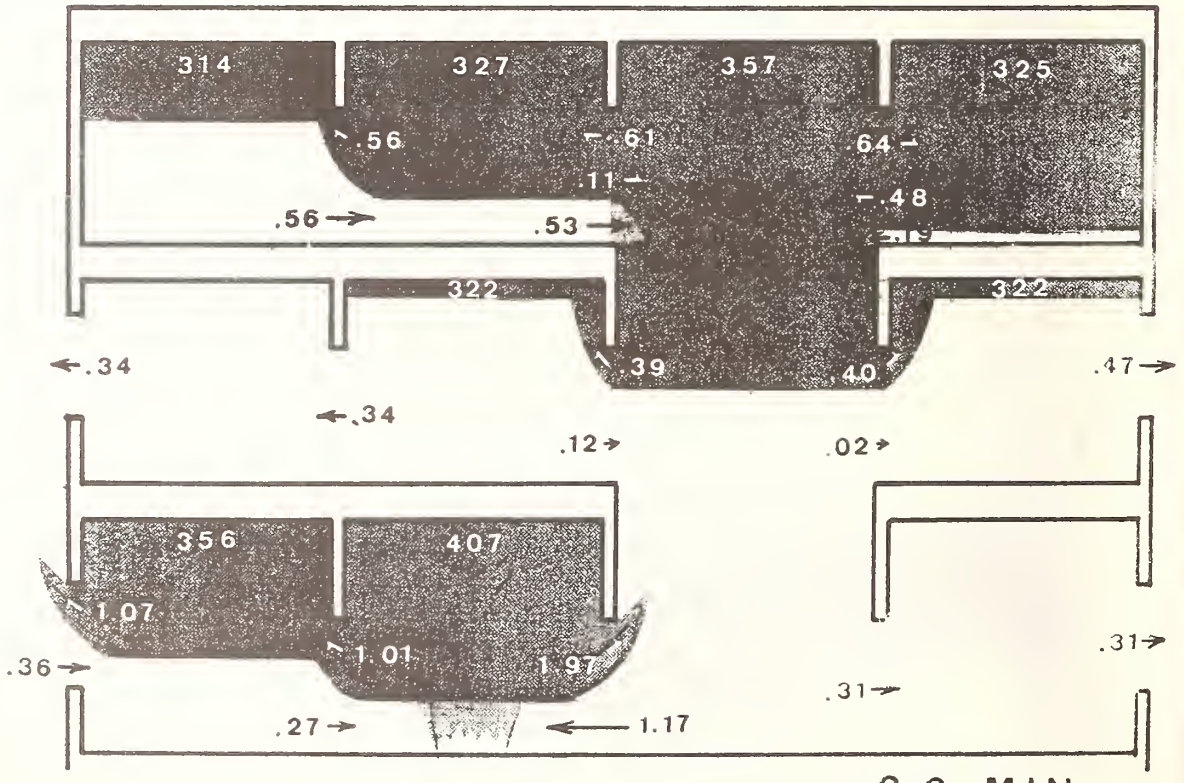
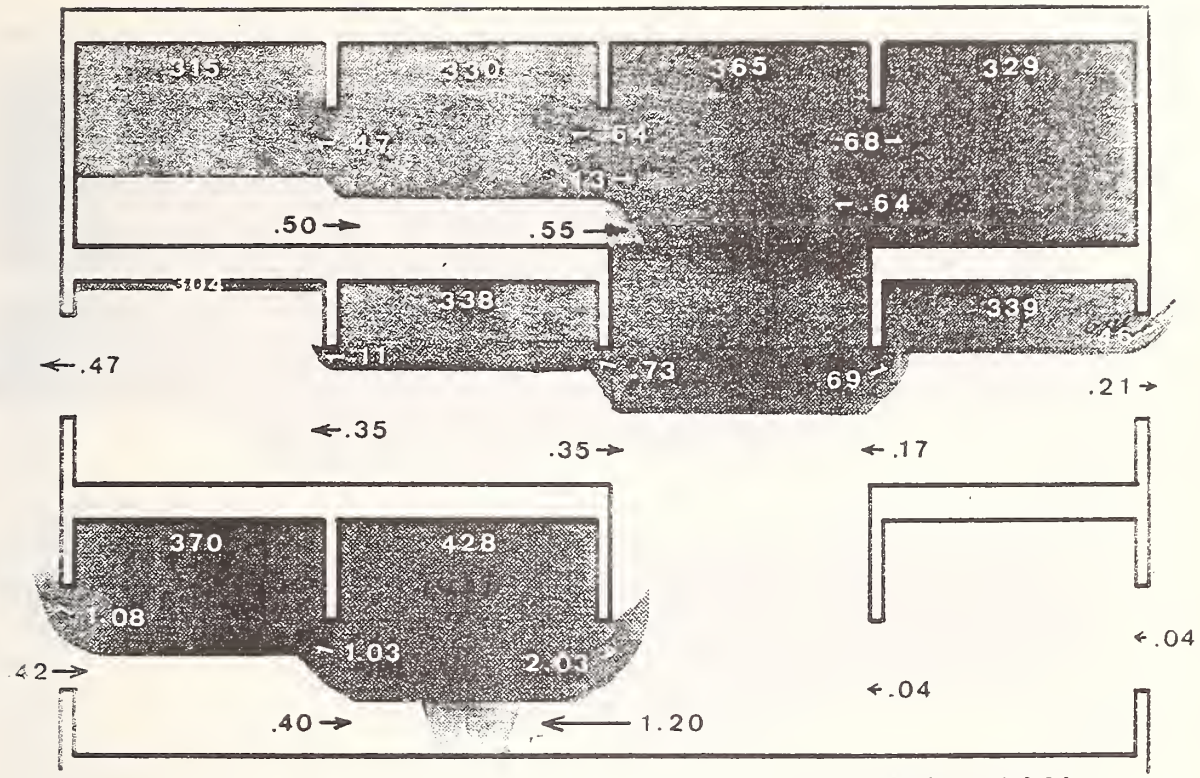

314
327
357
325
.56
.61
.64
.11
.48
.56
.53
322
322
.34
.39
.40
.47
.34
.12
.02
356
407
1.07
1.01
1.97
.36
.31
.31
.27
1.17
2.6 MIN

Fig. 26-c (4)



3.2 MIN

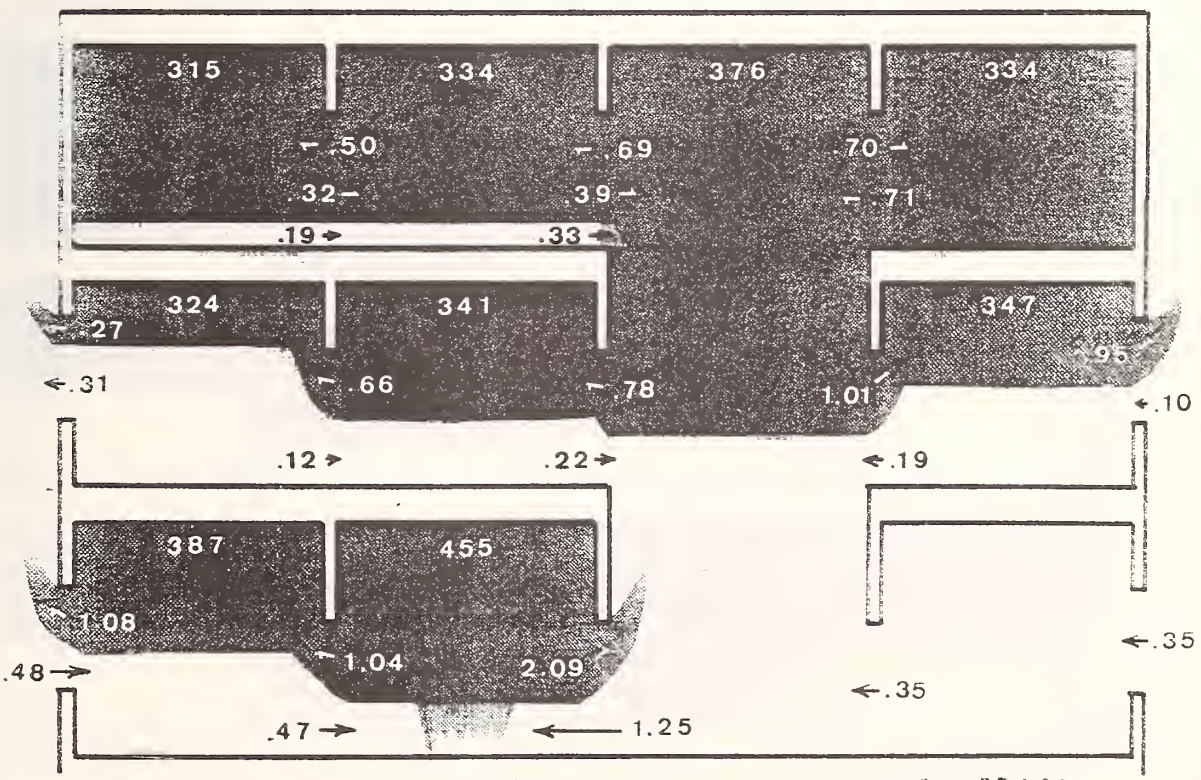
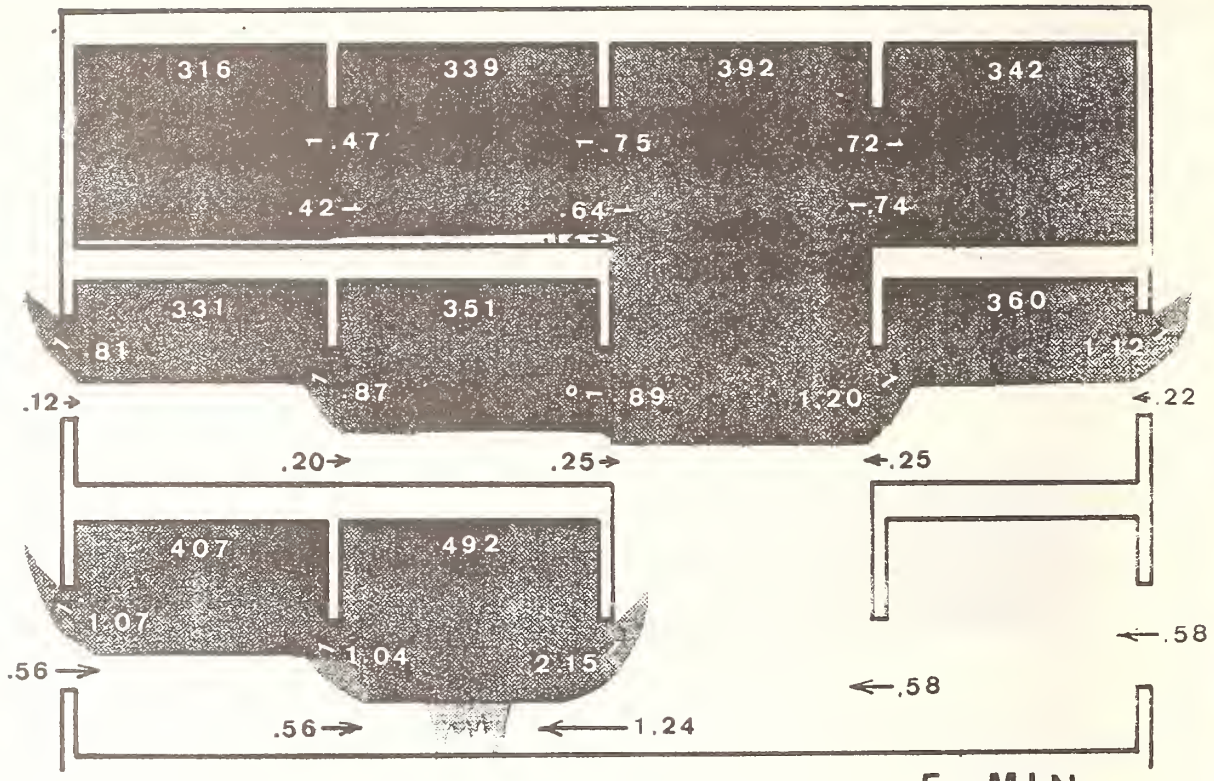


Fig. 26-c (5)

4 MIN


316
339
392
342
.47
.75
.72
.42
.64
.74
331
351
360
.81
.87
.89
1.20
1.12
.12
.22
.20
.25
.25
407
492
1.07
1.04
2.15
.58
.56
.58
.56
1.24
5 MIN

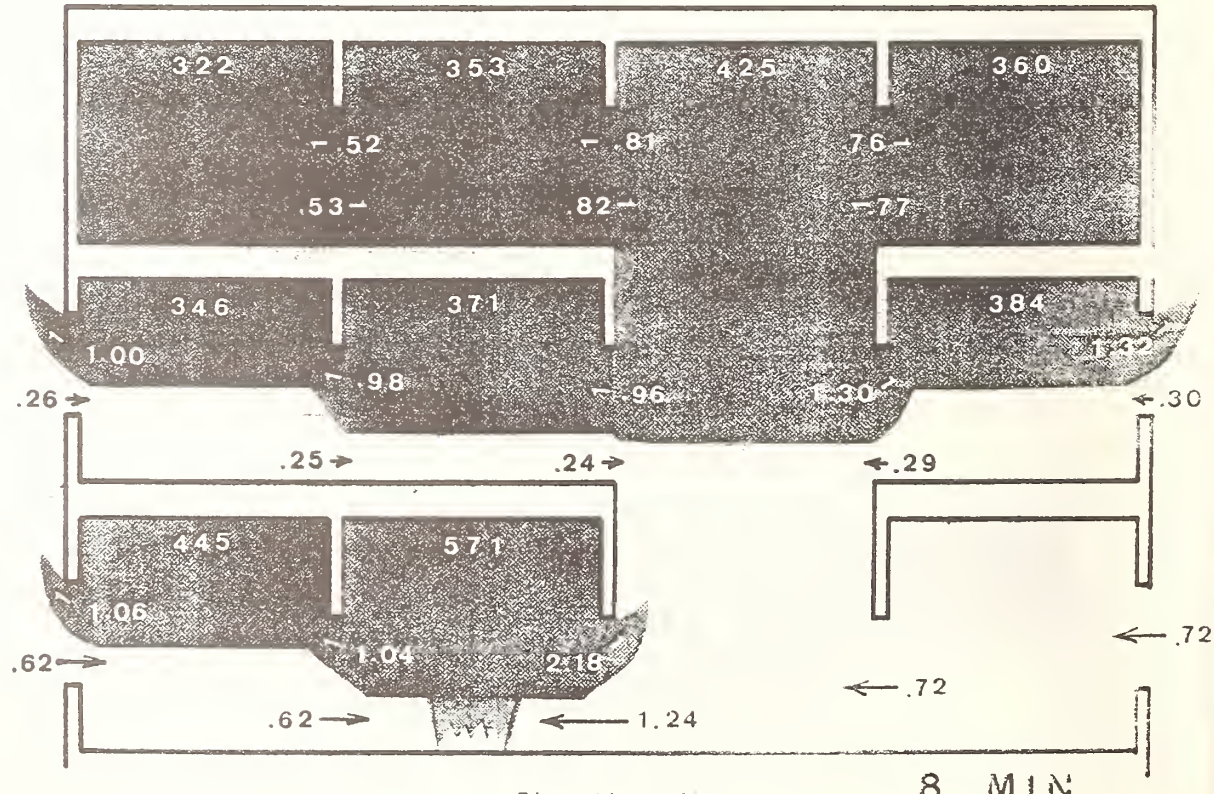
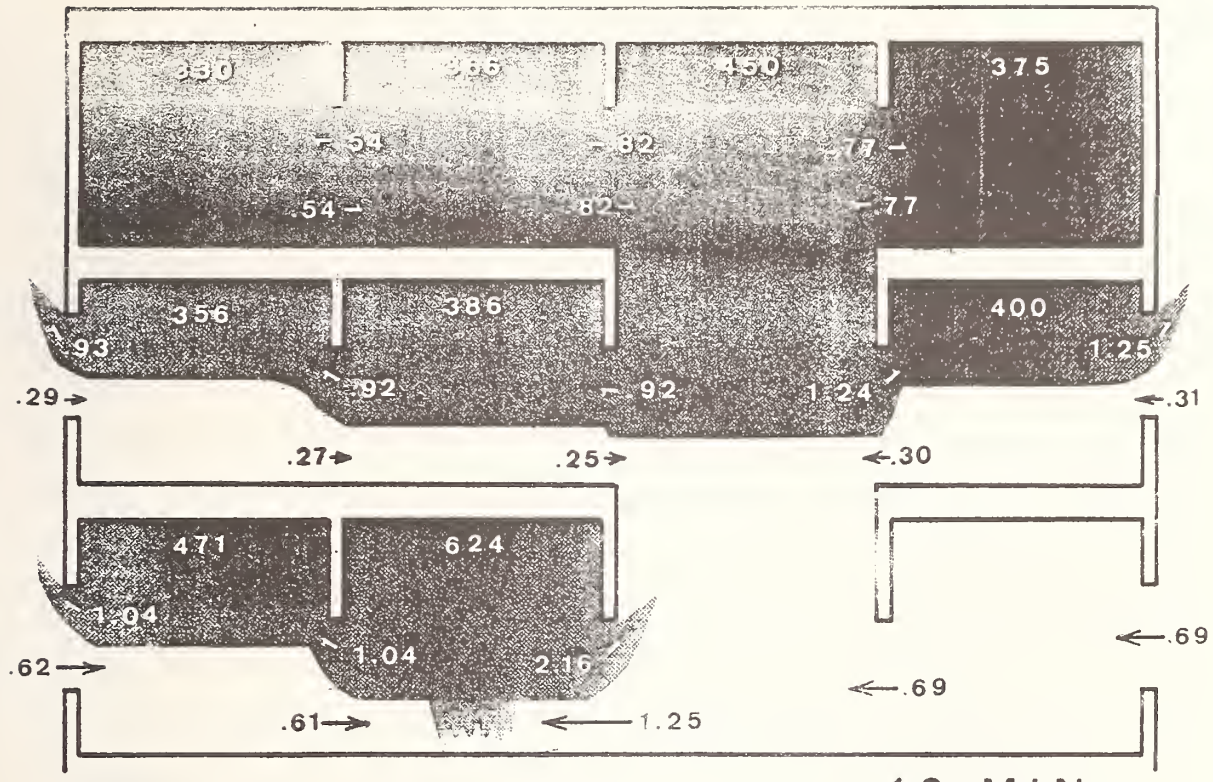

322
353
425
360
.52
.81
.76
.53
.82
.77
346
371
384
1.00
.98
.96
1.30
1.32
.26
.30
.25
.24
.29
445
571
1.06
1.04
2.18
.72
.62
.72
.62
1.24
8 MIN

Fig. 23-6 (c)


330
366
450
375
.54
.82
.77
.54
.82
.77
356
386
400
.93
1.25
.92
.92
1.24
.29
.31
.27
.25
.30
471
624
1.04
1.04
2.16
.62
.69
.61
1.25
.69
12 MIN

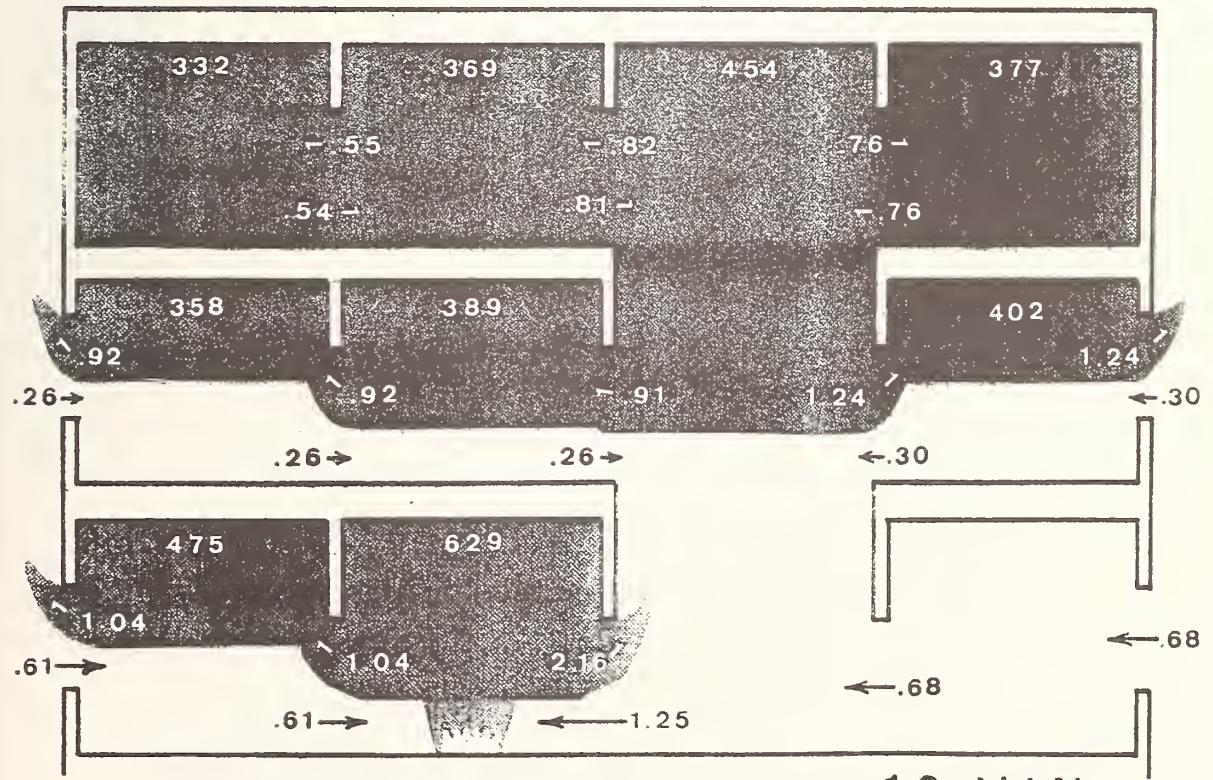

332
369
454
377
.55
.82
.76
.54
.81
.76
358
389
402
.92
1.24
.92
.91
1.24
.26
.30
.26
.26
.30
475
629
1.04
1.04
2.16
.61
.68
.61
1.25
.68
16 MIN

Fig. 26-c (7)

STATISTICAL ANALYSIS OF FIRE SPREAD PROCESS IN HOUSES

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C O N T E N T S

I. Introduction

Fire spread process is dominated by various factors such as live load, interior finish materials, condition of openings, fire extinguishment, etc. There are already many studies on the effect of these individual factors by experimental methods, but statistical studies how the factors functionate at actual fire scenes where the factors are joined together are very few. I think, this is because besides the fire spread phenomenon is very complex and munifold, on-the-spot surveys of fire incidents are attended with many difficulties.

Fortunately, I could have a chance to get considerably detailed fire incident reports concerning to residential fires ignited from living room or kitchen, the number of which is about 1,000. With the fire incident reports, I have done the statistical analysis of fire spread process and the trial of prediction of whole room fire (frequently with flashover) occurrence. This paper is the report of the results.

By the way, in the recent fire researches it is indicated that fire spread process has several phases. Examining various sorts of fire spread process, it seems that there are some cases which have not distinct phases. But, it may be an effectual methods for examining the effects of various fire protections to consider that fire spread process has several phases. So, in this paper the analysis is done under the assumption that the fire spread process has six phases shown at Table 1.

II. Analysis by individual factors

In this paragraph, the results of the statistical analysis

on the effects of the individual factors which dominates fire spread process is discussed.

First, it is necessary to decide the method used for measuring the effects of the individual factors. Based on the assumption stated previously, the fire spread process can be regarded as the transition of phases. Therefore, the effect of factors can be considered as the effect given to the easiness of the transition of phases. This easiness of the transition of phases can be measured with the following two values.

rate of fire spread = n_i/n

transition probability = n_{i+1}/n_i

where n; number of total samples

n_i; number of samples which arrived at $_i$th phase

Analysing the relation between these values and the factors, the effect given to the fire spread process by the factors can be inquired.

By the way, there are various factors which dominate the fire spread process, and also there are various statistical indexes for the factors in analyzing with the statistical methods. However, in selecting the factors or their statistical indexes used for the analysis, they must be essential for the fire spread process, and it is desirable that the independency between the factors is preserved. Being considered these matters, the factors which is shown Table 2 are selected for the analysis.

Fig. 1.1 - 1.8 show the results of the analysis of the rates of fire spread, and Fig. 2 shows the transition probabilities between phases.

To my thinking, the construction of these results are as

follows:

(1) There are considerable differences among the effects of the factors, and the effects depend upon the stage of transition of phases.

For example, concerning to the effect of 'Ignition Pattern', Fig. 2 shows that its effect is high at the stage of transition from Ceiling Phase to Whole Room Phase, but is not so high at the other stages. Specially, it can be understood that at this stage, most of the fires which break out by the ignition pattern from range and the likes to oils and fats and reach at the Partially Burning Phase is extinguished, and this makes the rate of fire spread of this category very different from others. (Fig. 1.1)

Generally speaking, it can be pointed out that the factors which is selected in this analysis shows the highest effect at the stage of transition from Ceiling Phase to Whole Room Phase. After the Inter-Room Phase, the effect of the factors are not distinct except the effect of 'Structure', and it is necessary for more detailed analysis of the stage after the Whole Room Phase to add the factors concerning to the fire extinguishment activity by fire brigades.

(2) The fire which has been extinguished at very early stage of fire spread such as Primary Ignition Phase is likely not to be informed to the fire station in Japan, therefore, the transition probability from Primary Ignition Phase to Partially Burning Phase is considered actually lower than the result given by this analysis. Thus, the analysis of this stage of

fire spread is attended with difficulties.

(3) Doing such statistical analysis as this, it is desirable that the independency between the factors is preserved. However, from the result of χ^2 test shown at Table 3, the independency between the factors is not necessarily preserved, so, the construction of the result of analysis of these sorts cannot but be discreet.

For example, although the factor of 'Structure' shows comparatively high effect at the stage of transition from Partially Burning Phase to Ceiling Phase, this result is considered to be produced by the correlation between 'Structure' and the other certain factor.

III. Analysis by composite factor with the Theory of Quantification

In this paragraph, the factors used for anlyzing by individual factors are composed with the Theory of Quantification, and the relation between the composite factor and the Whole Room Fire (flash over) occurrence is discussed.

Analyzing fire spread process by the composite factor, as the external criterion is given as nominale scale namely phases and the factors are also given as nominal scale, the statistical methods such as Multiple Regression Analysis used for the analysis by the variables given as interval scale cannot be applied. So, in analyzing fire spread process, the 2nd sort of Theory of Quantification developed by Chikio HAYASHI* is used.

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* The Director of Institute of Statistical Mathematics

This method aims to determine the value x_{jk} (category value for factor j, category k), and the category value is determined in the condition that the correlation ratio** calculated with sample score α_i given as below expression.

$$\alpha_i = \sum_j \sum_k \delta_i(jk) \cdot x_{jk}$$

where, $$\delta_i(jk) = \begin{cases} 1 & ; \text{When arbitrary case responses to factor } j \text{, category } k \\ 0 & ; \text{Except above} \end{cases}$$

After estimating the value for x_{jk}, the higher is the effect of the factor, the larger is the range*** in the factor, and also the larger the partial correlation of the factor toward the external criterion, thus the effect of various factors can be compared each other. The further detailed explanation is attached as the appendix after the V_{th} paragraph.

With this method, it is possible to analyze using the six phases as the external criterion, but in this paper, as the analysis with six phases is too complex and the selected factors show high effects at the stage of transition from Ceiling Phase to Whole Room Phase, recomposing the six phases to two stages namely the stage before flashover (Primary Ignition Phase, Partially Burnining Phase, and Ceiling Phase) and the stage after flashover (Whole Room Phase, Inter-Room Phase, and Whole House Phase), the analysis is made using these two stages as the external criterion.

** the ratio of external variance to total variance

*** the range of factor j means the remainder between maximum and minimum of x_{jk} ($k = 1, 2, \cdots\cdots, k_j$)

Fig. 3 shows the results of the analysis with the Theory of Quantification. Looking at the range and the partial correlation, it can be understood that for Whole Room Fire occurrence, the effect of 'Alert Time to Station' is the highest among the factors, and the effects of 'Extinguishment in the Early Stage of Fire Spread', 'Ignition Pattern', 'Rate of Combustible Area on Vertical Face', and 'Combustibility of Ceiling' are comparatively high, however,'Rate of Combustible Area on Horizontal Face' shows low effect.

IV. Prediction of Whole Room Fire occurrence

Using the results of the analysis by the Theory of Quantification, Whole Room Fire occurrence may be predicted.

Fig. 4 shows the distributions of sample scores of the two stages defined in the IIIrd paragraph. From this figure, it can be understood that Whole Room Fire occurs with the higher probability, as the sample score increases, further it may be also understood that there is the discriminant point whether Whole Room Fire occurs or not. Based on this distribution of sample scores, the discriminant point $\alpha_0 = 0.23$ is given in the condition of minimizing the error of discrimination, and using this discriminant point, the rate of success of discrimination is 79%.

For example, in the case that 'Ignition Pattern' is '1; range and the likes to oils and fats', 'Rate of Combustible Area on Vertical Face' is '3; 70%', 'Combustibility of Ceiling' is '3; combustible material', 'Rate of Combustible Area on Horizontal

Face' is '4; 100%', 'Openings' is '3; 6 $m^{5/2}$', 'Structure' is '3; wooden structure', 'Extinguishment in Early Stage of Fire Spread' is '1; being done', and 'Alert Time to Station' is '2; 4 minutes', the sample score αi comes to be 0.36, and the rate of success of discrimination is 79% when Whole Room Fire is considered to occur.

Next, the results of the trial of estimating the relation between the probability of Whole Room Fire occurrence and the sample score are discussed.

Fig. 5 shows the result of estimating parameters in the case of normal distribution from the distribution of sample scores of the two stages with maximum likelihood method, provided that the rate of the number of samples of the each stage to the number of total samples is multipled to the distribution. Further, Fig. 6 shows the distribution of probability of Whole Room Fire occurrence, assuming that above estimated normal distribution is proper. This probability is calculated as follows:

$$P_i(x) = \pi_i f_i(x) / \{\pi_1 f_1(x) + \pi_2 f_2(x)\}$$

where, $P_i(x)$; Probability of success of the prediction that the case, the sample score of which is x, belongs to i group.

$f_i(x)$; Normal distribution of i group.

π_i ; Rate of the number of samples belonging to i group to the number of total samples.

Though Fig. 6 is regarded as the figure which shows only intuitively the relation between the probability of Whole Room Fire occurrence and the sample score as the normal distributions do not follow the distributions of sample score enough, it can be understood that the larger is the sample score, the higher is

the probability of Whole Room Fire occurrence.

By the way, for certifying the propriety of the discrimination and the prediction of Whole Room Fire occurrence, following problems to be examined remain:

(1) Independency between factors;

Table 4 shows the correlations between factors, using the category value which is obtained from the analysis with the Theory of Quantification. Though the correlations between factors are generally low except the one, 0.46, between 'Structure' and 'Combustibility of Ceiling', it must be examined the effect given to the discrimination or the prediction by such correlations between factors.

(2) Fitness of the model;

In the Theory of Quantification, the linear sum of category value is adopted as the model. But, for estimating the fire spread process, better statistical model than the merely linear sum model may exist.

(3) Rate of Whole Room Fire occurrence in the population;

In the discrimination and the prediction of Whole Room Fire, the rate of Whole Room Fire occurrence is given from its number of the sample. But, Stated previously, the fire being extinguished in the very early stage of fire spread are likely not to be informed to fire stations, so the actual rate of Whole Room Fire occurrence may be lower than the one used in this analysis.

V. Conclusions

Through the analysis by the individual factors and the analysis by composite factor with the Theory of Quantification, though it is natural, it has been ascertained that the factors concerning to fire extinguishment has considerably high effect for fire spread, and further, the effect of interior finish materials and live fuel etc. which was indicated by an experimental method has been also ascertained by the statistical method.

Further, using the results of the analysis by the Theory of Quantification, the trial of the prediction of Whole Room Fire occurrence has been made, and several problems concerning to the prediction has been clarified. In the future, if such problems as stated in the IV_{th} paragraph is examined well, the relation between the Whole Room Fire occurrence and the factors will be able to be established, further it will be possible to make cost-benefit analysis.

TAB. 1 PHASES OF FIRE SPREAD

PHASE	EXPLANATION	STATISTICAL INDEX
1; PRIMARY IGNITION PHASE	Initial phase of fire spread.A few materials including ignition source and primary ignited material are burning.	Damaged materials do not exceed two sorts.
2; PARTIALLY BURNING PHASE	Combustion area is limited to the part of fire outbreak room.Furnitures or walls are burning but flame does not touch ceiling yet.	Damaged materials exceed three sorts,and burnt area of ceiling = 0.
3; CEILING PHASE	The phase from the beginning of flame spread over ceiling until whole room fire (flashover) occurrence.	Burnt area of ceiling ≠ 0.
4; WHOLE ROOM PHASE	The phase that whole room is enveloped in flames, generally after flashover.	Floor space of fire outbreak room × 0.8 ≤ Burnt area of floor < Floor space of fire outbreak room × 1.2.
5; INTER-ROOM PHASE	In the adjacent room of fire outbreak room, fire spread starts.	Floor space of fire outbreak room × 1.2 ≤ Burnt area of floor.
6; WHOLE HOUSE PHASE	Greater part of house is enveroped in flames.	Total floor area of house × 0.7 ≤ Burnt area of floor.

TAB. 2 FACTORS AND CATEGORIES

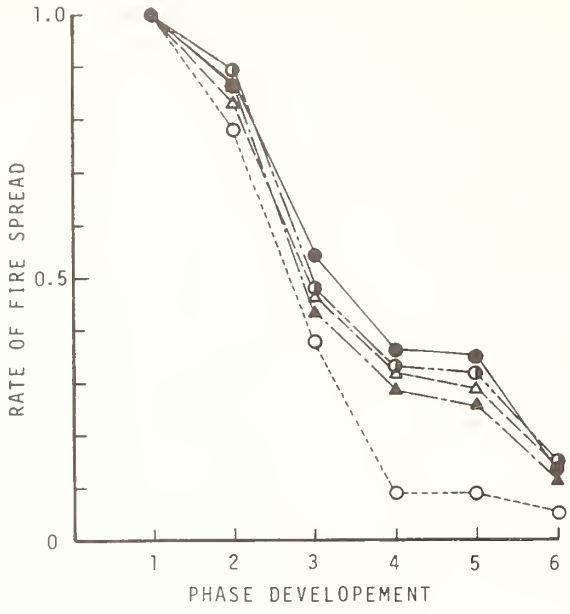
	FACTOR	EXPLANATION OF CATEGORY
IGNITION FACTOR	IGNITION PATTERN	1 Ignition pattern from small kitchen range,range,or water heater to oils and fats (typical ignition pattern at kitchen). 2 Ignition pattern from certain ignition source to imflamable material, oils and fats or explosive substance excluding the pattern stated as 1 3 Ignition pattern from appratus to fiber goods or wastes. 4 Ignition pattern from tobacco to fiber goods or wastes. 5 Ignition pattern from match,lighter,candle or stick of incense to fiber goods or wastes. 6 Ignition pattern from certain ignition source to furnishings or furnitures. 7 Ignition pattern except above 1 - 6 or the ignition pattern is unknown.
FIRE SPREAD FACTOR	RATE OF COMBUSTIBLE AREA ON VERTICAL FACE *	1 0 - 25 (%) 2 25 - 50 3 50 - 75 4 75 - 100 (Fire Outbreak Room)
	COMBUSTIBILITY OF CEILING **	1 Non-combustible material 2 Fire retardant material 3 Combustible material (Fire Outbreak Room)
	RATE OF COMBUSTIBLE AREA ON HORIZONTAL FACE *	1 0 - 75 (%) 2 75 - 100 (Fire Outbreak Room)
	OPENINGS ($\Sigma A\sqrt{H}$)	1 0 - 2.5 ($m^{5/2}$) 2 2.5 - 5.0 3 5.0 - 10.0 4 10.0 - (Fire Outbreak Room)
	STRUCTURE	1 Fire proof structure 2 Fire protective structure 3 Wooden structure
EXTINGUISHMENT FACTOR	EXTINGUISHMENT IN THE EARLY STAGE OF FIRE SPREAD***	1 Being done 2 Not being done
	ALART TIME TO STATION ****	1 - 3 (min.) 2 3 - 5 3 5 -

* In the case that there are combustibles such as combustible furnitures,they are projected to the vertical face (wall) and the horizontal face (floor), and the projected part is regarded as combustible.Next,the projected area and the area of combustible interior finish materials are summed up on the vertical face and the horizontal face,and the rate of the each summed up combustible area to the area of the each face is calculated.

** The testing method of combustibilities of interior finish materials is decided by the law.The order 1 to 3 corresponds to the order of combustibilities.

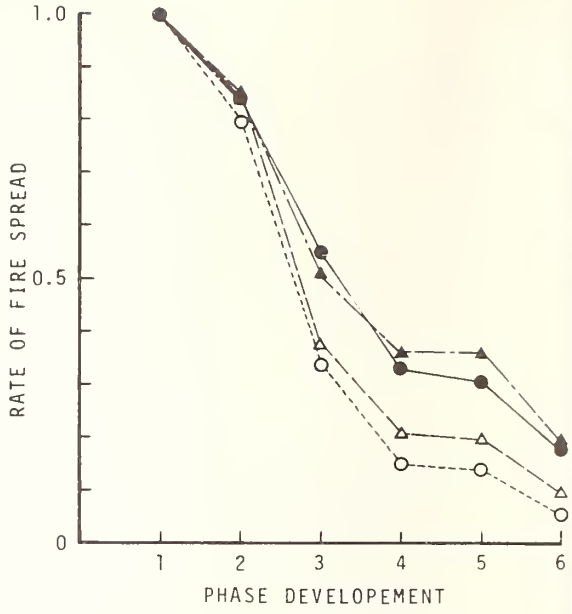
*** Fire extinguishment activity in the early stage of fire spread (generally before flashover) with fire extinguishment equipments such as fire extinguishers.

**** Elapsed time from the ignition time (estimated) to the alert time in fire station.



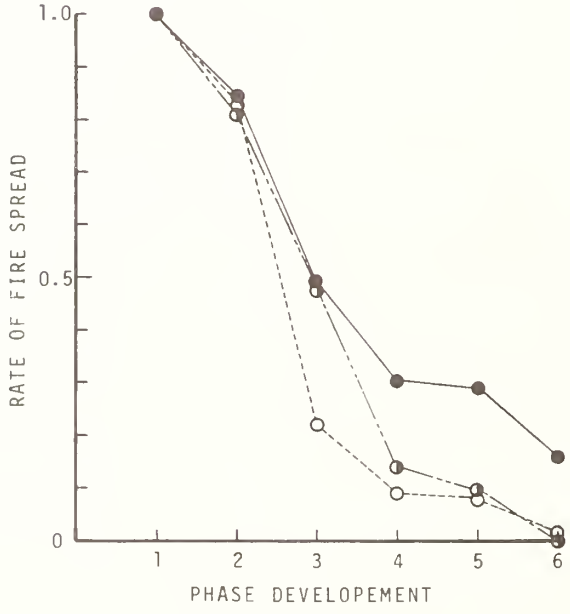
○ RANGE → OILES
△ APP. → FIBER,WASTES
◑ TOBACCO → FIB.,WAST.
▲ MATCH → FIBER,WAST.
● FURNISHING,FURNITURE

FIG. 1 - 1
IGNITION PATTERN



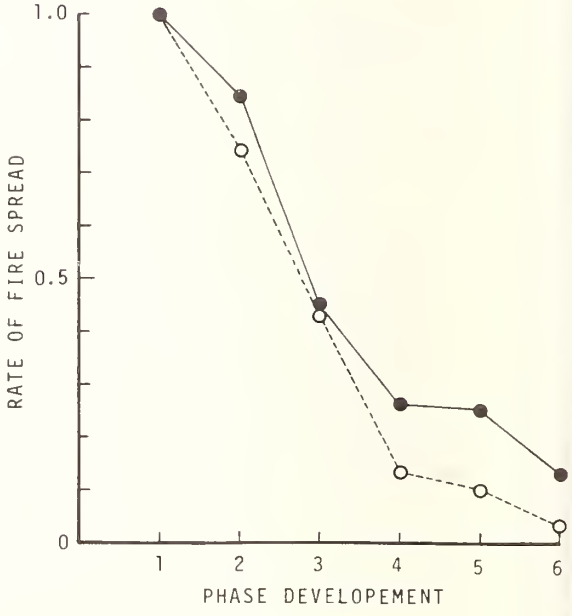
○ 0 - 25 (%)
△ 25 - 50
▲ 50 - 75
● 75 - 100

FIG. 1 - 2
RATE OF COMBUSTIBLE AREA
ON VERTICAL FACE



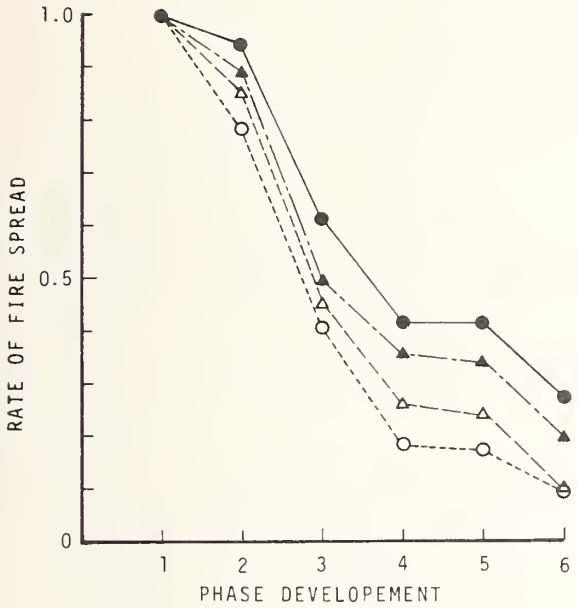
○ NON-COMBUSTIBLE M.
◑ FIRE RETARDANT M.
● COMBUSTIBLE M.

FIG. 1 - 3
COMBUSTIBILITY
OF CEILING



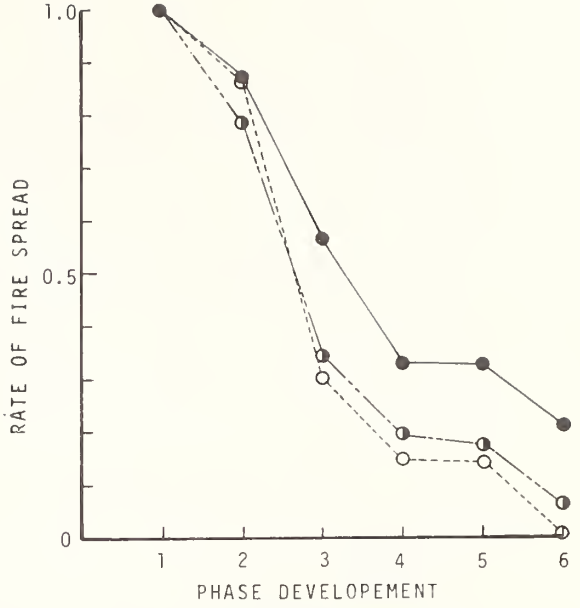
○ 0 - 75 (%)
● 75 - 100

FIG. 1 - 4
RATE OF COMBUSTIBLE AREA
ON HORIZONTAL FACE



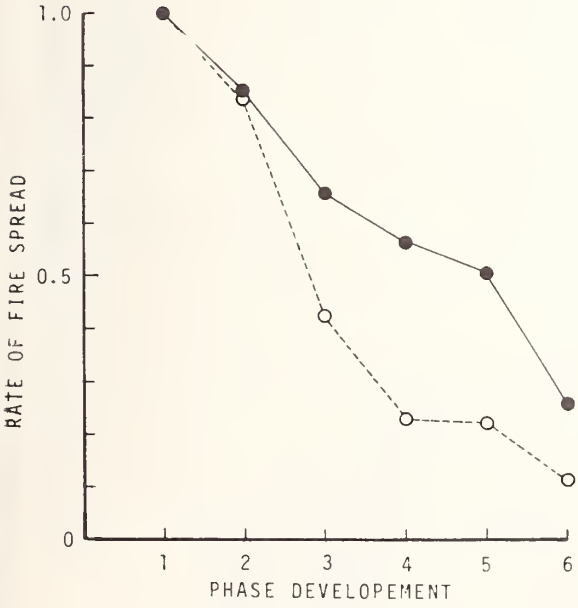
○ 0 - 2.5 ($m^{5/2}$)
△ 2.5 - 5.0
▲ 5.0 - 10.0
● 10.0 -

FIG. 1 - 5
OPENINGS



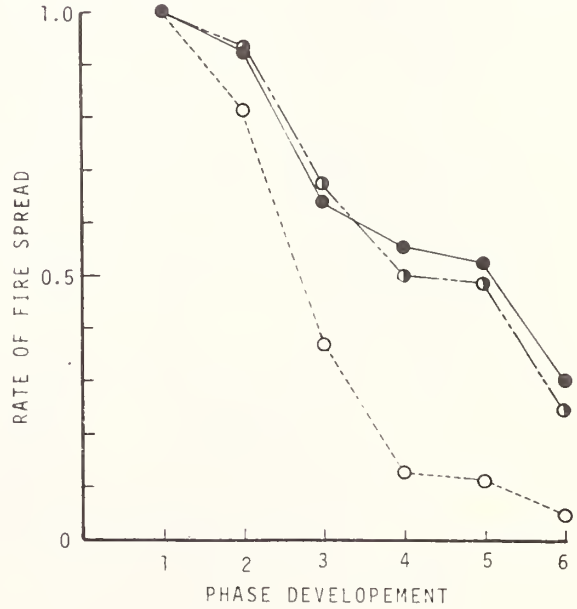
○ FIRE PROOF STRUCTURE
◑ FIRE PROTECTIVE STRUCTURE
● WOODEN STRUCTURE

FIG. 1 - 6
STRUCTURE



○ BEING DONE
● NOT BEING DONE

FIG. 1 - 7
EXTINGUISHMENT IN THE EARLY
STAGE OF FIRE SPREAD



○ - 3 (MIN.)
◑ 3 - 5
● 5 -

FIG. 1 - 8
ALERT TIME
TO STATION

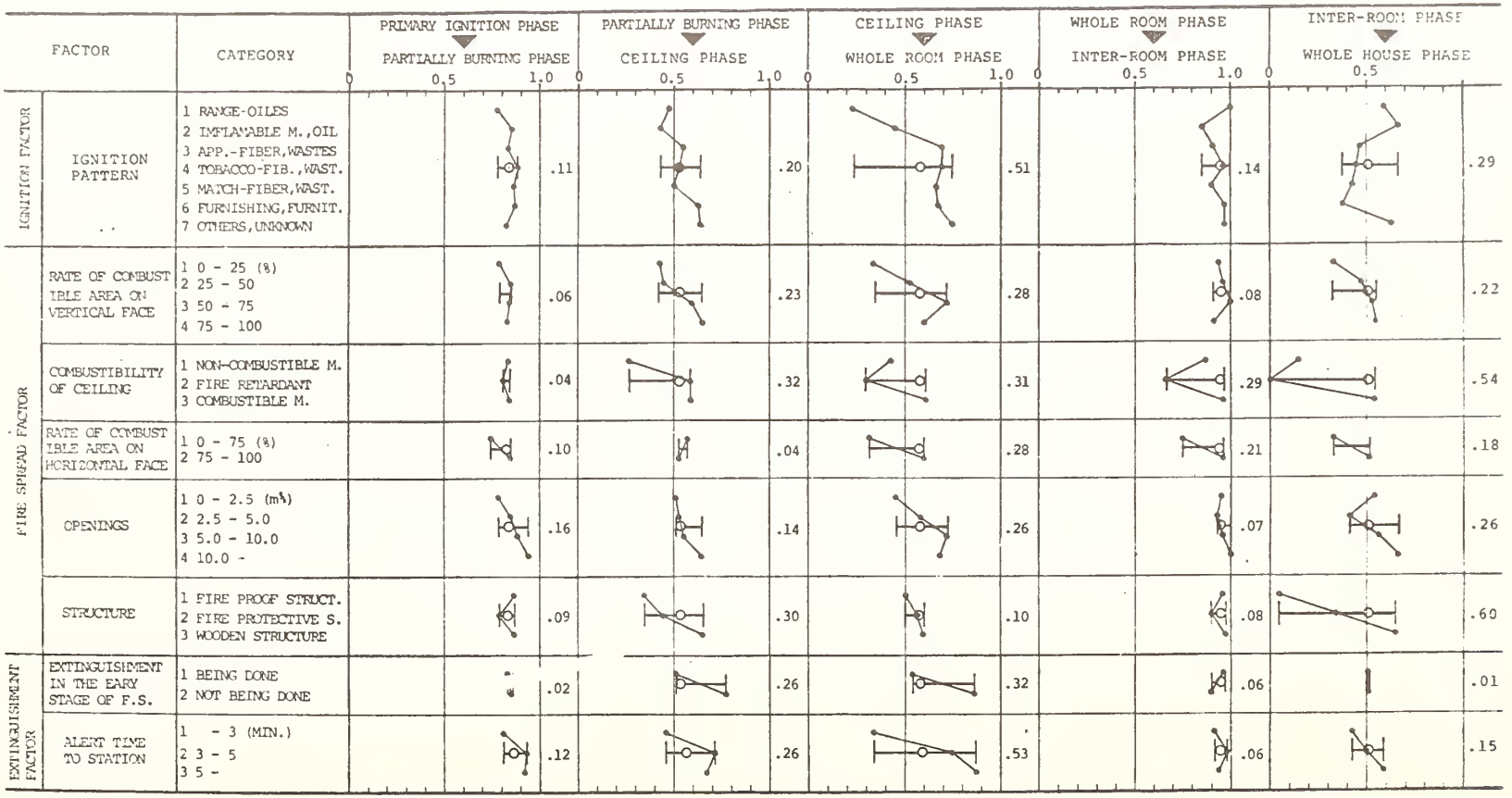


FIG. 2 TRANSITION PROBABILITY BETWEEN PHASES

TAB. 3 THE RESULT OF χ^2 TEST CONCERNING TO THE RELATION BETWEEN FACTORS

	IGNITION PATTERN	RATE OF COMBUSTIBLE AREA ON VERTICAL FACE	COMBUSTIBILITY OF CEILING	RATE OF COMBUSTIBLE AREA ON HORIZONTAL FACE	OPENINGS	STRUCTURE	EXTINGUISHMENT IN THE EARLY STAGE OF F.S.	ALERT TIME TO STATION
IGNITION PATTERN	-	χ^2_2 = 35.4 $\chi^2_{.005}$ = 37.2	40.1 28.3	57.9 18.5	150.1 37.2	7.8 28.3	23.5 18.5	92.2 28.3
RATE OF COMBUSTIBLE AREA ON VERTICAL FACE	×	-	33.6 18.5	10.3 12.8	16.8 23.6	50.0 18.5	3.2 12.8	1.6 18.5
COMBUSTIBILITY OF CEILING	o	o	-	35.9 10.6	33.0 18.5	382.0 14.9	1.0 10.6	6.1 14.9
RATE OF COMBUSTIBLE AREA ON HORIZONTAL FACE	o	×	o	-	18.4 12.8	22.4 10.6	0.0[2] 7.8	1.1 10.6
OPENINGS	o	×	o	o	-	25.1 18.5	5.8 12.8	35.3 18.5
STRUCTURE	×	o	o	o	o	-	5.4 10.6	14.7 14.9
EXTINGUISHMENT IN THE EARLY STAGE OF F.S.	o	×	×	×	×	×	-	11.8 10.6
ALERT TIME TO STATION	o	×	×	×	o	×	o	-

Note : o : The null hypothesis, " Relation does not exist between factors " can be denyed.
× : The null hypothesis, " Relation does not exist between factors " cannot be denyed.
(Significant level ; 0.5 %)

	FACTOR	CATEGORY	SAMPLE	CATEGORY VALUE	RANGE	PARTIAL CORRELATION
IGNITION FACTOR	IGNITION PATTERN	1 RANGE→OILES	202	-0.129	0.316	0.087
		2 IMFLAMABLE M.,OIL	66	-0.071		
		3 APP.→FIBER,WASTES	85	0.029		
		4 TOBACCO→FIB.,WAST.	158	-0.022		
		5 MATCH→FIBER,WAST.	81	0.054		
		6 FURNISHING,FURNIT.	70	0.086		
		7 OTHERS,UNKNOWN	114	0.186		
FIRE SPREAD FACTOR	RATE OF COMBUSTIBLE AREA ON VERTICAL FACE	1 0 - 25 (%)	87	-0.150	0.285	0.076
		2 25 - 50	318	-0.058		
		3 50 - 75	117	0.135		
		4 75 - 100	254	0.062		
	COMBUSTIBILITY OF CEILING	1 NON-COMBUSTIBLE M.	137	-0.116	0.210	0.051
		2 FIRE RETARDANT M.	31	-0.175		
		3 COMBUSTIBLE M.	608	0.035		
	RATE OF COMBUSTIBLE AREA ON HORIZONTAL FACE	1 0 - 75 (%)	46	-0.027	0.028	0.005
		2 75 - 100	730	0.001		
	OPENINGS	1 0 - 2.5 ($m^{\frac{5}{2}}$)	279	-0.014	0.120	0.024
		2 2.5 - 5.0	288	-0.015		
		3 5.0 - 10.0	179	0.030		
		4 10.0 -	30	0.105		
	STRUCTURE	1 FIRE PROOF STRUCT.	122	-0.093	0.157	0.048
		2 FIRE PROTECTIVE S.	273	-0.046		
		3 WOODEN STRUCTURE	381	0.063		
EXTINGUISHMENT FACTOR	EXTINGUISHMENT IN THE EARLY STAGE OF F.S.	1 BEING DONE	701	-0.033	0.342	0.086
		2 NOT BEING DONE	75	0.309		
	ALERT TIME TO STATION	1 - 3 (MIN.)	440	-0.203	0.497	0.193
		2 3 - 5	218	0.252		
		3 5 -	118	0.293		

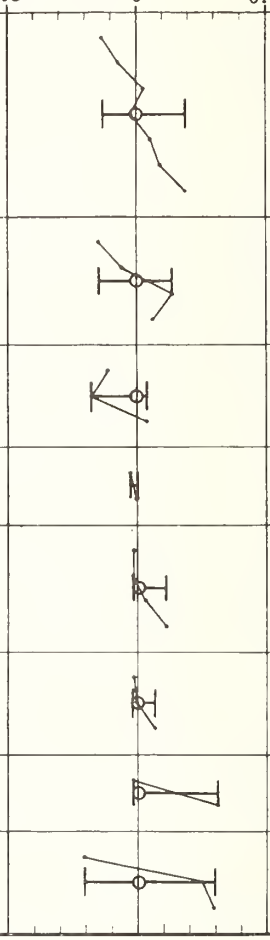


FIG. 3 THE RESULTS OF THE ANALYSIS WITH THE THEORY OF QUANTIFICATION

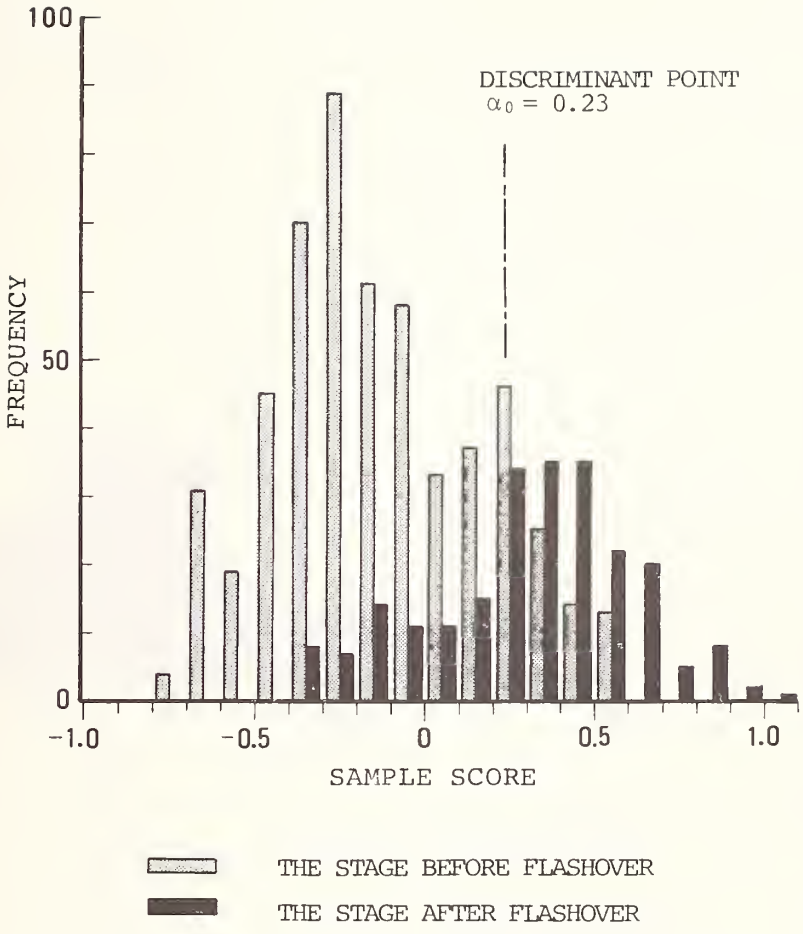
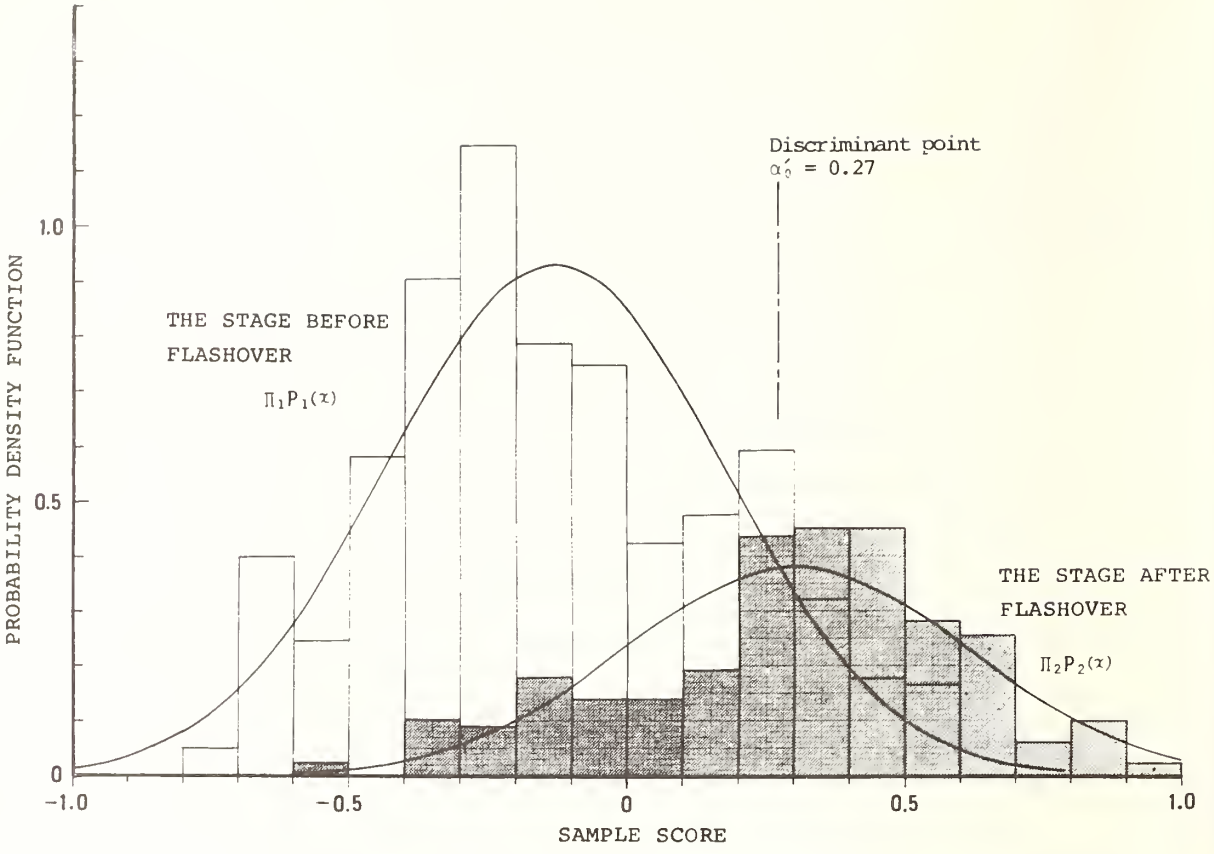


FIG. 4 FREQUENCY DISTRIBUTION OF SAMPLE SCORES



NOTE : $\Pi_1 P_1(x) = \frac{\Pi_1}{\sqrt{2\pi}\sigma_1} e^{\frac{(x-m_1)^2}{2\sigma_1^2}}$

$\Pi_1 = 0.702, \quad m_1 = -0.130, \quad \sigma_1 = 0.301$

$\Pi_2 P_2(x) = \frac{\Pi_2}{\sqrt{2\pi}\sigma_2} e^{\frac{(x-m_2)^2}{2\sigma_2^2}}$

$\Pi_2 = 0.298, \quad m_2 = 0.308, \quad \sigma_2 = 0.319$

Assuming that the normal distribution is proper, the discriminant point α_0' is 0.27, and the rate of success of discrimination is 80%. The discriminant point and the rate of success of discrimination estimated from the normal distribution are nearly equal to the ones directly estimated from the frequency distribution of sample scores.

FIG. 5 PROBABILITY DENSITY FUNCTION OF SAMPLE SCORES IN THE CASE OF NORMAL DISTRIBUTION

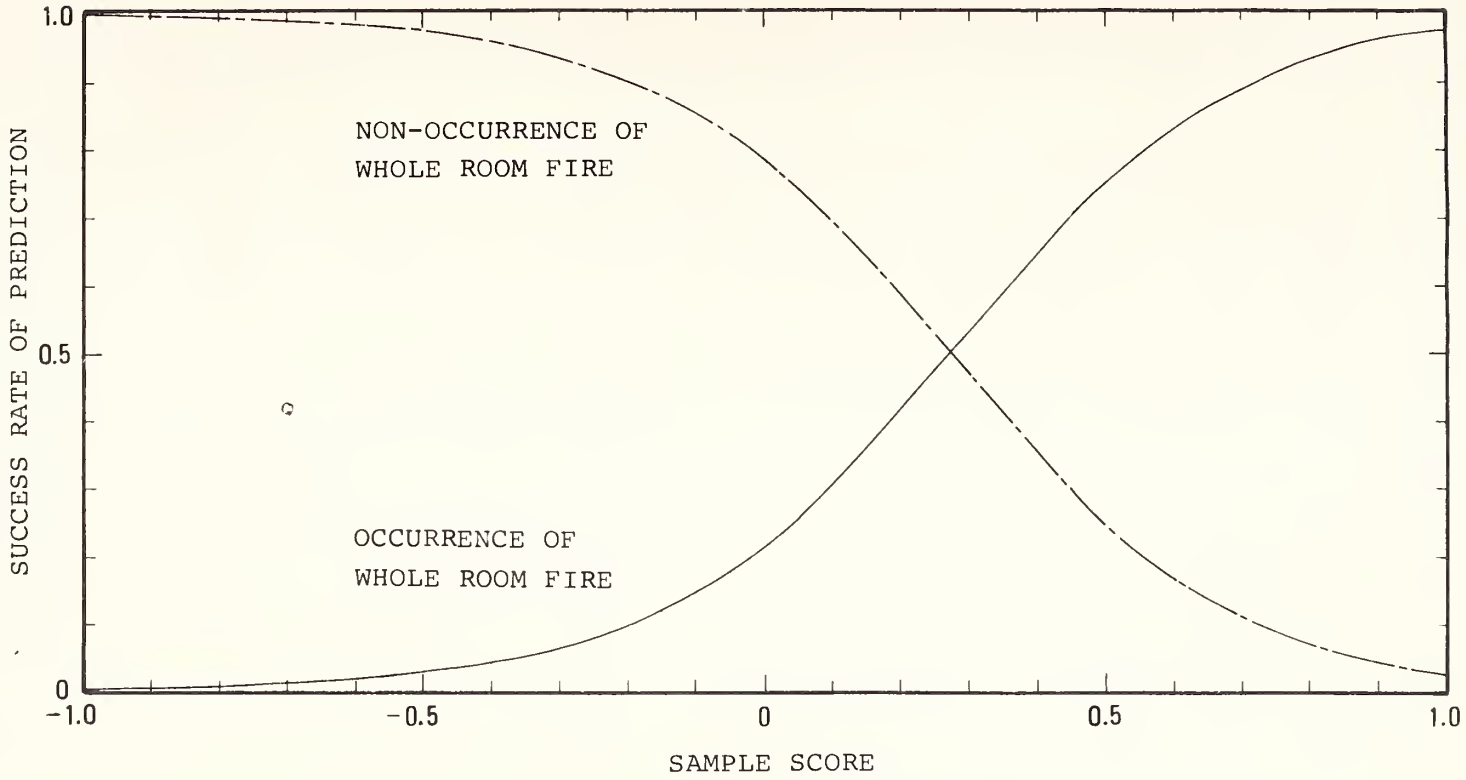


FIG. 6 PREDICTION OF PROBABILITY OF WHOLE ROOM FIRE (FLASHOVER) OCCURRENCE

TAB. 4 CORRELATION MATRIX

	IGNITION PATTERN	RATE OF COMBUSTIBLE AREA ON VERTICAL FACE	COMBUSTIBILITY OF CEILING	RATE OF COMBUSTIBLE AREA ON HORIZONTAL FACE	OPENINGS	STRUCTURE	EXTINGUISHMENT IN THE EARLY STAGE OF F.S.	ALERT TIME TO STATION
IGNITION PATTERN	1.000	0.030	0.095	0.178	0.150	-0.001	0.130	0.210
RATE OF COMBUSTIBLE AREA ON VERTICAL FACE		1.000	0.119	0.070	-0.031	0.197	0.064	0.017
COMBUSTIBILITY OF CEILING			1.000	0.191	0.141	0.456	-0.004	0.064
RATE OF COMBUSTIBLE AREA ON HORIZONTAL FACE				1.000	0.089	0.123	0.008	0.053
OPENINGS					1.000	0.140	0.059	0.129
STRUCTURE						1.000	-0.023	0.069
EXTINGUISHMENT IN THE EARLY STAGE OF F.S.							1.000	0.122
ALERT TIME TO STATION								1.000

A P P E N D I X

Theory of Quantification (II)

Each case of fire incident responses to one of the categories of individual factors, as being showed Fig. A-1. First, the value x_{jk} (category value for factor j , category k) is considered as the variable to be calculated.

Next, the linear sum α_i of the category values which the arbitrary case i responses is considered. Then, the category value x_{jk} is calculated in the condition that the variance of α_i between groups (stages) is maximum and the variance of α_i within the same group (stage) is minimum. That is, α_i is given as follows:

$$\alpha_i = \sum_j \sum_k \delta_i(jk) \cdot x_{jk} \tag{1}$$

where, $\delta_i(jk) = \begin{cases} 1 & ; \text{When an arbitrary case responses to factor } j \text{ , category } k. \\ 0 & ; \text{except above} \end{cases}$

then, using α_i , values indicated below are calculated.

$$\text{total variance;} \quad \sigma^2 = \frac{1}{n} \sum_{i=1}^{n} (\alpha_i - \bar{\alpha})^2$$

$$\text{external variance;} \quad \sigma_b^2 = \sum_{t=1}^{T} (\bar{\alpha}_t - \bar{\alpha}) \cdot \frac{n_t}{n} \tag{2}$$

where, n; number of total samples

n_t; number of samples belonging to group t

$$\bar{\alpha} = \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{R} \sum_{k=1}^{K_j} \delta_i(jk) \cdot x_{jk}$$

$$\bar{\alpha}_t = \frac{1}{n_t} \sum_{i=1}^{n_t} \sum_{j=1}^{R} \sum_{k=1}^{K_j} \delta_i(jk) \cdot x_{jk}$$

then, x_{jk} is determined in the condition as follows:

$$\frac{\partial \eta^2}{\partial x_{uv}} = 0 \tag{3}$$

where, $\eta^2 = \frac{\sigma_b^2}{\sigma^2}$ (correlation ratio)

the equation (3) is expanded as follows:

$$\frac{\partial \eta^2}{\partial x_{uv}} = \frac{1}{\sigma^2}\left(\frac{\partial \sigma_b^2}{\partial x_{uv}} - \eta^2 \frac{\partial \sigma^2}{\partial x_{uv}}\right)$$

so, the next equation must be statisfyed.

$$\frac{\partial \sigma_b^2}{\partial x_{uv}} = \eta^2 \frac{\partial \sigma^2}{\partial x_{uv}} \tag{4}$$

(2) is substituted for (4), the result is arranged as follows:

$$\sum_{t=1}^{T} \frac{n_t}{n}(\bar{\alpha}_t - \bar{\alpha})\left(\frac{\partial}{\partial x_{uv}} \cdot \bar{\alpha}_t - \frac{\partial}{\partial x_{uv}} \cdot \bar{\alpha}\right)$$

$$= \eta^2\left(\frac{1}{n}\sum_{i=1}^{n} \alpha_i \cdot \frac{\partial \alpha_i}{\partial x_{uv}} - \bar{\alpha} \cdot \frac{\partial}{\partial x_{uv}} \cdot \bar{\alpha}\right) \tag{5}$$

where,

$$\left.\begin{aligned}
\frac{\partial}{\partial x_{uv}} \alpha_i &= \frac{\partial}{\partial x_{uv}} \sum_j \sum_k \delta_i(jk) \cdot x_{jk} = \delta_i(uv) \\
\frac{\partial}{\partial x_{uv}} \bar{\alpha}_t &= \frac{1}{n_t} \frac{\partial}{\partial x_{uv}} \sum_{i=1}^{n_t} \sum_j \sum_k \delta_i(jk) \cdot x_{jk} = \frac{1}{n_t} \sum_{i=1}^{n_t} \delta_i(uv) \\
\frac{\partial}{\partial x_{uv}} \bar{\alpha} &= \frac{1}{n} \frac{\partial}{\partial x_{uv}} \sum_{i=1}^{n} \sum_j \sum_k \delta_i(jk) \cdot x_{jk} = \frac{1}{n} \sum_{i=1}^{n} \delta_i(uv)
\end{aligned}\right\} \tag{6}$$

(6) is substituted for (5) and the result is arranged as follows:

$$\sum_j \sum_k \left(\sum_{t=1}^{T} \frac{g_t(jk) \cdot g_t(uv)}{n_t} - \frac{n_{jk} \cdot n_{uv}}{n}\right) \cdot x_{jk}$$

$$= \eta^2 \sum_j \sum_k \left(f(jk, uv) - \frac{1}{n} \cdot n_{uv} \cdot n_{jk}\right) \tag{7}$$

where,

$$\left.\begin{aligned} g_t(jk) &= \sum_{i=1}^{n_t} \delta_i(jk) \\ n_{jk} &= \sum_{t=1}^{T} g_t(jk) \\ f(jk, uv) &= \sum_{i=1}^{n} \delta_i(jk) \cdot \delta_i(uv) \end{aligned}\right\} \quad (8)$$

then, the substitutions are done as follows:

$$\left.\begin{aligned} H &= \{ h_{uv}(jk) \} \\ X &= \{ x_{jk} \} \\ F &= \{ f_{uv}(jk) \} \end{aligned}\right\} \quad (9)$$

where,

$$h_{uv}(jk) = \sum_{t=1}^{T} \frac{g_t(jk) \cdot g_i(uv)}{n_t} - \frac{1}{n} n_{jk} \cdot n_{uv}$$

$$f_{uv}(jk) = f(jk, uv) - \frac{1}{n} n_{uv} \cdot n_{jk}$$

then, the correlation ratio η^2 is determined as the eign value and category value x_{jk} is determined as the eign vector in the following equation for eign value:

$$HX = \eta^2 FX \quad (10)$$

FACTOR	CATEGORY	CATEGORY VALUE	1st GROUP				--------	Tth GROUP		
			1	2	----------	n_1		1	----------	n_T
1	1 2 ⋮ k_1	x_{11} x_{22} ⋮ x_{1k_1}	✓	✓		✓		✓		✓
2	1 2 ⋮ k_2	x_{21} x_{22} ⋮ x_{2k_2}	✓	✓		✓		✓		✓
⋮	⋮	⋮								
R	1 2 ⋮ k_R	x_{R1} x_{R2} ⋮ x_{Rk_R}	✓	✓		✓		✓		✓

NOTE: ✓ indicates the category that case i responses.

FIG. A - 1

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Theme

MODELING

OF FIRE

EXPERIMENTAL STUDY OF COMPARTMENT FIRES USING MODEL BOXES

by

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Preface

The rational design of fire protection engineering in buildings requires a thorough understanding of the fire behaviour, and it is known that the behaviour of fires in compartments is dependent on many factors. Kawagoe and Sekine[1] reported that openings could be the biggest controlling factor, and their experiments and theory have been supported by most researchers throughout the world.

The behaviour of a fire in a compartment depends on the basic burning characteristics and shape of the combustibles, and their position as well as on the compartment and its properties. In particular, the burning characteristics of lining materials have a significant influence on the growth and behaviour of compartment fire, but there is little information concerning their assessments.

Studies on compartment fires have been made mainly with compartments composed of noncombustible wall materials and very little work has been done with compartments composed of combustible interior linings.

While it is necessary to consider combustion prevention measures, for the fire protection of buildings, compartments are living spaces and an indue emphasis on the demand for fire protection may lead to undue interference with other necessary physical or human engineering requirements. In other words, fire safety should be considered as a total design of compartment space.

At present, even though detailds of the burning behaviour

of compartments are still unknown, it is considered necessary to develop immediate measures for taking into account quantitatively the influence of materials on fire risk with the help of some suitable method. An attempt has been made to clarify the influence of interior linings using model tests within which the interaction of the burning of interior combustibles could be easily grasped.

1. The Test Models

In preparing the model, although similarity becomes an obvious problem, at this stage the tests were carried out using rectangular boxes for the compartment as previously used by other researchers such as S. Yokoi[2], K. Kawagoe[1], P. H. Thomas[3], D. Gross[4], and etc., without giving much attention to the problem of similarity. The openings in the models used in these tests are in direct contact with the atmosphere, and air flows into the compartment without any resistance. However, as the flow of air into the burning compartments of actual buildings generally passes through the corridor, a corridor portion was added to the model as shown in Figure 2. This method has an advantage in that the total amount of smoke emanating from the burning compartment and the total amount of air entering into the burning compartment could be measured. In this report, the former type will be named as simple model box (Fig. 1), while the latter will be known as dwelling model box (Fig. 2).

The size of the models and the openings is shown in

Table 1, and the models are classified by three different sizes.

2. Experimental Procedure

Since the shape of the openings is a major factor that governs compartment fire, the tests were conducted with openings as the main variable factor while varying the kinds of interior linings and the amount of other combustibles.

In other researchers' studies, the openings are situated at both the front and back of the compartments. However, since it was decided to quantify the smoke release characteristics during the burning of the compartment, only one opening was provided in these tests.

The tests were divided into two categories, namely, those made for the purpose of clarifying the burning characteristics of various kinds and thicknesses of linings in the compartment and those made for the purpose of clarifying the phenomenon of the interaction of the burning of linings and other comustibles. In the former only the crib (and linings) used for an ignition source was (were) varied, while in the latter, specific fire load (the weight of fuel per unit compartment volume) was varied as in previous investigations (Table 2 & 3).

The sticks used for the ignition source for the first group of tests had a cross section of 2 x 2 cm and were cut to a particular length (ℓcm). Sticks were arranged on a square of side ℓ cm and separated at a spacing of 2 cm.

This ignition source was placed at the corner of the model, 5 cm away from the side walls in the case of SHL type and 2 cm in the case of SHS type as shown in Table 1. The source was ignited after inserting an alcohol soaked insulation board of the dimensions 1 cm x 1 cm x ℓcm into the bottom layer.

In the second group of tests the fire load was, for simplicity, in the form of wooden cribs. The cross section of the sticks was 2 cm x 2 cm and the cribs were placed on the whole surface of the bottom layer at intervals of 2 cm and 5 cm away from the side walls. The ignition method adopted was the same as that used for the first group, except that the width of the insertion of the alcohol soaked insulation board was limited to the width of the opening.

3. Method of the Analysis of Results

Measurements and observations were made of the mass loss, smoke density, CO-concentration and dynamic pressure in the fixed passage. Since the purpose of these tests was to quantify the smoke and gasses that diffuse through buildings during fires, the measurements of smoke and gases were made outside the compartment after oxidation in the compartment. The values obtained from the tests were arranged as follow.

3.1 Burning Rate

The value of the burning rate is fundamental characteristic in the analysis of various phenomena of burning.

Perhaps because the initial stage of fire is within the unstable period, the burning rate has often determined by the time for the mass of unburnt combustibles to fall from 80% to 50% or from 80% to 30% of its initial value.

However, observations show that the production of smoke and gases during the initial stage of fire is large, especially when the internal linings are combustible. Therefore, the progress of the fire is divided into two periods, namely, the flashover period and the steady state period, and the results are arranged for the former case. An instantaneous burning rate was determined from the gradient of the total weight loss curve and a mean burning rate from the change in the weight during the relevant period.

3.2. Characteristics of Smoke and Gas Generation

Evaluation of the hazard of the smoke generated from a compartment fire can be made by the extinciton coefficient or by the smoke generation rate which is given by the product of the flow rate of combustion gas including smoke particles and the concentration of the gas.

The smoke hazard in terms of fire prevention engineering should be evaluated in relation to evacuation under a fire condition, and it means that it should be evaluated by the flow rate of the smoke in the building.

As the unit of smoke concentration in terms of fire prevention engineering, the extinction coefficient given by the equations is used, and the relation between extinction

coefficient and visibility through the smoke has been clarified by T. Jin.

$$I = I_o e^{-C_s L}$$

$$C_s = \frac{1}{L} \ln \frac{I_o}{I}$$

where

I : light intensity with smoke

I_o: light intensity without smoke

L : length of light path (m)

C_s: extinciton coefficient (1/m)

To express the extinciton coefficient in this equation, many symbols such as ε, τ, σ, D and etc., are used. However, although it is not satisfactorily confirmed yet, the range of the concentration of the smoke generated from a fire is very wide. Therefore it cannot definitely be said that the above eqations are applicable for the smoke concentration of a wide range, as long as the smoke concentration is measured by the light transmittance, because there are overlaps of smoke particles in the light beam path. Consequently in this report the simbol, C_s, is used to express the extinction coefficient in the meaning of the smoke concentration.

When smoke is produced in a smoke accumulating chamber of a particular volume, the smoke generation rate S is given as the following equation:

$$S = \frac{dC}{dt} = V \cdot \frac{dC_s}{dt}$$

where

S : smoke generation rate (m^2/min or $C_s m^3$/min)

V : volume of smoke accumulating chamber (m^3)

But this equation is not applicable to obtain the rate of the smoke generated from a compartment fire, because a smoke accumulating chamber of a very large volume will be needed, which is impossible. In such a case, it can be obtained by the product of the flow rate of the combustion gas and the smoke concentration, which are measured at each given time.

As the methods of the measurement, two ways could be considered: one is the measurement at the opening of the compartment and the other is the measurement in the flow passage of a fixed cross-section where the smoke is passing.

In the former method, measurement at many points will be necessary because the neutral zone changes with the fire growth. What is more important here, since the smoke cannot be measured by the light transmittance direcly in the flaming, a temperature compensation type sucking smoke meter must be employed for measuring smoke concentration. In this case, smoke particles would be adhered to the sucking pipe and condense, and this makes a big difference in the measured values.

Furthermore, the smoke generation rate which should be obtained here is that for the smoke dispersing in the building. Since compartment fires are in most cases ventilation controlled fires, oxidation of the smoke particles takes

place also outside the opening when the opening area is small. Therefore the smoke concentration after the oxidation should be measured away from the opening.

For these reasons, the latter method of measurement is taken to obtain the smoke generation rate in this report. And it is also because of the assumption that closer approximate values would be obtained by this method than the former one, although the absorption of smoke particles to the walls of the flow passage cannot be neglected. Therefore the smoke generation rate is given as follows:

$$\frac{dC}{dt} = C_{si} \cdot \frac{dv}{dt}$$

$$= C_{si} \cdot \alpha A \sqrt{2g \Delta p \cdot \rho \frac{273+\theta}{273}}$$

where

C_{si} : extinction coefficient

α : coefficient of flow (dimensionless)

A : cross-sectional area of flow passage

Δp : dynamic pressure in flow passage

ρ : smoke density

θ : temperature of flow passage

And the same consideration was taken for the measurement and calculation of the CO gas release rate. From the product of velocity and the measured concentration, the respective rate of smoke and CO gas generation were calculated.

These were claculated by a TOSBAC-2000 computor. A smoke generation coefficient was obtained by calculating the smoke generation rate per unit of burning rate.

4. Results and Discussion

4.1. Tests for the Burning Characteristics of Internal Linings

i) Flashover (F.O) and Its Time (F.O.T)

The phenomenon of flashover (F.O) is well known as a special burning phenomenon associated with compartment fires. As is clearly seen from a Figure 4.1, there is a rapid rise in temperature and a rapid generation of smoke.

In qualitative terms, flashover generally refers to a rather rapid transition from a localized fire in one portion of a compartment to a much more intense fire in which every exposed combustible surface in the compartment is undergoing pyrolysis, at least, if not burning.[5]

However, it is very difficult to determine exactly the transitional point by experiment, because this transitional phenomenon moves through a rapid continuum.

J. B. Fang[6] proposed an average upper room gas temperature of 450°C - 650°C as the boundary between limited and full involvement from the spontaneous ignition of paper.

In the instant when flashover occurs, many changes of behaviour like the emission of flame and smoke from the opening, increase in the room temperature and radiation to the floor etc., take place. Therefore, we might expect to obtain the instant of flashover by measuring the aforementioned values. However, in reality, experiments revealed that there are two major difficulties in determining actual flashover time. One is that flashover takes place not in

instantaneous jump, but over a small but finite time. Secondly, as shown in Table 4, the points at which the various factors, like smoke and flame, begin to change within its time are different. In this study flashover time was determined mainly by observation of the variation of the temperature at three-quarters of the compartment height in the centre of the compartment. Generally, the time lapse prior to F.O. varies with the amount of heat received by the materials and the kinds of materials, and it is considered to be largely influenced by the pyrolysis characteristics and thermal properties of the materials and the ratio of the volume of compartment to the burning rate of the ignition source (Fig. 3 - 5, Table 5).

In other words, flashover is expected to take place when the ratio of the amount of inflow air and the concentration of the flammable gases accumulated in a compartment (i.e. the flammable gases not yet finished reacting which are released by the burning of materials in the compartment including interior linings) satisfies a certain range of conditions. Therefore the time to reach flashover (F.O.T) is determined in relation to the size of the fire source, pyrolysis properties of the materials, the volume of the compartment, openining factors and etc.

ii) Burning Rate

As shown in Figure 6, the burning rate varies largely with time. The following formula is used as the general

formula of the burning rate of the compartment.

$$R = 5.5\ A\sqrt{H}\ (kg/min)$$

However, when the internal linings are combustible, there is an acceleration due to the burning of the material as shown in Table 6 - 7, and accordingly it is necessary to make an adjustment dependent on the characteristics of the material.

$$R = \alpha_M \cdot 5.5\ A\sqrt{H}\ (kg/min)$$

In other words, this value α_M represents the acceleration of combustion of the material and has a tendency to increase with the decrease in size of the opening as shown in the table. In models, when their proportions of the shape are same, there is a tendency for the heat loss from the surface to increase and the burning rate to decrease, since the ratio of the surface area of the compartment to the volume of it increases with the decrease in the surface area. Therefore, analysis was done again and the tendency is shown in Figure 7.

Furthermore, it is generally pointed out that even the same material makes a large difference in its burning characteristics according to whether the material is used as the ceilings or as the walls. In order to experimentally clarify this phenomenon in a compartment fire, the burning rate was determined by varying the attitude of the material used and the results are shown in Table 8. When the burning rate per unit exposed surface area is considered, the area

of combustible materials used per unit volume is found to have a larger influence than even the position and it is confirmed from these tests that the burning area or in other words the surface area of the combustibles becomes an important factor.

Furthermore, the heat loss from the walls cannot be neglected. Since the heat loss from the wall composed of thin boards could be more significant than that of thick boards, room temperature should be higher for the latter. Consequently, in the case of compartment fires, the burning rate for a wall composed of thin board could be lower than for one of thick board although thin board is generally more flammmable. For these reasons, the burning rate is expected to reach the maximum at an optimum balanced condition of heat release by pyrolysis and heat loss from the wall as shown in Fig. 8.

iii) Generation of Smoke and CO Gas

In our experiments, dynamic pressure, temperature and concentration of smoke and gas were measured in the hood at one point, as mentioned in 3.2. The values obtained were scattered widely because, unlike the measurement of weight loss, the measurements of varying smoke and gas concentration and of dynamic pressure are difficult to make.

Therefore we can only discuss the characteristics of smoke and CO gas generation from a compartment in general terms. Some examples of the test results are shown in

Tables 9 & 10 and Figs 9 & 10.

Generally, the trends for smoke and CO gas generation rate are analogous to that for the burning rate. They differ in that the measurements of the smoke density vary with the space where smoke is accumulated in the compartment, or in other words, with the depth of soffit.

As shown in Figures 11 & 12, the greater the volume of accumulated smoke, the greater the oxidation ratio of smoke particles is within the compartment and hence the smoke generation rate is small. Furthermore, when the opening factor is small, dense smoke is generated because the inflow of air is retarded.

iv) Back Draft Phenomenon

Whilst the burning process in compartments has not been sufficiently understood, the combustible gases accumulated in the compartment are considered to play an important role.

To support the above, the variation of the amount of air inflow through the air inflow section equipped at the end of the corridor in the dwelling model box is shown in Figure 13.

The air inflow is rapidly retarded with the flashover and a vibration phenomenon is observed. This is caused by the rapid oxidization of gases accumulated in the compartment, and this remarkable occurrence is known as the back draft phenomenon.

4.2. Interactional Burning of Linings and Other Contents

Representative results of the experiments are shown in Figures 14 - 16. As a general tendency, the rate of release of smoke and CO gas is high in the early stage of the fire even when there are combustibles in the compartment and this tendency becomes more remakable when the internal linings are readily flammable. Therefore, emphasis was placed on the behaviour in the early stage of fire.

i) Burning Rate

Compartment fires after flashover can be classified into fuel controlled and ventilation controlled fires, according to the ratio of the amount of combustibles to the opening factor.

Generally it is said that the burning rate in a compartment fire is a fixed value, determined only by the parameter of the opening factor. However, when the linings are combustible the burning rate changes with time as shown in Figure 17.

It is generally understood that the burning of linings develops with time from the pyrolysis burning to the surface burning which is the burning of solids. Namely even when the compartment conditions imply that it is a ventilation controlled fire, the compartment fire initially develops through pyrolysis burning controlled by the exposed surface area and burning characteristics of all the combustible materials. Therefore, the burning rate is generally high

in the early stages of a fire.

When the linings are combustible, the burning rate differs greatly from the estimated value of $R = 5.5\ A\sqrt{H}$ especially in the early stage of the fire. On the contrary, when the lining materials are noncombustible, burning rate is the same as the estimated value. In both cases the amount of fuel affects the burning rate as shown in Figure 19.

To represent the burning rate of the compartment fire, we have the following formula of Kawagoe, Sekine, and Thomas, which was established theoretically and proved experimentally.

$$R = 5.5 \sim 6.0\ A\sqrt{H}$$

However, the burning rate in the flashover period, determined by the above formula as shown in Figures 20 & 21, could not establish the above proportional relationship. This may be attributed to the following.

In the previous section on the tests for the properties of materials, we mentioned that the opening factor ($A\sqrt{H}$), volume of compartment (V), and exposed surface area of combusibles (A_S) etc., are the factors that have an effect on the burning rate in a compartment fire.

That is to say, the burning of substances in enclosed space, such as in furnaces, is determined by the excess air ratio, in other words, air supply in relation to the concentration of flammable gases produced by pyrolysis.

Therefore, the value of V should be the effective free shape volume, V_E, where oxidation takes place. V_E is obtained by deducting the volume of combustibles in the

compartment from the volume of the compartment. For these reasons, in connection with the early stages of fire, which involves pyrolysis burning, it is necessary to adopt the following parameter.

$$B_f \text{ (Burning character)} \propto \frac{\text{excess air ratio}}{\text{rate of pyrolysis}} \propto \frac{(A\sqrt{H}/V_E)}{A_S}$$

When Figures 20 & 21 were rearranged, a strong correlation was noticed as shown in Figures 22 & 23. The following empirical formulae are derived from Figures 22 & 23.

When the interior linings are non-combustible (Fig. 22),

$$R_v = 3.0\ B_f^{0.8}$$

$$\text{i.e. } R = 3.0\ (A\sqrt{H})^{0.8} \cdot (A_S \cdot V_E)^{0.2}$$

where

$$R_v = (R/A_S)/V_E$$

and when the interior linings are plywood (Fig. 23),

$$R_v = 6.0\ B_f^{0.8}$$

$$\text{i.e. } R = 6.0\ (A\sqrt{H})^{0.8} \cdot (A_S \cdot V_E)^{0.2}$$

Accordingly, by arranging for B_f, these empirical formulae can be appicable to a wide range of the volume of the compartment, 0.16 m^3 - 27 m^3. However, they cannot be applied generally and adjustments should be made for the type and shape of the combustibles. The applicable range for the value of B_f would be between 0.003 and 0.4.

ii) Generation Rate of Smoke and CO

Since there is a difference between pyrolysis burning

and surface burning in regards to the relation between burning and compartment temperature, the release rate of smoke depends on the stage of fire.

As shown in Figures 14 - 16, and Table 11, the release rate of smoke and gases is high in the early stage of the fire. For this reason, it is necessary from the point of view of fire protection engineering to quantify the burning characteristics especially in the early stage of the fire, namely in the flashover period which is important for the prevention of the loss of human life.

The smoke production rate expressed here as $S_v (=S/A_s \cdot V)$ is shown in Figures 24 & 25. It is expected that by improving the method of measurement, correct values with higher accuracy can be obtained.

For plywood,

$$S_v = 250\ B_f^{0.3}$$

$$S = 250\ (A\sqrt{H})^{0.3} \cdot (A_s \cdot V_E)^{0.7}$$

For non-combustible materials,

$$S_v = 120\ B_f^{0.3}$$

$$S = 120\ (A\sqrt{H})^{0.3} \cdot (A_s \cdot V_E)^{0.7}$$

where S is release rate of smoke (C_s m^3/min or m^2/min)

$$S_v = (S/A_s)/V_E$$

$$S_v = a \cdot (S/A_s)/V_E$$

Although $A\sqrt{H}$ was the main controlling factor in the case of the burning rate, the value $A_s \cdot V_E$ takes its place in the case of the smoke generation rate.

The smoke generation rate in a compartment fire depends on the smoke generation coefficient of interior linings and commodity likewise in the case of burning rate. Since plywood and cribs are wood materials, the amount of the smoke generated when they burn, the smoke generation coefficient, could be considered to be approximately the same. Therefore, the smoke generation rate of the materials which have very different burning properties could be obtained by making adjustment using the relative smoke generation coefficient, 'a', with wood materials taken as 1.

iii) Vibrational Burning

The burning process in a ventilation controlled fire is considered to be close to the upper limit of burning of flammable premixed gases. Kawagoe has pointed out in his experiments the phenomenon of scrambling for oxygen in the compartment in the case of compartment fire. Here, when the variation of the amount of air flow through corridor is considered as shown in Figures 27 & 28, a clear regularity was found in the restriction of air inflow caused by the increase in the amount of gas intermittently released at regular intervals by strong oxidation of smoke particles accumulated in the compartment. The range of this vibrational burning becomes more remarkable when the amount of combustible material is low.

4.3. Full Scale Fire Test

In order to clarify the interrelationship between the model tests and a large scale fire, tests were conducted using a building which is scheduled to be destroyed and a test building specially constructed for this purpose.

i) Experimental Procedure

The accuracy and repeatability of full scale fire test generally decrease with the increase in the size of the building. However, the experimental procedure and the ignition method were carried out in the same manner for each trial run.

ii) Ignition Method

Wood cribs, which are constructed of 12 pieces of 2 cm x 2 cm x 60 cm spruce sticks per layer, were placed at the corner of a compartment and ignited by inserting an alcohol soaked stick (1 cm x 1 cm x 60 cm) at the bottom layer.

iii) Test Results

a) Flashover

We use the variation of temperature as a simple indicator for the growth of compartment fire. In many cases, this temperature is measured at a level of 3/4 the height of the building.

The variation in temperature in the main tests is

shown in Figure 29. The time at which flahsover (as defined by temperature rise) took place could then be determined. However, even for the same interior material, the temperature profile varied with the volume of compartment and the form of opening as shown in the figure.

b) Burning Rate

Parallel to the model tests, large scale fire tests were conducted by constructing a building of floor area 9 m^2 (3.6 (W) x 2.7 (D)) with a ceiling height of 2.6 m. For an office building with combustibles tipically arranged, tests were conducted to clarify the effect of changing from gypsum board to decorated plywood.

The variation in the weight of the building was measured every 15 seconds by loading the whole building over a weighing mechanism made of I beams.

As shown in Figure 30, a clear difference was recognized due to the burning characteristics of the linings; a burning rate of 60 kg/min was measured with plywood whereas 22 kg/min was measured for gypsum board, about 2.7 times more.

Furthermore, the burning rate as calculated from the empirical formulae derived from model tests fairly well agreed with the actual measurements:
for PVC film laminated plywood,

$$R = 6.0\ (A\sqrt{H})^{0.8} \cdot (A_S \cdot V_E)^{0.2}$$

$$= 6.0\ (4.2)^{0.8}\ (51.1 \times 24.3)^{0.2}$$

$$= 78.6 \text{ kg/min}$$

for gypsum boards, using the formulae for non-combustibles,

$$R = 3.0\ (4.2)^{0.8}\ (12.3 \times 24.3)^{0.2}$$

$$= 29.6 \text{ kg/min}$$

c) Excess Air Ratio

The amount of air inflow was measured by fitting a dynamic pressure measuring pipe to the lower half of the opening. Assuming the combustibles to be wood, the excess air ratio determined from the burning rate and amount of inflow air calculated previously for a theoretical air amount of 3.975 m^3/kg is shown in Figure 31. This shows that the burning has low excess ratio when the linings are plywood, and hence the release of smoke and gases is large. Furthermore, the number of ventilation cycles calculated from the amount of inflow air is about 250 - 350 cycles/hr.

d) Quantification of Smoke and CO

In order to determine the release rate of smoke and CO, it is necessary to measure accurately the flow rate of air released and the concentration of smoke and CO contained in it. In these experiments, since the smoky gases are at high temperature, the smoke concentration was measured by sucking the smoke using a rubber tube and a light transmitter type concentration meter having a constant light path length. The extinction coefficient measured this way is not accurate as smoke particles adhere to the

rubber tube owing to the high temperature of the smoke, and much larger coefficients are expected in reality. For these reasons, it is necessary in future research experiments to develop methods to measure dense smoke of high temperature.

5. Conclusions

As mentioned at the outset, the purpose of this experimental research is to find out the factors that control the characteristics of compartment fire and to understand quantitatively the characteristics of compartment fires. The detailed consideration of the empirical formulae obtained from these experiments is an important topic left for the future. However, the results obtained so far are summarized here for the time being.

1) The influence of internal linings on the growth of compartment fire is extremely large, and if they are combustible, a remarkable flashover phenomenon is observed and the release rate of smoke and CO gas accompanying this phenomenon is also very large.

2) The time elapsed before flashover is determined from an interrelationship between the size of the ignition source and the combustibility of the linings.

3) The duration of a compartment fire can be divided into

four main periods, namely the fire growth period, flashover period, steady state burning period and deterioration period. Smoke generation in the flashover period is remarkably high.

4) The opening factor, the surface area of combustibles and volume of compartment where oxidation takes place can be given as the main factors that govern the burning in the flashover period of compartment fire.

5) When the amount of combustibles is large, the influence of the burning characteristics of the linings is smaller and this influence becomes even smaller when the opening is small.

References

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6) Fang, J. B. : Fire Building in a Room and the Role of the Interior Finish Materials, NBS Technical Note 897 National Bureau of Standards, Washington, D.C., June, 1975

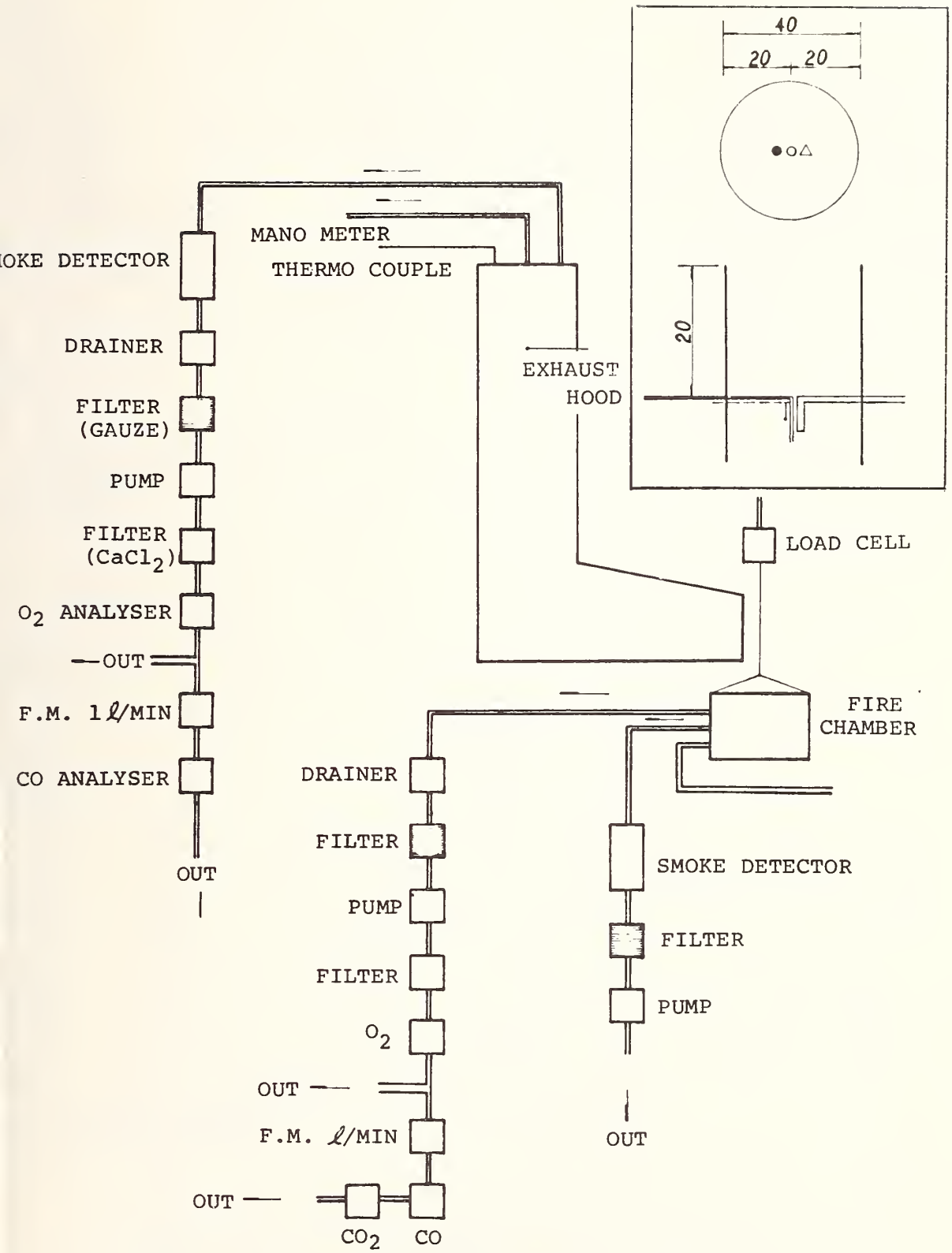
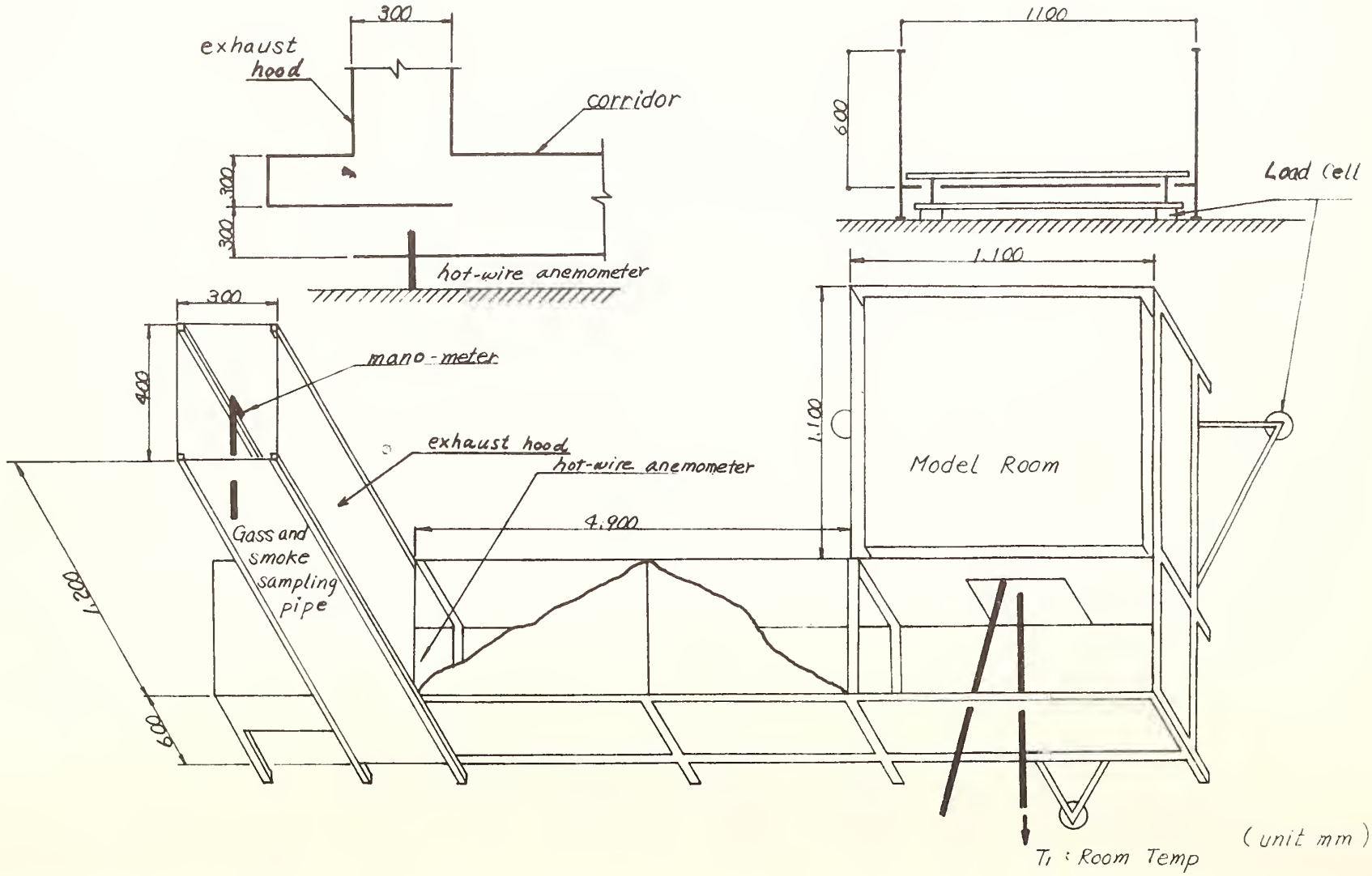
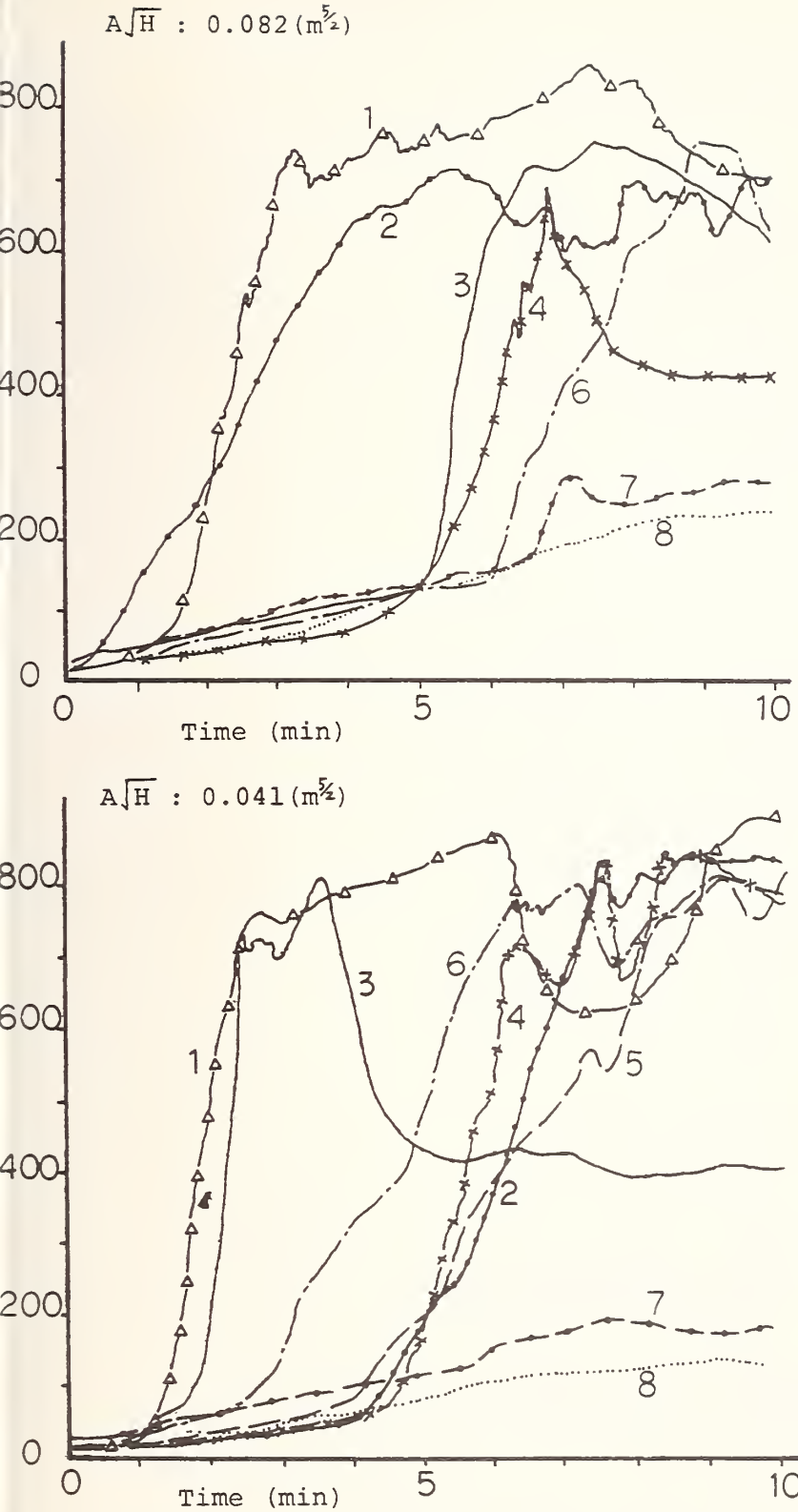


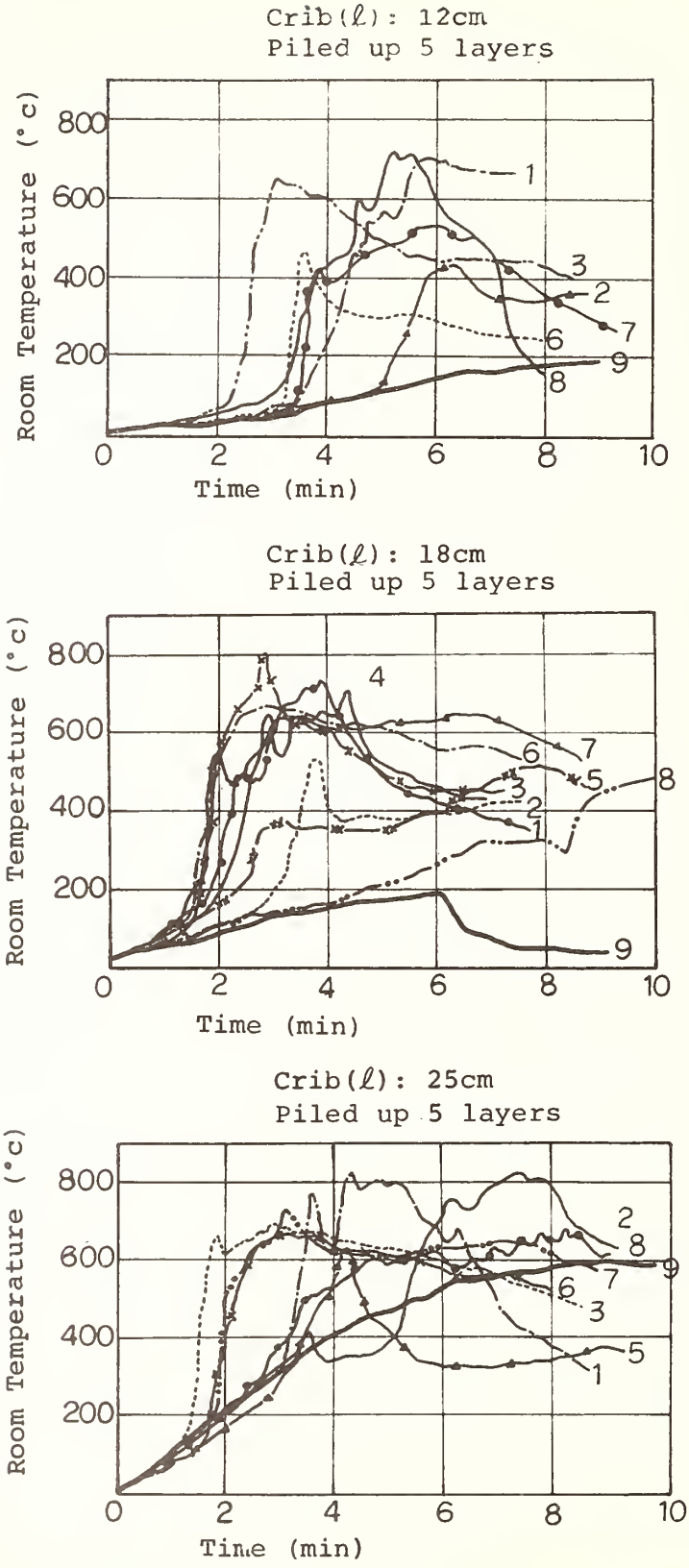
Fig. 1 Experimental Arrangement for Simple Model Box


300
exhaust hood
corridor
300
300
hot-wire anemometer
1100
600
Load Cell
1,100
300
mano-meter
400
exhaust hood
hot-wire anemometer
1,100
Model Room
4,900
Gass and smoke sampling pipe
1,200
600
T1 : Room Temp
(unit mm)



1. Fibre Insulation Board
2. Plywood
3. Plywood (Decorated by Polyester)
4. Fibre Board
5. Plywood (Treated)
6. Plywood (Decorated by Melamine)
7. Gypsum Board
8. Steel Plate

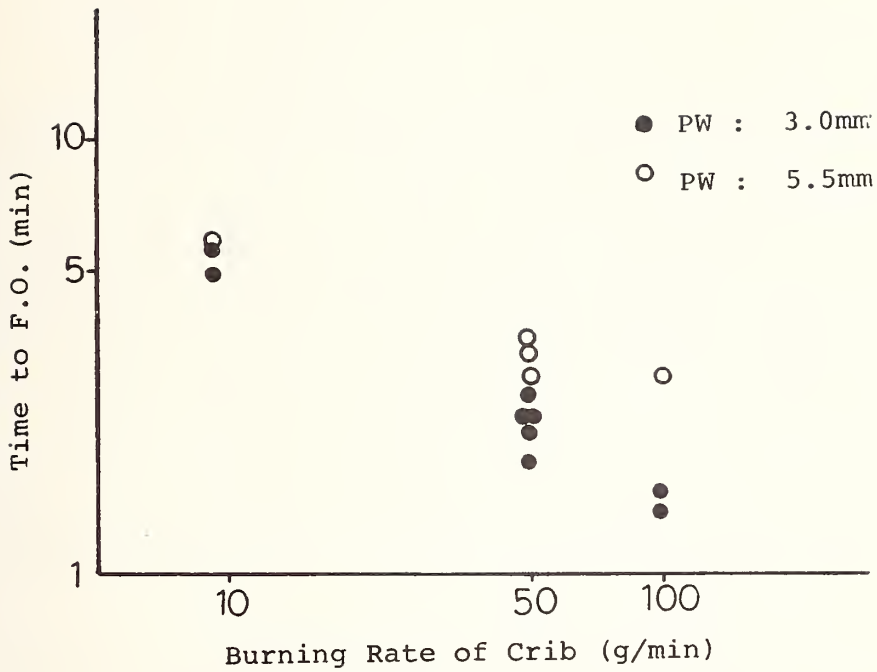
Fig. 3 Temperature Profile in Compartment of Various Linings (Model : SHSA)



1. Linen
2. PVC Film(B)
3. PVC Film(A)
4. Rayon
5. Glass Fiber Clot
6. Sliced Veneer
7. DAP Paper
8. Rayon (Treated)
9. None

Fig. 4 Temperature Profile in Compartment vs Various Ignition Source

(Model:SHSA, Opening:1/4, $A\sqrt{H}$:0.04$m^{5/2}$
Lining Material:Various Cloth Covering Steel Plate)



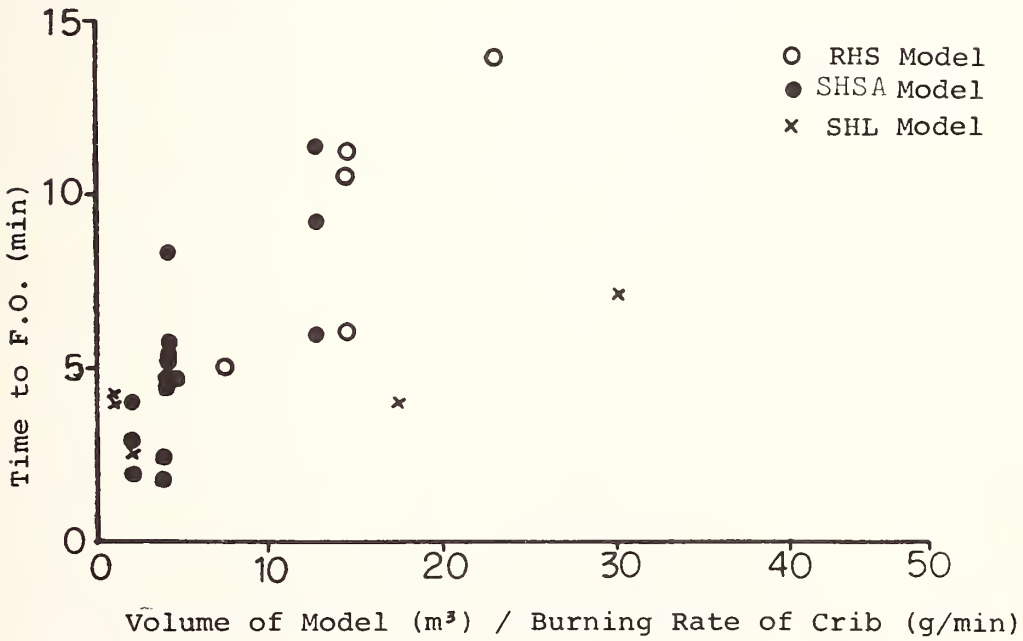


Fig. 5a Relation Between the time to reach F.O. and the Burning Rate of Ignition Source

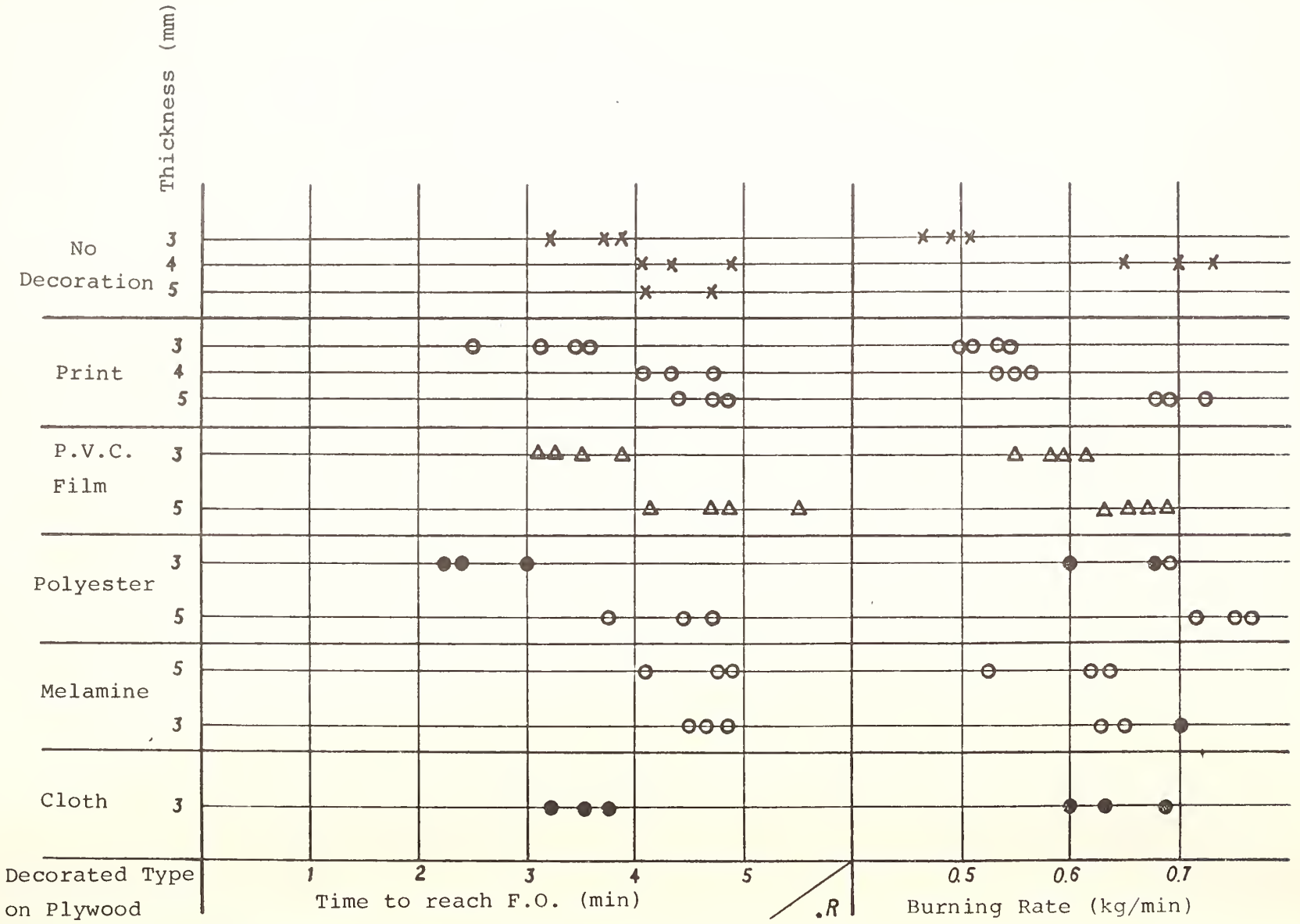
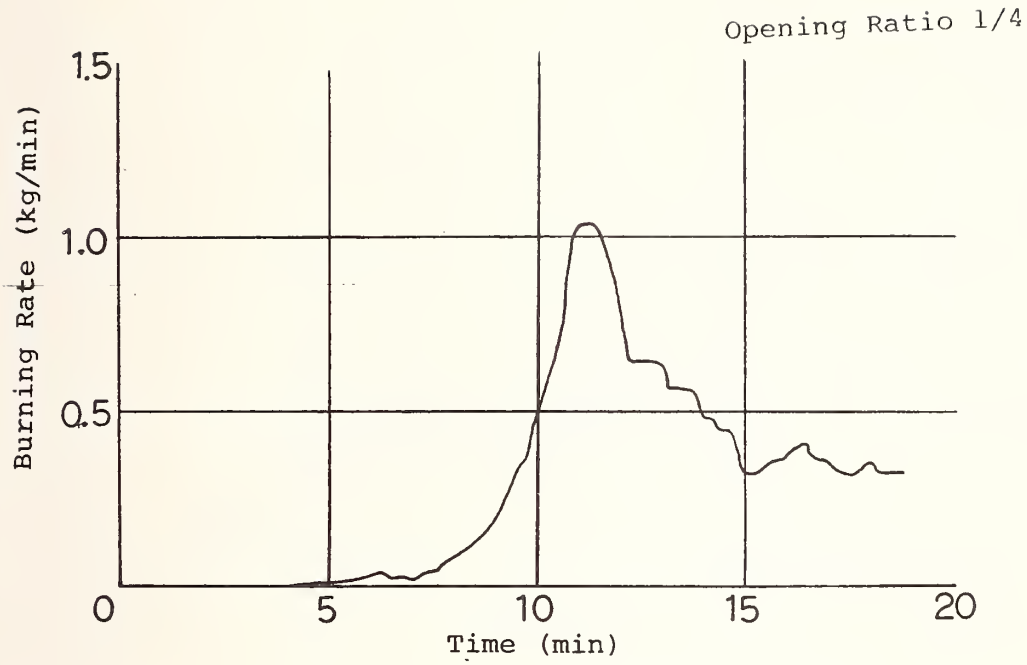


Fig. 5b Relation Between the Time to Reach F.O. and



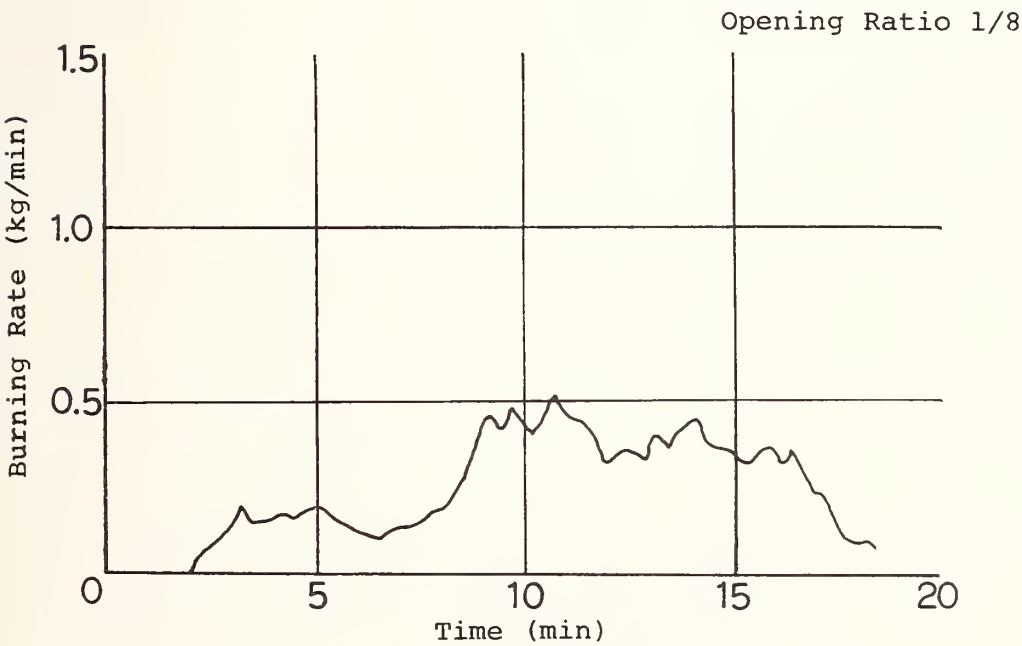
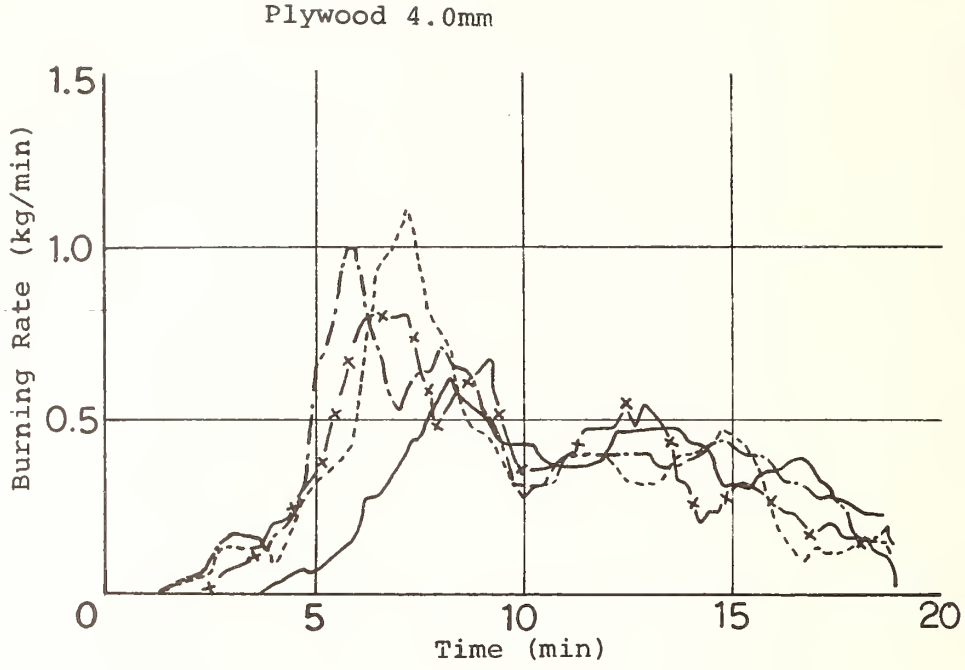


Fig. 6-a Variation of Burning Rate vs Time
(Model:RHS, Material:Plywood 3mm)



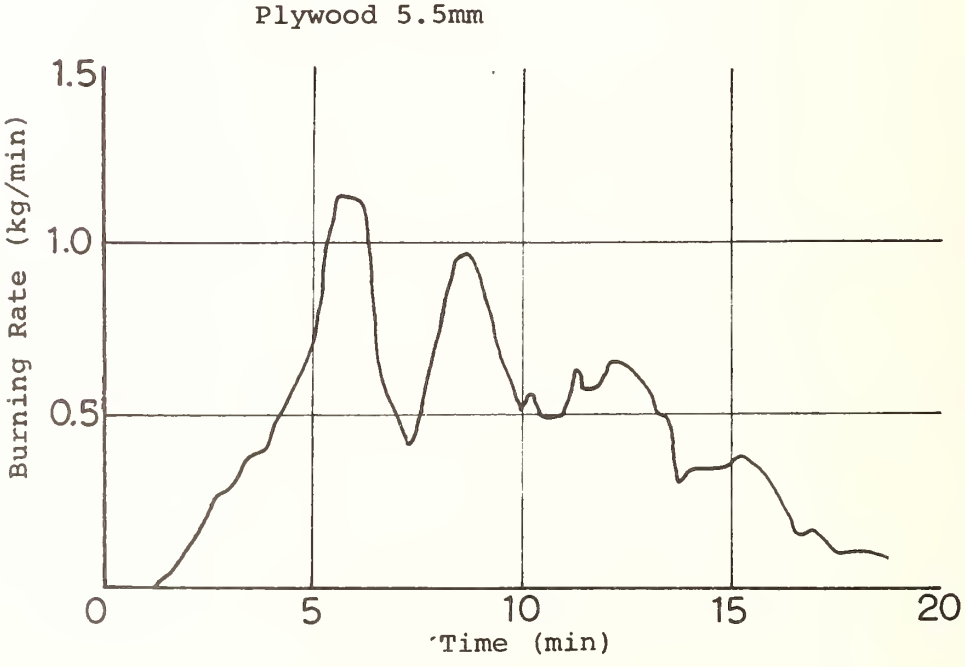


Fig. 6-b Variation of Burning Rate vs Time
(Model:RHS, $A\sqrt{H}$:0.07$m^{5/2}$)

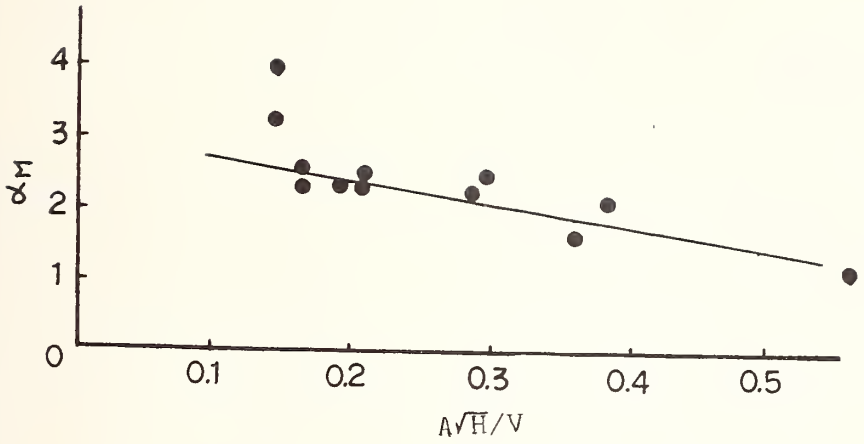


Fig. 7 Burning Rate vs α_M

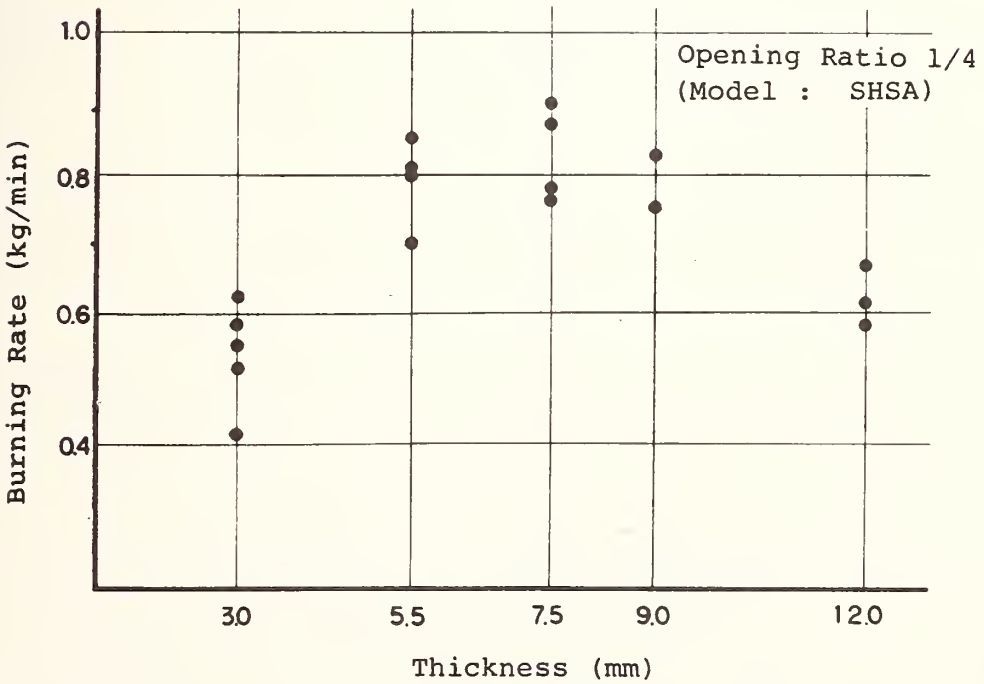


Fig. 8 Effect of Thickness on Burning Rate
(Model:SHB, A H:0.04m, Linings:Plywood)

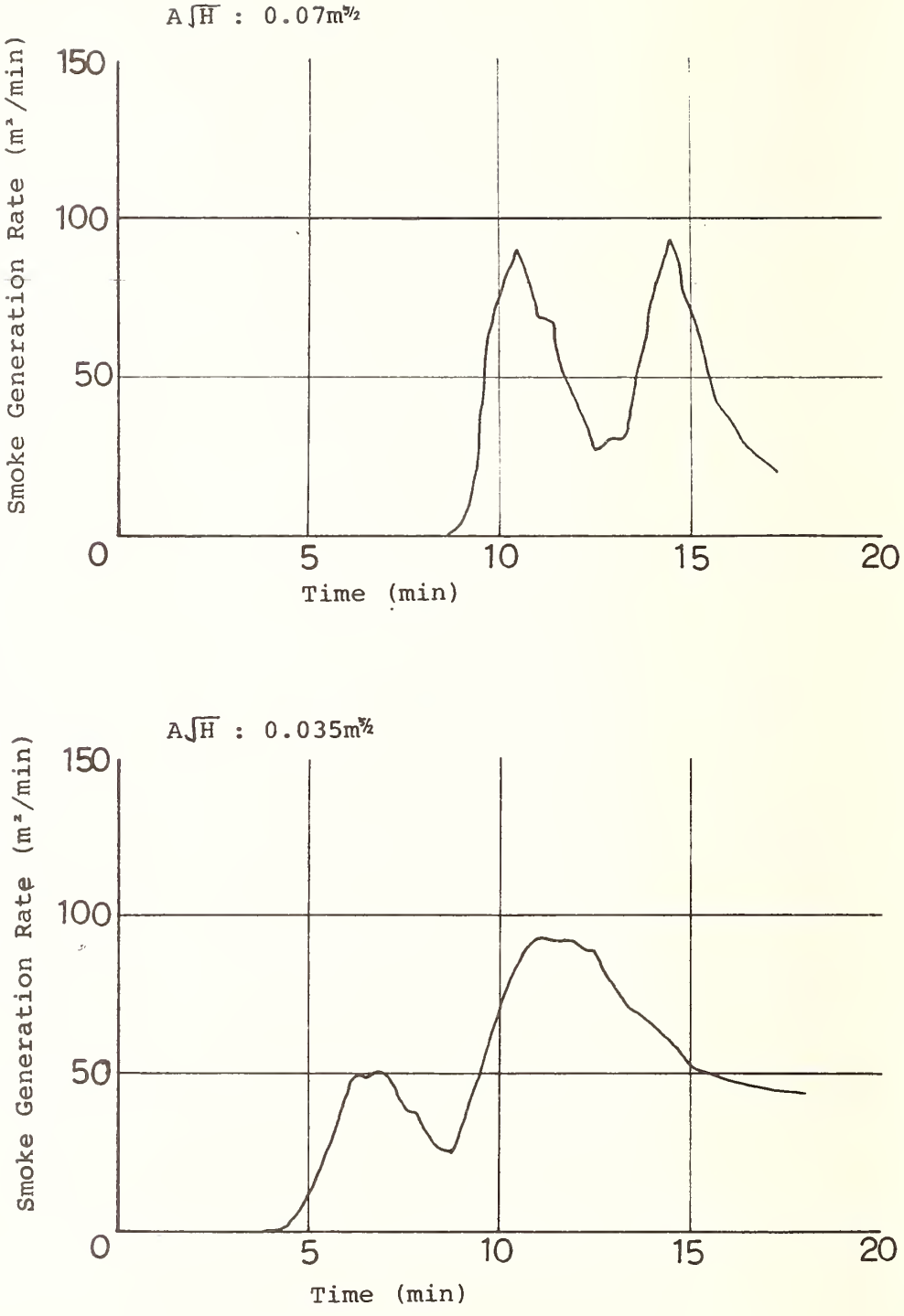
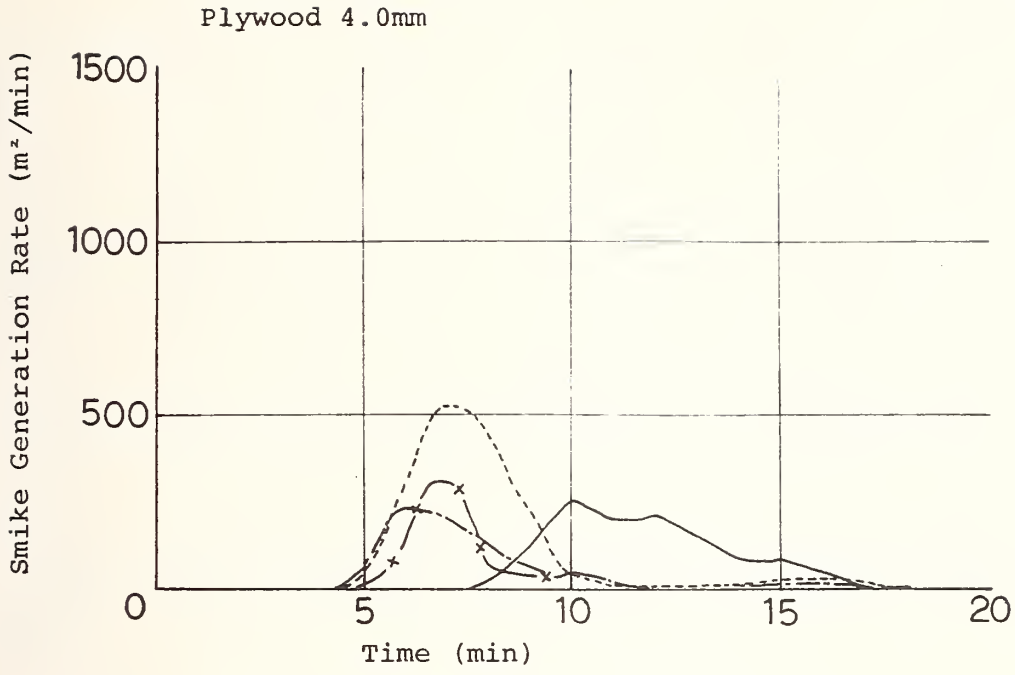


Fig. 9-a Variation of Smoke Generation Rate vs Time (Model:RHS, Lining :Plywood 3mm)



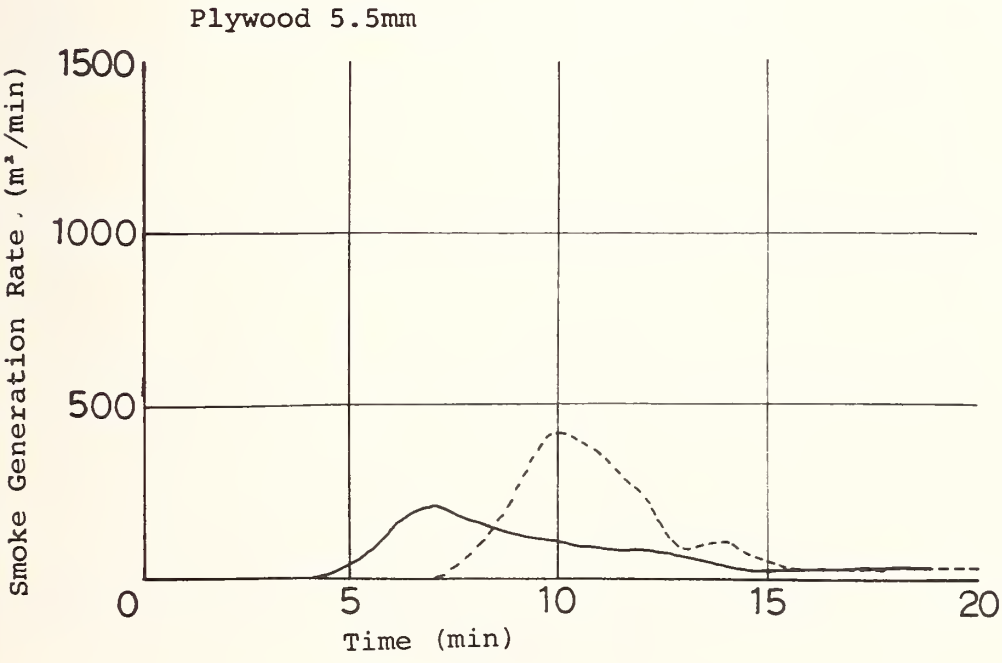


Fig 9-b Variation of Smoke Generation Rate vs Time (Model:RHS, $A\sqrt{H}$:0.07m$^{5/2}$)

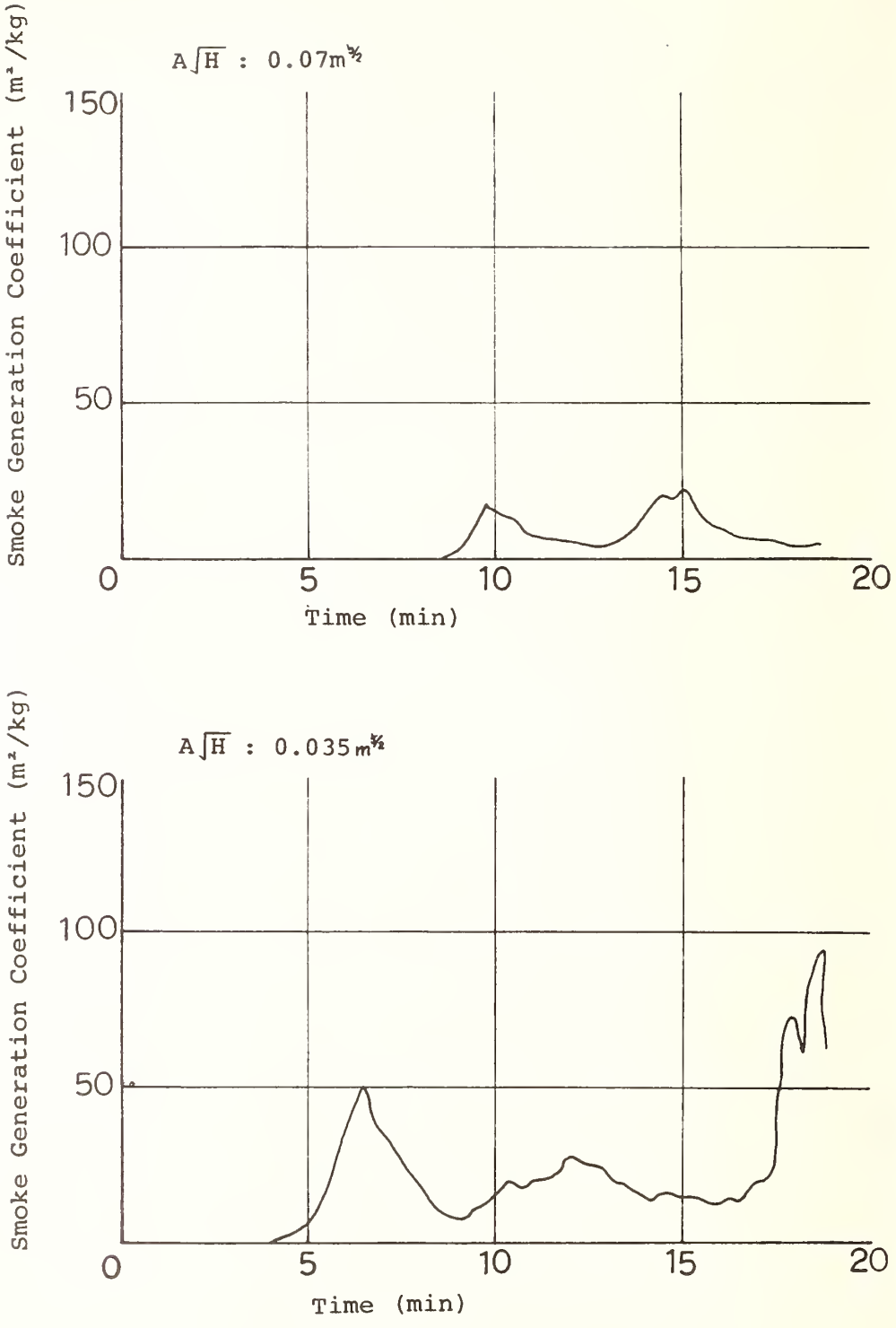


Fig. 10-a Variation of Smoke Generation Coefficient vs Time (Model:RHS, Lining :Plywood 3mm)

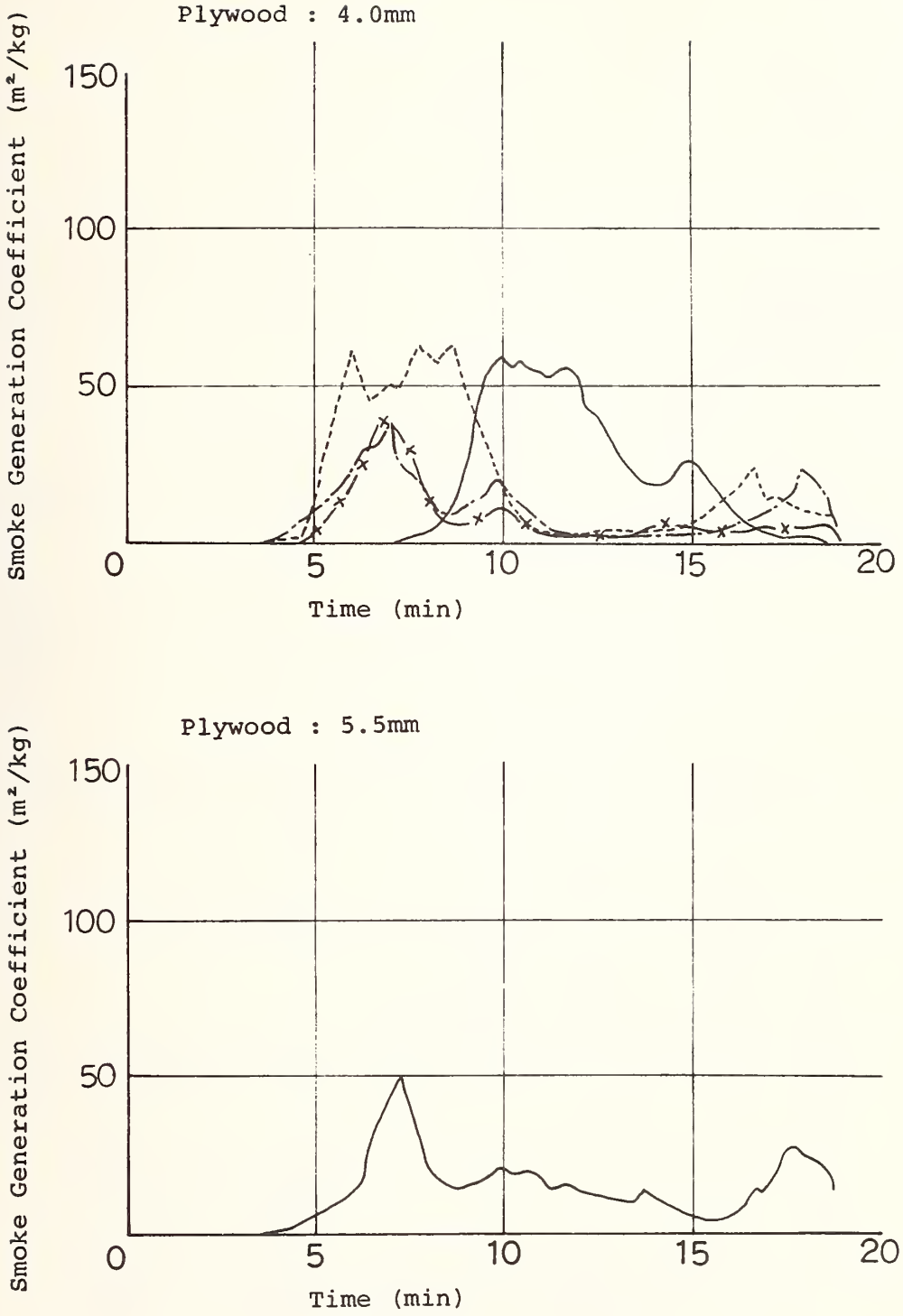


Fig. 10-b Variation of Smoke Generation Coefficient vs Time (Model:RHS, $A\sqrt{H}$:0.07$m^{\frac{5}{2}}$)

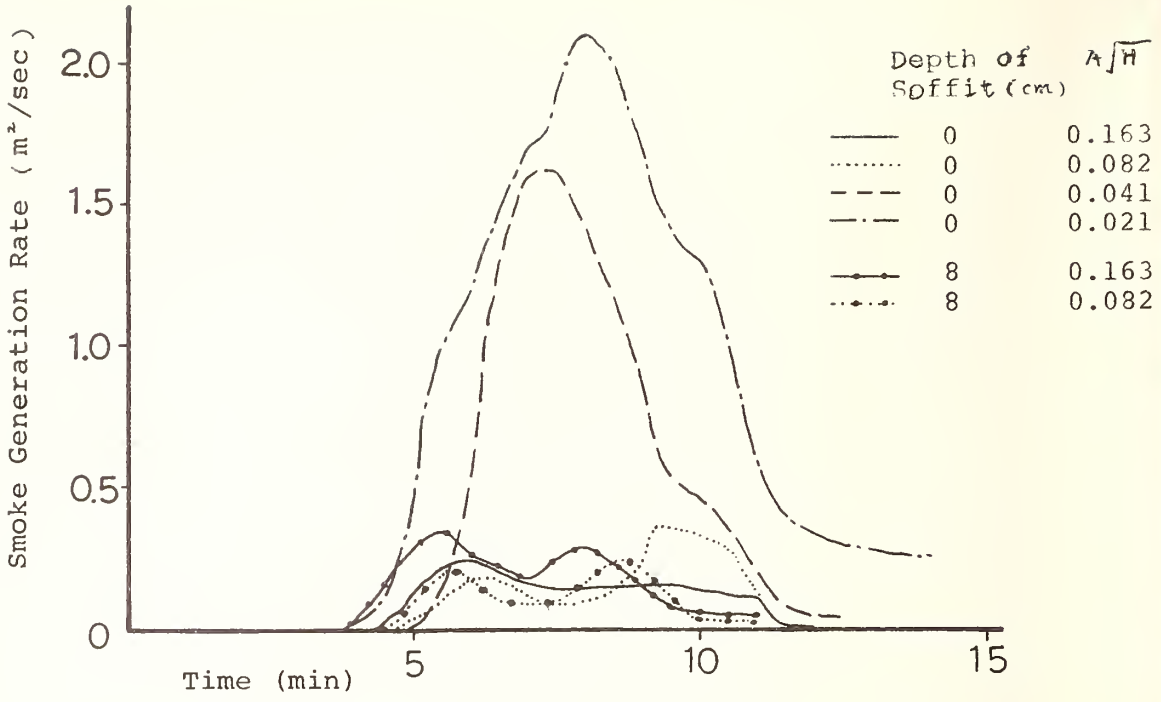


Fig. 11 Relation Between Smoke Generation Rate and Size of Opening (Model:SHSA, Linings:Plywood)

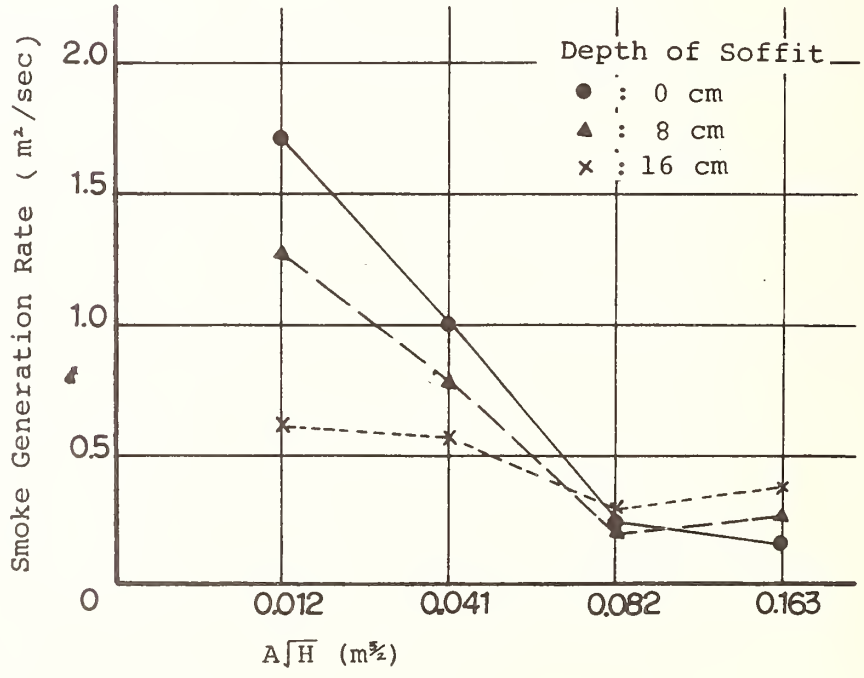


Fig. 12 Smoke Generation Coefficient vs $A\sqrt{H}$ (Model : SHSA, Linings : Plywood)

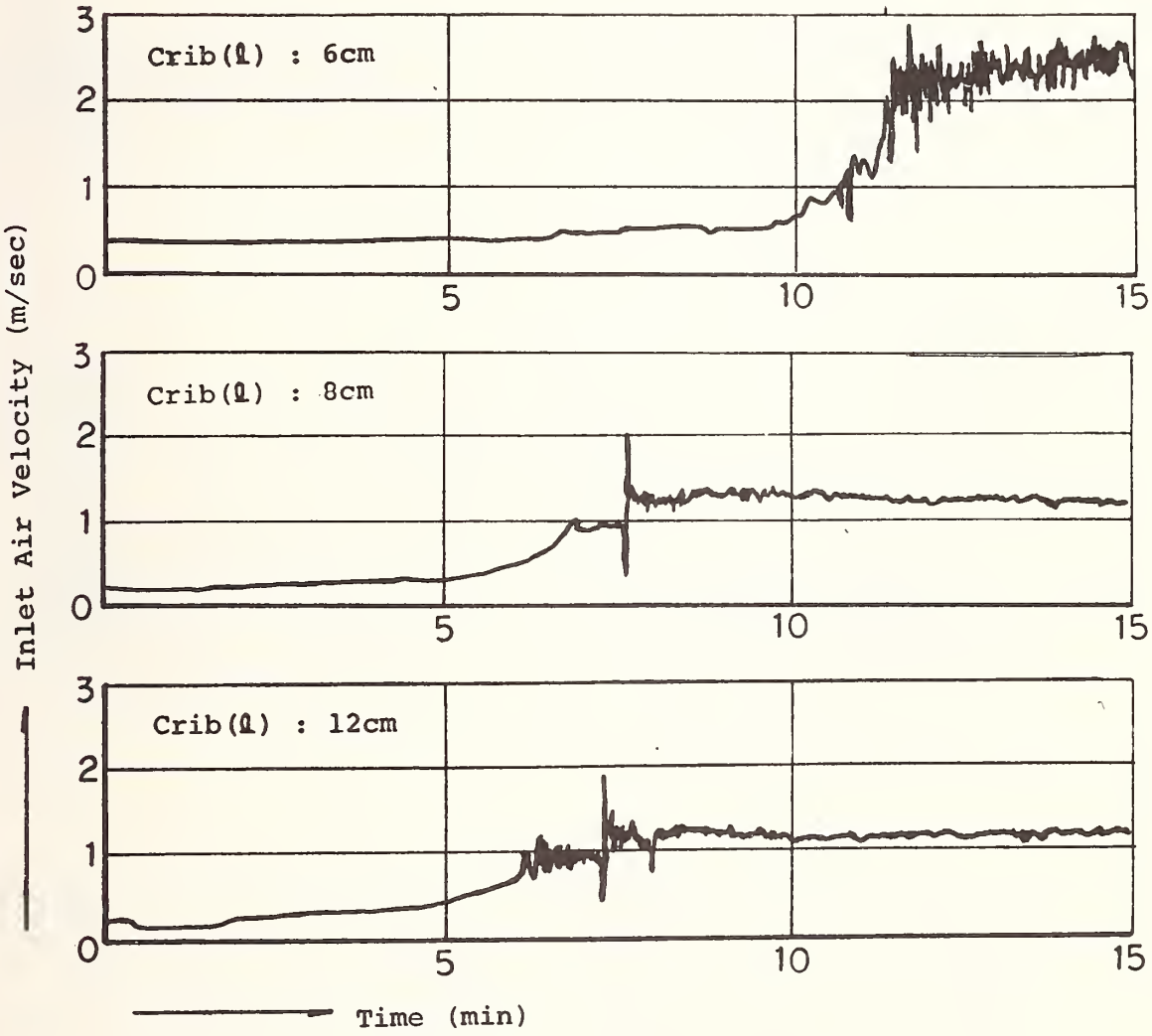


Fig. 13 Back Draft of Inflow Air
(Model:RHS, Lining :Plywood 4mm)

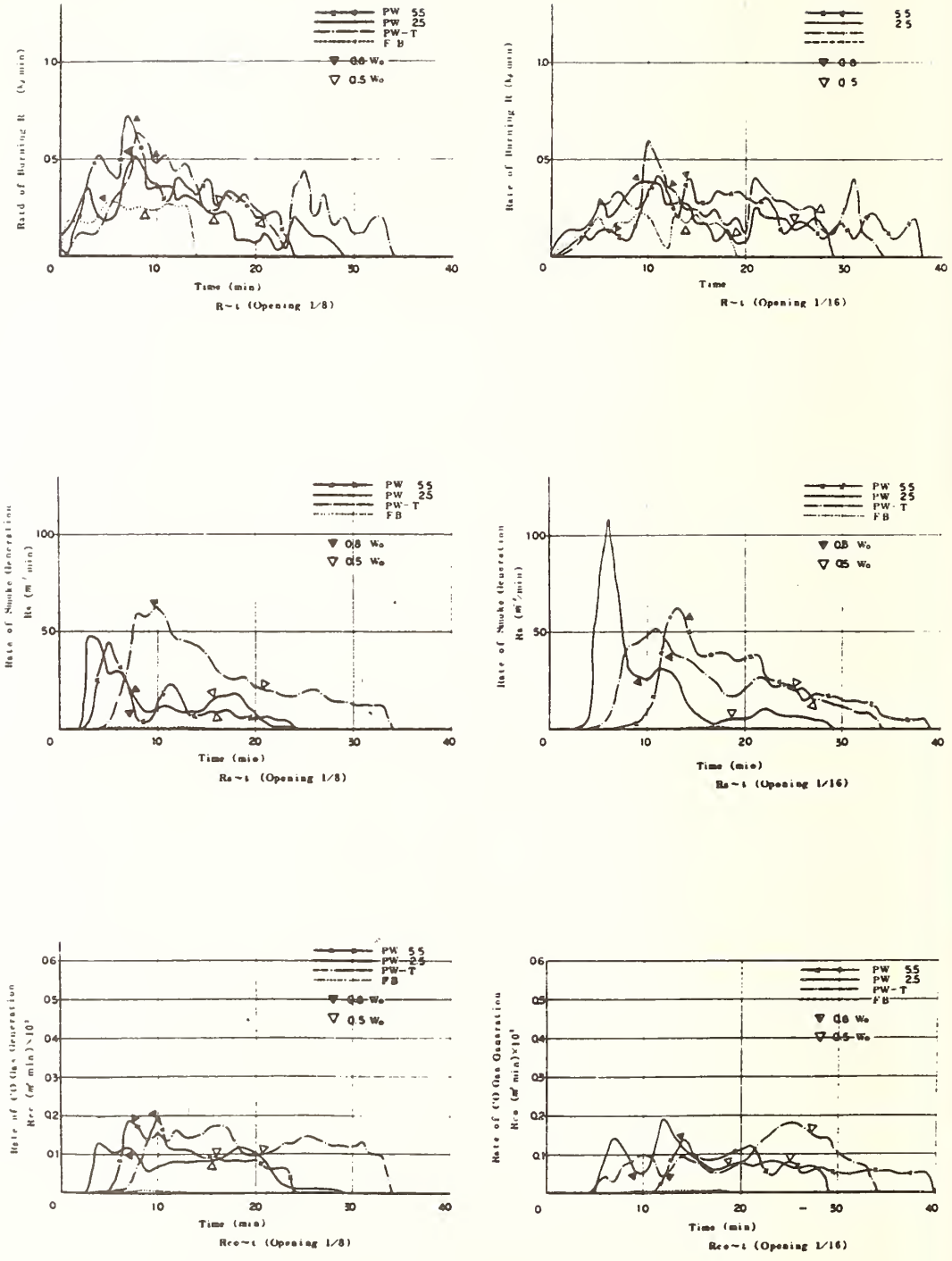


Fig 14 Example of Test Results (1) Fire Load 3.2kg

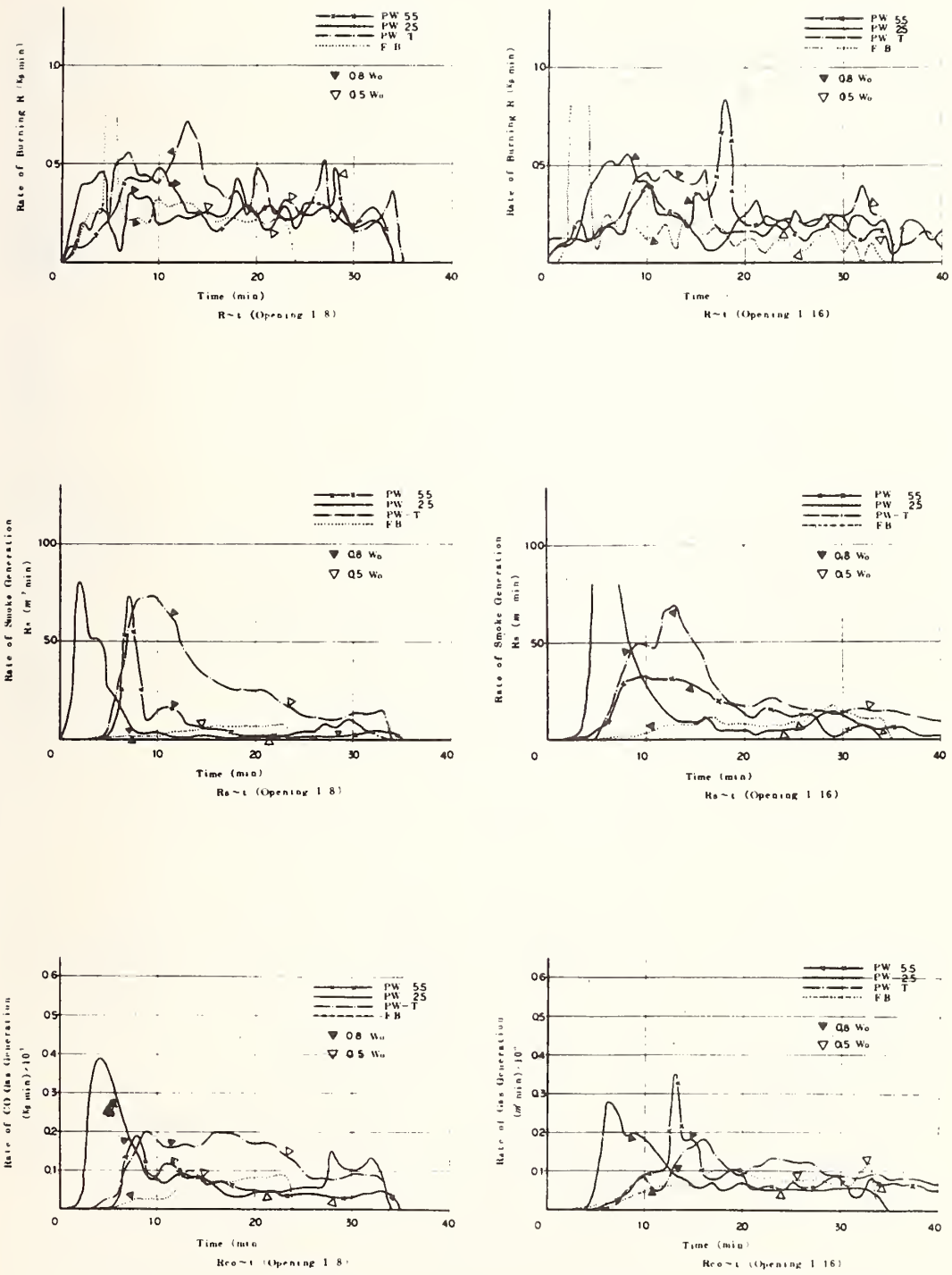


Fig 15 Example of Test Results (2) Fire Load 6.4kg

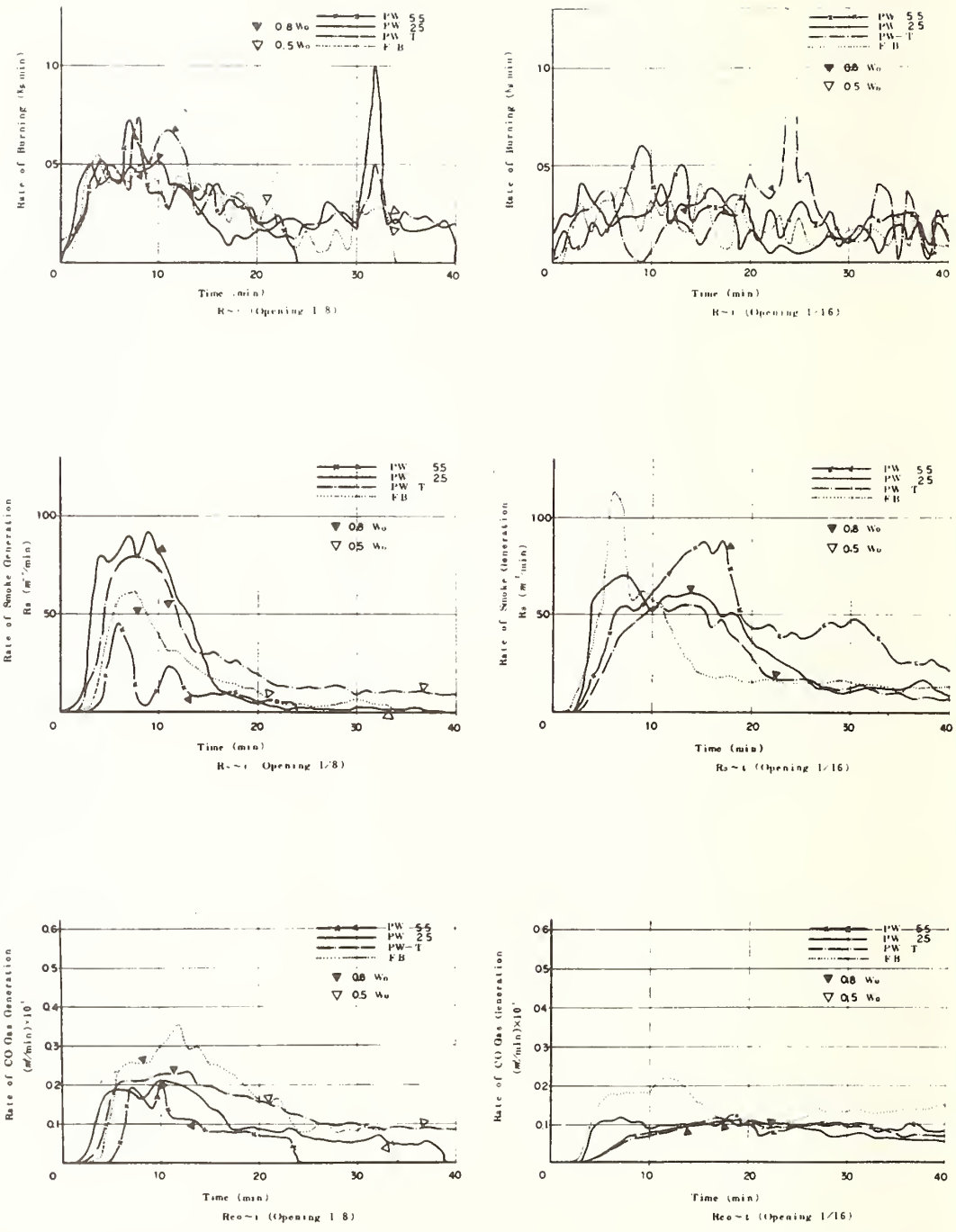


Fig 16 Example of Test Results (3) Fire Load 12.8kg

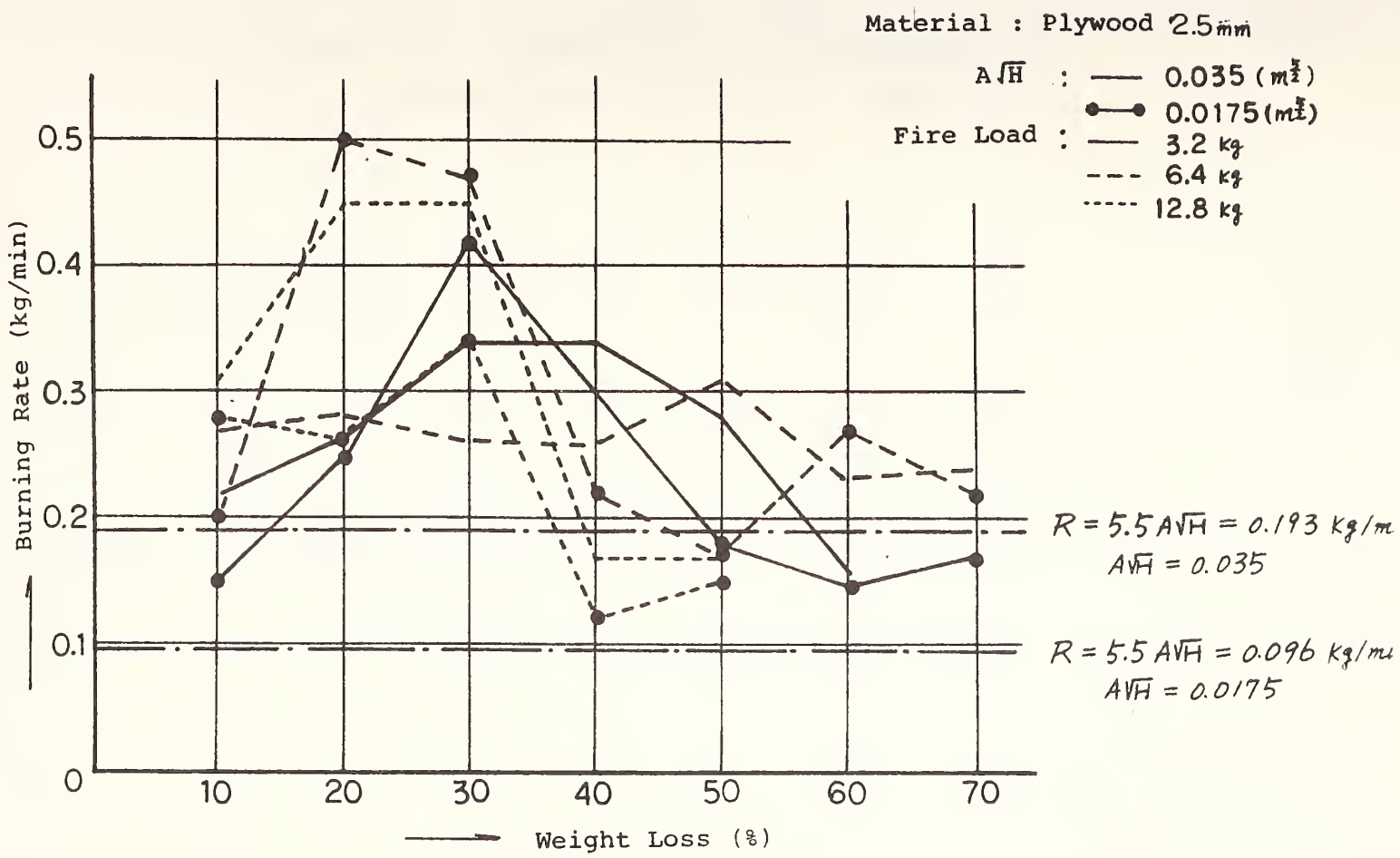


Fig. 17 Variation of Burning Rate in Each 10% of Combustibles
(Model:SHB, Lining :Plywood)

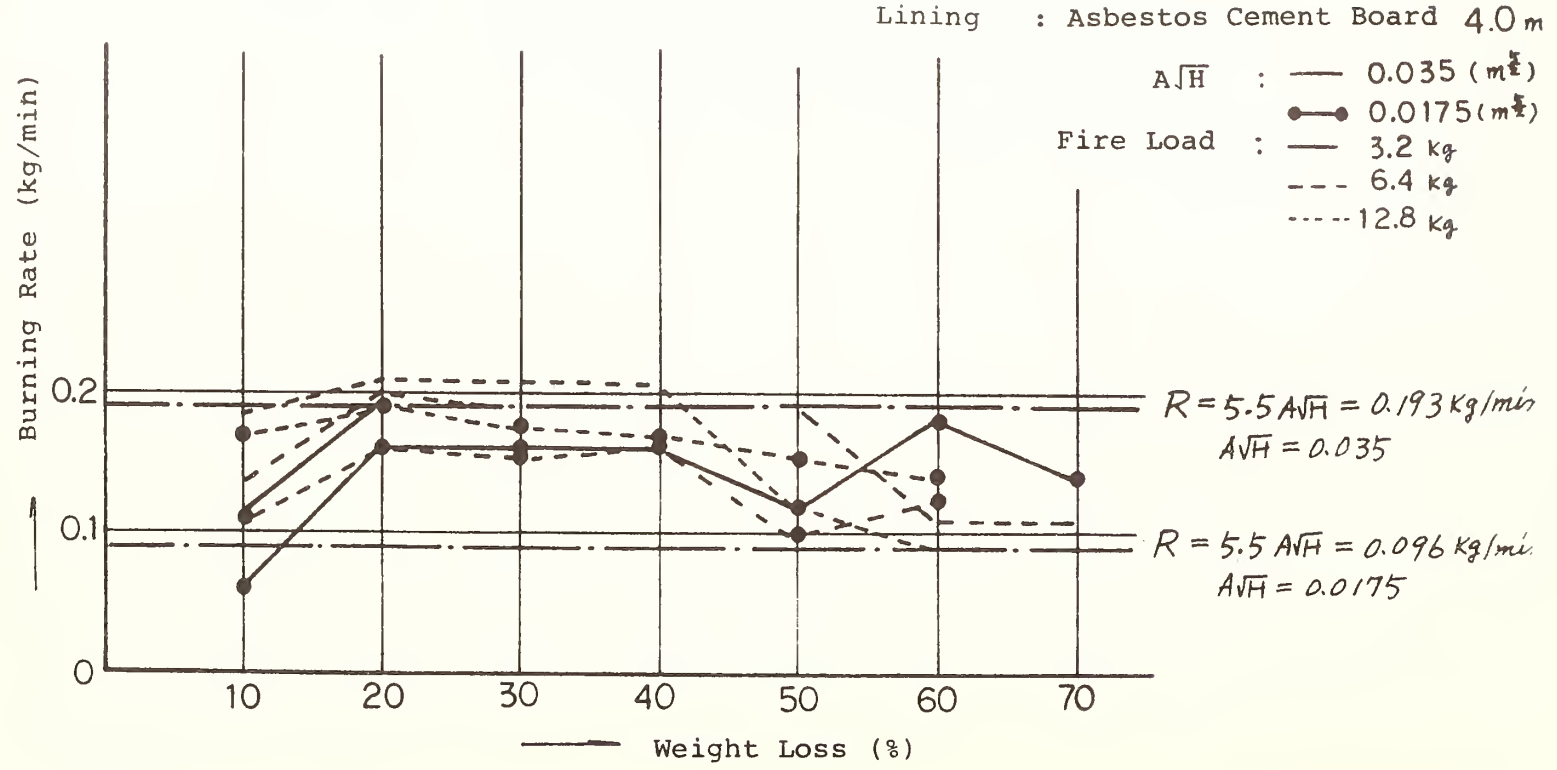
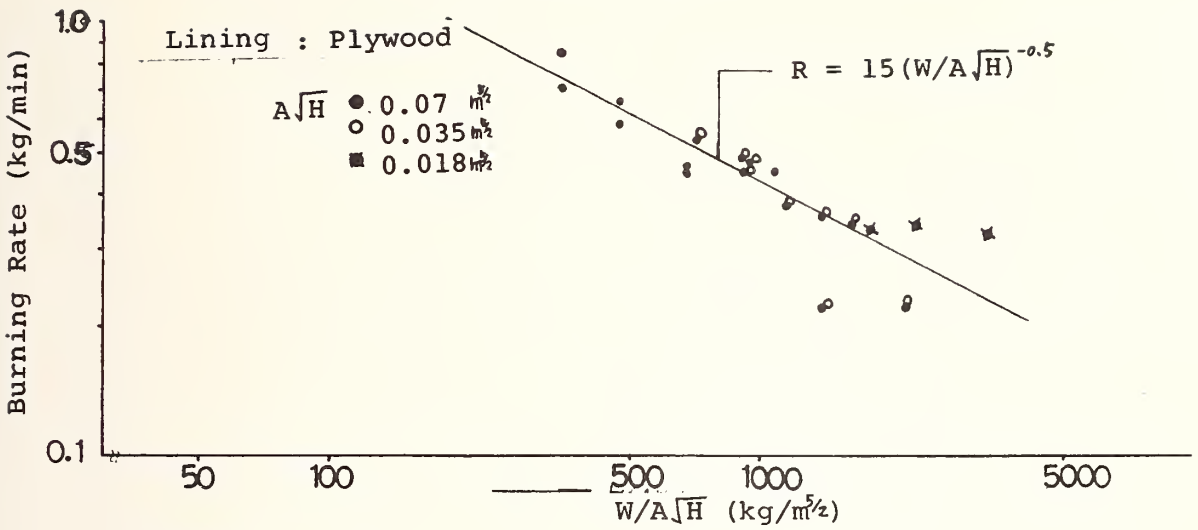
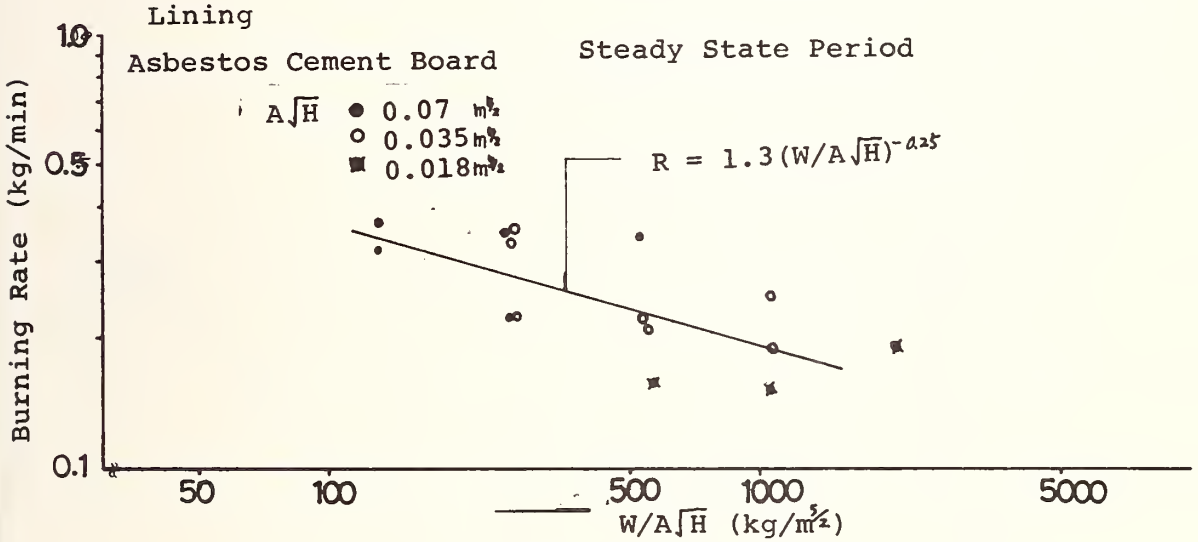


Fig. 18 Variation of Burning Rate in Each 10% of Combustibles
(Model:SHB, Lining :Asbestos Cement Board)





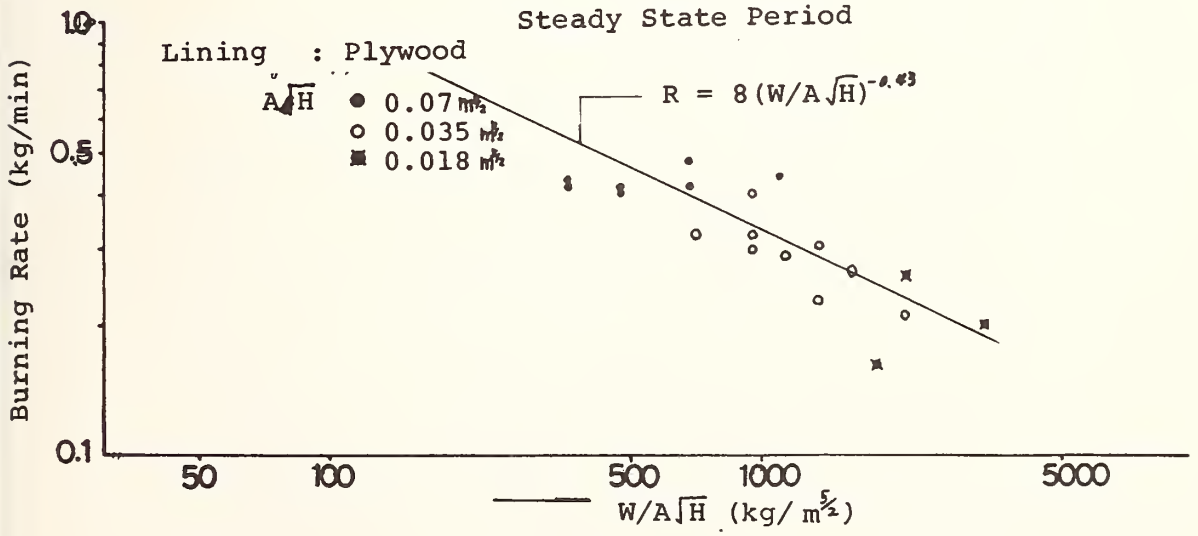


Fig. 19 Burning Rate vs Fire Load
(Model:SHB, W:Specific Fire Load (kg/m²))

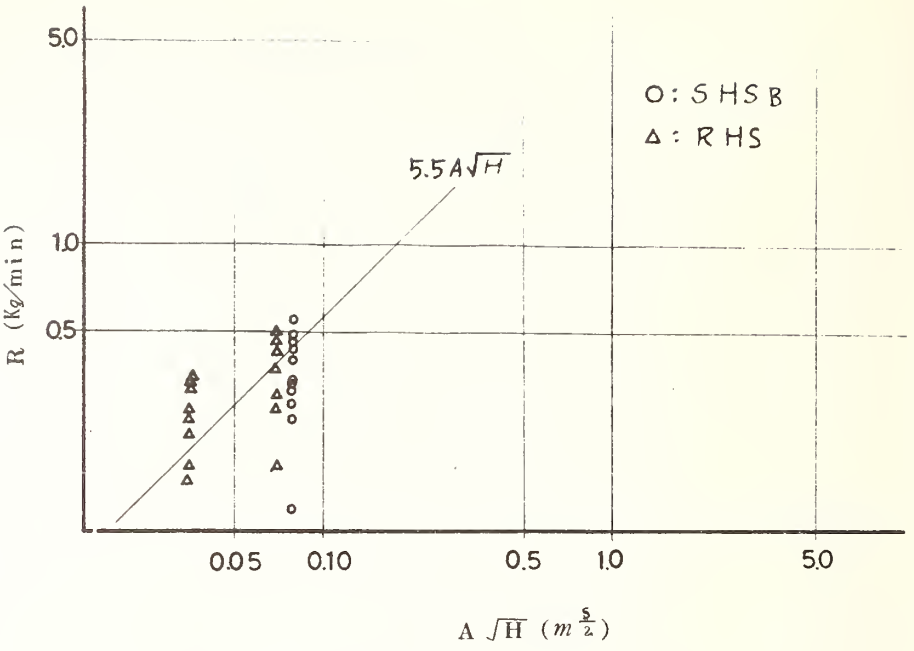


Fig 20 R~A$\sqrt{H}$(1)
Lining : Non-combustible

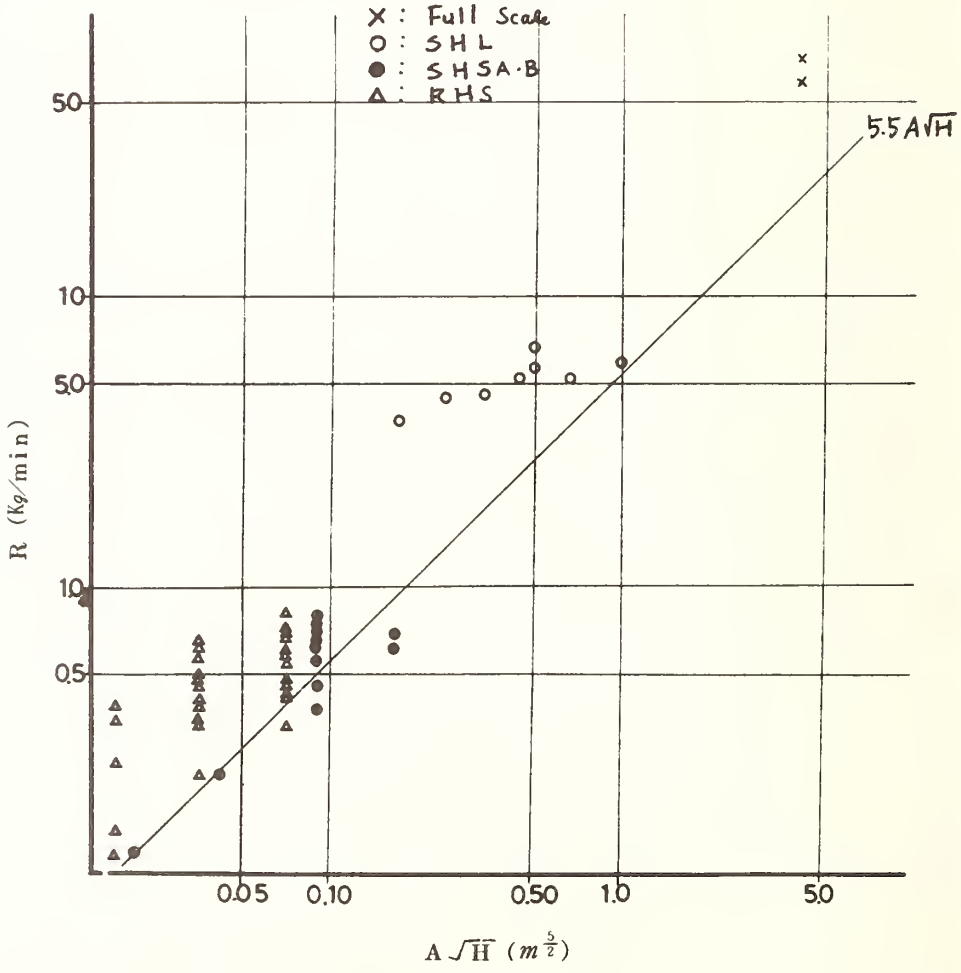


Fig 21 R~A$\sqrt{H}$(2)
Lining : Plywood

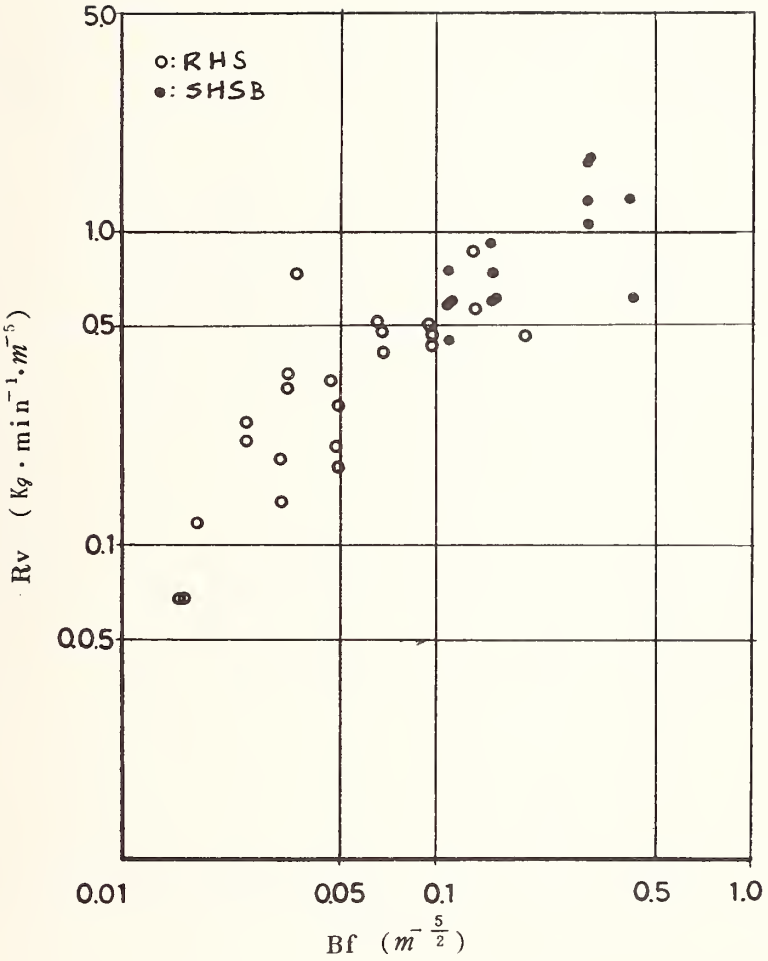


Fig. 22 B_f vs R_V (Lining : Non-combustible)

$Rv = (R/As) / V_e$

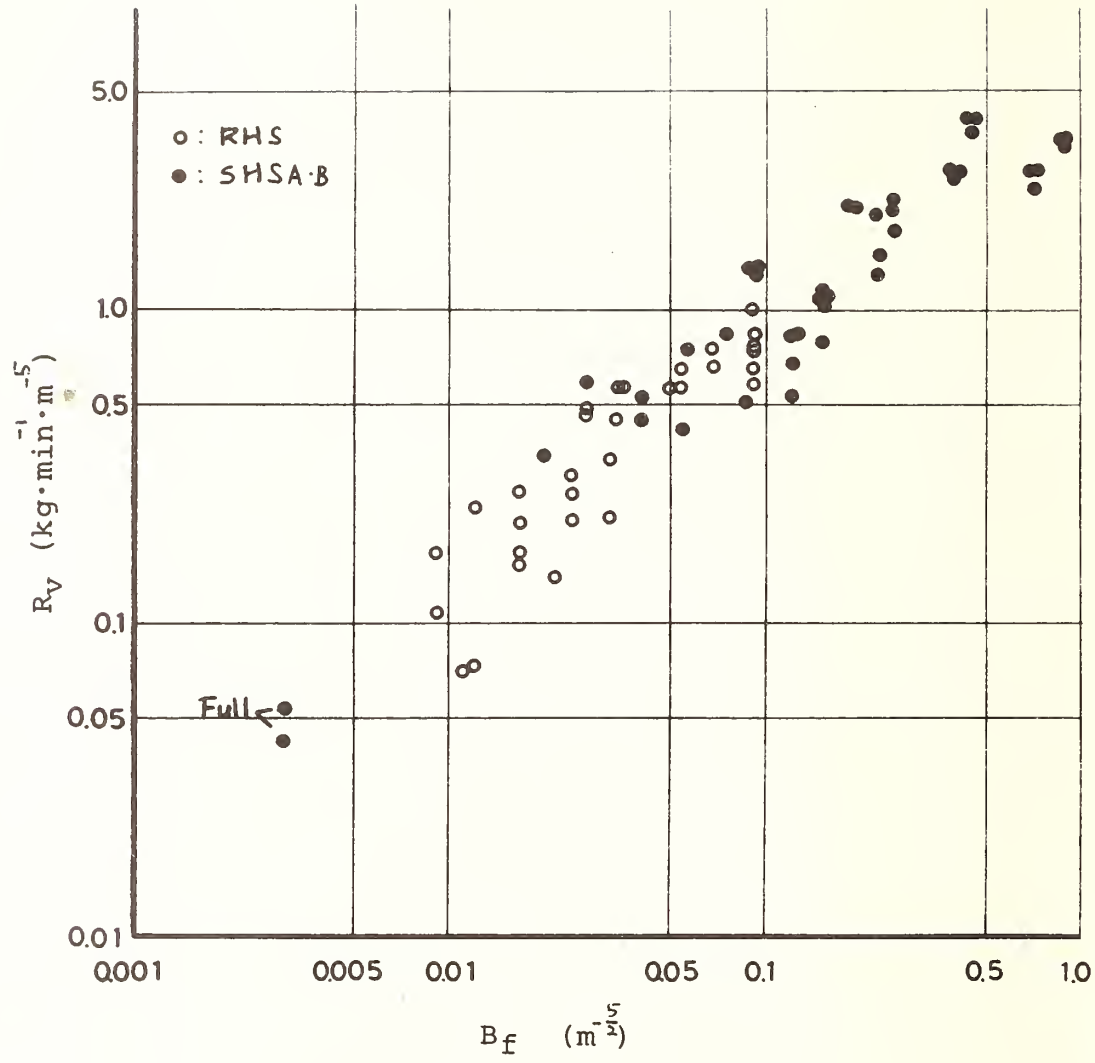
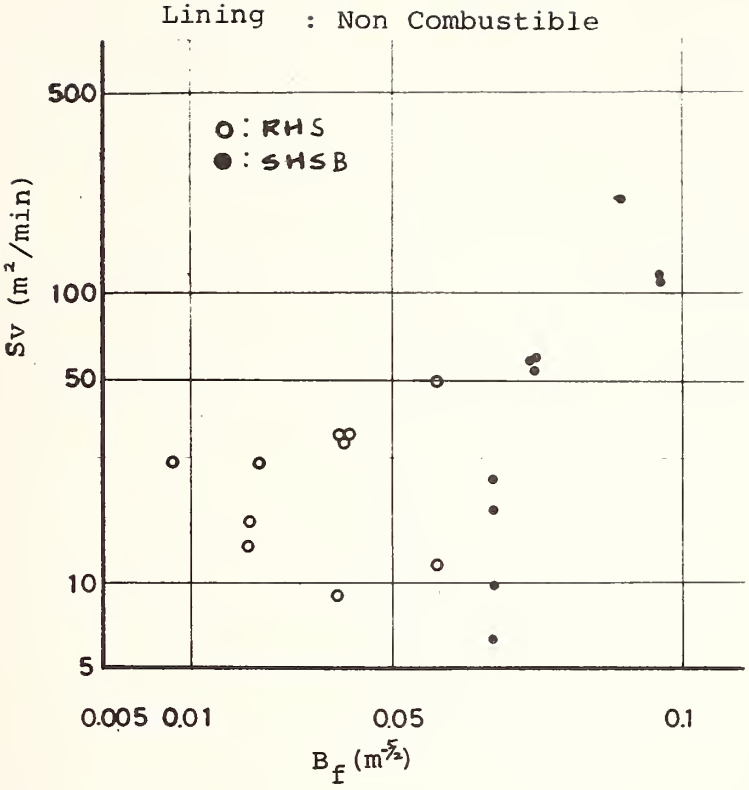


Fig. 23 B_f vs R_V (Lining : Plywood)

$Rv = (R/As) / V_E$



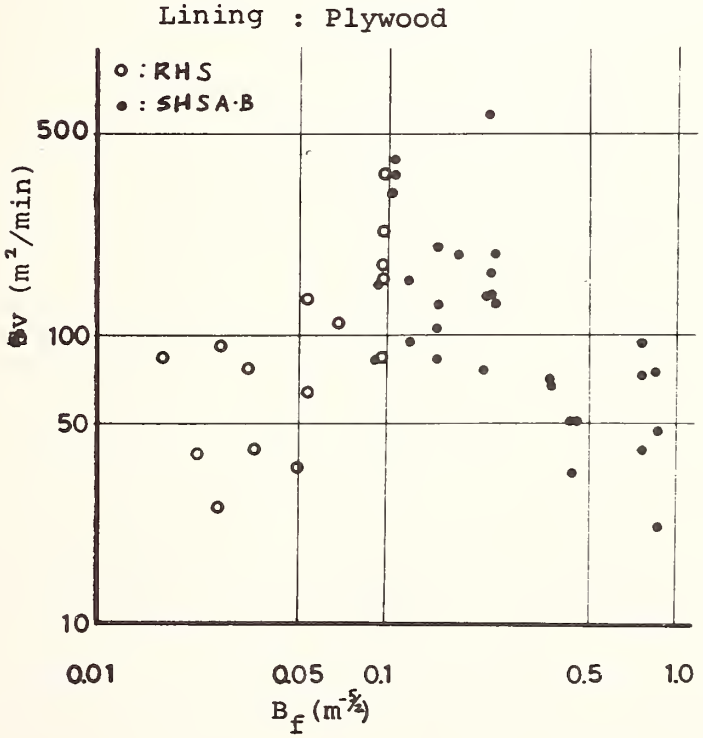


Fig. 24 B_f vs S_v

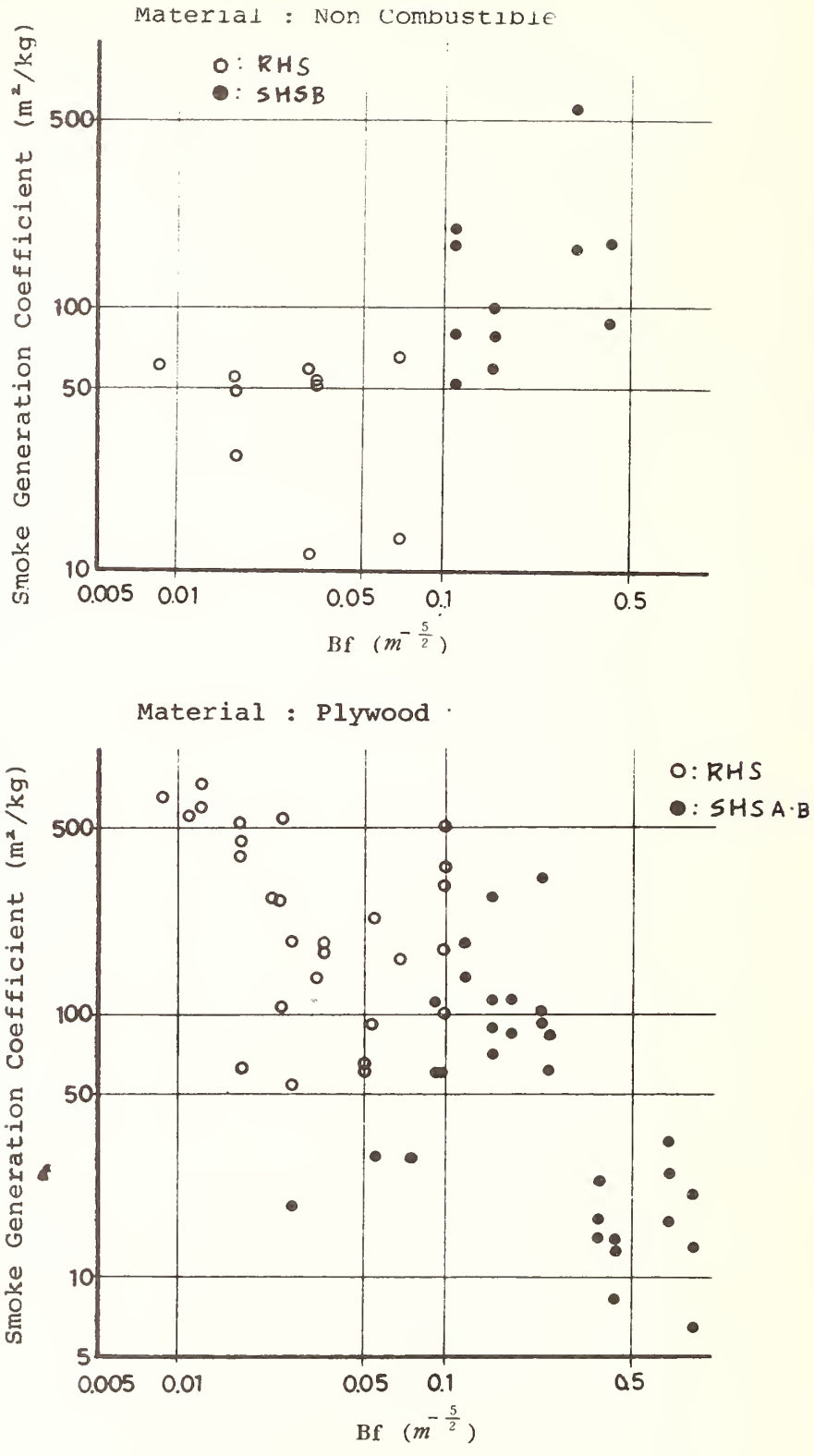
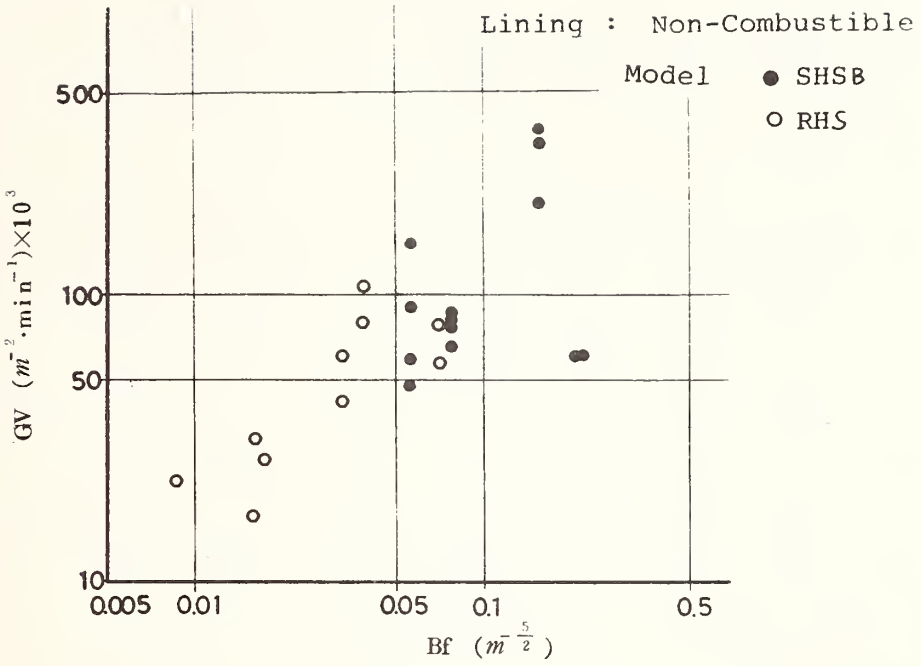


Fig. 25 B_f vs Smoke Generation Coefficient (K)



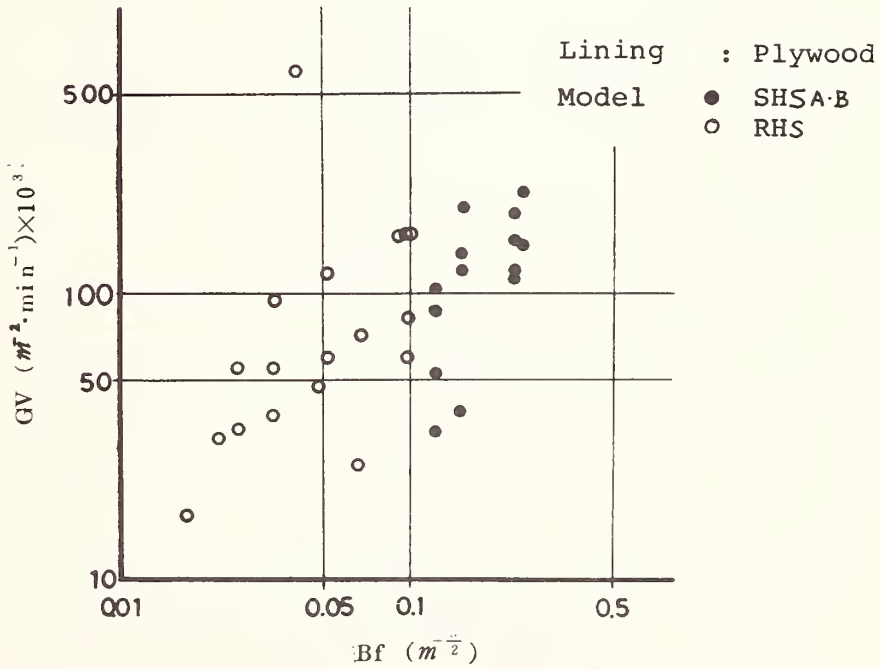


Fig. 26 B_f vs G_V, G_V = ((CO ℓ/m)/A_S)/VE

Gv = (CO Gas l/min/As)/V_E

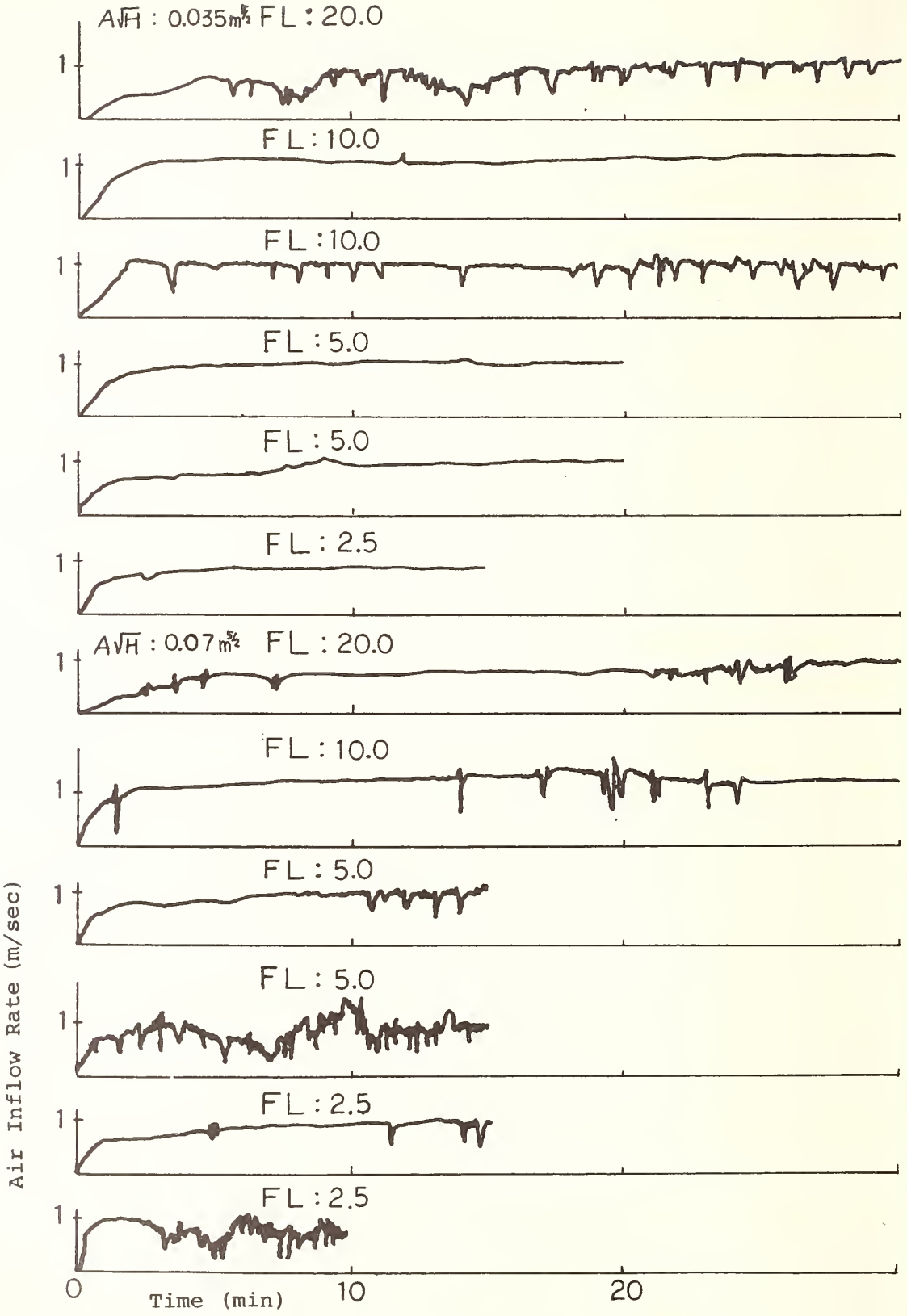


Fig. 27 Vibration of Air-inflow at Vent (Asbestos Parlite Board)

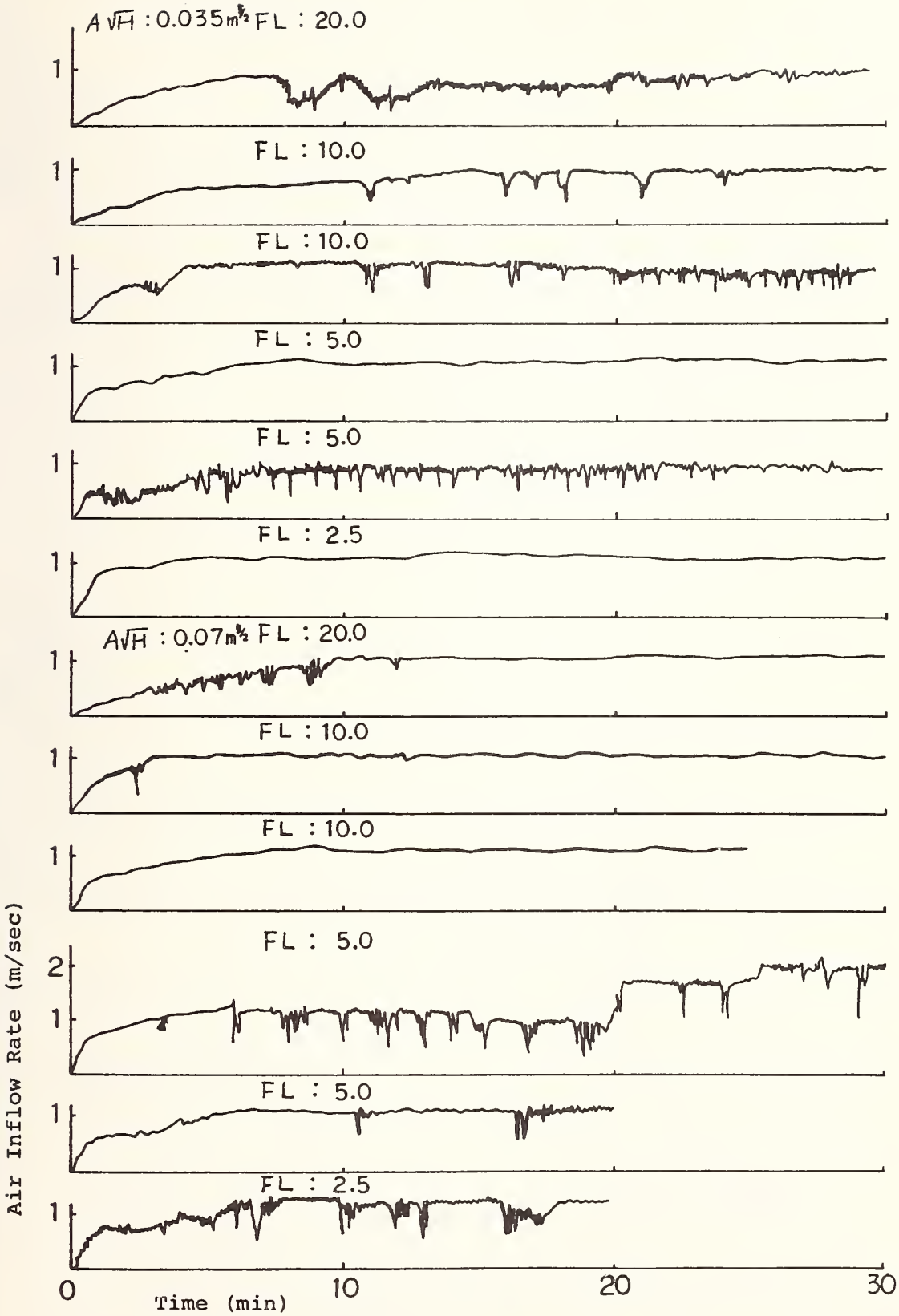


Fig. 28 Vibration of Air-inflow at Vent (Plywood)

Symbol	Lining	V (m^3)	$A\sqrt{H}$ ($m^{\frac{5}{2}}$)	$V/A\sqrt{H}$
———	PW -4	23.5	1.97	11.8
- - - - - -	PW -4	22.9	2.91	7.9
—·—·—	PW (Print)	18.6	3.06	6.1
— — —	PW (PVC)	25.8	3.18	8.1
—··—··	PW (PE)	25.8	3.18	8.1
—●—●—	PW	63.1	4.55	13.9

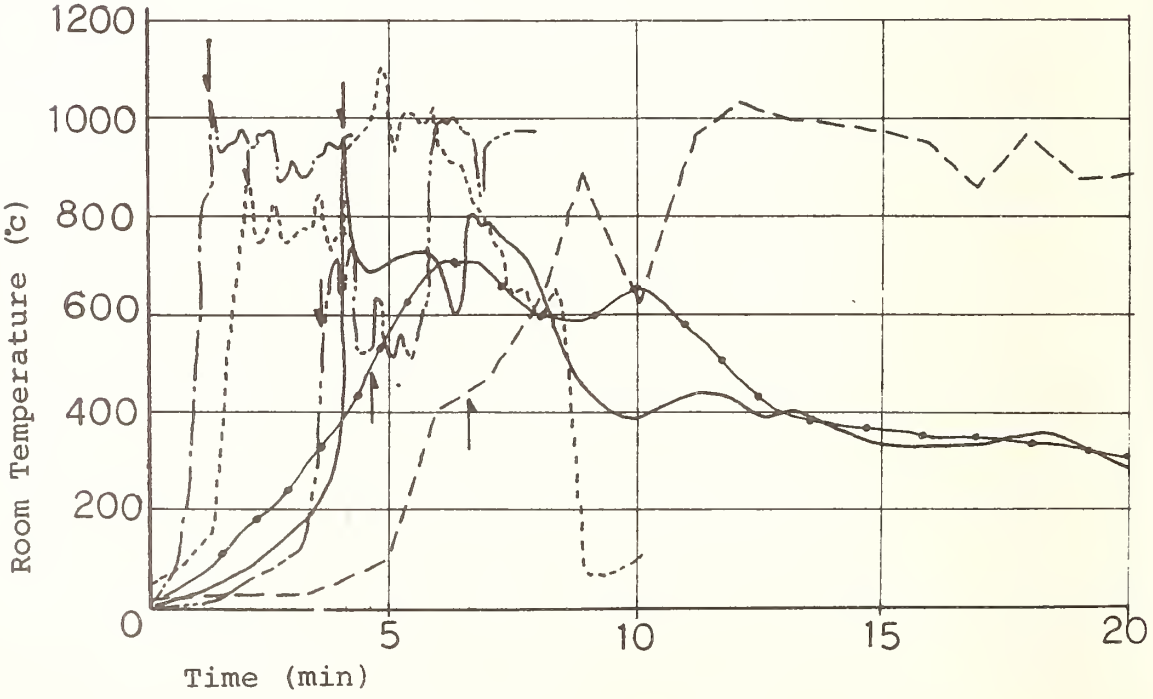


Fig. 29 Room Temperature on Various Full Size Fire Test

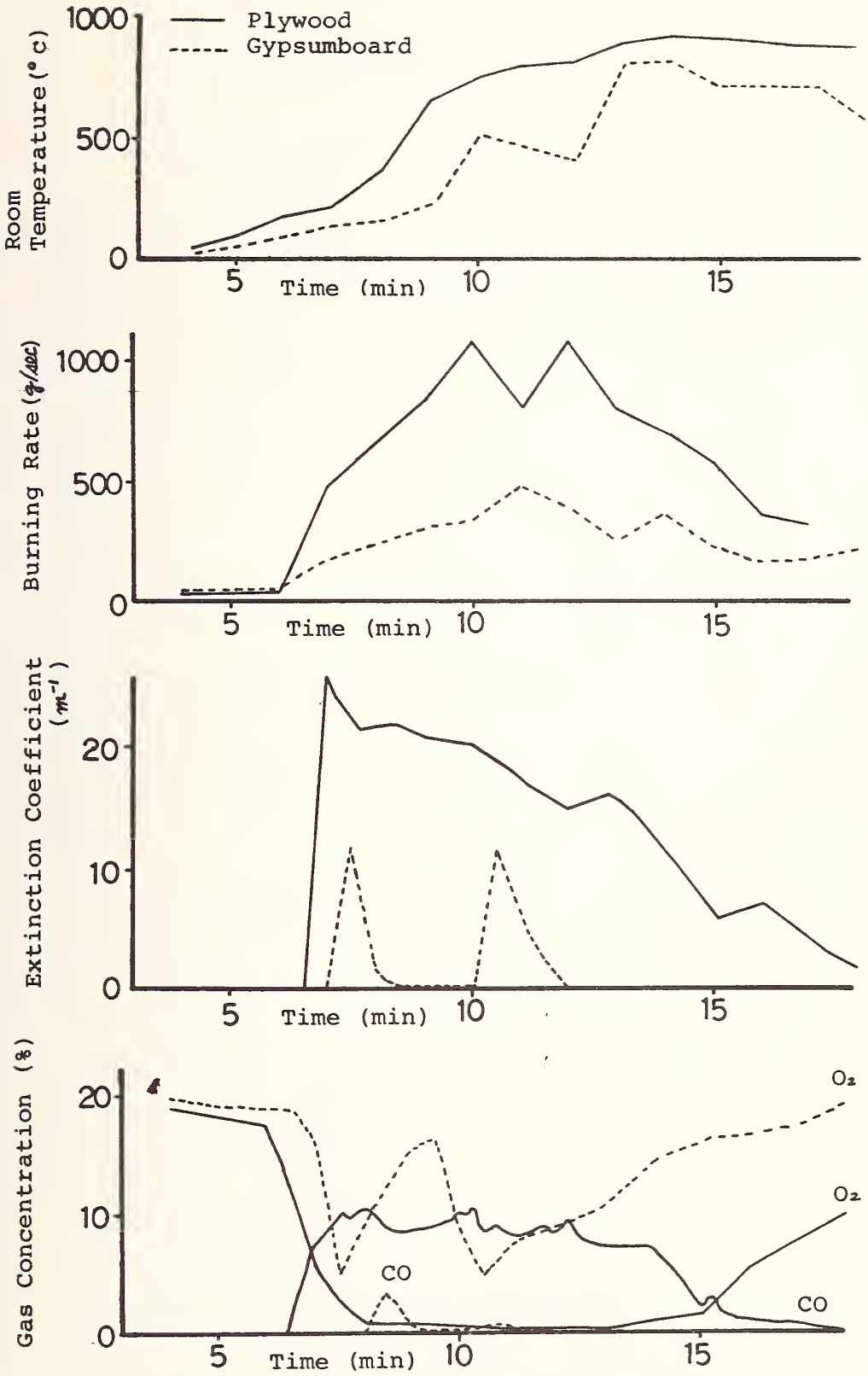


Fig. 30 Influence of Combustibility of Interior Linings in Full Size Fire Test
(Room Size : 3.6(W)x2.7(D)x2.6(H)m, $A\sqrt{H}$: $4.2m^{\frac{5}{2}}$)

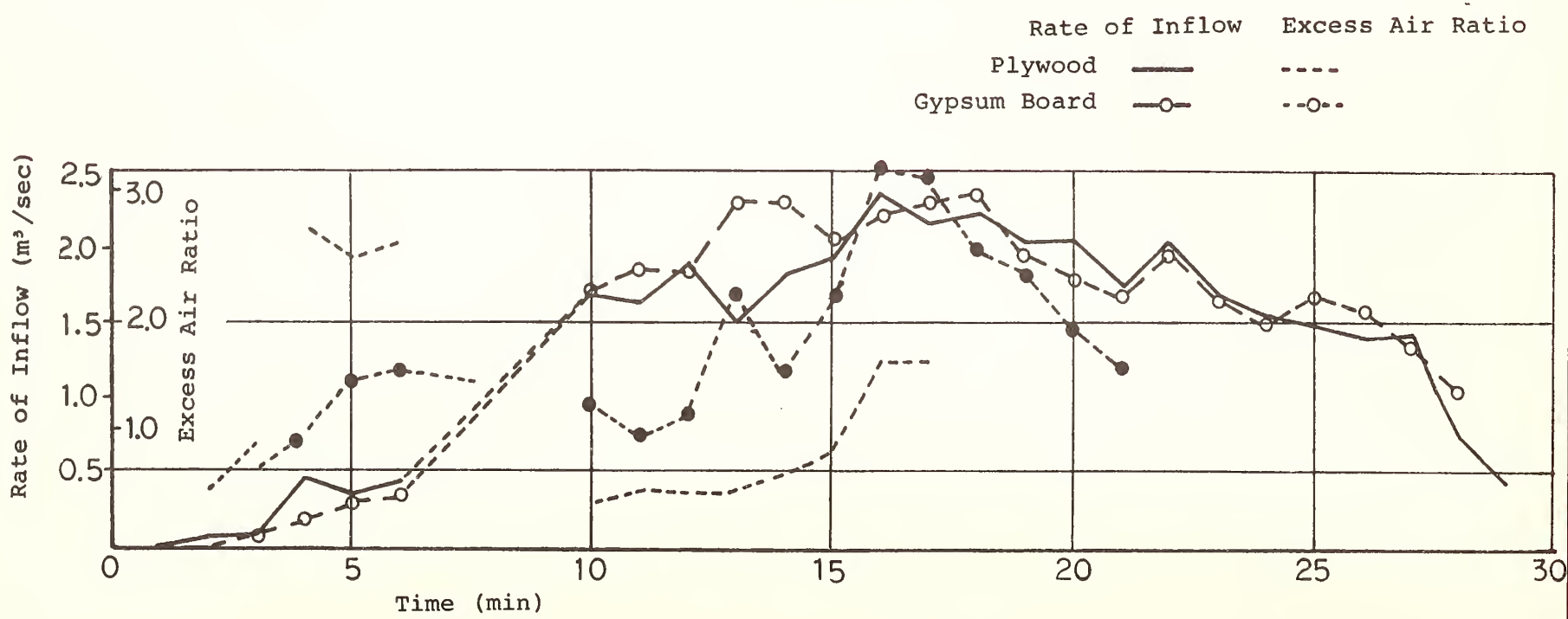


Fig. 31 Excess Air Ratio in Full Size Fire Test
(Room Size: 3.6(W)x2.7(D)x2.6(H)m, $A\sqrt{H}$: 4.2$m^{\frac{5}{2}}$)

Table 1 Size of Model and Opening

	Type (D·W·H)m	Opening ratio	Height of opening (m)	Width of opening (m)	Depth of soffit (m)	Opening factor ($m^{\frac{1}{2}}$)
A*	S-H-L-I (1.0x2.0x1.0)	1/2 1/3 1/4 1/8	1.0	1.0	0	1.0 0.667 0.500 0.250
	S-H-L-2 (0.9x1.8x0.9)	1/2 1/3 1/4 1/8	0.82	0.9 0.6 0.45 0.225	0	0.668 0.445 0.334 0.167
	S-H-S-A (0.48x0.98x0.48)	1/2 1/4 1/8 1/15	0.48	0.98	0, 0.08, 0.16	0.163 0.082 0.041 0.021
	S-H-S-B (0.45x0.90x0.45)	1/4 1/8 1/15	0.35	0.37 0.163 0.083	0.10	0.080 0.040 0.020
	S-V-S-I (0.48x0.48x0.98)	1/2 1/4 1/8 1/15	0.98	0.45	0, 0.15, 0.3	0.234 0.117 0.058 0.029
B*	R-H-S-1 (0.91x1.11x0.55)	1/4 1/8 1/15	0.35	0.34 0.17 0.08	0.10	0.070 0.035 0.018

A*: Simple Model Box

B*: Dwelling Model Box

Table 2 Example from Fire Load Survey

Type	Volume of Compartment V(m)	Amount of Combustibles W(kg)	Ratio of Combustibles (%)			Specific** Fire Load W/V (kg/m²)
			Wooden Materials	Textile	Plastics	
Dwelling House	38.88	980	91.8	5.1	3.1	25.2
Office	324.00	3,920	89.3	3.1	7.6	12.1
Fibre Goods Sale Counter	264.60	3,070	73.3	17.9	8.8	11.6
Average	209.16	2,657	84.8	8.7	6.5	16.3

* From the data of Hamada Laboratory of Science University of Tokyo.

** Calculated by the author.

Table 3 Specific Fire Load

Model Box	Weight of Crib (kg)	Fire Load (kg/m²)		Specific Fire Load (kg/m²)	
		without lining	with lining	without lining	with lining
Simple Model Box S-H-S-B	2.5	5.32	6.58	11.06	15.33
	5.0	10.63	13.16	22.12	30.67
	7.5	15.96	19.74	33.19	46.01
	10.0	21.28	26.32	44.25	61.35
	20.0	42.55	52.63	88.50	122.70
Dwelling Model Box R-H-I	2.5	2.48	3.29	4.50	6.87
	5.0	4.95	6.58	8.99	13.74
	10.0	9.90	13.16	17.98	27.47
	20.0	19.8	26.32	35.97	54.95
	3.2	3.7	4.22	5.76	8.79
	6.4	6.34	8.44	11.51	17.85
	12.8	12.67	16.88	23.02	35.16

The floor area and volume of the model box change as follow:

S-H-S-B without lining; floor area = 0.47m² volume = 0.226m³
with lining , = 0.38m² = 0.163m³

R-H-I without lining; = 1.01m² = 0.556m³
with lining ; = 0.76m² = 0.364m³

Table 4 Transition Point of Burning Behaviour
(Model : RSH, Linings : Plywood)

Ignition Source ℓ(cm) Layer	Opening Ratio	Thickness (mm)	Transition Point (min) Observation	Room Temp.	Hood Temp.	Radiation	Average
17-5	1/4	3	4'15"	4'00"	4'30"	4'40"	4'17"
14-4	1/4	"	3'10"	3'00"	3'10"	2'50"	3'02"
6-4	1/4	"					
17-5	1/8	"	3'30"	2'10"	3'40"	3'10"	3'08"
14-4	1/8	"	8'00"		8'20"	7'30"	7'56"
6-4	1/8	"	5'45"	6'10"	12'00"	11'30"	8'52"
17-5	1/4	5.5	5'45"	4'20"	6'00"		5'22"
14-4	1/4	"	7'50"	7'20"	7'00"	7'20"	7'30"
6-4	1/4	"	∞	∞	∞	∞	∞
17-5	1/8	"	5'00"	5'40"	5'40"	4'40"	5'15"
14-4	1/8	"	4'50"	4'15"	4'40"	4'20"	4'34"
6-4	1/8	"	(11'00") (23'00")	(11'00") (21'50")	22'40"	(24'00")	(11'00") (22'53")
17-5	1/4	9	6'30"	7'10"	7'20"	7'30"	7'08"
14-4	1/4	"	5'30"	5'10"	5'10"	5'10"	5'15"
6-4	1/4	"	∞	∞	∞	∞	∞
17-5	1/8	"	4'10"	3'50"	4'30"	3'40"	4'02"
14-4	1/8	"	6'50"	6'05"	6'20"		6'24"
6-4	1/8	"	∞	∞	∞	∞	∞

Table 5 Relation between F.O.T. and Opening Ratio

Volume of Model Box	Opening Factor $(A\sqrt{H})\ m^{5/2}$	Burning Rate of Ignition	F.O.T. (min)	Distance between Wall & Ignition
1.77m (SHL-1)	1.0	70.0 (g/min)	8'00"	5 cm from wall
	0.7	"	7'30"	"
	0.5	"	8'25"	"
	0.25	"	10'30"	"
1.17m (SHL-2)	0.445	100.0	7'45"	"
	0.334	"	6'50"	"
	0.167	"	6'25"	"
0.19 (SHS A)	0.07	35.0	6'55" (2'47")	2 cm from wall
	0.035	"		"

Table 6 Burning Rate and Acceleration Factor

Volume of Compartment (m)	$A\sqrt{H}$	Burning Rate (kg/min)	α_M
1.77	1.0	5.9	1.16
	0.5	6.2	2.26
	0.25	4.5	3.27
1.17	0.445	5.2	2.10
	0.334	4.6	2.50
	0.167	3.8	4.10
0.19	0.07	0.73	1.60
	0.035	0.52	2.30
27.0	4.2	60.0	2.60
27.0	4.2	55.0	2.38 (PVC)

Table 7 α_M Value in Each Period (Model : RHS)

Material	Thickness (mm)	Opening Ratio	Burning Rate (kg/min)			α_{M_0}	α_{M_1}	α_{M_2}
			F.O. (R_0)	$0.8W_0 \sim 0.5W_0$ (R_1)	$0.8W_0 \sim 0.2W_0$ (R_2)			
Plywood	3	1/4	0.9	0.53	0.39	2.34	1.38	1.01
"	"	"	0.57	0.60	-	1.48	1.56	-
"	"	"	0.5	0.32	0.28	1.30	0.83	0.73
"	"	1/8	0.42	0.40	0.45	2.18	2.07	2.33
"	"	1/16	0.5	0.38	0.54	5.15	3.92	5.57
"	4	1/4	1.15	0.72	0.48	2.99	1.87	1.25
"	"	"	1.2	0.55	0.45	3.11	1.43	1.17
"	"	"	0.57	0.42	0.4	1.48	1.09	1.04
"	"	"	0.9	0.54	0.57	2.34	1.40	1.48
"	"	"	0.11	0.75	0.49	0.29	1.95	1.27
"	5.5	"	-	0.51	-	-	1.32	-
"	"	"	0.7	0.75	0.36	1.82	1.95	0.94
"	"	"	0.8	1.1	0.59	2.08	2.85	1.53
Treated Plywood	3	1/4	0.8	0.46	0.35	2.08	1.19	0.91
"	"	"	0.65	0.46	0.42	1.69	1.19	1.09
"	"	"	0.17	-	-	0.44	-	-
"	4	"	0.8	0.5	0.39	2.08	1.30	1.01
"	"	"	0.8	0.49	0.51	2.08	1.27	1.32
"	"	"	0.5	-	-	1.30	-	-
"	5.5	"	0.4	0.51	-	1.04	1.27	-

Table 8 Burning Rate and Smoke Generation Rate per Unit Exposed Area
(Model : SHSA, Crib(ℓ) : 12 cm)

Material	Opening Ratio	Part of Lining		Burning Rate		Smoke Generation Rate	
		Wall	Ceiling	Burning Rate (kg/min)	Burning Rate per Unit Area (kg/min·m²)	Smoke Generation Rate (m²/min)	Smoke Generation Rate per Unit Area (1/min)
Plywood	1/4	o	o	0.8	0.65	27.0	21.77
	1/4	o	o	0.65	0.52	16.8	13.55
	1/4	o	-	0.52	0.61	21.0	24.71
	1/4	o	-	0.48	0.56	15.0	17.65
	1/4	o	-	0.49	0.58	14.4	16.94
	1/4	-	o	0.2	0.47	4.5	10.47
	1/8	o	o	0.44	0.16	21.0	16.94
	1/8	o	o	0.60	0.47	10.5	24.42
	1/8	o	-	0.3	0.35	6.0	7.06
	1/8	o	o	0.5	0.40	6.0	4.84
	1/8	-	o	0.2	0.47	6.6	15.35
	1/8	o	-	0.3	0.35	4.2	4.94
	1/8	-	o	0.2	0.47	——	——

Table 9 Burning Rate and Smoke Generation Rate of Various Materials

(Model : SHSA)

Material	Opening Ratio	Part of Lining		Burning Rate		Smoke Generation Rate	
		Wall	Ceiling	Burning Rate (kg/min)	Burning Rate per Unit Area (kg/min·m²)	Smoke Generation Rate (m²/min)	Smoke Generation Rate per Unit Area (l/min)
Decorated Plywood(A) (Melamine)	1/4	o	o	0.3	0.24	12.0	9.68
	1/4	o	o	0.5	0.40	21.0	16.94
Decorated Plywood(B) (Melamine)	1/4	o	o	0.5	0.40	13.2	10.65
	1/8	o	o	0.5	0.40	24.0	19.35
Fiber Board	1/4	o	o	0.7	0.56	27.0	21.77
	1/4	o	o	0.7	0.56	19.2	15.48
	1/8	o	o	0.8	0.65	15.0	12.10
Fiber Insulation Board	1/4	o	o	0.6	0.61	9.0	7.26
	1/4	o	o	0.8	0.65	10.5	8.47
	1/8	o	o	0.8	0.65	5.4	4.35

Table 10 Example of Test Results Related to the CO Gas Generation

Materials	Opening Patio	Inter Lining Area (m^2)	CO Gas Generation Rate (l/min)	Rate per Unit Area (l/min·m^2)	CO Gas Generation Rate (l/min)	CO Gas Generation Rate per Unit Area (l/min·m^2)	CO Gas Generation Coefficient (l/kg)	CO_2/CO
Plywood	1/4	1.24	4.50	3.63	67.5	54.4	6.3	14.9
	1/8	1.24	2.65	2.14	65.5	52.8	8.5	25.0
	1/4	0.85	2.50	2.94	23.5	27.6	7.5	6.1
	1/8	0.85	2.15	2.53	40.0	47.1	7.2	14.9
	1/4	0.43	1.20	2.79	23.0	53.5	6.0	19.2
	1/8	0.43	1.30	3.02	10.0	23.3	6.5	76.9
Decorated Plywood (A) (Melamine)	1/4	1.24	3.9	3.15	117	94.4	13.0	33.0
	1/8	1.24	4.2	3.39	21	16.9	14.0	50.0
Decorated Plywood (B) (Melamine)	1/4	1.24	1.8	1.45	12	9.7	3.6	66.7
	1/8	1.24	3.5	2.82	76	61.3	7.0	21.7
Fiber Board	1/4	1.24	5.25	4.23	134	108.1	7.50	13.4
	1/8	1.24	2.0	1.61	111	89.5	6.50	52.6
Fiber Insulation Board	1/4	1.24	3.2	2.58	60	48.4	4.0	20.0
	1/8	1.24	1.8	1.45	19	15.3	2.25	10.5

Table 11 Smoke and CO Gas Generation Rate in Each Fire Duration

Material	Opening Ratio	Fire Load (kg)	Smoke Generation Rate (m^2/min)			CO Gas Generation Rate (m^3/min)		
			Wo ~ 0.8Wo	0.8Wo~0.5Wo	0.5Wo~0.3	Wo~0.8Wo	0.8Wo~0.5Wo	0.5Wo~0.3Wo
Plywood (5.5mm)	1/8	3.2	22.96	13.93	—	0.131	0.136	—
	1/8	6.4	28.45	3.95	—	0.120	0.059	—
	1/8	12.8	19.02	2.58	—			—
	1/16	3.2	37.40	35.55	—	0.081	0.093	—
	1/16	6.4	40.23	14.96	—	0.158	0.080	—
	1/16	12.8	54.26	36.30	—	0.077	0.091	—
Asbestos Cement Board (4.0mm)	1/8	3.2	0.120	0.73	0.56	0.001	0.004	0.007
	1/8	6.4	0.57	2.94	6.51	0.003	0.048	0.077
	1/8	12.8	43.25	24.95	—	0.186	0.262	—
	1/16	3.2	0.25	0.710	0.89	0.002	0.011	0.012
	1/16	6.4	1.07	8.03	—	0.064	0.079	—
	1/16	12.8						

Tanaka: I have a question on figures 4 and 7. The results from the experiments and the actual calculations seem to correlate very well. There seems to be a fluctuation. Is this due to the difference in burning rates? Is this an input received or acquired from the actual results or was this calculated?

MacArthur: The figure that you referred to (4) is a comparison of the IITRI program during dressing. There are several answers to that question. Some of that correlation at the top of the curve is variation in the burn rate in the program, I guess. Some other problem there are from instability in the mathematical solution of the equation. I am sorry I don't think I should go any further without someone from IITRI to correct me if I am wrong. But I think even with what I said the stability of the program to follow the number is quite significant. I know this program does involve some adjustive conferences as many of these programs do and they have been adjusted to be of good value.

Tanaka: I don't have your paper with me. I would like to ask a question about the slides. I am referring to figure 8. How much time was taken to do this calculation?

MacArthur: Well I will turn that over to the gentleman of Notre Dame.

Szewczyk: These are non-dimensional times that are given at the bottom of the figure, however, for each unit of time it was approximately one hour computer time associated on the IBM 371-58.

Tanaka: At this time I would like to explain why I am asking this question. In the case of the Japanese Railroad there is a committee on fires in tunnels. We do similar kinds of models there too. Was the burning rate arbitrarily given according to the model? I'm sure it's not a big problem.

Szewczyk: The burning rate was selected to compare with the burning rate that the NBS quarter-tests use, the specific value at the present time I cannot remember. However, that is in our report. Jim, perhaps maybe you would be able to recall it. I just don't recall the number of BTU's. It is a volumetric heat source that is put in over a series of six cells in the burn room at the base of the burner.

Tanaka: Are you saying that you measured or calculated the heat loss of the kinetic energy And then you calculated or measured what was the amount of the energy that came out, the effluent energy.

Szewczyk: Well the heat source itself is a volumetric heat source over several cells then through the full energy equation the temperature is calculated for the remaining cells from that given heat input.

Tanaka: Thank you very much. If possible I would like to compare your calculation or your figures with what I have. Do you think that would be possible.

Szewczyk: Yes.

Tanaka: When there is a fire is there a model of a fire plume? I don't see one here. In the case of a compartment fire I think that a model of a fire plume is necessary. How much has been done on a plume model? I'm talking in very general terms.

Szewczyk: In all the models there is a plume model. They differ a little. My model and ARFARS model use a plume model developed by Stewarts and Dr. Fang at NBS. Professor Emmons' model uses the more massive model for a buoyant plume and the Notre Dame model is essentially a plume model in itself.

Tanaka: If there is a flame inside the plume model, do you take into account the temperature and other factors involved? Do you calculate those other factors too?

Szewczyk: In full volume models the flame temperature is either specified or assumed by assuming an equivalent radiation intensity from flame. In field models the temperature is calculated everywhere and I would not say that we would call that a flame temperature yet, but we're getting close to it. One of the problems that we had is how to best represent the radiation from flame and plume and that's the problem we all have and that is an important research topic and I think we should all address it. It is certainly a problem with my model and seems to be in other models.

Emmons: I might add to that in the Harvard model we use as MacArthur said the classical plume Warton-Taylor and Turner. It is calculated as though all of the material has burned. The heat is heat at the surface, however, above the fire was a flame which would radiate and the radiation was calculated using flame temperature as measured by George Markstien of Factory Mutual and the emissivity as measured by Mr. Markstein.

Tanaka: I would like to learn something from you. For the flame temperature is it all right to understand that the flame temperature is the same for all materials?

MacArthur: I can only speak for my model. What we have done very recently is to attempt to relate the radiation from the fire to the smokiness of material that's burning. In other words we have a very crude method of calculating the flame in the emissivity. I don't know how good it is but it's better than having the same emissivity for all types of materials as in previous situations. This all starts back to the point John made about getting the radiation right. I'd like to add that as a particular function of the way we do things we would like to have radiation measurements for flames on vertical surfaces, fires that are upside down and concealed fires. We'd like to have simple engineering calculations that are sensitive to the job but the only tested calculations for horizontal surfaces with a cylindrical fire above and that's clearly not right for a fire wall.

Tanaka: I'm not sure if this is a question, but the model of Dr. Quintiere and my model uses the work fire plume but I don't think we can really call this a fire plume. I think it's more or less a thermal plume. If we are to burn the wall when there is a big fire the temperature is very high, the plume is very high. Do you remember I think it was last year in the summer we did conduct an experiment in this area? When we burn in Japan, a big chair, the flame goes up to about four meters sometimes to six which means the flame is higher than the height of the room. So I would like to ask you if indeed this is a fire plume or if this is more or less a thermal plume.

Szewczyk: I can only speak for what my program does. We recognize that there are significant heat transfers from that region of the plume from which we don't see flames, which is not emitting light. Our model tries to take that into account like heating material when it's in the plumes but not in the flames. We don't have a method of taking the actual combusting flame and bending it around and over the ceiling or out the door as we should, so I would very much appreciate someone who can model the flame and the hot plume above it, and some other configuration other than just straight up in an enclosed fire. I think the point you made is that the heat transfer from the hot gasses that are not actually in the fire is very significant in the development and in a way we take the radiance horizontally into account. I think we do in our aircraft model. We're working on that but for smaller situations it might not be that important. I hope I answered your question.

Quintiere: I would just like to add some thoughts of my own, but agree with everything you said. I think from my point of view we have not really modeled the fire. We are simply superimposing some features of the fire onto this control volume approach. When one looks at the results of the control volume approach, particularly in assessing their accuracy, for example, the prediction of burning rate of the materials in the room. As John DeRis has stated the radiation from the fuel flame is very significant. I don't believe these models are in a state yet of doing that accurately. This is an area for growth. In addition we in our laboratory feel the entrainment of air into the fire is not reasonably modeled with the current state of heat in a fire plume or a thermal plume calculation.

Chaiken: You have been looking at plume models and tunnel fires and there is a basic problem in mathematical modeling of the plumes. It was essentially a three dimensional problem in the fact that you can't have extreme lines crossing each other. And this caution gives rise to the entrainment type parameters to indicate the mixing that can go on in a plume. Dr. Quintiere here indicated we don't have any good mathematical representation of work on how to calculate these entrainment parameters. I think this requires room plume models having developed good measurements on those entrainment parameters. I agree with Tanaka about the effect of height above a fire source or heat source. I don't think it makes much difference if it is a fire plume or thermal plume but don't consider reaction chemistry. It is just a question of temperature. It's height that is as important an aspect to me as spread of flame.

Tanaka: I am very interested in this problem too. As for the train tunnel fires I am very interested in the progress of fires in such areas. The problem of entrainment is a big issue for us. This problem is on the first level, initially a very important parameter. In the initial area we have to calculate how much entrainment there is in the initial stage. We have to measure the amount. A two dimensional field equation I think should be formulated. I think the big problem is how to grasp or understand the problem of entrainmer so we can have some kind of two dimensional field equation. One reason I came to this meeting was to see if you had some of the answers to the questions I have in mind.

DeRis: I would like to mention to you some current research in this area. Ed Bukowski is examining the entrainment experimentally. He conceived of the following experiments, mainly a fire or a thermal heat source that goes up and frames air and then it's captured by a box with an open bottom, but with a very small lip edge. He then controls the outlet stack vent on the box such that the layer filling the box remains at a precise height so that nothing spills out of the box. He then measures a chemical composition and other properties of this layer that was captured and which then is indicative of what has been entrained under these, since he has an accurate measurement of what the fire originally experienced. When I heard about his idea I immediately was sold. Very soon I told Phil Thomas and Bernie McCaffrey who is also running a very similar experiment in England. I'm sure that these two studies will not come up with the exact same parameters because there are many things to be measured and much work to be done. Another study that is being done is Franco Tamanini at Factory Mutual has set up a generalized or has gone further with Spalding Genmix of parabolic turbulent flow of boundary layer flow models and has calculated the entrainment for a two dimensional or radial axi-symmetric plume. He is currently doing some dimensional work in this area and he intends to perform a similar experiment funding permitted. To determine the effect of vitiation he is going to perform similar sort of experiments but under vitiated conditions and with the combustion in the plume. When it comes to describing the fire our best models were developed by Frank Stewart. However, in examining the models in detail they leave much to be desired. Frank Stewart's approach, his over-simplistic assumption that all the air is burnt at the instant of entrainment leaves us quite dissatisfied with the model. However, there are three different studies being undertaken at the present with the idea of resolving the conflict.

Rockett: It's too early to say anything or very much about the McCaffrey work in England but preliminary data suggests that the small fires get agreement with the codes, for large fires there are substantial differences. The other thing I thought worth mentioning, when you consider two dimensional calculations of observations by Bukowski and also here of Stanley Liu suggests that the door jet enters the lower part of the room, proceeds for substantial distance across the room and bends the plume over. In the case of Dr. Liu's experiment he had four separate burners evenly spaced across the room half way from the door to the back wall. The door jet played the two center burner flames over against the floor and they were tripped to the rear of the room and up through the back wall. The two outer flames were outside the door jet, actually leaned a little taller towards the door because of the recirculation from the back. No two dimensional calculation can take those kind of effects into account. We may talk more on this later.

Chaiken: Since we are talking about plume experiments I should refer to the experiments that Mathew carried out very recently at the Bureau of Mines in Pittsburgh, involving a fire source at the base of a wind tunnel against a forced convection. In this particular experiment we are very much interested in the reverse flow where the combustion products move in the direction opposite to the inventilating air and we hope to analyze this data in terms of effective entrainment parameters. We have very detailed measurements on the flow velocity and the temperature profile as well as the ventilating air current that's required to prevent reverse flow.

Tanaka Presentation

Nelson: My name is Nelson and I have a few questions for Mr. Tanaka regarding your model. You have several patterns in which you have calculated the flow of smoke in an open dynamic system. Has any proof testing been done to determine the validity of your model?

Tanaka: Actually I made this kind of model to bring to the UJNR Panel Meeting, so we have not done this proof testing yet. I would like to do this proof testing by using models. However, the model that I presented to you can probably not be used for a very high building of more than three stories that I can predict. As for the fire plume I think we have some drawbacks in this model. So perhaps it cannot be applied to explaining the fire plume. This is just a model of the first primary stage so I would like you to understand it as such.

Nelson: I asked that question primarily to see if the angle of repose that we have seen in the smoke test is much shallower than the graphics would indicate. This may just be graphic art. I do not need an answer to that. Could I ask about the data base with Mr. Morshita, the half of the statistical model? Do the statistics in Japan actually go to the depth of relating these variables to the individual phases or rounds of fire?

Tanaka: Are you referring to the accuracy of the data?

Nelson: Yes, particularly in terms at each of the phases. The correlation between the opening and passing of phase four to phase five or of a combustible finish in passing from phase two to phase three. This seems to be an extremely complex matrix of interrelationships.

Tanaka: Yesterday in the progress report of systems I think I referred to this problem. Generally speaking in Japan, the data has to be reported to the Fire Defense Agency of the Department of Home Affairs. As for Tokyo Fire Agency they do have an investigative chart which is quite detailed and they do have such data on the fire incidences.

Nelson: The work is very similar to the work done by Berlin at the National Fire Protection Association in Boston. I will send him a copy of this report.

Chaiken: Have the fire people in the United States seen the fire investigation form that is used by the Tokyo fire department?

Tanaka: There is an original form that is used when there is a fire occurence which gives a detailed report on a fire. The Fire Agency in Tokyo has a format which deals with the investigation of fires. It is about half of this form here and there are six or seven pages of that. Data that I used for this research also includes diagrams so what I include is data and diagrams that the Fire Agency acquires when it tries to discuss the fire content measures for their fire fighting policies.

Watanabe: Let me add that the Tokyo Fire Agency has a person who specializes in reports and he would take a report of the fire and sometimes he goes to the public and sometimes he is criticized. Because he specializes in these reports, he can get a detailed report of a fire.

Emmons: This last step is very important. Firemen are very busy and do not have time to make careful observations, especially of some of these fine details. Therefore it's very important that there be a special person trained for this purpose who sometimes can go to the fire in any case and carefully question the firemen, fire officers, and members of the public. It's a very important step.

Quintiere: Mr. Tanaka, I would like to ask some questions on your work on flow motion. Probably I have more questions than I can state at this time. Maybe I can see you later? We have made some measurements in a two-compartment model on flow through two doorways that is qualitatively in agreement with your calculations, particularly in this regard that you indicate both cold and hot air entering through a doorway. This is an improvement on previous models, to the extent that we can define a thermal layer. This layer is not always well-defined, but we observe this pattern for some experimental situations. One question I have, I wonder if any of the calculations you have shown have reached steady state?

Tanaka: Most of them are almost at that state, however, the walls of the room have thermal capacity and will probably increase in temperature slowly. Just concerning the ceiling itself, most of them have almost come to steady state.

Quintiere: As I understand it the flow at each doorway then would appear to be equal?

Tanaka: The flow rate is about 0.01 or 0.02, I'm not sure which it was exactly but we don't measure after that. So actually you're right and it should be equal but I do think there is a discrepancy because of the problem in the calculation. If I may add on the same subject, the amount of air that comes into the room and the amount that goes out of the room in this case there is a difference and, depending on the amount of heat in the room, there is a big difference. As I said many times already I think this is a problem for the modeling of the fire plume. I think there is a low temperature layer beneath it and I think there is this discrepancy because we don't take into consideration all of the factors.

Quintiere: One more question. I haven't studied your paper, perhaps you have considered mixing between the hot and cold layers in your calculations? We have seen that to be a significant phenomenon in the jet from the doorway yet we have no good quantitative model for this phenomenon.

Tanaka: For this we are not thinking about or considering mixing hot or cold. As I said that this is just the first step in the work of modeling. One of the big problems of mixing hot and cold is that for a high building. For example, in a stairwell the hot air will rise and I think there is a big issue there, so at this point in time for our modeling we did not include that. What we are trying to do at this time is to make some kind of framework for future works.

Emmons: We have detailed study of individual components. In this case the field models are of major importance. We must have filed models to study specific components in order to really understand what is happening in those components and in interpreting the data. At the present time we see that computers are only capable of handling, and then barely, the two dimensional field models. If you wish to include the entire enclosure and that is quite out of the question at the present time to attack fire in an entire building that is a multi-story building. Many attempts are being carried out at the present time to applying models which accept components and their interactions and steal the whole fire from empirical or scientific data, whichever is available on specific components, and try to put it together. Each of the models are different in many finer details. This is not because the models are in any fundamental way different. They are all fundamentally the same thing. One author happened to work on this phase while other authors worked on that phase first. In the DACFIR model we have the most detailed study of the growth of the fire itself by maneuvering fuel in many small pieces. Other models merely accept an empirical burning rate on the experiment, others merely use use an arbitrary heat rate in order to study a flow phenomenon. In this paper by Mr. Tanaka we have I think the first attempt to include the flow through many rooms. This could very easily be coupled to one of the other models from which fire is treated in greater detail. But there has not been time yet. We all need to work on various pieces and so naturally it is hoped that we can get to the point where the various numerical treatment can be such that we can all use the others sub-programs with relatively little fixing. This project has only just begun.

Theme
TOXICITY

RESEARCH ON EVALUATION OF RELATIVE TOXICITIES OF COMBUSTION PRODUCTS OF VARIOUS MATERIALS

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ABSTRACT

The toxicities of combustion products of typical materials are evaluated by animal tests using mice, and the relative degrees of toxicity hazards are quantitatively clarified. The weights of the materials when generating combustion products sufficient to cause collapse of mice under given exposure conditions are obtained according to conditions of combustion. It is shown that the relative degrees of danger from toxicities of combustion products of materials may be expressed by the ratios of their weights.

On heating at 850°C, the combustion products of polyamide, polyacrylonitrile and wool indicate toxicities approximately 20 times, approximately 15 times and approximately 10 times, respectively, of lumber (Japanese cedar, lauan). Melamine resin-impregnated sheet and foamed polyurethane combustion products indicate toxicities of approximately 5 times and untreated plywood products approximately 2 to 3 times that of lumber.

On heating at 550°C, polyamide, polyacrylonitrile and melamine resin-impregnated sheet combustion products show toxicities of approximately 15 times, approximately 10 times and approximately 2 to 3 times, respectively, of the toxicity of lumber combustion products.

In comparisons of toxicities in heating identical materials at 850°C and 550°C, the toxicities at the former temperature are higher on the whole. In particular, the toxicity of combustion products of melamine resin-impregnated sheet is greatly increased when heating temperature is raised.

1. INTRODUCTION

It has been clarified through animal tests and gas analysis tests in research on toxicities of combustion products in the past that CO, HCN and HCl among combustion products are particularly harmful to the human body[1)-3)]. Based on these studies, there have been quantitative evaluations of toxicities made by animal tests for CO, CO_2, HCN and HCl considered to be the principal toxic gases in combustion products generated from building materials and objects accomodated in buildings, and in addition, of O_2 deficiency occurring incidentally during fire[4)]. In such manner, the methods of evaluating the toxicities of these gases are being studied along with clarification of the compositions and quantities of the combustion products generated inside buildings during fires.

However, since the compositions of the products generated from a material due to combustion or thermal decompositon are extremely complex, depending on the material, it is not possible to make an overall evaluation of the toxicity of the combustion products of the material from only analysis tests of a gas of specific components. In such case, evaluations by animal tests in addition to gas analyses would be appropriate. Although there has been research work making detailed physiological and toxicological studies of the toxicities of combustion products[5)], it is thought to be significant at present for general evaluations of relative toxicity hazards of combustion products of various materials to be made also.

In case of comparing the relative degrees of toxicities of combustion products of various materials exposing animals to the combustion products under given conditions, there are methods of comparison by mortality of the animals, and of comparison by length of time until the animals indicate a certain symptom (for example, death).

As a concrete method of evaluating relative toxicity, there is for example the method of burning samples of constant conditions (identical weights, identical volumes) under a number of combustion conditions to obtain the mortality of animals according to combustion conditions[6),7)]. There is

also the evaluation method of median lethal dose (LD_{50}) in toxicology where weights of samples are varied and the weight of sample at which 50% of animals tested die is obtained statistically[8),9)].

Further, there is the method of selecting a certain material (such as lumber which is used in general) as the reference material, and burning it and some other material separately under given conditions to judge whether the other material is safe compared with the reference material through the lengths of time required for animals to show symptoms (time from start of inhalation of combustion products until a certain symptom is shown)[10)].

From the standpoint of finding a material producing extremely great toxicity from among a large number of materials, it may be said that this method can be recognized as a comparatively appropriate one for evaluating relative toxicity in consideration of the simplicity of operations. However, it is difficult to classify in detail the toxicities of the combustion products of the various materials by this method.

The study reported here is of tests varying weights and heating temperatures of samples exposing animals to combustion products produced and making overall comparison studies of the toxicities of combustion products of many materials by obtaining collapse times of animals according to the various conditions. Hereinafter, when referring to the toxicity of a certain material it is meant the toxicity of the combustion product of that material.

2. METHOD OF TESTING

The materials used for testing were those indicated in Table 1. Except for polyamide, the materials were made into specimens 10 mm wide and 50 mm long (thickness according to the specific commercial product), dried in an oven at temperatures of 45 to 55°C for at least 24 hours, then left in a desiccator containing silica gel for more than 24 hours, upon which they were tested.

The testing apparatus was as indicated in Fig. 1, comprised

mainly of a combustion tube and a combustion chamber of 55-liter capacity made of transparent glass. The combustion tube of quartz glass (inside diameter 60 mm, length 210 mm) is held inside a tubular electric furnace. Alumina marbles are packed inside the combustion tube to a depth of 50 mm and this layer of marbles is air-permeable.

While supplying air at a flow rate of 4 liters per minute from the bottom of the combustion tube, the temperature in the tube was maintained at the specified level (850°C or 550°C), after which specimens were introduced and burned. The animals used for the experiments were mice (weight 20 ± 1 g, dd strain, male).

The combustion products generated were introduced into the exposure chamber inside which 5 revolving cages each holding one mouse were installed. The conditions of mice causing the cages to revolve were recorded as electrical pulses by proximity switches, and were also observed visually. The collapse times of mice were measured by the method described above. In this study, collapse time was defined as the length of time from start of test until the point that a mouse could no longer make its cage revolve. The testing time was taken to be 15 minutes maximum, but when all 5 mice collapsed and then died, the test was discontinued even if 15 minutes had not elapsed.

3. RESULTS AND CONSIDERATIONS

It was possible to observe the states of motion of the animals during the tests in more or less good condition, and the only case in which it became impossible to see inside the chamber because of smoke was when PVC was tested. Mice which survived 15 minutes of exposure were observed for one week after testing, and none of these died. Temperature rise in the exposure chamber was about room temperature plus 2°C even at the highest. Therefore, it was judged that temperature rise did not have much influence on collapse times of mice.

The results obtained on weights of samples and collapse times of mice are indicated in Table 2 in case of 850°C and

in Table 3 in case of 550°C.

The relations between weights of samples and collapse times of mice were as indicated in Figs. 2 through 19. The summarization of these results is as indicated in Fig. 20. It was learned that the equation below could be applied as an experimental formula expressing the relations between the two.

$$W = kT^P \qquad (1)$$

where

W : weight of sample (g)

T : collapse time (min)

k, P : constants

The constants k, P and determining coefficient r^2 are indicated in Tables 4 and 5. However, it was difficult for Eq. (1) to be applied to heating at 550°C in the cases of PVC and fire-retardant plywood since values of T were greatly scattered.

In the range that sample weights were too light (and consequently, the amount of toxic products generated small), mice were not forced to the extent of collapse in the short periods of time of the experiments. In effect, T could not be determined.

When the weight of a sample was heavier than a certain degree, the combustion products generated were of such large quantity that toxic action was great and collapse time became roughly constant regardless of weight of sample.

Therefore, under the testing conditions of this study, Eq. (1) was applicable for toxicity evaluation when the weight of sample was within a certain range, in effect, when T was in a certain range.

As can be seen in Fig. 20, the range of T in which relative evaluations could be made of all materials tested was approximately 2.5 to 3.5 minutes.

When T is in the above range, if a certain value of T is set and the corresponding weights of various materials determined, the relations between the weights of the various materials are thought in effect to express the relations of

the degrees of toxicities of combustion products of these materials.

For example, to compare lauan and polyacrylonitrile in heating at 850°C, that the estimated values of W of the two when T = 3 are 4.18 g and 0.28 g, respectively, can be obtained from Eq. (1) or Fig. 20. The weight ratio of lauan to polyacrylonitrile from these values will be as follows:

$$\frac{4.18}{0.28} = 14.9$$

In other words, it may be said that at a high temperature range of 850°C the toxicity of the combustion products of polyacrylonitrile is approximately 15 times stronger than that of lauan. This comparison is made for weights of materials to generate combustion products required for collapse of mice at time T.

From the standpoint of toxicities of combustion products, the weight of polyacrylonitrile having equal toxicity as 1 g of lauan will be approximately 0.07 g.

For such a value of the ratio to be the same for any value of T in the range of 2.5 to 3.5 minutes, the straight lines indicated in Fig. 20 must all have the same gradients. This means that the value of P in Eq. (1) should be the same for all of the materials. As indicated in Table 4 and Table 5, the differences between the values of P for the various materials were not very great.

The weight ratio of lauan to polyacrylonitrile for T of 2 to 4 was 14 to 16.

Next, a comparison of toxicities of lauan according to difference in heating temperature was made in a similar manner. When T = 3, the W of lauan for the cases of heating at 850°C and 550°C were 4.18 g and 7.38 g, respectively. Consequently, the weight ratio of the two were the following:

$$\frac{7.38}{4.18} = 1.77$$

In effect, it may be seen that the toxicity of lauan when

heated at 850°C is approximately double that when heated at 550°C.

The values of W for the various materials estimated with T = 3 are given in Table 6. The table indicates the ratios of W of the reference material (Japanese cedar or lauan) to the Ws of the various materials as R_C and R_L, respectively. These values express the relative toxicities of the various materials against the reference materials, and were determined by the following equations.

$$R_C = \frac{W \text{ of Japanese cedar}}{W \text{ of individual material}}$$

$$R_L = \frac{W \text{ of lauan}}{W \text{ of individual material}}$$

For materials of value of P in Eq. (1) being -1 the following equation will hold true.

$$W \cdot T = K = \text{const.} \qquad (2)$$

From the results given in Tables 4 and 5, since the values of P of the various materials were taken to be close to -1, the mean values K_m of K for the various materials assuming Eq. (2) to be valid were determined, the results being as shown in Table 7. The values of R_C' and R_L' in the table were obtained as follows, similarly to the previously mentioned R_C and R_L.

$$R_C' = \frac{K_m \text{ of Japanese cedar}}{K_m \text{ of individual material}}$$

$$R_L' = \frac{K_m \text{ of lauan}}{K_m \text{ of individual material}}$$

The coefficients of variation of K_m are roughly in the range of 10 to 20%, but for PVC and fire-retardant plywood they are in excess of 30%. Except for these two materials it will be possible to evaluate relative toxicity by the value of K_m. On comparison of Table 6 and Table 7, it may be said that evaluations of relative toxicities of various materials by R_C, R_L, R_C' and R_L' are more or less in agreement.

Roughly speaking, the following may be said when the

degrees of toxicity per unit weight of the various materials are compared based on the figures indicated in Tables 6 and 7.

In heating at 850°C, Japanese cedar, lauan and hardboard which are cellulosic materials have roughly the same degrees of toxicity. Of the materials tested, those with extremely high toxicities are clearly polyamide and polyacrylonitrile. When these materials are compared with lumber (Japanese cedar, lauan), polyamide indicates a toxicity approximately 20 times greater and polyacrylonitrile 15 times greater. The two kinds of melamine-impregnated sheet and foamed polyurethane may be said to have roughly the same degrees of toxicity, approximately 5 times that of lumber. The toxicity of wool is approximately 3 times that of these three and approximately 10 times that of lumber. Since untreated plywood shows approximately double to triple the toxicity of lumber it will require special caution among cellulosic materials. An accurate comparison cannot be made for fire retardant-treated plywood since there is much scattering in the value of T, but it may be said to have toxicity somewhat stronger than lauan and Japanese cedar.

In heating at 550°C, the results show that the toxicities of Japanese cedar and lauan are roughly of the same degree as in the case of heating at 850°C. A clear-cut evaluation cannot be made for fire retardant-treated plywood since scattering in value of T is comparatively great similarly to the case of heating at 850°C, but it is thought the toxicity is higher than for Japanese cedar and lauan. The toxicity of melamine-impregnated sheet #2 is given as 2 to 3 times that of lumber, but the multiplication rate is smaller compared with the case of heating at 850°C. The toxicities of polyamide and polyacrylonitrile are extremely high as in heating at 850°C, and compared with lumber, polyacrylonitrile shows an approximately ten-fold toxicity and polyamide an approximately fifteen-fold toxicity.

Next, the toxicities of the same material heated at 850°C and 550°C were compared. As a whole, the toxicities were lower for heating at 550°C. The reason for this is the higher combustion speed of material the higher the heating temperature

and faster rate of increase in concentration of toxic combustion products in the exposure chamber. Compared with the toxicity in case of heating at 550°C, the toxicity in case of heating at 850°C was approximately 1.5 times with Japanese cedar and approximately 1.8 times with lauan. That of melamine resin-impregnated sheet #2 was 3.4 to 4 times and it may be considered that the toxicity of this material is increased greatly at high temperature.[1] Polyacrylonitrile was approximately 2.6 times and polyamide approximately 2.2 times greater in toxicity at 850°C.

In case of evaluating the toxicity of the combustion product of a material by causing the test animal to inhale it until some kind of symptom appears, there will be various factors for variation such as scatter in the animals themselves. For example, the condition of generation of toxic products will vary due to variation in combustion speed of the sample according to the shape and size of the sample, and temperature distribution inside the combustion furnace. Since there is considerable difficulty technically for these variations to be eliminated, a more accurate method of evaluation of toxicity must await further research for development. However, it is thought the method of relative evaluation by weight of material as in this present study, although approximate, is fairly effective in such cases as selection of materials.

4. CONCLUSIONS

(1) It was possible to evaluate relative toxicities of combustion products of various materials more or less quantitatively from the relation between collapse time of mice and the weight of material required to cause collapse of mice during combustion.

(2) The relation between collapse time T of a mouse and weight of material W may roughly be expressed by the following equation:

$$W = kT^P$$

As a result of determining constant k and P for individual

materials, the equation below is valid when it is considered that P = -1.

$$W \cdot T = K = \text{const.}$$

It is indicated that toxicity evaluations by the two equations will lead to roughly the same results.

(3) In heating at 850°C, the toxicities of combustion products of Japanese cedar, lauan and hardboard are approximately equal. Polyamide and polyacrylonitrile combustion products are of extremely great toxicities, being approximately 20 times and approximately 15 times that of lumber combustion products, respectively. The toxicities of melamine resin-impregnated sheet and polyurethane products are roughly equal, being approximately 5 times that of lumber products. The toxicity of the combustion products of wool is approximately 10 times that of the combustion products of lumber, while that in the case of untreated plywood is roughly twice that in the case of lumber.

(4) In heating at 550°C, the combustion products of Japanese cedar and lauan indicated toxicities of roughly the same degree. The toxicities of polyamide and polyacrylonitrile combustion products are respectively approximately 15 and 10 times the toxicity of the combustion products of lumber.

(5) On comparison of heating of identical materials at 850°C and 550°C, toxicities are lower for heating at 550°C in all cases. Compared with toxicity in heating at 550°C, the toxicity in case of heating at 850°C is approximately 1.5 times with Japanese cedar and approximately 1.8 times with lauan. With melamine resin-impregnated sheet #2, this is 3.5 to 4 times, while with polyacrylonitrile and polyamide they are approximately 2.6 times and 2.2 times, respectively.

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10) Ministry of Construction Notification No. 1231, August 25, 1976.

Table 1. Materials Tested

Material	Form	Thickness (mm)	Density (g/cm^3)
Japanese cedar	Board	10	0.42
Lauan	Board	10	0.46
Hardboard	Board	3.5	0.96
Untreated plywood	Board	5.3	0.52
Fire retardant-treated plywood	Board	5.5	0.65
Melamine resin-impregnated sheet #1	Rigid sheet	0.8	1.45
Melamine resin-impregnated sheet #2	Rigid sheet	1.4	1.31
Polyacrylonitrile	Cloth		
Polyamide (Nylon 66)	Rod	12.8 (diam.)	1.14
Wool	Cloth		
Polyurethane	Rigid foam	10	0.029
Polyvinyl chloride (PVC)	Flexible sheet	3	1.60

Table 2. Test Results (850°C Heating)

Specimen	Weight (g)	Collapse Time (min)				
		1	2	3	4	5
Japanese cedar	1.84	6.36	5.40	7.68	6.90	4.78
	2.50	3.75	4.10	4.72	4.87	4.40
	4.43	2.90	2.90	2.92	2.88	3.05
	5.70	2.45	2.19	2.34	2.40	2.43
	7.52	2.15	2.40	2.40	1.88	2.24
	8.90	1.98	2.28	1.98	2.10	1.94
Lauan	1.90	6.55	5.87	5.30	5.85	5.65
	2.50	4.75	4.00	4.72	3.80	4.28
	3.06	3.80	3.32	3.35	4.60	4.50
	4.32	2.70	2.30	2.40	2.62	2.45
	5.66	2.25	1.80	2.35	2.24	2.60
	7.00	1.80	1.75	2.14	2.34	1.95
	9.45	1.75	1.80	2.04	1.75	1.78
Hardboard	2.21	4.40	3.90	3.24	4.23	4.09
	3.23	3.52	2.85	3.72	3.77	3.82
	3.93	2.96	2.75	2.15	2.41	3.00
	5.00	2.22	2.30	2.03	2.60	2.45
	6.36	2.61	1.85	1.90	2.30	1.80
	7.50	1.73	1.85	1.46	1.91	1.62
Untreated plywood	1.34	3.48	3.30	3.18	2.90	3.60
	1.80	2.60	2.95	2.85	2.95	3.20
	2.68	2.20	2.13	2.15	2.15	2.40
	3.80	1.90	1.70	1.55	1.47	1.85
	5.00	1.57	1.48	1.65	1.50	1.50
Fire retardant-treated plywood	2.00	3.16	3.64	4.07	4.62	4.00
	2.66	2.42	2.62	2.71	2.50	2.20
	4.38	1.42	1.85	1.80	2.25	1.93
	6.75	1.77	1.95	2.05	2.25	1.78
	8.66	1.60	1.55	1.39	1.63	1.55

Table 2 (Cont'd)

Specimen	Weight (g)	Collapse Time (min)				
		1	2	3	4	5
Melamine resin-impregnated sheet #1	0.51	3.90	2.95	3.37	4.75	3.65
	0.71	2.31	3.00	2.85	3.05	-*
	1.00	2.80	2.50	2.17	2.92	2.75
	1.25	2.12	2.28	2.45	2.34	2.22
	1.50	1.71	2.15	1.62	1.85	1.99
Melamine resin-impregnated sheet #2	0.61	4.55	3.76	3.04	3.70	3.08
	1.00	2.28	2.40	2.50	2.38	2.05
	1.16	2.40	2.07	2.15	2.42	2.00
	1.40	1.75	1.62	1.94	1.75	2.06
	1.67	1.69	-	1.75	1.65	1.67
	2.10	1.62	1.52	1.38	1.50	1.47
Polyacrylonitrile	0.19	4.82	4.50	3.70	4.64	2.82
	0.21	3.30	3.83	3.60	4.25	3.30
	0.35	2.50	2.84	2.50	2.20	2.53
	0.38	2.35	2.20	2.55	2.18	2.46
	0.53	1.97	1.72	1.55	1.56	1.38
	0.28	3.60	2.80	2.94	2.93	2.55
	0.45	2.18	2.29	1.95	1.78	1.88
Polyamide (Nylon 66)	0.15	3.58	4.10	3.20	3.37	3.30
	0.24	2.01	-	2.61	3.46	2.48
	0.36	2.24	2.32	1.90	1.61	1.69
	0.58	1.40	1.16	0.95	1.15	1.30
Wool	0.34	3.12	-	4.17	3.61	4.07
	0.47	3.37	3.47	3.55	2.62	2.95
	0.60	2.20	2.15	2.05	1.95	2.21
	0.81	2.40	2.00	2.05	1.70	2.15
	1.03	1.96	1.85	1.87	1.83	1.35
Polyurethane	0.50	3.77	4.20	3.70	3.30	4.05
	0.74	2.85	2.10	2.45	2.40	3.08
	0.91	2.50	2.45	2.00	2.20	2.15
	1.15	1.90	2.88	2.50	1.90	1.82
	1.45	1.60	1.80	1.58	1.95	1.52
	1.75	1.63	1.70	1.45	1.55	1.25

Table 2 (Cont'd)

Specimen	Weight (g)	Collapse Time (min)				
		1	2	3	4	5
Polyvinyl chloride	12.0	7.90	6.45	5.80	7.85	8.90
	19.0	6.15	7.55	7.60	6.17	5.16
	31.6	5.05	4.10	6.25	4.75	7.75
	41.50	4.75	5.90	4.15	4.30	6.05

* Measurement not possible due to defective rotation of cage.

Table 3. Test Results (550°C Heating)

Specimen	Weight (g)	Collapse Time (min)				
		1	2	3	4	5
Japanese cedar	3.68	4.46	5.46	5.00	4.95	4.67
	4.51	3.35	4.10	3.82	4.10	4.62
	5.44	3.42	3.10	3.25	3.28	3.15
	7.15	2.92	2.38	3.01	2.96	3.06
	10.00	2.68	2.51	2.18	2.28	2.18
Lauan	3.20	5.54	6.12	5.87	6.27	6.00
	4.54	4.75	4.63	4.73	4.20	3.85
	5.70	3.91	3.27	4.00	4.20	4.10
	7.61	2.70	2.85	2.97	2.92	3.05
	9.92	2.49	2.50	2.23	2.20	2.52
Fire retardant-treated plywood	2.41	4.39	3.85	3.07	3.50	4.00
	3.00	4.65	3.25	3.67	3.72	4.50
	4.20	2.76	3.15	2.95	2.70	3.30
	4.95	3.75	2.55	2.15	1.95	2.95
	5.33	3.00	2.90	2.30	2.50	2.57
Melamine resin-impregnated sheet #2	1.65	5.30	5.20	4.72	5.56	4.20
	2.15	3.33	3.90	3.50	3.70	3.42
	2.86	2.90	2.83	2.55	3.16	3.15
	3.63	2.31	2.90	2.50	2.40	2.75
	4.64	2.20	2.25	2.28	2.35	2.57
Polyacrylonitrile	0.43	5.28	5.05	5.05	4.20	4.52
	0.66	2.86	2.87	3.15	3.35	2.83
	0.84	2.75	2.90	2.57	2.60	2.80
	1.04	2.60	1.82	1.85	2.16	2.48
	1.24	1.90	1.80	1.84	2.00	1.90

Table 3 (Cont'd)

Specimen	Weight (g)	Collapse Time (min)				
		1	2	3	4	5
Polyamide (Nylon 66)	0.39	3.22	3.25	3.34	3.45	2.84
	0.45	3.37	2.72	3.40	2.91	2.68
	0.71	2.12	2.23	1.55	1.95	1.95
	1.01	1.48	1.52	1.35	1.55	1.50

Table 4. Regression Coefficients of Materials (850°C Heating)

Specimen	k	P	r^2
Japanese cedar	19.91	-1.34	0.92
Lauan	15.79	-1.21	0.87
Hardboard	12.11	-1.09	0.80
Untreated plywood	8.90	-1.53	0.94
Fire retardant-treated plywood	13.04	-1.42	0.75
Melamine resin-impregnated sheet #1	4.05	-1.53	0.83
Melamine resin-impregnated sheet #2	3.12	-1.27	0.90
Polyacrylonitrile	0.86	-1.03	0.86
Polyamide (Nylon 66)	0.68	-1.11	0.88
Wool	1.68	-1.13	0.79
Polyurethane	2.58	-1.19	0.84
Polyvinyl chloride	2.65	-1.36	0.43

Table 5. Regression Coefficients of Materials (550°C Heating)

Specimen	k	P	r^2
Japanese cedar	25.69	-1.23	0.88
Lauan	26.87	-1.18	0.91
Fire retardant-treated plywood	13.08	-1.07	0.61
Melamine resin-impregnated sheet #2	11.37	-1.22	0.88
Polyacrylonitrile	2.32	-1.06	0.92
Polyamide (Nylon 66)	1.48	-1.09	0.92

Table 6. Relative Comparison by Estimated Value of W

(Case of T=3)

Heating Temp.	Specimen	W (g)	R_C	R_L
850°C	Japanese cedar	4.59	1.0	0.9
	Lauan	4.18	1.1	1.0
	Hardboard	3.65	1.3	1.2
	Untreated plywood	1.66	2.8	2.5
	Fire retardant-treated plywood	2.74	1.7	1.5
	Melamine resin-impregnated sheet #1	0.76	6.0	5.5
	Melamine resin-impregnated sheet #2	0.77	6.0	5.4
	Polyacrylonitrile	0.28	16.4	14.9
	Polyamide (Nylon 66)	0.20	23.0	21.0
	Wool	0.48	9.6	8.7
	Polyurethane	0.70	6.6	5.6
	Polyvinyl chloride	-	-	-
550°C	Japanese cedar	6.63	1.0	1.2
	Lauan	7.38	0.9	1.0
	Fire retardant-treated plywood	-	-	-
	Melamine resin-impregnated sheet #2	2.96	2.2	3.3
	Polyacrylonitrile	0.72	9.2	10.3
	Polyamide (Nylon 66)	0.44	15.1	16.8

Table 7. Relative Comparison by Value of K_m

Heating Temp.	Specimen	K_m Mean Value of K(=W·T)	Standard Deviation	Coeff. of Variation of K_m (%)	R_C'	R_L'
850°C	Japanese cedar	13.93	2.95	21.2	1.0	0.9
	Lauan	12.65	2.50	19.8	1.1	1.0
	Hardboard	11.40	2.03	17.8	1.2	1.1
	Untreated plywood	5.94	1.21	20.4	2.4	2.1
	Fire retardant-treated plywood	9.83	3.10	31.5	1.4	1.3
	Melamine resin-impregnated sheet #1	2.65	0.64	24.2	5.3	4.8
	Melamine resin-impregnated sheet #2	2.60	0.38	14.6	5.4	4.9
	Polyacrylonitrile	0.85	0.11	12.9	16.4	14.9
	Polyamide (Nylon 66)	0.64	0.12	18.8	21.8	19.8
	Wool	1.52	0.28	18.4	9.2	8.3
	Polyurethane	2.25	0.42	18.7	6.2	5.6
	Polyvinyl chloride	149.10	55.60	37.3	0.1	0.1
550°C	Japanese cedar	19.61	2.84	14.5	1.0	1.1
	Lauan	21.43	2.18	10.2	0.9	1.0
	Fire retardant-treated plywood	12.58	2.59	20.6	1.6	1.7
	Melamine resin-impregnated sheet #2	8.88	1.32	14.9	2.2	2.4
	Polyacrylonitrile	2.19	0.24	11.0	9.0	9.8
	Polyamide (Nylon 66)	1.37	0.15	10.9	14.3	15.6

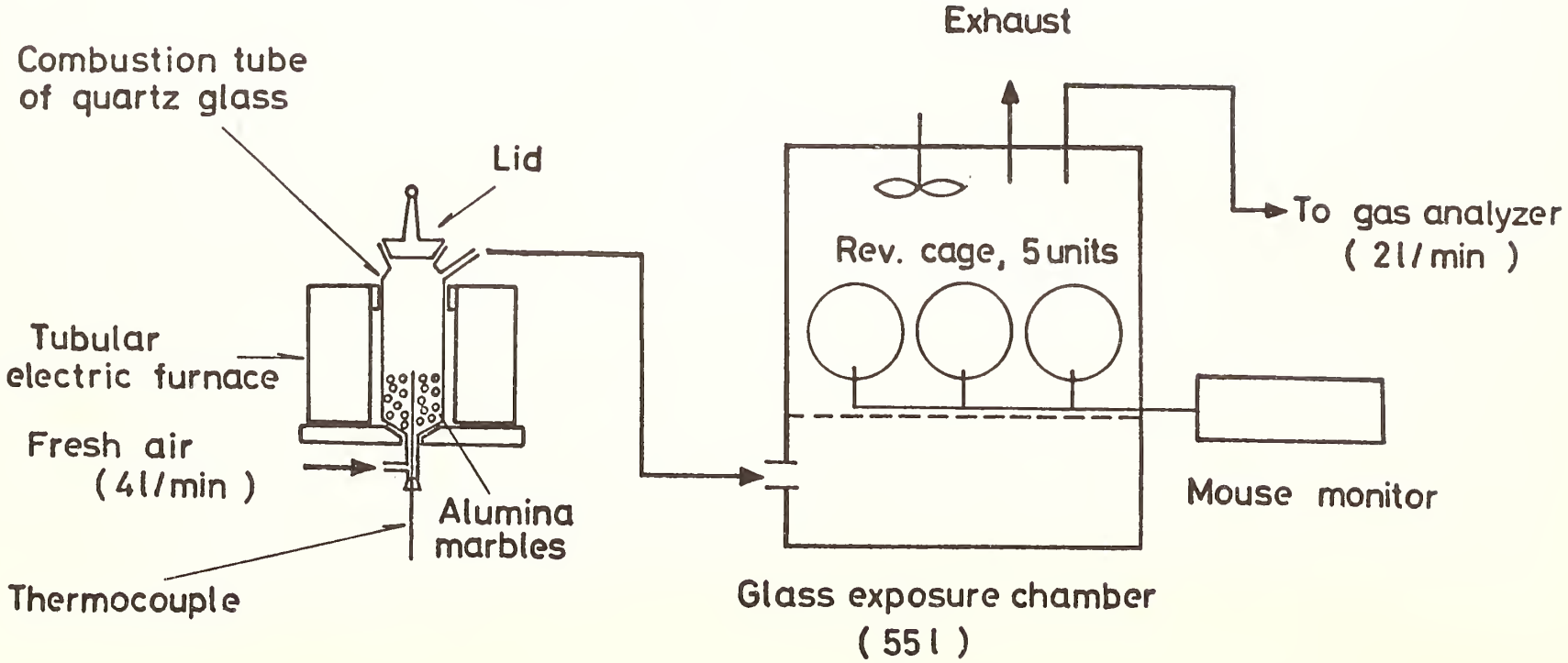

Fig. 1 — Testing apparatus.

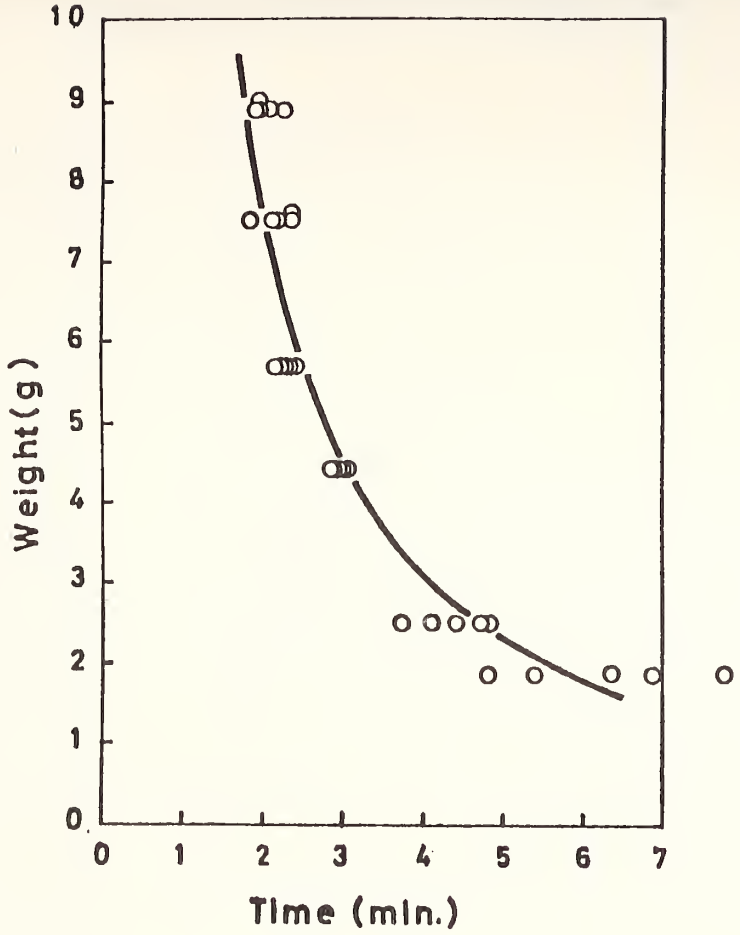

Fig. 2 — Specimen weight vs. collapse time, Japanese cedar (850°C heating).

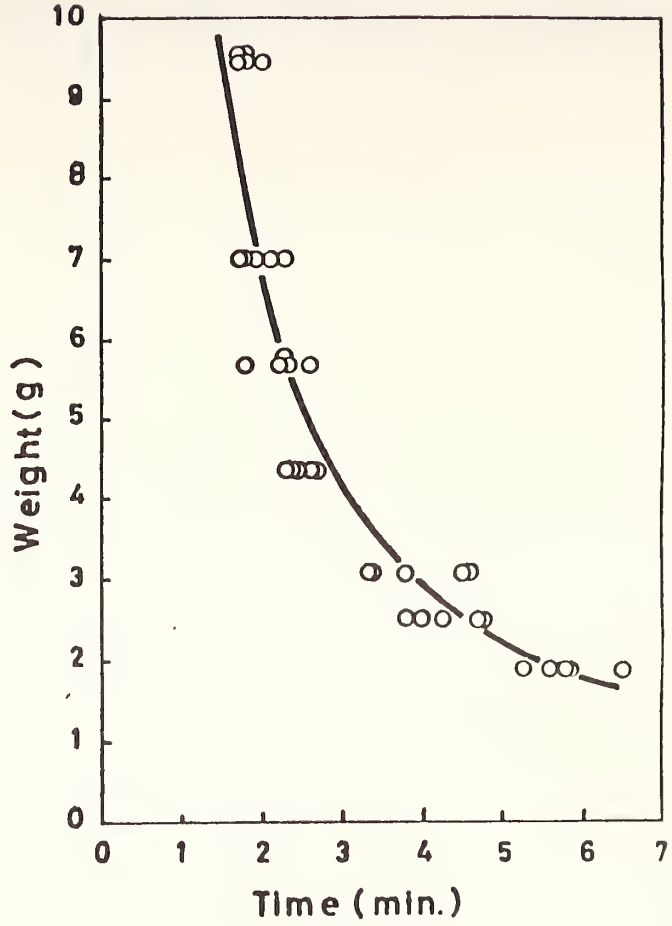

Fig. 3 — Specimen weight vs. collapse time, lauan (850°C heating).

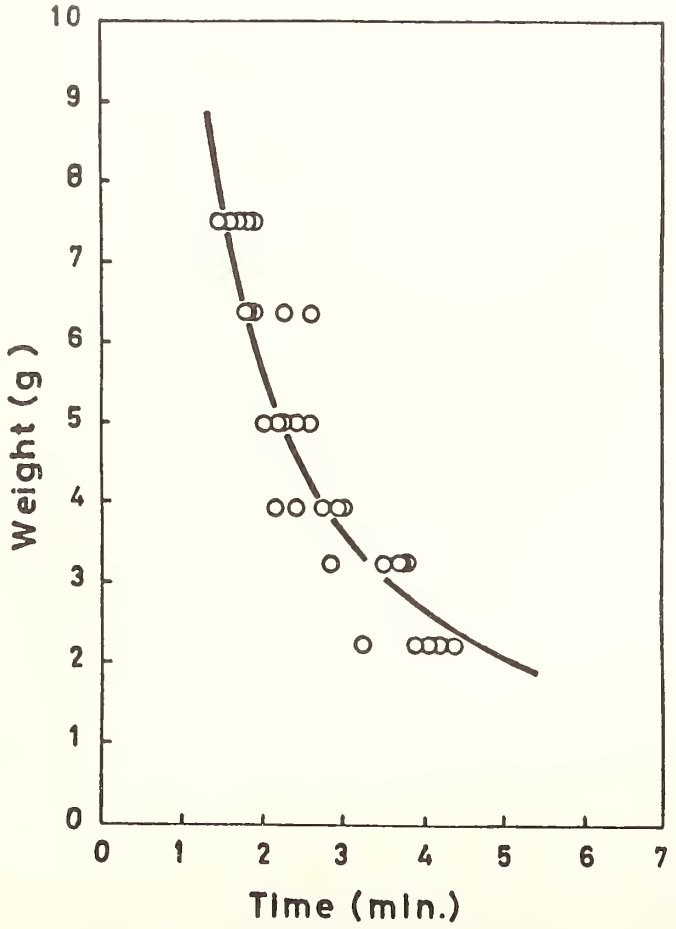

Fig. 4 — Specimen weight vs. collapse time, hardboard (850°C heating).

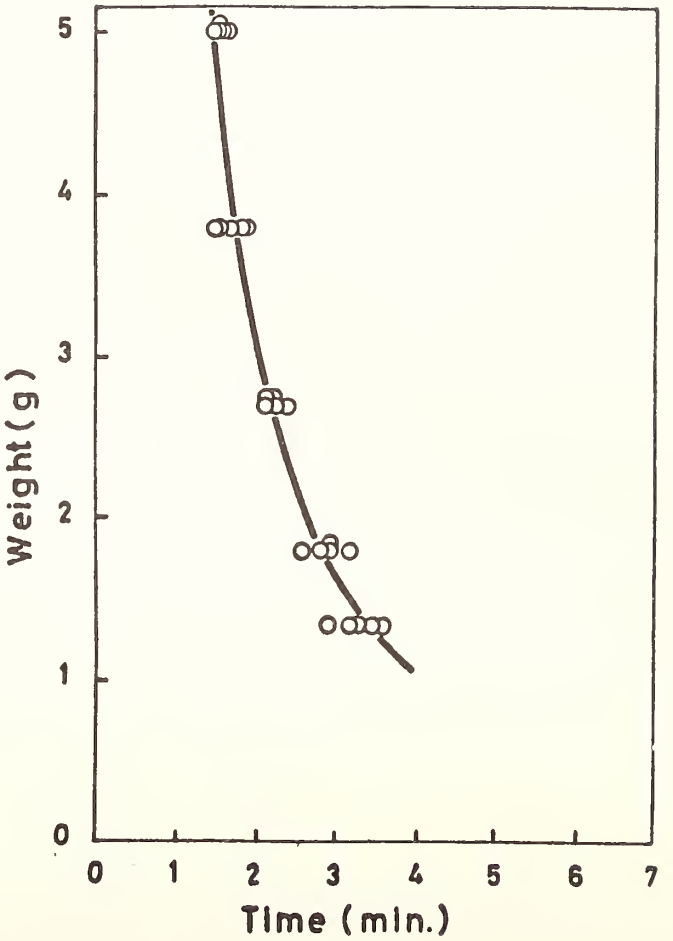

Fig. 5 — Specimen weight vs. collapse time, untreated plywood (850°C heating).

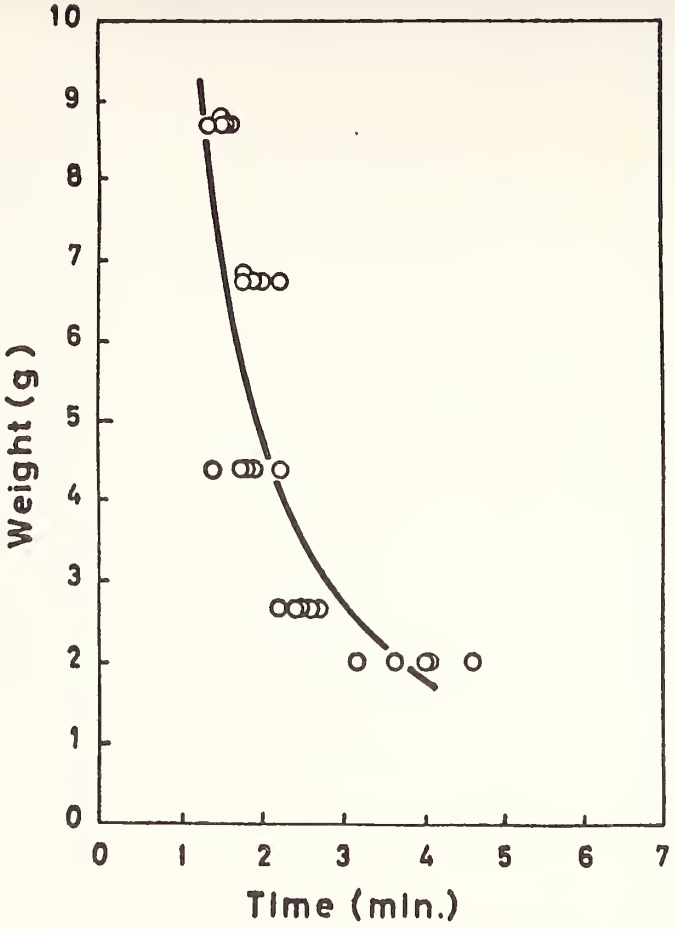

Fig. 6 — Specimen weight vs. collapse time, fire retardant- treated plywood (850°C heating).

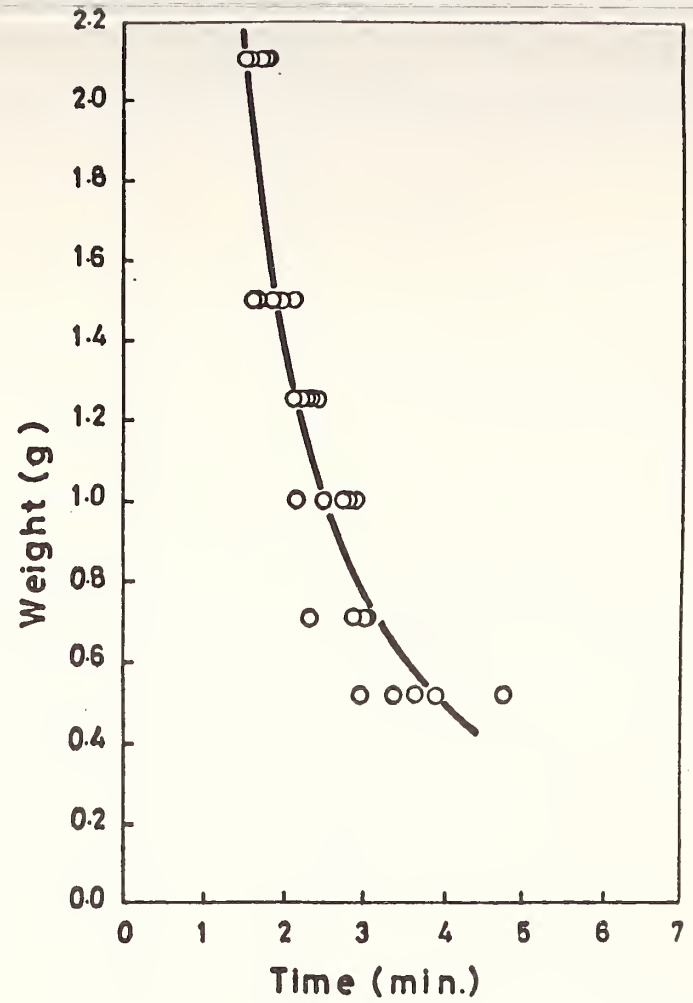

Fig. 7 — Specimen weight vs. collapse time, melamine resin- impregnated sheet #1 (850°C heating).

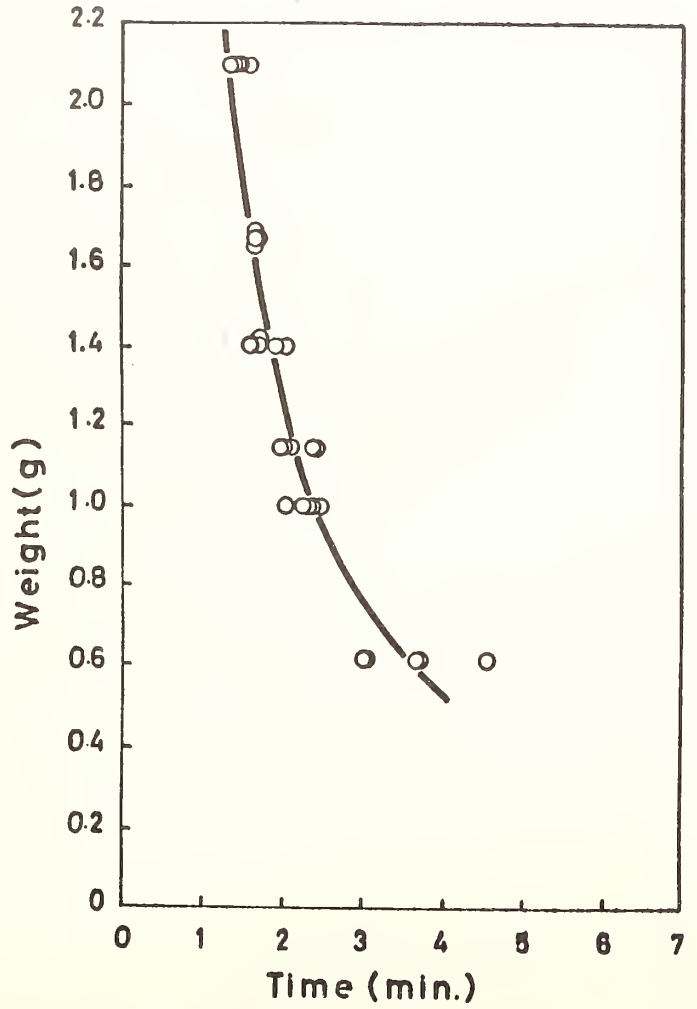

Fig. 8 — Specimen weight vs. collapse time, melamine resin-impregnated sheet #2 (850°C heating).

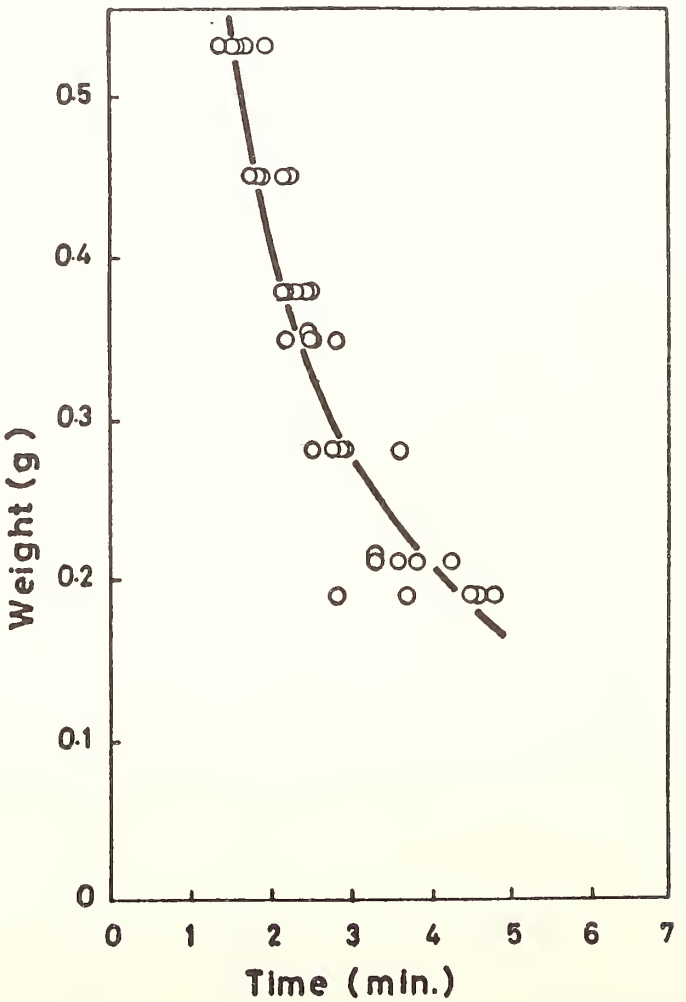

Fig. 9 — Specimen weight vs. collapse time, polyacrylonitrile (850°C heating).

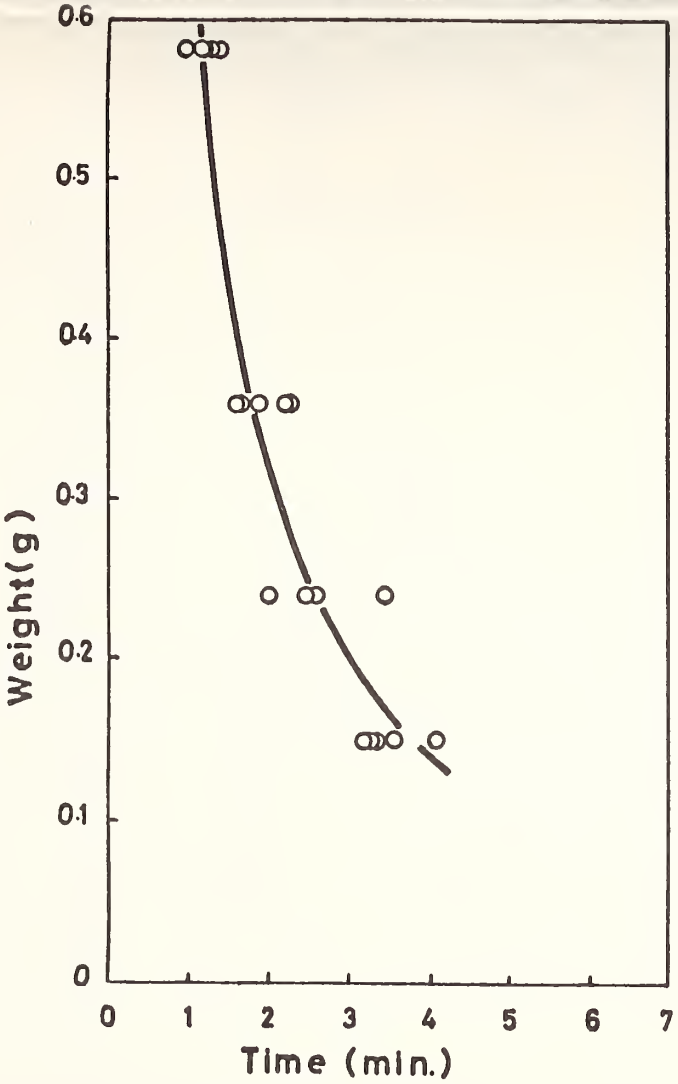

Fig. 10 — Specimen weight vs. collapse time, polyamide (Nylon 66) (850°C heating).

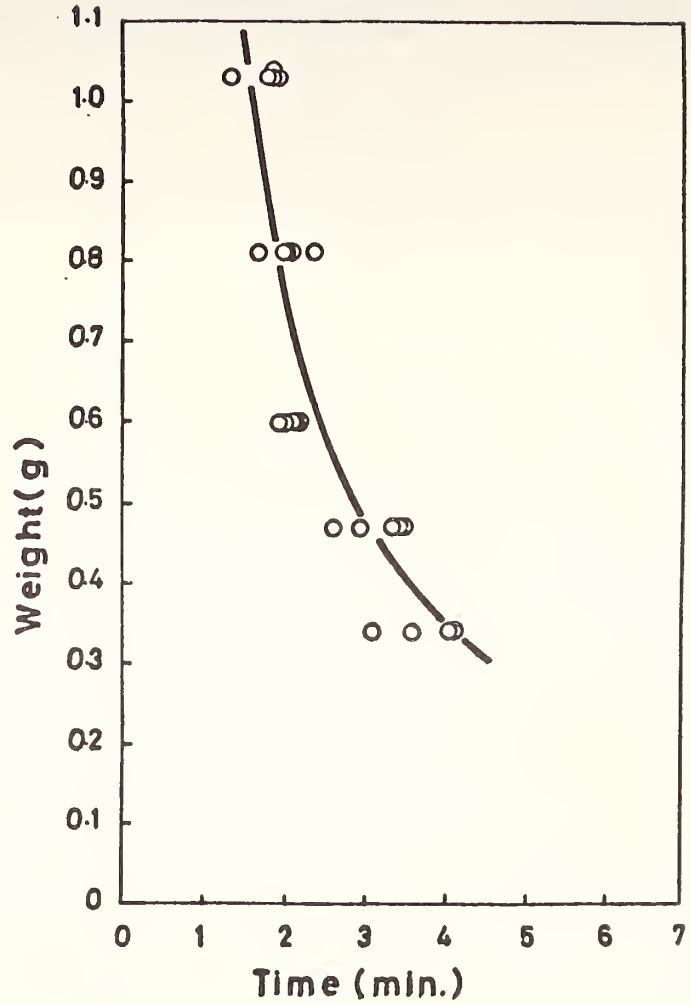

Fig. 11 — Specimen weight vs. collapse time, wool (850°C heating).

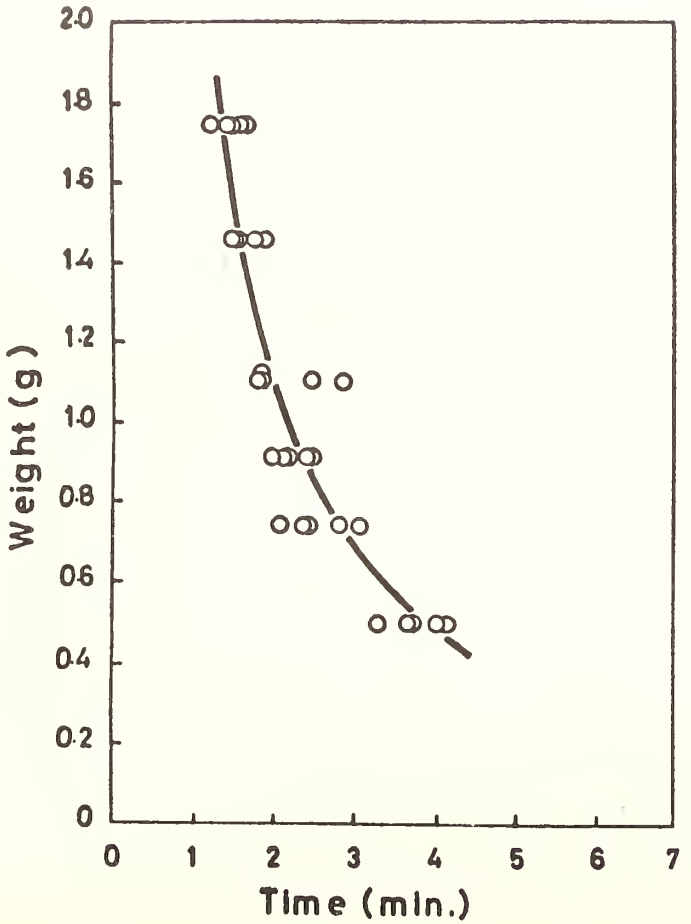

Fig. 12 — Specimen weight vs. collapse time, polyurethane (850°C heating).

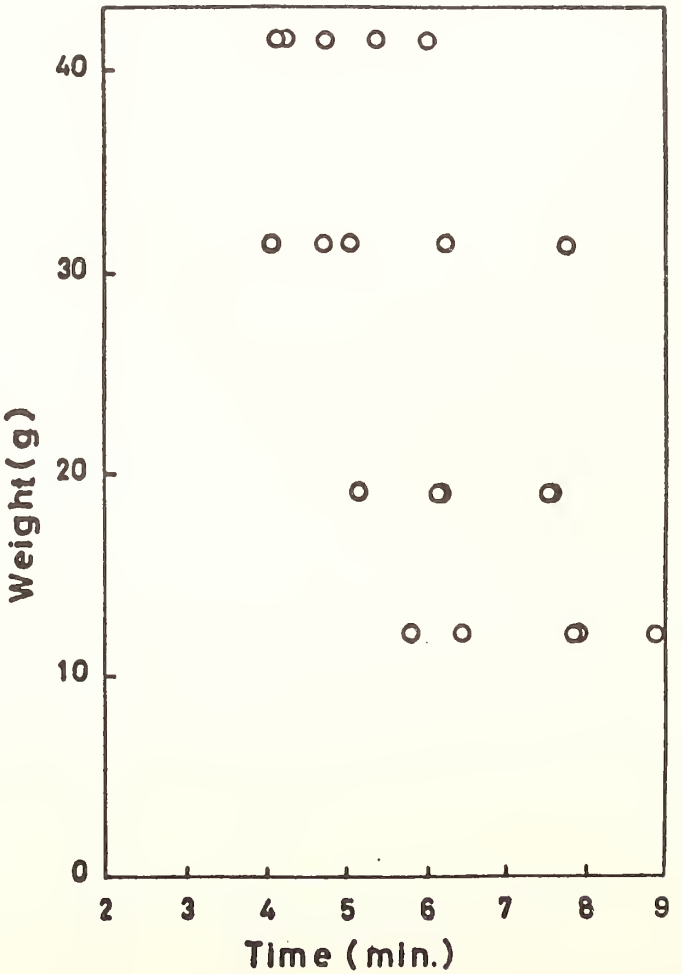

Fig. 13 — Specimen weight vs. collapse time, polyvinyl chloride (850°C heating).

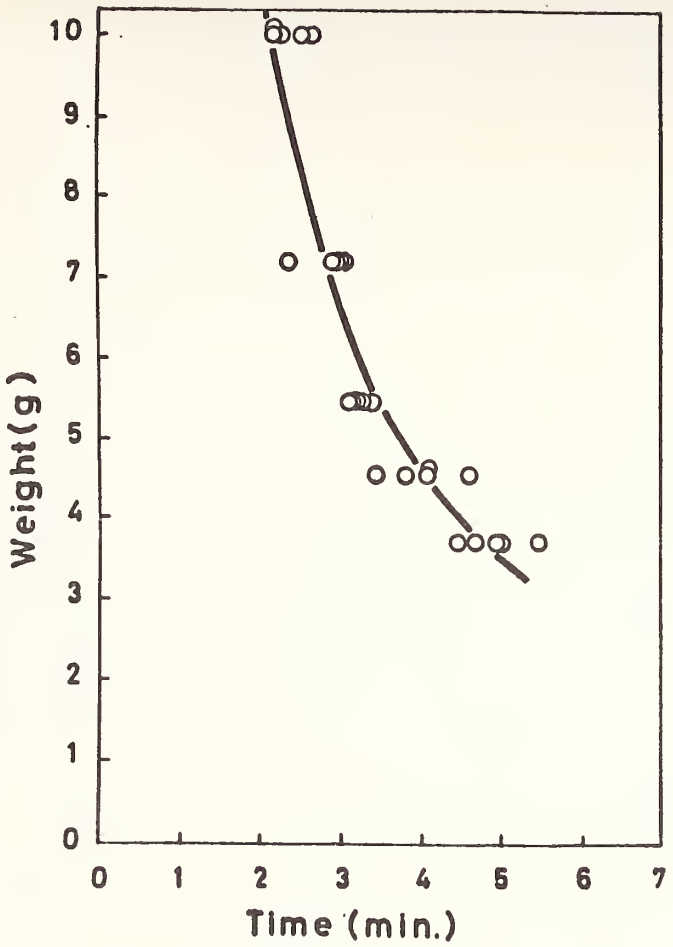

Fig. 14 — Specimen weight vs. collapse time, Japanese cedar (550°C heating).

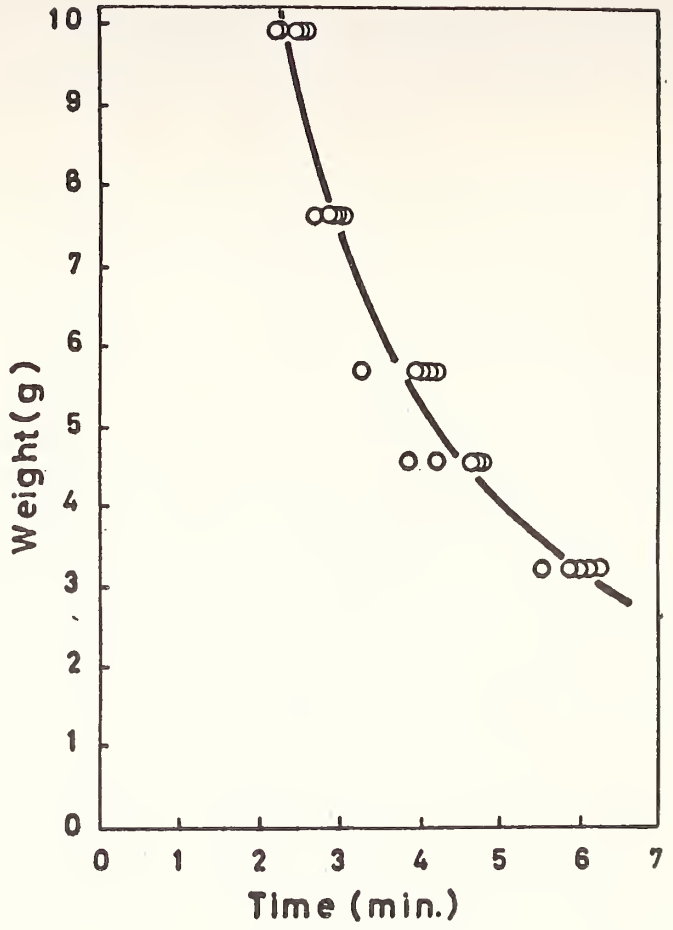

Fig. 15 — Specimen weight vs. collapse time, lauan (550°C heating).

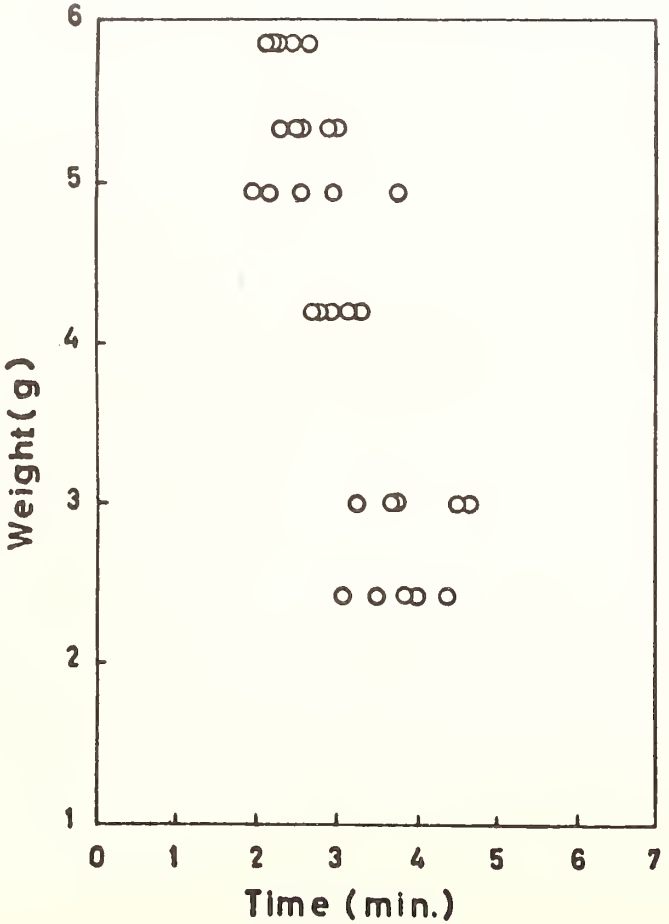

Fig. 16 — Specimen weight vs. collapse time, fire retardant-treated plywood (550°C heating).

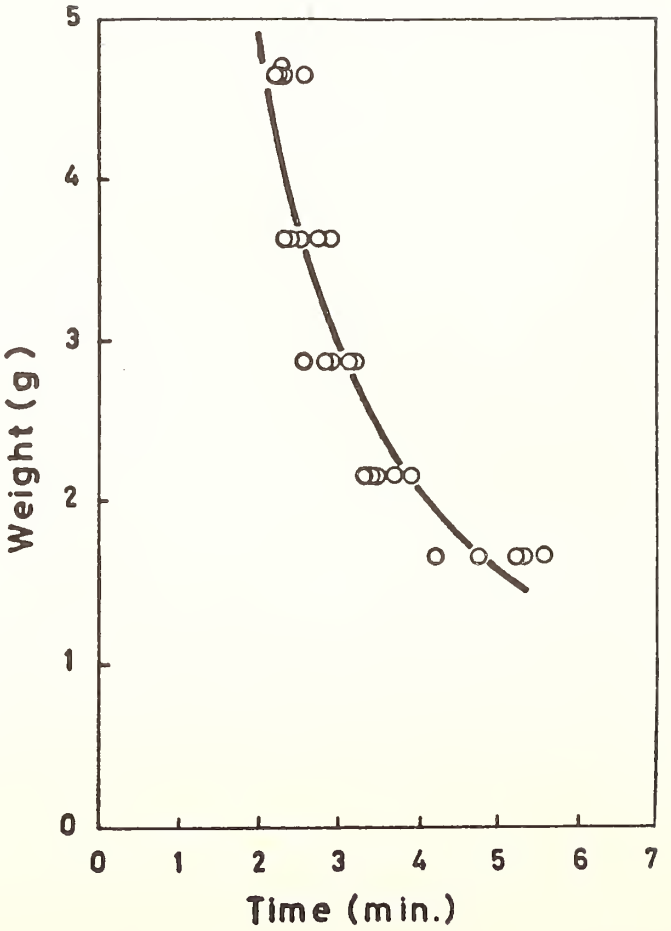

Fig. 17 — Specimen weight vs. collapse time, melamine resin-impregnated sheet #2 (550°C heating).

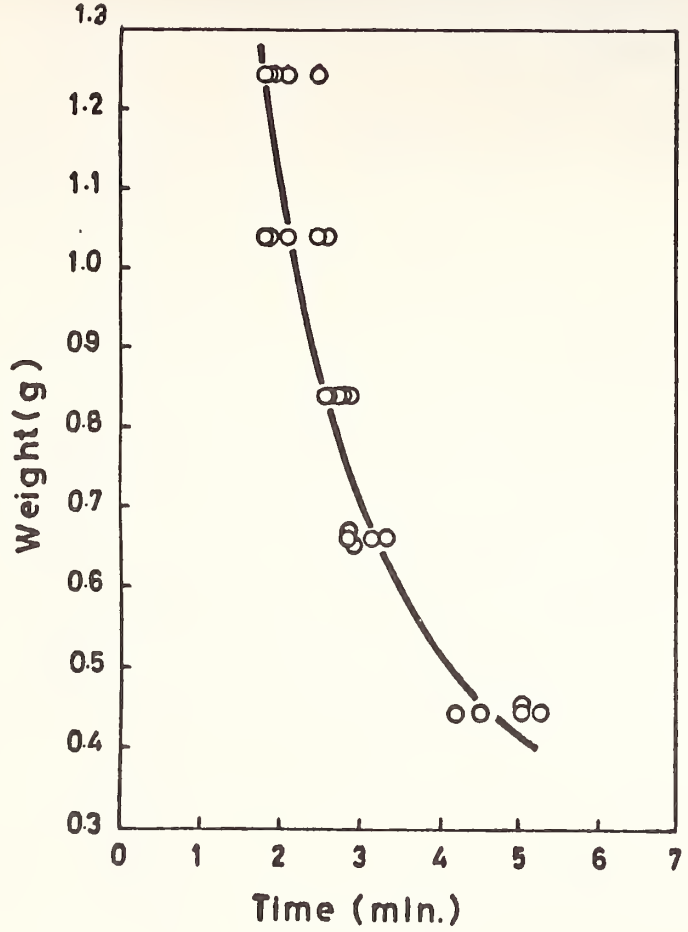

Fig. 18 — Specimen weight vs. collapse time, polyacrylonitrile (550°C heating)

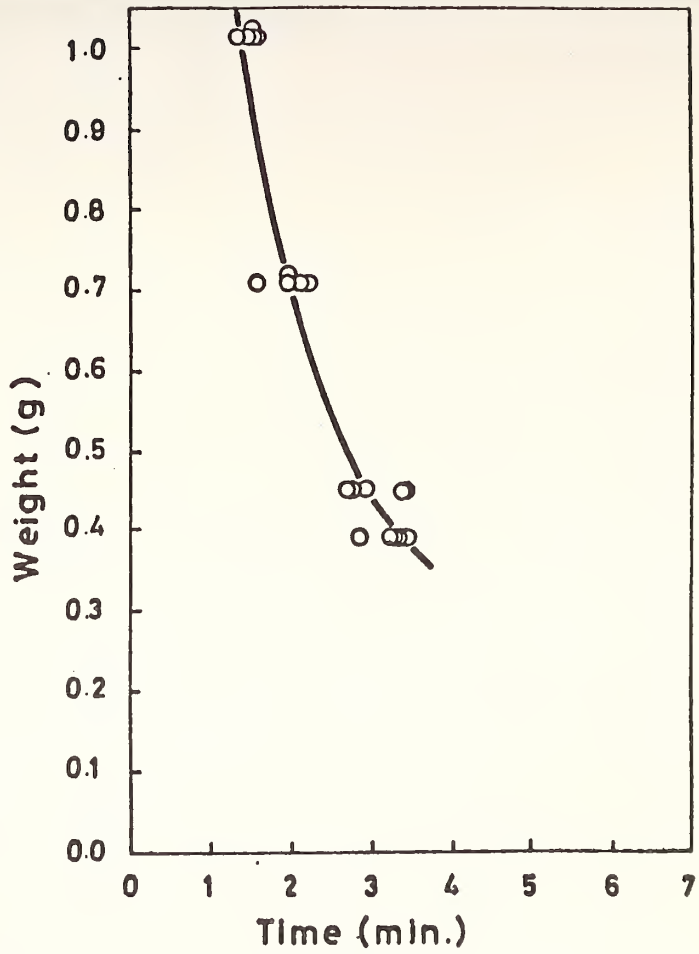

Fig. 19 — Specimen weight vs. collapse time, polyamide (Nylon 66) (550°C heating).

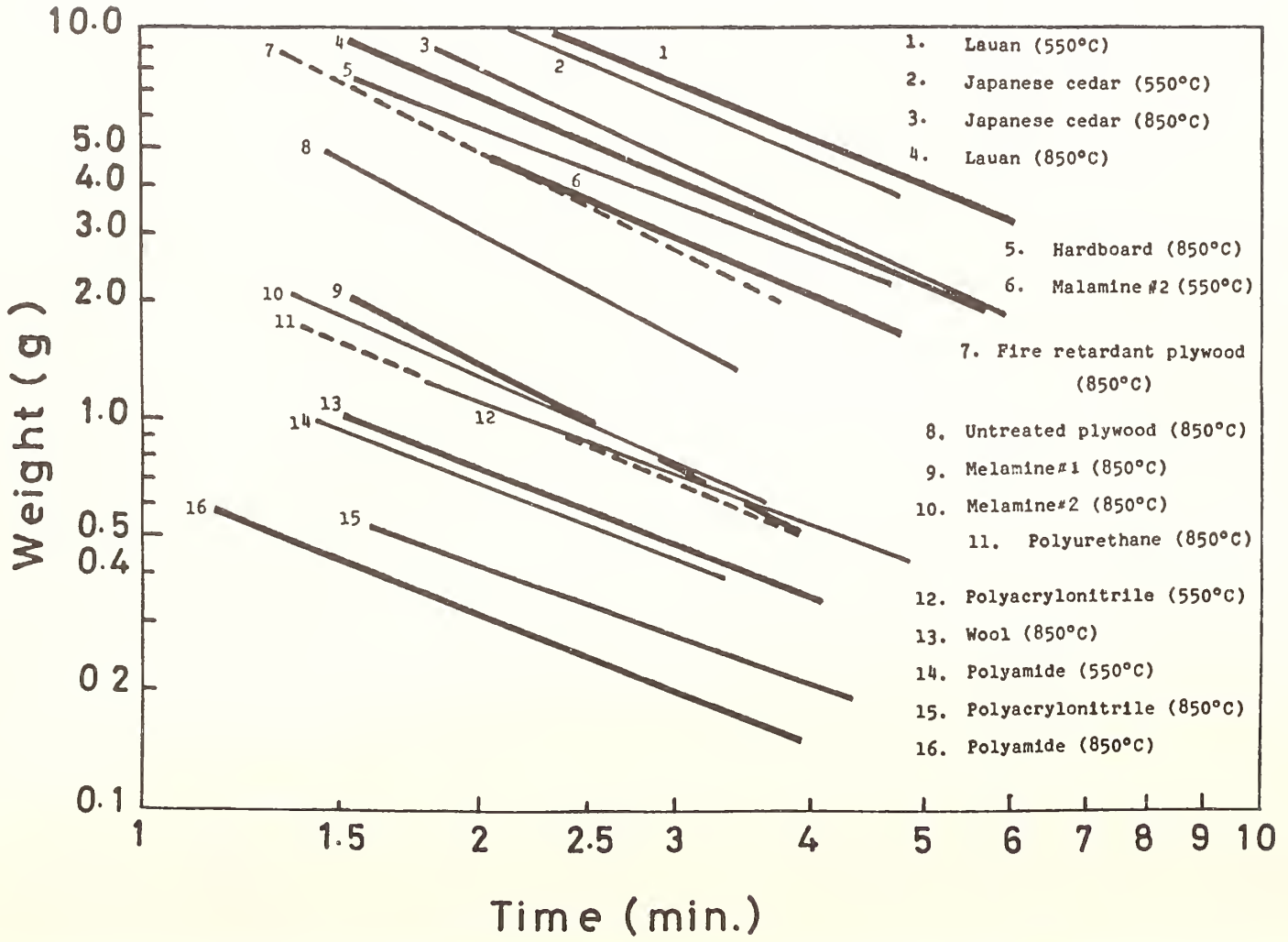

Fig. 20 — Specimen weight vs. collapse time for various materials.

RESEARCH ON EVALUATION OF TOXICITIES OF COMBUSTION GASES GENERATED DURING FIRES

by

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ABSTRACT

The toxicities to human beings of CO, CO_2, HCl and HCN from among combustion gases produced from building materials and articles accomodated in buildings during fires, and O_2 deficiency occurring from combustion of these materials are evaluated through animal tests using mice. Evaluation of toxicity is done by collapse index or lethality index (products of gas concentration inhaled by mouse and duration of inhalation exposure until collapse or death), or 50-percent lethal concentration (gas concentration at which 50% of mice inhaling gas die). It is shown that in exposure at high concentration for a short period of time the toxicities of CO, HCl and HCN under a condition of constant or rising concentration may be evaluated by the collapse index or lethality index. The former is approximately one fifth of the latter. Regarding O_2 deficiency, it is shown that determination of these indices is not possible. However, as the effect of reducing the lethality index of CO or HCN in a gaseous mixture accompanied by O_2 deficiency, it is shown to be possible to evaluate the injuriousness of O_2 deficiency. The toxicities of CO and HCN are found to be roughly arithmetic. Values of 1.06%, 175 ppm and 5.20% are obtained as 50-percent lethal concentrations of CO, HCN and O_2 deficiency, respectively, at exposure of 15 minutes.

1. INTRODUCTION

The authors carried out studies through animal tests and gas analysis tests in order to investigate the toxicities of combustion products generated from materials under various conditions of combustion[1)-3)]. As a result, it was found that of the combustion products CO, HCN and HCl are especially toxic to the human body. This result was deduced qualitatively on comparison studies of behaviors of test animals inhaling combustion products and concentrations of toxic gases in the combustion products. However, to be able to quantitatively discuss the toxicities of combustion products of materials or the toxicities of combustion products generated during building fires, it is necessary to know the compositions and amounts of the combustion products generated and to establish a method of evaluating the toxicities of the harmful gases contained. The studies reported herein are of CO, CO_2, HCN and HCl thought from results obtained in the past to be the principal injurious gases in combustion products generated from building materials and articles accomodated in buildings and O_2 deficiency which occurs concommitantly during fire, taking the single gas components and gaseous mixtures and evaluating their toxicities quantitatively through animal tests.

Evaluating the toxicity of a gas means grasping quantitatively through animal tests the relations between exposure conditions such as gas concentration and inhalation time and symptoms such as collapse and death. The concrete methods for this are evaluation by the product of gas concentration and inhalation time, and evaluation by 50-percent lethal concentration. The first method is one of evaluating the toxicity of a gas through the product C·T (unit: %·min or ppm·min) of the concentration C of the gas being inhaled by animals and the inhalation time T until a certain symptom is shown. Consequently, it can be said that the smaller the value of the above product the greater will be the toxicity of the gas. This evaluation method was considered as expressing the safe exposure criterion of toxic gas in a working environment, in effect, a method of evaluating the toxicity of gas at low

concentration and long duration of inhalation exposure. Bartek et al.[4], proposed this method theoretically to evaluate the toxicities of single gas components or gaseous mixtures at high concentrations and short durations of inhalation exposure during fires. Saito[5] called the product of gas concentration and duration of inhalation time until animal death as toxicity coefficient, and as a result of seeking the toxicity coefficient of CO for mice, obtained the values 1.35-4.0%·min. The second method consists of maintaining exposure time constant and varying gas concentration in stages to which animals are exposed, obtaining by statistical methods the concentration at which just 50% of the animals are killed. This concentration is called the 50-percent lethal concentration and is expressed by the notation LC_{50}. LC_{50} signifies the average lethal concentration of gas at a given length of inhalation time and is an application of the concept of median lethal dose (LD_{50}) used in case of chemicals.

LC_{50} assumes a different value when duration of inhalation time differs even with the same toxic gas, while it is not applicable to cases such as during fires where gas concentration varies with time. In this case, the value of the product of gas concentration and inhalation time is obtained as the value of the concentration-time curve C(t) integrated to time T, and the first method is convenient from the standpoint of fire engineering. Therefore, in this study, evaluation of gas toxicity at high concentration and short period of exposure was attempted mainly by the first method. When gas A is being inhaled by animals the product of concentration C and inhalation (exposure) time T is called the exposure index, and is expressed by the symbol I_E^A. As previously described,

$$I_E^A = C \cdot T = \int_0^T C(t)dt$$

Especially, with time T, the exposure index when the time from start of inhalation until collapse (collapse time) is taken is called the collapse index I_C^A, while the exposure index when the time T is taken to be the time from start of inhalation to time of death (deceased time) is called the lethality index I_L^A. When a gaseous mixture of multiple components (A, B, C .....) is

being inhaled, the exposure indices for the various component gases until death are taken for example to be I_E^A, I_E^C ...., and the lethality indices when the component gases are single gases to be I_L^A, I_L^B, I_L^C ..... . In this case, when it is assumed that there are no interactions between component gases and the toxicities are completely arithmetic, the equation below will hold true.

$$(I_E^A/I_L^A) + (I_E^B/I_L^B) + (I_E^C/I_L^C) + ... = 1$$

In the above equation, the exposure index of a certain gas in the gaseous mixture up to death divided by the lethality index when that gas is in single form is to be taken as the index ratio.

As a special method besides the above, there is the one of evaluating the toxicity of a gas from the relation between the quantity of gas absorbed in the body of an animal, generally the quantity in serum, and the symptoms developed. Yamamoto, et al.[6], obtained 1.67 ± 0.36 μg/ml as the quantity of HCN in serum at time of collapse. Kishitani[7] obtained values of 34 to 44% as the percentages of CO hemoglobin when mice are killed. Since the method of obtaining these figures is not directly tied to gas concentrations inside buildings or duration of inhalation exposure, it is inconvenient from the standpoint of fire engineering. However, it is possible for an accurate judgment to be made of the toxic effect of a specific component gas in the toxicity of a combustion product gas of complex composition through measurement of the quantity of that gas in serum.

2. TESTING

Mice were exposed to single gases or mixtures of CO, CO_2, HCN, HCl and O_2 (deficiency) and collapse times and lethal times were measured. In this report, the term "collapse" indicates the condition of a mouse losing control of use of its four limbs and becoming prostrated on its belly. The testing (exposure) time was made 15 minutes in general, and mice not killed during testing were observed for one week after

testing while being cared for and monitored in fresh air. The mice used were males of dd strain weighing 20 ± 1 g. With regard to CO and O_2, exposure tests were made for both constant and variable concentration conditions, but tests were performed only at condition of increasing concentration in case of HCl and condition of constant concentration in case of HCN. Regarding CO_2, since it is of low toxicity compared with other gases, the injurious effects only in case of mixtures with CO and other gases were investigated.

Testing was done adjusting the concentration of gas in the exposure chamber (made of transparent glass) after which a mouse was placed in the chamber from an entrance provided at the top of the chamber and exposed to the gas (testing at constant concentration condition), or several mice were placed in the chamber beforehand after which gas was sent in to expose the mice to the gas (testing at variable concentration condition). Fig. 1 shows the apparatus for exposure tests of conditions of constant concentration. The exposure chamber (inside volume 8ℓ) contains a sensor for O_2 analysis, a fan, and a small container accomodating KCN solution, while the top lid of the chamber has an entrance for mice, an air supply inlet, an exhaust vent-hole, and a micro-burette containing H_2SO_4. The top lid is also equipped with rubber balloons for maintaining the interior of the chamber at normal pressure. HCN was generated by dropping H_2SO_4 into KCN solution. Other gases used were standard commercial gases in pressurized cylinders. CO and CO_2 in the amounts for adjusting their concentrations to the required levels were taken from cylinders by syringes and introduced in the chamber. The concentration of HCN was adjusted by the quantity of KCN solution placed in the small container. The O_2 concentration was lowered to the specified level while sending N_2 into the chamber at the same time allowing the gaseous mixture of N_2 and air to be naturally exhausted from the chamber.

Fig. 2 indicates a test apparatus for the condition of rising concentration of HCl. HCl was generated by dropping H_2SO_4 on NaCl while heating, and the HCl generated, after

washing and desiccating with concentrated H_2SO_4, was sent into the exposure chamber (inside volume 56ℓ) made of transparent glass. The condition of concentration increase of HCl in the chamber was varied by adjusting the amount of H_2SO_4 dropped and the degree of heating. For tests under conditions of increasing concentration of CO and decreasing concentration of O_2, the same chamber was used directly sending in CO or N_2 while adjusting flow by flow meter, at the same time causing mixed gas to be exhausted naturally from the chamber.

Gas concentrations inside the exposure chamber were measured by CO_2 infrared gas analyzer for CO, polarograph-type continuous oxygen analyzer for O_2, a potentiometric method for HCl, and a pyridine-pyrazolone colorimetric method for HCN.

3. RESULTS

3.1 Single Gas

(1) CO: The relations between CO concentration under a condition of constant concentration and collapse time and deceased time were as shown in Fig. 3. The mean value and standard deviation of the collapse index I_C^{CO} were 1.11%·min and 0.25%·min (n = 26), respectively. The mean value and standard deviation of the lethality index I_L^{CO} were 6.42%·min and 1.85%·min (n = 27), respectively. The ratios of survivals and deaths during testing at the various CO concentrations were as shown in Table 1. When CO concentration was 1% or less, there were hardly any mice which died. In tests under conditions of increasing concentration, the condition of rise in CO concentration in the exposure chamber was varied in 5 ways (A-E). The relations between the CO concentration-time curves and deceased times of mice in the chamber for the individual tests are shown in Fig. 4. In the figure, the deceased times of mice are indicated on the curves of CO concentration at which exposures were made. For Test E, the value of I_L^{CO} was taken at a considerably higher level compared with those of the other tests. Fig. 5 shows the relation of I_L^{CO} and the maximum

concentration of CO inhaled by mice while alive (the concentration at which mice died in this case). At maximum exposure condition of 1% or less a trend is seen of I_L^{CO} becoming larger. The mean value and standard deviation of I_L^{CO} in Tests A to D were 9.15%·min and 3.20%·min (n = 24), respectively. The I_L^{CO} under a condition of increasing concentration was generally larger compared with that at constant concentration.

(2) HCN: The relations between HCN concentration under a condition of constant concentration and collapse times and deceased times of mice were as shown in Fig. 6. The mean value and standard deviation of collapse index I_C^{HCN} were 227 ppm·min and 66 ppm·min (n = 36), respectively. The mean value and standard deviation of lethality index I_L^{HCN} were 1033 ppm·min and 309 ppm·min (n = 25), respectively. All mice died during testing when HCN concentration exceeded 200 ppm, but at 100 to 200 ppm there were mice which were not killed during testing, as indicated in Table 2.

(3) HCl: The tests of exposure to HCl under conditions of increasing concentration were divided into high-concentration tests (A-D) and low-concentration tests (E-J), the former being carried out until mice died, while the latter were terminated at 15 minutes regardless of whether or not mice died. The HCl concentrations in the exposure chamber in the various tests are given in Fig. 7. The collapse indices I_C^{HCl} and lethality indices I_L^{HCl} in high-concentration tests are indicated in Table 3, and the exposure indices I_E^{HCl} at 15 minutes in low-temperature tests in Table 4. The mean value and standard deviation of I_C^{HCl} were 2.11%·min and 0.74%·min (n = 12), respectively. The mean value and standard deviation of I_L^{HCl} were 9.07%·min and 2.34%·min (n = 11), respectively. The values of I_E^{HCl} of mice which were not killed during testing but died within one week after the tests were 1.9 to 8.8%·min, while those of mice still surviving after one week were 0.4 to 2.0%·min.

(4) O_2 Deficiency: The relation between O_2 concentration under a condition of low O_2 concentration with no variation in concentration and deceased times of mice were as shown in Fig. 8. The mortality rate of mice depended strongly on concentration, and as indicated in Table 5, 7 out of 10 were killed at 5.0%, but at 5.5% only 2 out of 12 died. Regarding lethality index $I_L^{O_2}$, even when considering (21-O_2 exposure concentration) x (deceased time) in the sense of evaluating decrease in O_2 concentration, it rapidly grew large with increase in O_2 concentration, and could not be considered as being roughly constant. Fig. 9 shows the test results under conditions of declining O_2 concentration. The conditions of decrease in O_2 concentration were of five kinds as shown in the figure and the mice died when O_2 concentration was lowered to 3-4% with practically no relation to O_2 concentration-time curves. The mean value and standard deviation of O_2 concentration at time of death in this case were 3.43% and 0.35% (n = 30). Similarly to the case of constant concentration, it was not possible to determine a roughly constant $I_L^{O_2}$.

(5) Fifty-percent Lethal Concentrations of CO, HCN and O_2: The 50-percent lethal concentrations LC_{50} were obtained by the method of Behrens[8] which utilizes cumulative mortality. The cumulative mortalities of CO, HCN and O_2 are as indicated in Table 1, Table 2 and Table 5, respectively. In Table 1, to the 2 mice which died at concentration of 1.0%, the two mice which died at 0.4 to 0.8% and would of course have died at 1.0% are added to obtain 4 mice. To the 8 mice that survived at 1.0%, the 1 mouse that survived at 1.2 to 2.0% and would of course have survived at 1.0% is added to obtain 9 mice. Mice which survived at 0.4 to 0.8% are not taken into account considering it to be unclear whether they would have survived at 1.0%. The cumulative mortality at 1.0% obtained in this manner would be 4/13. Fig. 10 shows the relations between the exposure concentrations of the

various gases and cumulative mortalities illustrated on a regular probability paper. In the case of CO, assuming from the results indicated in Table 1 that mice died 100% at 1.4% CO, and survived 100% at 0.4% CO, the following conversion was made for CO concentration C (%):

$$C \rightarrow (C + 0.4)/(1.4 - C)$$

The reason for the conversion was that linearity could not be obtained when CO concentration was taken without modification on the abscissa of Fig. 10. Obtaining the LC_{50}s of CO, HCN and O_2 through linear interpolation between concentrations above and below cumulative mortality of 50%, they were 1.06%, 175 ppm and 5.20%, respectively. Practically the same values are obtained when determinations are made from the approximate straight lines given in Fig. 10.

3.2 Gaseous Mixtures

(1) CO + HCN: The results on seeking exposure indices I_E^{CO} for CO and exposure indices I_E^{HCN} for HCN at deceased times of mice subjected to exposure to gaseous mixtures of CO and HCN having various concentration ratios are as indicated in Table 6. With lethality indices of CO and HCN respectively I_L^{CO} = 6.42%·min and I_L^{HCN} = 1033 ppm·min (mean value obtained from previously-mentioned results), the relations with the index ratios I_E^{CO}/I_L^{CO} and I_E^{HCN}/I_L^{HCN} are as indicated in Fig. 11. The mean value and the standard deviation of the sum of the two index ratios were 0.90 and 0.12 (n = 18). In this case, the values of combining 0.15% CO and 140 ppm HCN or 130 ppm HCN were omitted because they were extremely larger than the other values. The mean value of the sums is somewhat lower than the value (= 1) when the toxicities of CO and HCN are completely arithmetic.

(2) CO + O_2, HCN + O_2: The exposure indices and index ratios of CO and HCN at deceased times of mice in exposure tests to gaseous mixtures combining CO and O_2 deficiency, and HCN and O_2 deficiency, are indicated in

Table 7 and Table 8. Fig. 12 shows the relations of index ratios and O_2 concentrations. The index ratio will be a value close to 1 if there were no effect of O_2 deficiency. With O_2 concentration below approximately 14%, the index ratio became lower with decrease in O_2 concentration, but at 16% O_2 this trend was indistinct. In this case, the index ratios of CO and HCN both indicated more or less the same trend.

(3) $CO + CO_2 + O_2$, $CO + CO_2 + HCN + O_2$: The results of tests on gaseous mixtures combining CO, CO_2 and O_2 deficiency are indicated in Table 9, and the results on gaseous mixtures further adding HCN in Table 10. The mean values of the index ratios of CO obtained from these results, and the mean values of the sums of the index ratios of CO and HCN plotted for the corresponding O_2 concentrations are indicated in Fig. 13. The approximate straight line in the figure is identical to the one indicated in Fig. 12. Since the above mean values were all close to this approximate straight line, the toxic effect of CO_2 in these gaseous mixtures were not clearly recognized.

4. CONSIDERATIONS

4.1 Single Gas

The evaluation of toxicity by collapse index or lethality index assumes that these indices are more or less constant values regardless of gas concentration and exposure time if the species and size of animal, and variety of gas are definite. If constant values are taken, it will mean that these indices will indicate the extent of the toxicity of that gas as values specific to the gas. Although these are variations in the collapse indices and lethality indices of CO, HCN and HCl, it may be said that these are not related very much to exposure time and concentration in case of high concentration and short exposure time. When evaluating these gases, it will be adequate from a fire engineering standpoint for

the mean values of the indices obtained in the test results of this study to be used.

Seen from the results, the collapse indices of CO and HCN are applicable up to exposure at relatively low concentration, but it is difficult for lethality indices to be applied below a certain concentration. In case of constant-concentration exposure for 15 minutes, hardly any mice die below approximately 1% with CO and approximately 200 ppm with HCN, and a long period of time is required until decease. In effect it is estimated that the lethality index will become high. This can also be said for CO under a condition of rising concentration, and the results show that lethality index will become very high at maximum exposure concentration below around 1%. Further, considering that 1.06% and 175 ppm were obtained as the 50-percent lethal concentrations of CO and HCN, respectively, it is thought that the lethality index can be amply applied if the greater part of maximum exposure concentrations is of lethal concentration or higher.

In the case of CO, the lethality index under a condition of rising concentration is higher than that under a condition of constant concentration. This may be because resistance to CO is produced to some degree in mice in exposure to conditions of rising concentration when concentration at the initial stage of exposure is very low. It is estimated that the lethality index of HCl in exposure under constant concentration conditions will be more or less the same as for CO. This is because there is not very much difference between the mean values of lethality indices of the two under conditions of increasing concentrations. The ratios of collapse indices to lethality indices obtained from the mean values of the two will be as follows:

$$I_C^{CO}/I_L^{CO} = 1.11/6.42 = 0.17 \quad \text{(Constant Concentration)}$$

$$I_C^{HCN}/I_L^{HCN} = 227/1033 = 0.22 \quad \text{(Constant Concentration)}$$

$$I_C^{HCl}/I_L^{HCl} = 2.11/9.07 = 0.23 \quad \text{(Rising Concentration)}$$

Therefore, the collapse index will be approximately 1/5 of the lethality index.

An index could not be obtained for O_2 deficiency. This was probably due to the fact that the mode of action of the injuriousness of O_2 deficiency on living bodies differs from those of CO and HCN. The dependency of the injuriousness of O_2 deficiency on concentration is particularly great. This is clear from the fact that as a result of exposing mice to a condition of decreasing O_2 concentration, all mice died when O_2 concentration became around 3 to 4% regardless of the kind of O_2 concentration-time curve. It is said that the equation below by Ostwald is applicable to the lethal actions of various toxic substances[9].

$$1/T = KC^p$$

where T is time of death, C is concentration of toxic substance, and K and p are constants. When p = 1, it will be the same as for the formula for defining lethality index. When O_2 concentration is taken to be C (%) and time of death to be T (min), the following equation will hold true for the test results of this study where mice are exposed to low-concentration O_2:

$$1/T = 50.9C^{-3.63}$$

The toxicity of HCl is characterized by the fact that mice are killed after a certain length of time has elapsed after testing. This is because HCl causes pulmonary edema. When mice were exposed to HCl under a condition of increasing concentration the mice died after testing at exposure indices of 1.9 to 8.8%·min. The exposure indices of mice which did not die after tests were 0.4 to 2.0%·min. Consequently, the limit of the exposure index in order for mice not to die after testing is at around 2%·min.

The 50-percent lethal concentration $LC_{50}(CO)$ of CO

was 1.06% and the 50-percent lethal concentration $LC_{50}(HCN)$ of HCN was 175 ppm. The ratio between the two will be as follows:

$$LC_{50}(CO)/LC_{50}(HCN) = 1.06/(175 \times 10^{-4}) = 60.6$$

The ratios between average lethality indices of CO and HCN under conditions of constant concentration will be as follows:

$$I_L^{CO}/I_L^{HCN} = 6.42/(1033 \times 10^{-4}) = 62.1$$

In effect, HCN has a toxicity approximately 60 times stronger than that of CO. Accordingly, when there is a large quantity of materials generating HCN during combustion (materials containing nitrogen) inside a building it will be extremely hazardous during fire.

4.2 Gaseous Mixture

With gaseous mixtures of CO and HCN, the reason that the sums of the index ratios are very large in case of combining 140 ppm HCN or 130 ppm HCN with 0.15% CO is that the concentrations of both gases are low being in ranges where lethality indices are not applicable. Except for these two cases, the sums of index ratios are roughly close to 1 with the average being 0.90. Although this average is smaller than 1 the difference is slight, and therefore, there will be no serious error in considering that the toxic effects of CO and HCN are arithmetic in general. This is probably due to the fact that both are chemical asphyxiating gases and the action modes of their toxicities are similar. HCl, which is an irritative gas having a different mode of action damages the respiratory tract and lungs and there is a possibility that it will contrarily hinder absorption of CO and HCN into the body. In such case, the toxic effects of HCl and the other gases will not be arithmetic. Gaume et al.[10] have recognized this phemonenon with a gaseous mixture of NH_3, an irritative gas, and CO.

Regarding the harmful effect of O_2 deficiency in a gaseous mixture, in lieu of the fact that it is not possible to evaluate the toxicity of O_2 deficiency itself, it is possible to evaluate it as an effect of lowering the lethality indices or collapse indices of other coexisting gases. Further studies will be required in order to relate this diminishing effect to O_2 concentration and quantify it. However, seen from the results, lowering of O_2 concentration to around 16% does not have such great toxicity and it is thought there will not be much error in evaluating just the toxicities of the coexisting CO and HCN. It may be said that the toxic effect of CO_2 in a gaseous mixture is not such that it will influence the lethality indices of other gases.

5. CONCLUSIONS

As a result of investigating the toxicities of various gases at high concentrations and short-time exposures by animal tests using mice, the following may be said.

(1) The toxicities of CO, HCN and HCl may be evaluated by collapse indices or lethality indices. The average collapse indices of CO and HCN at conditions of constant concentrations are 1.11%·min and 227 ppm·min, respectively, while the average lethality indices are 6.42%·min and 1033 ppm·min, respectively. The average lethality index of CO at a condition of increasing concentration is 9.15%·min.

(2) The average collapse index and average lethality index of HCl under a condition of rising concentration are 2.11%·min and 9.07%·min, respectively. The limit of the exposure index in order for mice not to die after inhaling HCl is approximately 2%·min.

(3) The collapse index is approximately 1/5 of lethality index.

(4) It is not possible for O_2 deficiency to be evaluated by collapse index or lethality index. When O_2 concentration is declining, mice will die when O_2 concentration reaches approximately 3-4%. This does not have much relation with the

rate of decline in concentration.

(5) When mice are exposed for 15 minutes to CO, HCN and O_2, the 50-percent lethal concentrations of these gases are 1.06%, 175 ppm and 5.20%, respectively.

(6) HCN has a toxicity 60 times stronger than CO.

(7) In a gaseous mixture of CO and HCN, the toxicities of CO and HCN are arithmetic.

(8) The injuriousness of O_2 deficiency in a gaseous mixture may be evaluated by its effect in lowering collapse indices or lethality indices of coexisting gases. This effect is not very distinct at O_2 concentration of around 16%.

(9) The toxicity of CO_2 in a gaseous mixture is very weak compared with the toxicities of coexisting CO, HCN and O_2 deficiency, and at least is not of the extent of affecting the deceased times of mice.

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Table 1. Ratios of Survival and Death (CO)

Exposure Time: 15 min

CO Concentration (%)	Number Survived	Number Died	Cumulative Mortality
2.0	0	3	28/28
1.8	0	3	25/25
1.6	0	3	22/22
1.4	0	6	19/19
1.2	1	9	13/14
1.0	8	2	4/13
0.8	9	1	2/20
0.6	9	1	1/28
0.4	10	0	0/37

Table 2. Ratios of Survival and Death (HCN)

Exposure Time: 15 min

HCN Concentration (%)	Number Survived	Number Died	Cumulative Mortality
200	3	5	15/18
180	2	2	10/15
175	3	3	8/16
160	4	0	5/17
150	4	2	5/21
140	2	3	3/21
130	4	0	0/22
100	2	0	0/24

Table 3. Collapse Index and Lethality Index of Mouse Exposed to HCl under Condition of Rising Concentration

Test	Collapse Time (min)	Collapse Index I_C^{HCl} (%·min)	Time of Death (min)	Lethality Index I_L^{HCl} (%·min)
A	12.50	2.80	17.83	8.7
	11.50	1.96	14.92	5.5
	11.75	2.10	19.17	11.7
B	13.58	2.60	20.00	12.0
	10.08	0.80	18.17	8.0
	12.83	2.06	19.42	11.3
C	10.92	2.30	15.92	8.8
	12.17	3.40	17.92	12.2
	9.42	1.40	15.25	7.0
D	11.50	2.64	14.50	7.3
	9.67	1.10	14.50	7.3
	11.08	2.14	1 day after test[1)]	8.8[2)]

1) Died in fresh air after testing.

2) Exposure index I_E^{HCl}.

Table 4. Exposure Index of HCl and Survival or Death after Testing

Test	Time of Death	Exposure Index I_E^{HCl} (%·min)
E	Immediately after test	4.4
	1 day after test	4.4
	1 day after test	4.4
F	6 hours after test	2.9
	1 day after test	2.9
	1 day after test	2.9
G	2 days after test	2.0
	3 days after test	2.0
	Survived[1)]	2.0
H	1 hour after test	1.9
	1 hour after test	1.9
	Survived	1.9
I	Survived	0.5
	Survived	0.5
	Survived	0.5
J	Survived	0.4
	Survived	0.4
	Survived	0.4

1) Survived 1 week after test (observation period)

Table 5. Ratios of Survival and Death (O_2 Deficiency)

Exposure Time: 15 min

O_2 Concentration (%)	Number Survived	Number Died	Cumulative Mortality
3.0	0	4	31/31
3.5	0	4	27/27
4.0	0	6	23/23
4.5	0	8	17/17
5.0	3	7	9/12
5.5	10	2	2/15

Table 6. Exposure Index at Deceased Time in Exposure to Gaseous Mixture of CO and HCN

Exposure Time: 15 min

CO Conc. (%)	HCN Conc. (ppm)	Deceased Time (min)	CO		HCN		$(I_E^{CO}/I_L^{CO}) + (I_E^{HCN}/I_L^{HCN})$
			Exposure Index I_E^{CO} (%·min)	Index Ratio[1] I_E^{CO}/I_L^{CO}	Exposure Index I_E^{HCN} (ppm·min)	Index Ratio[2] I_E^{HCN}/I_L^{HCN}	
0.75	130	3.33	2.50	0.39	433	0.42	0.81
	130	3.75	2.81	0.44	488	0.47	0.91
	100	3.83	2.87	0.45	383	0.37	0.82
	100	3.50	2.63	0.41	350	0.34	0.75
	70	4.33	3.25	0.51	303	0.29	0.80
	47	6.00	4.50	0.70	282	0.27	0.97
	30	7.17	5.38	0.84	215	0.21	1.05
	25	Survived	-	-	-	-	-
0.50	110	3.92	1.96	0.31	431	0.42	0.73
	99	5.33	2.67	0.42	480	0.46	0.88
	50	7.50	3.75	0.58	375	0.36	0.94
	30	8.50	4.25	0.66	255	0.25	0.91
	30	8.00	4.00	0.62	240	0.23	0.85
	20	Survived	-	-	-	-	-
0.25	180	3.58	0.90	0.14	644	0.62	0.76
	160	4.33	1.08	0.17	693	0.67	0.84
	150	5.67	1.42	0.22	851	0.82	1.04
	120	6.17	1.54	0.24	740	0.72	0.96
	80	9.83	2.46	0.38	786	0.76	1.14
	70	Survived	-	-	-	-	-
0.15	180	5.25	0.79	0.12	945	0.91	1.03
	170	Survived	-	-	-	-	-
	170	Survived	-	-	-	-	-
	150	Survived	-	-	-	-	-
	140	14.67	2.20	0.34	2054	1.99	2.33
	130	13.75	2.06	0.32	1788	1.73	2.05

1) I_L^{CO} = 6.42 (%·min), 2) I_L^{HCN} = 1033 (ppm·min)

Table 7. CO Exposure Index at Deceased Time in Exposure to Gaseous Mixture of CO and O_2 Deficiency

Exposure Time: 15 min

O_2 Concentration (%)	CO Concentration (%)	Deceased Time (min)	Exposure Index I_E^{CO} (%·min)	Index Ratio[1] I_E^{CO}/I_L^{CO}
6	1.00	2.00	2.00	0.31
	1.00	2.75	2.75	0.43
	0.75	2.75	2.06	0.32
	0.75	3.50	2.63	0.41
	0.50	4.75	2.38	0.37
	0.50	3.75	1.88	0.29
	0.25	7.50	1.88	0.29
	0.25	8.50	2.13	0.33
8	1.00	2.75	2.75	0.43
	1.00	2.50	2.50	0.39
	0.75	3.00	2.25	0.35
	0.75	3.75	2.81	0.44
	0.50	7.33	3.67	0.57
	0.50	5.50	2.75	0.43
	0.25	10.50	2.63	0.41
	0.25	12.17	3.04	0.47
10	1.00	3.00	3.00	0.47
	1.00	3.25	3.25	0.51
	0.75	3.75	2.81	0.44
	0.75	4.50	3.38	0.53
	0.50	9.50	4.75	0.74
	0.50	6.25	3.13	0.49
	0.25	Survived	-	-
	0.25	Survived	-	-
12	1.00	3.50	3.50	0.55
	1.00	2.83	2.83	0.44
	0.75	3.75	2.81	0.44
	0.75	4.00	3.00	0.47
	0.50	Survived	-	-
	0.50	Survived	-	-
	0.25	Survived	-	-
	0.25	Survived	-	-
14	1.00	5.50	5.50	0.86
	1.00	2.50	2.50	0.39
	0.75	4.00	3.00	0.47
	0.75	7.50	5.63	0.88
	0.50	10.00	5.00	0.78
	0.50	Survived	-	-
	0.25	Survived	-	-
	0.25	Survived	-	-
16	1.00	12.00	12.00	1.87
	1.00	4.00	4.00	0.62
	0.75	5.00	3.75	0.58
	0.75	Survived	-	-
	0.50	14.92	7.46	1.16
	0.50	Survived	-	-
	0.25	Survived	-	-
	0.25	Survived	-	-

1) I_L^{CO} = 6.42 (%·min)

Table 8. HCN Exposure Index at Deceased Time in Exposure to Gaseous Mixture of HCN and O_2 Deficiency

Exposure Time: 15 min

O_2 Concentration (%)	HCN Concentration (ppm)	Deceased Time (min)	Exposure Index I_E^{HCN} (ppm·min)	Index Ratio[1] I_E^{HCN}/I_L^{HCN}
6	105	2.17	228	0.22
	75	3.75	281	0.27
	58	11.50	667	0.65
	58	Survived	-	-
	40	14.92	597	0.58
	35	4.75	166	0.16
8	185	2.50	463	0.45
	130	3.50	455	0.44
	97	5.00	485	0.47
	82	6.17	506	0.49
	68	7.50	510	0.49
	60	Survived	-	-
	55	6.50	358	0.35
	50	Survived	-	-
	50	Survived	-	-
10	240	2.50	600	0.58
	215	2.50	538	0.52
	140	4.17	584	0.57
	116	6.00	696	0.67
	95	7.17	681	0.66
	75	Survived	-	-
	72	7.17	516	0.50
	45	Survived	-	-
12	210	3.67	771	0.75
	180	5.50	990	0.96
	170	8.00	1360	1.32
	160	5.75	920	0.89
	120	13.25	1590	1.54
	100	Survived	-	-
	100	5.25	525	0.51
14	180	6.50	1170	1.13
	160	6.00	960	0.93
	160	4.50	720	0.73
	140	8.25	1155	1.12
	140	Survived	-	-
	130	11.33	1473	1.43
	130	Survived	-	-

1) I_L^{HCN} = 1033 (ppm·min)

Table 9. Exposure Index at Deceased Time in Exposure to Gaseous Mixture of CO, CO_2 and O_2 Deficiency

Exposure Time: 15 min

O_2 Conc. (%)	5% CO_2				10% CO_2				20% CO_2			
	0.50% CO		0.75% CO		0.75% CO		0.75% CO		0.50% CO		0.75% CO	
	Deceased Time (min)	Exposure Index I_E^{CO} (%·min)	Deceased Time (min)	Exposure Index I_E^{CO} (%·min)	Deceased Time (min)	Exposure Index I_E^{CO} (%·min)	Deceased Time (min)	Exposure Index I_E^{CO} (%·min)	Deceased Time (min)	Exposure Index I_E^{CO} (%·min)	Deceased Time (min)	Exposure Index I_E^{CO} (%·min)
8	8.92	4.46	5.92	4.44	3.50	1.75	4.17	3.13	4.83	2.42	4.33	3.25
	6.58	3.29	2.42	1.82	7.50	3.75	3.75	2.81	6.50	3.25	2.83	2.12
	5.75	2.88	2.00	1.50	5.67	2.84	4.58	3.44	6.42	3.21	6.33	4.75
	7.08	3.54	4.17	3.13	10.00	5.00	5.50	4.13	4.58	2.29	2.67	2.00
	5.67	2.84	3.00	2.25	3.75	1.88	5.17	3.88	5.92	2.96	2.25	1.69
	6.42	3.21	7.00	5.25	6.50	3.25	4.67	3.50	10.00	5.00	2.50	1.88
12	9.17	4.59	7.67	5.75	5.67	2.84	6.58	4.94	6.17	3.09	5.33	4.00
	8.50	4.25	10.25	7.69	10.75	5.38	11.67	8.75	14.50	7.25	2.75	2.06
	6.75	3.38	3.00	2.25	9.08	4.54	7.42	5.75	9.33	4.67	5.75	4.31
	9.42	4.71	10.17	7.63	5.17	2.59	5.33	4.00	10.17	5.09	2.83	2.12
	13.33	6.67	5.50	4.13	7.75	3.88	6.58	4.94	10.50	5.25	6.83	5.12
	9.50	6.75	3.67	2.75	10.25	5.13	6.25	4.69	12.17	6.09	7.67	5.75
16	12.83	6.42	13.00	9.75	Survived	-	9.83	7.37	Survived	-	10.17	7.63
	10.67	5.34	9.17	6.88	9.17	4.59	Survived	-	5.50	2.75	6.17	4.63
	10.75	5.38	11.33	8.50	11.83	5.92	10.33	7.75	10.42	5.21	12.17	9.13
	Survived	-	9.42	7.07	Survived	-	9.08	6.81	Survived	-	14.83	11.12
	11.42	5.71	Survived	-	Survived	-	7.67	5.75	9.58	4.79	6.75	5.06
	7.58	3.79	7.17	5.38	12.08	6.04	10.17	7.63	Survived	-	12.92	9.67

Table 10. Deceased Time of Mouse Exposed to Gaseous Mixture of CO, CO_2, HCN and O_2 Deficiency (min)

Exposure Time: 15 min

HCN (ppm)	5% CO_2				10% CO_2			
	0.25% CO		0.50% CO		0.25% CO		0.50% CO	
	8%O_2	12%O_2	8%O_2	12%O_2	8%O_2	12%O_2	8%O_2	12%O_2
50	8.92	8.00	3.25	4.00	6.00	11.00	3.50	5.42
	6.75	11.17	4.50	4.00	8.50	10.83	3.67	5.25
	6.17	11.33	3.50	5.92	6.42	11.58	3.75	4.83
	6.33	13.00	3.67	4.67	8.08	12.08	4.00	4.50
100	3.42	7.83	3.08	4.92	3.92	7.42	2.00	3.17
	4.83	9.08	3.00	3.00	3.33	8.83	3.17	3.67
	4.50	6.42	2.83	3.25	3.67	9.67	2.50	3.58
	3.17	9.00	2.58	3.58	3.50	9.42	2.17	3.42

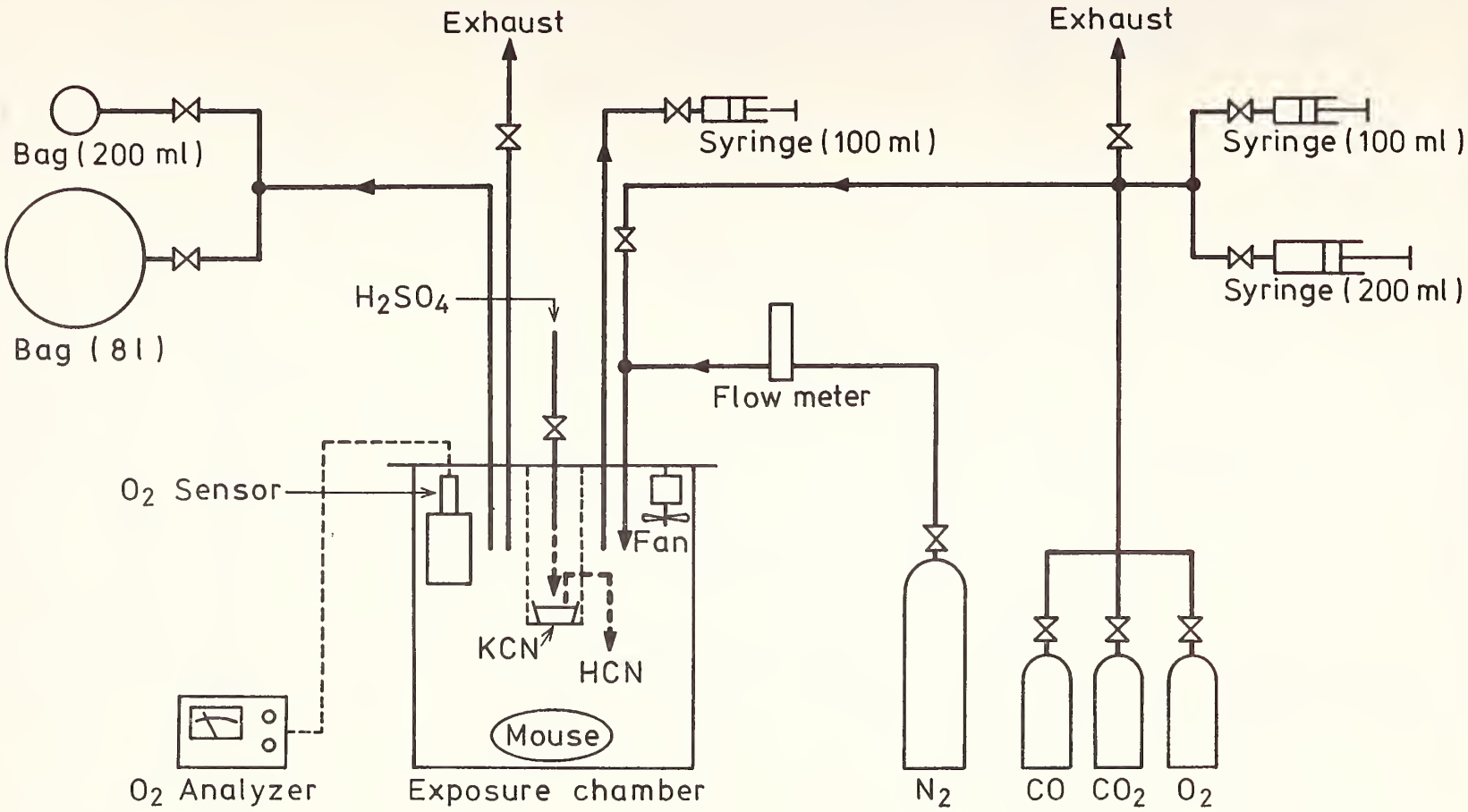

Fig. 1 — Constant concentration gas exposure test apparatus.

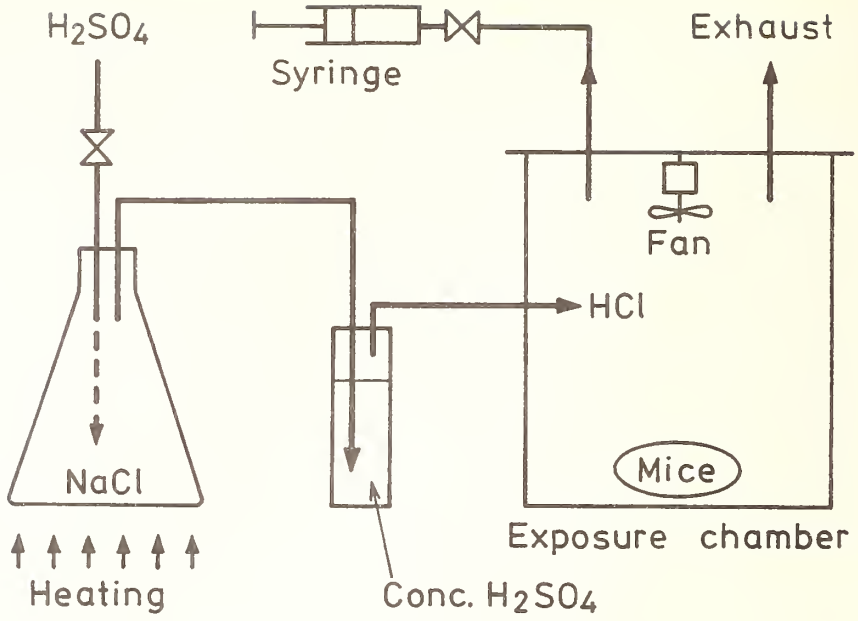

Fig. 2 — HCl exposure test apparatus.

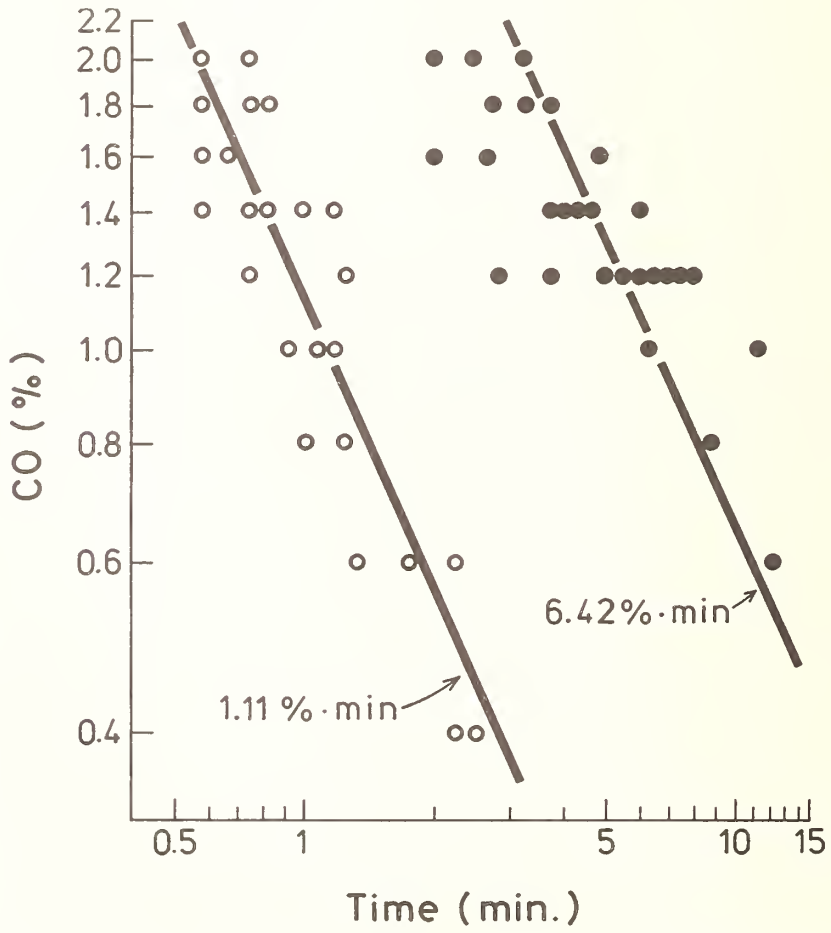

Fig. 3 — Collapse time and deceased time of mouse exposed to CO of constant concentration.

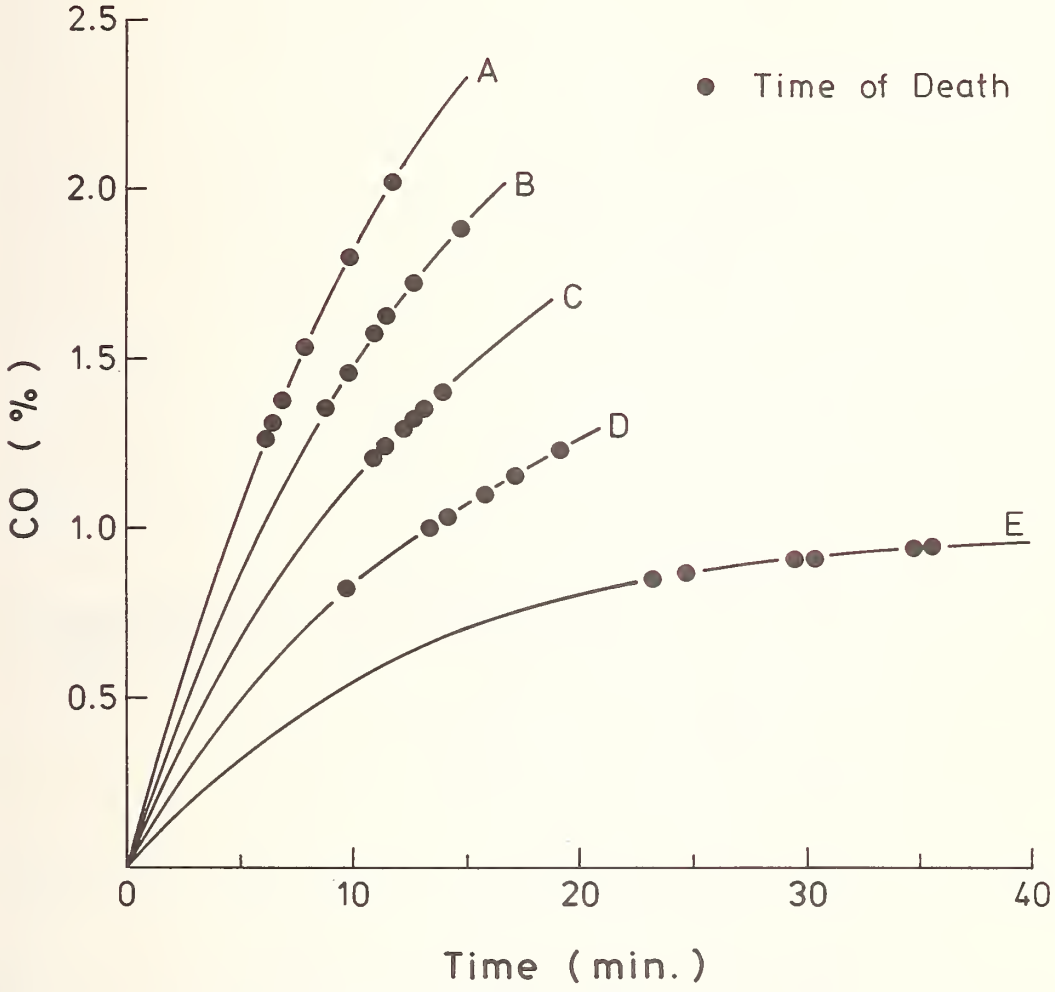

Fig. 4 — CO concentration in exposure chamber and deceased time of mouse.

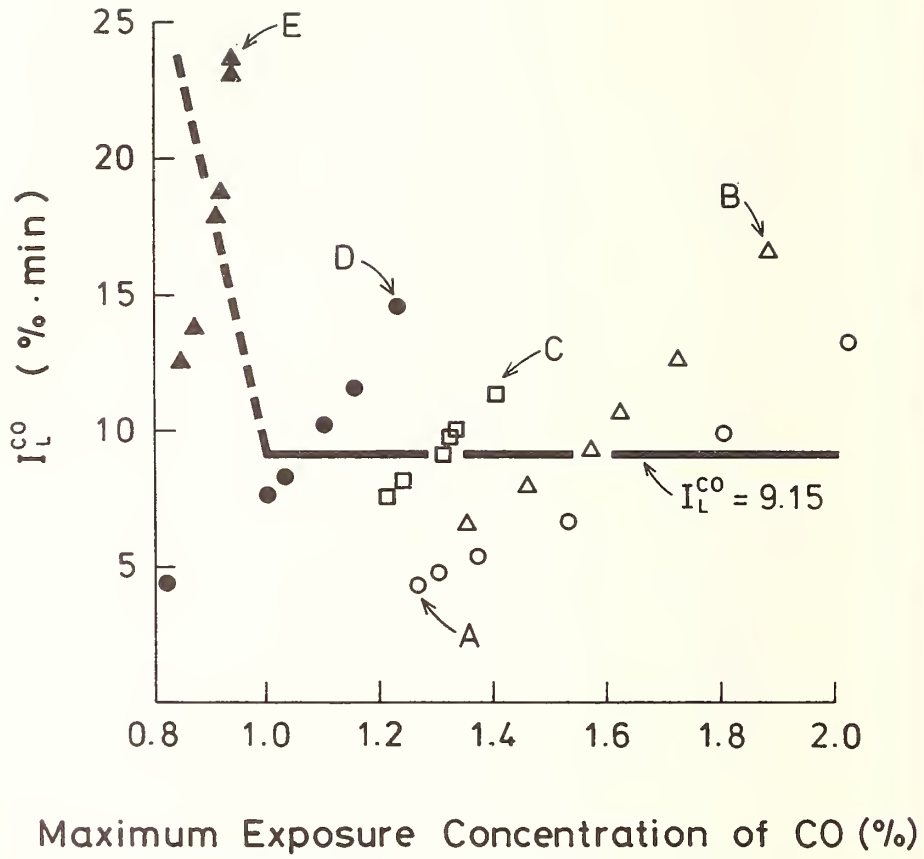

Fig. 5 — Maximum concentration of CO inhaled by mouse while alive and lethality index.

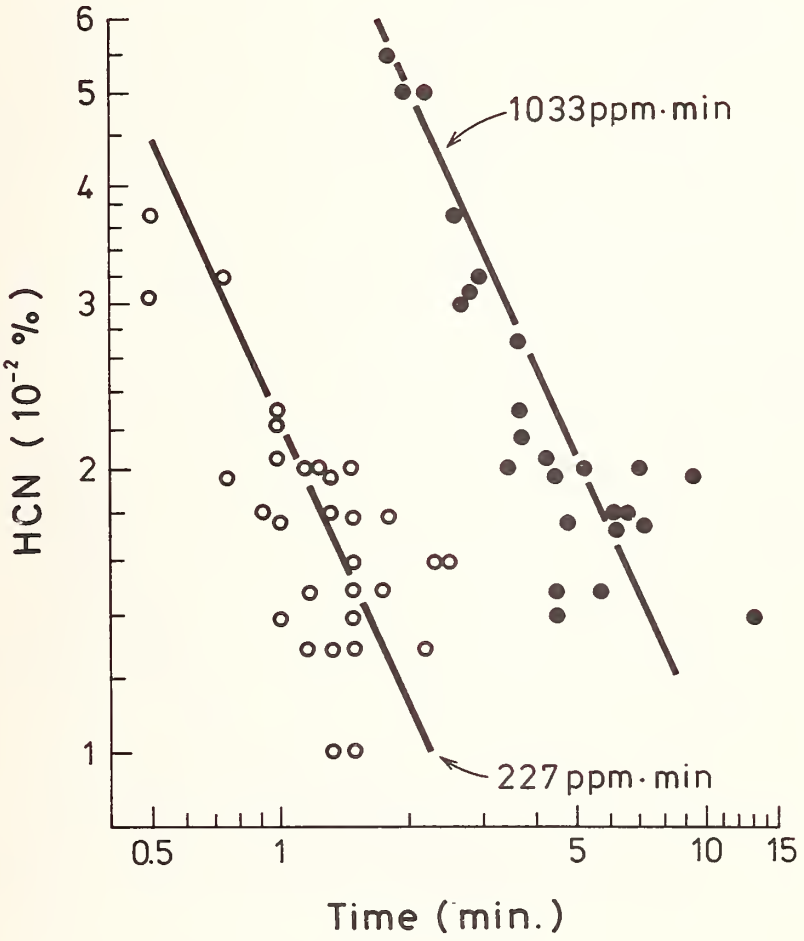

Fig. 6 — Collapse time and deceased time of mouse exposed to HCN of constant concentration.

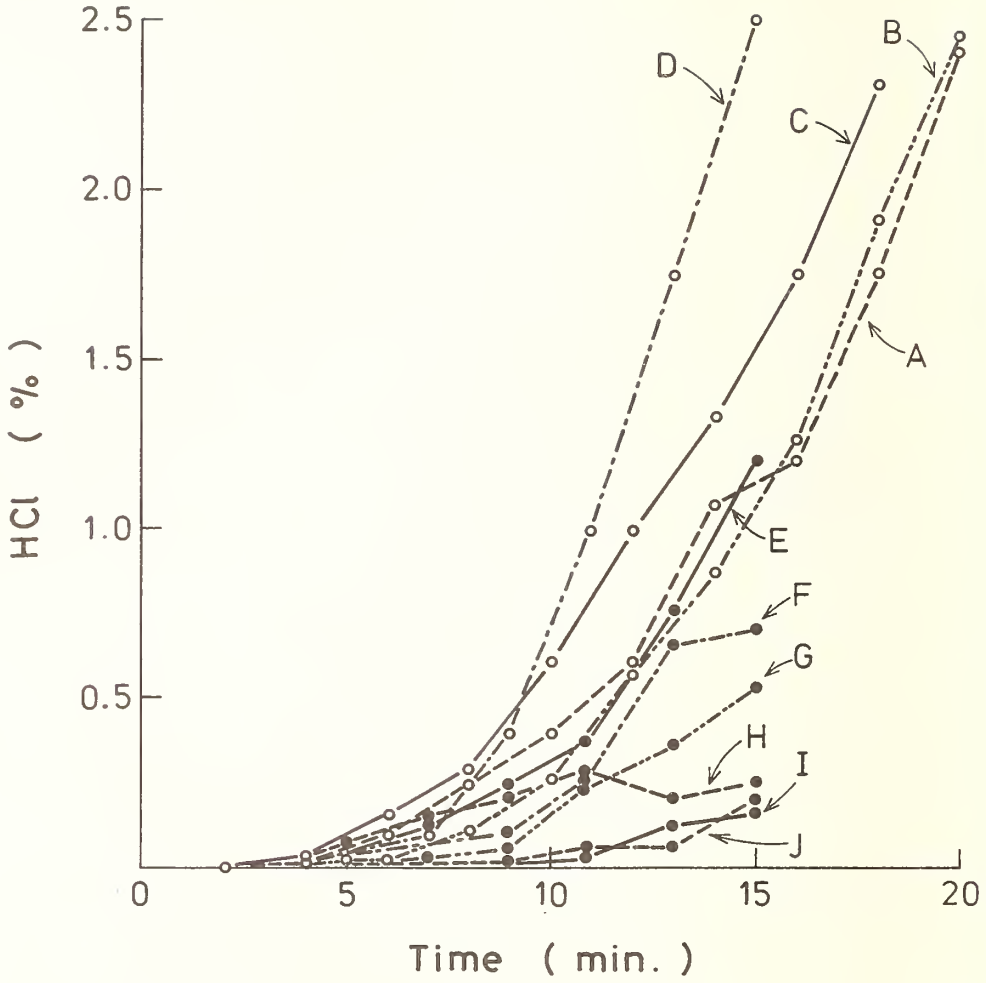

Fig. 7 — HCl concentration in exposure chamber.

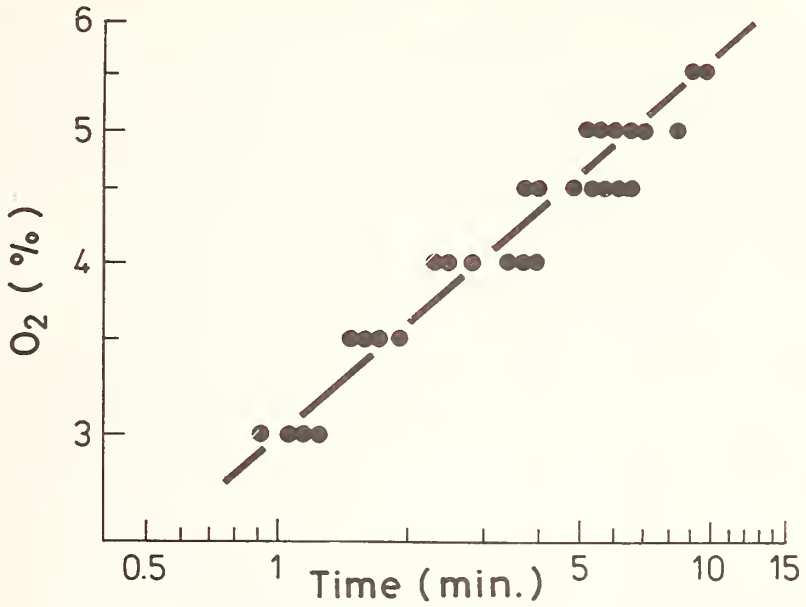

Fig. 8 — O_2 concentration and deceased time of mouse (at constant concentration).

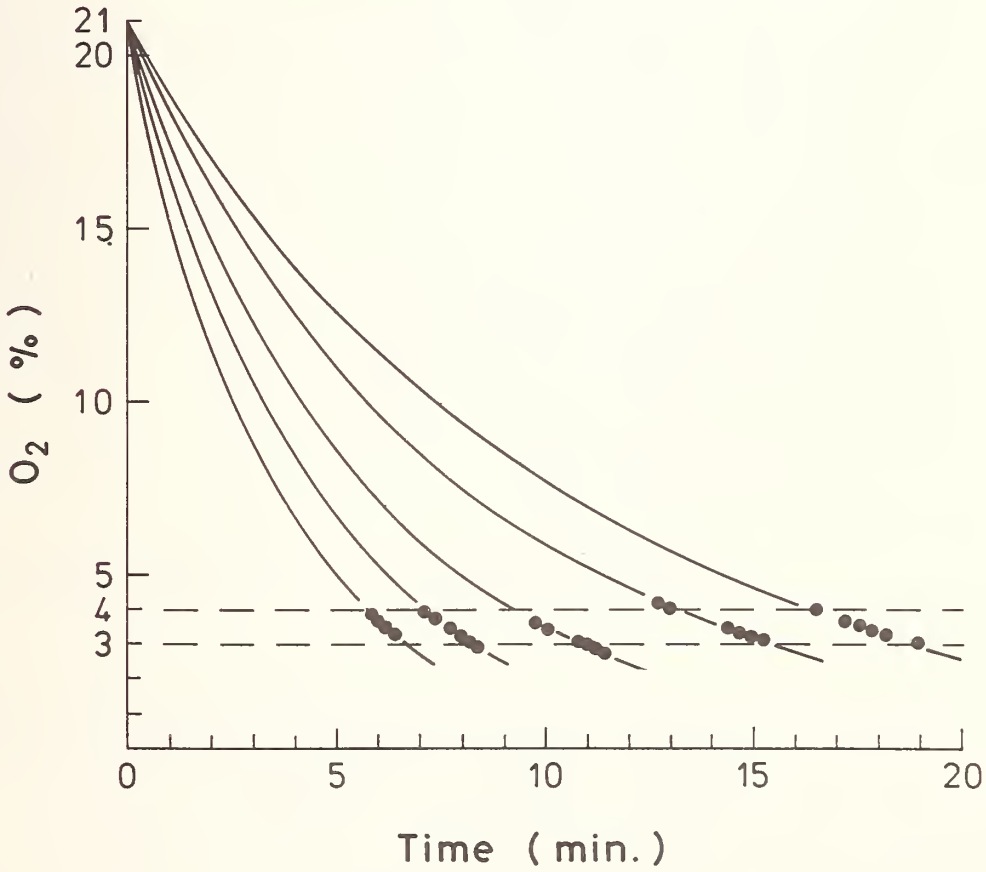

Fig. 9 — O_2 concentration and deceased time of mouse (at declining concentration).

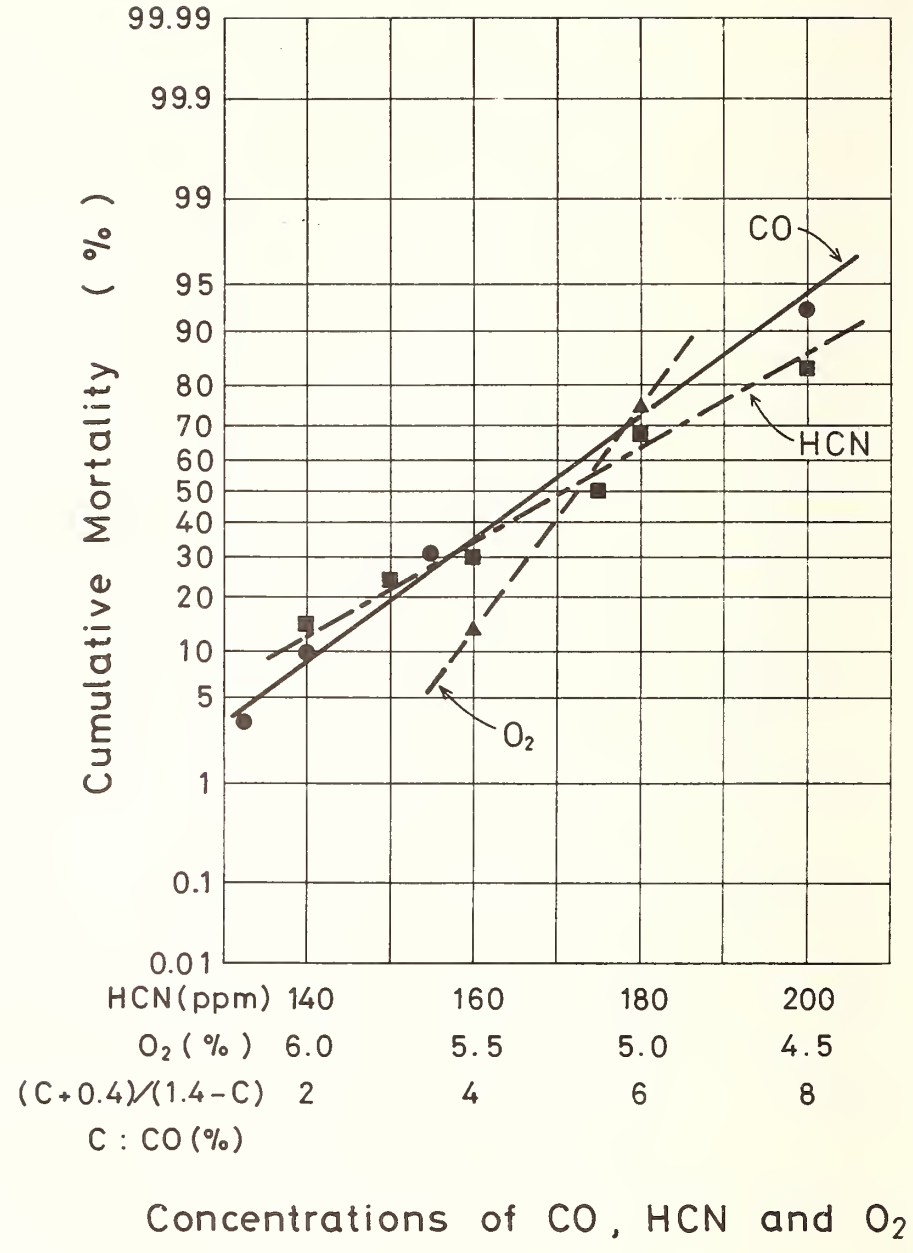

Fig. 10 — Exposure gas concentration and cumulative mortality of mouse (15-minute exposure).

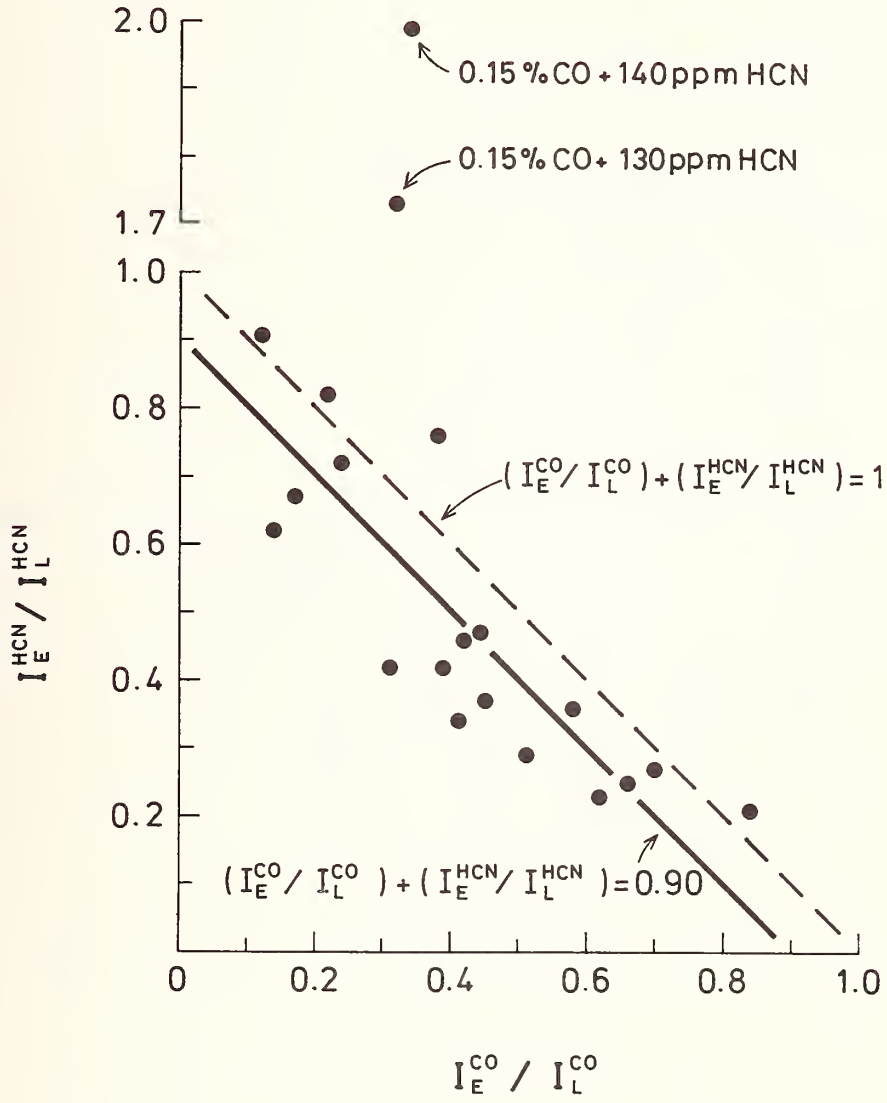

Fig. 11 – Ratio between exposure index and lethality index at deceased time in exposure to gaseous mixture of CO and HCN.

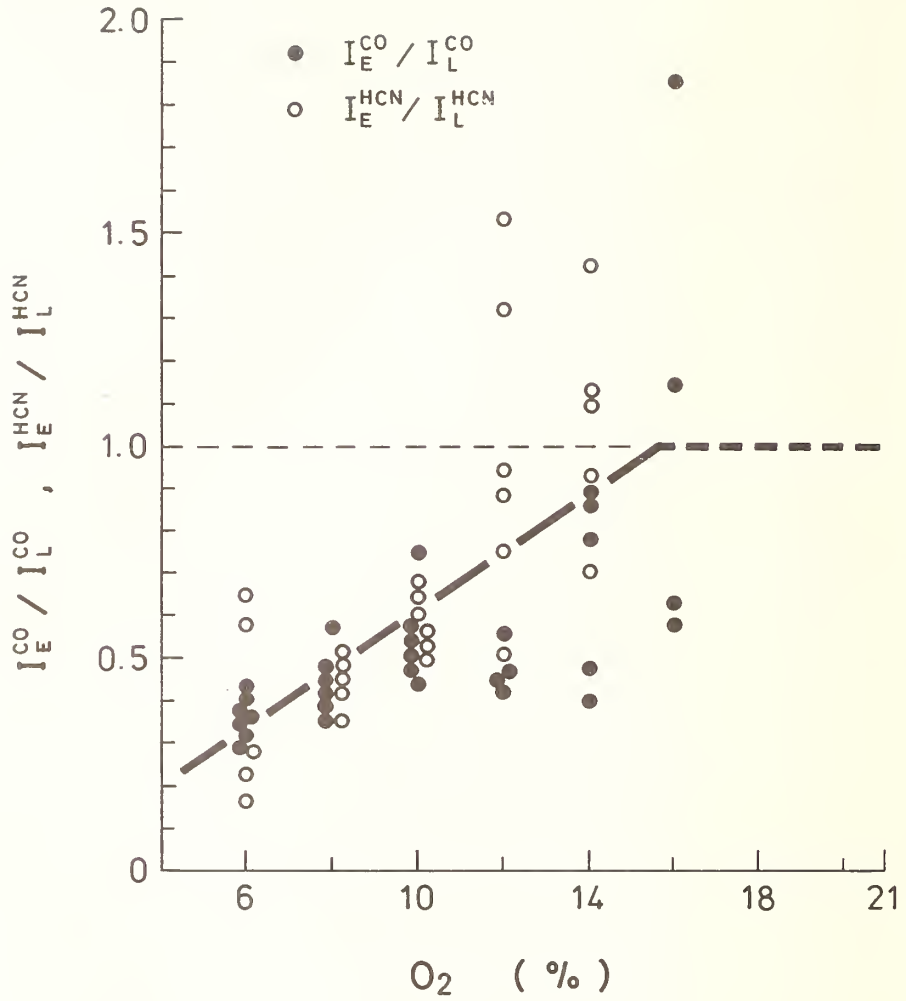

Fig. 12 — Ratio between exposure index and lethality index at deceased time in exposure to gaseous mixture of CO and O_2 deficiency or HCN and O_2 deficiency.

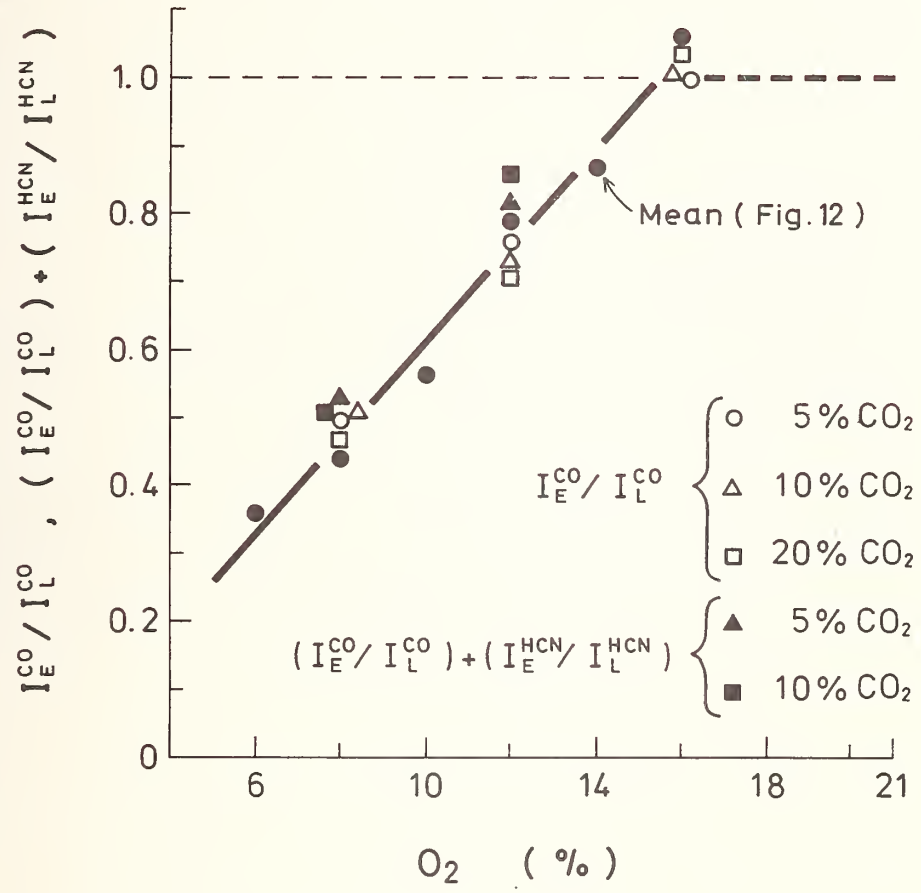

Fig. 13 – Ratio between exposure index and lethality index at deceased time in exposure to gaseous mixture of CO, CO_2 and O_2 deficiency, or CO, CO_2, HCN and O_2 deficiency.

On the Acute Toxicities of the Combustion Products of Various Fibers, with Special Reference to Blood Cyanide and Po_2 Values

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Introduction

The evaluation method of the toxicities of various materials at fires and the studies on the harmful effects of various combustion products are considered to be the main subjects in the toxicology on combustion. The present report chiefly concerns with the second item. Combustion toxicology generally deals with the gaseous form,therefore, inhalation route is the main entrance route of the toxicants into the bodies. There can be marked differences in concentrations and in distribution patterns of the toxic materials in the body with different routes of administration. That the above can hold for cyanide too was indicated in the author's previous experiments with rats and rabbits,in which two routes of administration,per os and inhalation routes, were used[1].

Since there is only a limited number of data on the distribution of cyanide in the body exposed to HCN gas[2,3,4,5,6], it seemed to be worthwhile ,as a first step to obtain such basic data, to determine the blood cyanide concentrations in the different parts of the body. The present report includes the data on blood Po_2 level as well as cyanide. This is based on the following considerations that this parameter can be used for a diagnosis,whether death is an asphyxial one or not,and that Po_2 can become a key to the problem of identity of the gases responsible for the toxic effects of the combustion products.

Materials and Methods

Materials Polyacrylonitrile(PAN),silk,wool and gauze were used for combustion experiments.The first three were obtained from Nippon-Boen-Kyokai and gauze(the Japanese pharmacopoeia)was purchased. The each material was cut to pieces of about 1.5cm square. Twenty gram of material was used in the experiments with the first three. In the case of gauze, 20g and 30g were used in Exp.Nos.1-4(see Table 1) and in Exp.No5, respectively.

Experimental apparatus and conditions They were virtually the same as those of the previous experiments[7] except slight modifications and only brief account is given here as follows. The sample was heated in a cylindrical cage made of a mesh of wire with an electric heater of 300w in a plastic combustion room measuring 30x30x50cm. The combustion product was lead through a 50cm-long plastic tube to a transparent plastic box which was used as an exposure room, to which a non-rebreathing valve was attached via a short piece of a plastic tube.

HCN inhalation experiment HCN was produced by addition of NaCN to H_2SO_4. To H_2SO_4 in a flat-bottomed flask, the diameter of and the height of which are 26cm and 36cm,respectively,with perforated rubber stopper, solid NaCN was added at proper intervals through one of the perforations. The rate of addition of NaCN was not fixed and it was changed during exposure,depending upon the state of the animal. Into the other perforation a glass tube with a diameter of 0.7cm was inserted and it was connected to the non-rebreathing valve by a short plastic tube.

Animals Male albino rabbits each weighing about 2,000g were used. After intravenous urethane injection(1g/kg,25%in saline),the animal was fixed supinely and a tracheal cannula was inserted following tracheotomy. The animal inhaled the gas of the exposure room(in combustion experiments)or HCN gas(in HCN experiments) through the non-rebreathing valve attached to the cannula. Combustion experiments were continued until ultimate cessation of respiratory movement of the chest,however, when respiration did not stop during 50-min exposure,the experiment was discontinued at that time. Immediately after the end of an experiment,the chest was opened and blood sample was drawn from the left heart,the right heart and the descending vena cava,respectively,in this order. The blood sample was stored in ice until determination,the start of which did not delay more than 30 min after sampling in the cases of cyanide and Po_2.

Toxicological determinations The whole blood cyanide determination was made by the method of Feldstein et al[8], triplicate determinations being done on each sample. COHb concentration was determined spectrophotometrically by van Kampen et al's method[9]. Before exposure,small amount of jugular vein blood was taken from each animal,and it was used for preparation of the calibration curve. Blood Po_2 was determined by Combianalyzer U. Prior to each analysis, the instrument was calibrated with standard gases. The O_2 concentration in the exposure room was continuously monitored by Beckmann O_2 analyzer. The respiratory rate of the animal was measured by counting of the movement of the chest per unit time. After thoracotomy,one lung was excised and fixed in formalin solution for subsequent microscopic examinations. The residual ash was weighed after each experiment and the vapoured ratio(%) was calculated according to the following equation, $\left(1 - \frac{\text{ash weight}}{\text{original weight}}\right) \times 100$.

Results

Survival time(ST, the time to ultimate cessation of respiration), blood cyanide,Po_2 and COHb values are summarized in Table 1.

HCN inhalation The ST ranged 5-14min. The cyanide concentration in the left heart blood averaged 3.4microg/ml,ranging from 1.24-5.53microg/ml. The mean value and range in the right heart blood were 2.2microg/ml and 1.04 -3.3microg/ml,respectively. The corresponding values in the blood of the descending vena cava were 1.6 microg/ml and 0.88-2.03 microg/ml,respectively. The ratio of the left heart to the right heart value was 1.2-1.7.The ranges and means(given in the bracket) of blood Po_2 of the left heart,the right heart and the descending vena cava were 19-80mmHg(43mmHg),7-33mmHg(22mmHg) and 7-23mmHg(15mmHg),respectively. The decreasing order of the Po_2 was identical with that of the cyanide concentration. The rabbit with high postmortem cyanide value showed high postmortem Po_2 value. The six animals in the present report could be divided into two subgroups,based on the magnitude of the blood Po_2 and cyanide values, one group consisting of 4 animals (Exp.Nos.1,2,4,5) with high cyanide and Po_2 values and the other one with low in the both.

PAN All the animals were killed during exposure and the range of the ST were 11-17min. As in the HCN experiment,the left heart blood showed the highest cyanide value.The next highest concentration was recorded in the right heart blood. The decreasing order of the cyanide concentration was the same as that of the HCN experiment. The same relation as that in the HCN experiment was predent between cyanide and Po_2 values. The concentration of COHb was very low. There was neither soot nor froth in the trachea macroscopically.

Silk None of the animals survived exposure and the ST was slightly longer in this group than in PAN group. The mean blood cyanide concentration in the left heart, in the right heart and in the descending vena cava were 4.9, 2.9 and 1.9 microg/ml,respectively. This group showed the highest cyanide concentration of all the groups. The difference was the greatest in the left heart blood, on the other hand, there was hardly marked difference among this,PAN and HCN groups with respect to the peripheral blood. As to the Po_2 values too, the silk group was the highest. As in the preceding two groups, the animal with high postmortem Po_2 value showed high cyanide value. The COHb level did not exceed 10%. In 5 out of 6 animals,froth was present in the upper respiratory tract,on the other hand,not any soot was macroscopically observed.

Wool All animals died during exposure. The ST ranged 15-50min. In this group cyanide concentration was very low compared with PAN and silk groups. On the other hand the COHb concentration was about the same as that in silk group. There were present in some animals both soot and froth in the trachea.

Gauze Only 2 out of 5 animals succumbed during exposure. The time were 32 and33 min,respectively. The other 3 animals showed severe respiratory depression after about 25-40min's exposure,but thereafter, showed the tendency to restore. The COHb levels were as high as 85% in the animals died during exposure,on the other hand,the value ranged 55-65% in animals survived exposure. Black particles were observed in the trachea in 1 died and 2 survived out of 5 animals,but no froth was observed.

The decrease of the exposure room O_2 concentration was not marked in experiments except thosewith gauze,the minimal concentration in which were 11-14%.

The vapoured ratio differed greatly from material to material. The mean values of gauze,wool,silk and PAN were 96,68,54 and 27%,respectively.

Discussion

PAN and silk were considered more dangerous materials at fires than wool and gauze on the basis of the length of the ST and this result was consistent with the previous results[7]. As to identity of the gases responsible for hazard too, the present study agreed with the previous results[7]. HCN was the main toxic gas produced from PAN and silk and CO was responsible for the toxicity of the gases released from gauze.

There were considerable differences as to the blood cyanide and Po_2 levels among different parts of the body within the same material. It is needless to say that to specify the source of the sample is very important in interpretation of the data. The close relation between blood cyanide and Po_2 values strongly indicates the influence of the ventilation at the last stage of the exposure on thesevalues. The inability of cardiac function to maintain the general circulation effectively at the last stage probably is the main cause of the concentration difference of cyanide among different parts of the body.

The cause of the intragroup difference in cyanide level,which was relatively great in HCN and PAN groups,remains to be solved,and for a detailed discussion on this problem,measurements of cardiac and respiratory functions and quantitative evaluation on them will be indispensable. As in the previous experiment,silk group showed the highest cyanide values. The ratio of silk group to HCN group amounted to as high as 1.4 with the left heart blood. This seemingly puzzling data is considered to indicate that relatively large amount of HCN was inhaled immediately before ultimate cessation of respiration,for there was not much difference in cyanide level among HCN,silk and PAN groups with respect to the blood in the descending vena cava.

According to Mithoefer et al[10],irrespective of the source of the samples, the blood Po_2 above 25mmHg is evidence against asphyxia as a cause of death. Since cyanide,in cotrast to CO, inhibits the utilization of O_2 by tissue, the higher postmortem Po_2 is expected in acute cyanide poisoning than in acute CO poisoning. The way,by which cyanide is introduced into the body, affects the Po_2 value. The postmortem Po_2 was lower in poisoning by inhalation than in that by oral route[1]. In the present study,the Po_2 in gauze group was generally low in compared with those in HCN,PAN and silk groups with respect to the three kinds of the blood samples.

Table 1. Summarized data of the results.

Materials	Exp.No	ST(min)	Cyanide(microg/ml) L	R	V	Po_2(mmHg) L	R	V
HCN inhalation	1	4.8	5.53	3.30		54	33	
	2	9.9	4.42	2.71	1.83	51	32	23
	3	14.0	1.24	1.04	0.88	19	11	9
	4	7.3	3.64	2.35	1.72	37	26	18
	5	11.1	3.72	2.18	2.03	80	20	16
	6	6.4	1.94	1.58	1.44	19	7	7
PAN	1	16.5	8.14	3.54	3.14	75	30	28
	2	14.1	1.55	1.47	1.34	12	6	6
	3	15.4	1.99	1.66	1.56	22	15	11
	4	16.6	1.49	1.44		19	13	
	5	11.2	2.92	1.93	1.37	40	17	16
	6	13.6	3.87	2.36	1.75	61	32	19
Silk	1	17.2	5.37	3.81	2.30	47	25	13
	2	16.7	3.18	1.97	1.48	28	18	16
	3	16.5	5.22	2.96	1.49	102	35	18
	4	15.5	4.31	3.03	2.05	57	29	17
	5	14.9	5.40	3.11	2.31	76	36	26
	6	16.4	5.96	2.79	1.63	98	42	29
Wool	1	25.1	0.11	0.11	0.09	3	4	4
	2	15.0	0.10	0.07	0.05	65	46	14
	3	31.8	0.13	0.13	0.12	9	4	5
	4	16.0	0.08	0.06	0.05	10	7	4
	5	50.0	0.39	0.29	0.29	44	16	16
			COHb(%)					
Gauze	1	33.0		86	84		5	3
	2	32.2	84	88	86	35	6	6
	3	survived	59	65	65	5	4	3
	4	survived	56	52	52	9	7	4
	5	survived	63	60	59	13	13	12

L:The left heart.R: the right heart.V: the descending vena cava.

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Theme
TOXICITY

FACTORS ACCELERATING THE GAS TOXICITY IN A FIRE

by

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Preface

Evaluation of toxicity of combustion gas in a building fire must be a synthetic evaluation of toxicities of all combustion products. In evaluating the toxicity of combustion products, the following four factors must be taken into consideration:

i) combustion product gases
ii) heat
iii) water vapor
iv) smoke particles

In so far as organic substances burn, the toxicity of combustion gas must be evaluated not by the toxicity of each component of it, but in correlation with the following three factors:

i) CO and CO_2 gases
ii) a decrease in O_2
iii) The inherent decomposition gases of a material which correspond to its chemical ingredients.

With regard to the evaluation of toxicity in a case where a plurality of kinds of gases coexist, it is now made clear that a similar joint action exists between some types of the gases.[1),2),3)] On the other hand, it is pointed out that an antagonistic joint action occurs in the coexistence of irritating gases, and this makes it difficult for us to evaluate the toxicity by gas analysis in a case where a plurality of kinds of gases are mixed together.

The inhabitants who are left within a building during a fire will receive direct physiological impediments caused by this factor combined with increasing temperature and humidity in the building. These factors, which also promote respiration, result in an increased volume of the gas introduced into a human body. Therefore, even when the particular gases considered are low in concentration, a dangerous level is reached in a shorter period of time than might usually be expected if the temperature and humidity are high. The same may be said of smoke particles. The effets of the temperature and humidity in limited combinations of some kinds of gases

have been reported by A. J. Pryor et al.[4]

In the study being presented here, fundamental experiments were carried out to determine the effects of smoke particles, temperature, and humidity on the toxicity of gases.

1. Influence of Smoke Particles

From the standpoint of fire safety engineering, smoke is regarded as a factor which obstructs the fire evacuation action of inhabitants from a building.

Thus an extinction coefficient that is most closely related to visibility is used as a unit for quantifying the amount of smoke. In this case, the size distribution and optical characteristics of smoke determine the extinction coefficient. It is thought, however, that smoke as a factor affecting the physiological effect of combustion products is determined by the mass density and chemical structure of the smoke particles and that there is little correlation between the extinction coefficient and the physiological effect of smoke particles.

As for a study of composition of smoke by means of chemical analysis, few investigators have conducted this type of research and the mode of its physiological action has not yet been elucidated. Accordingly the author conducted the experiments shown below to obtain a concept of the physiological action of smoke.

1) Experimental Apparatus and Procedure

The experiments were carried out by the use of the apparatus shown in Figure 1.1. The apparatus consists of a furnace, a mice exposure chamber, a smoke density meter, and a gas analysis meter. An attempt was made to determine the influence of smoke particles by exposing mice to smoke with smoke particles and to smoke without smoke particles.

A total of six mice were used in each of the experiments; that is, four mice were placed into the exposure chamber

and then one mouse was placed in each of the two glass tubes positioned on the downstream side of a smoke filter. An experimental procedure was repeated from 5 through 7 times under each condition.

2) Test Materials and Burning Condition

In these experiments, Japanese cedar, Treated Plywood, PMMA, and Acrylonitrile were the materials to be tested.

The kinds and amounts of combustion products vary according to the chemical composition of the material and to burning conditions, namely heating methods such as temperature, air supply, etc., as would be the case with a series of the present experiments. Therefore, in this study, the experiments were performed under the following burning conditions:

furnace temperature: 400°C - 600°C
air supply : 3 l/min
O_2 concentration : 21%, 15%

3) Mice and Mice Monitor

JCR-JCL female mice of 13g - 15g in their body-weight and four weeks after their birth were used as experimental animals and the time to ataxia of the mice was measured by using the rotary method of the light-shield type which had been developed by the author and the time to death by observation. In the light-shield type mice monitor, mice are placed into a cage of wire netting as shown in Figure 1.2 and the cage is covered, on a half surface of its one side, with a sheet of black paper shielding it from light. A mouse within the cage has the habit of rotating it by her own ability in an effort to escape when a toxic gas is introduced. The rotation of the cage can be recorded by utilizing a lamp and photocell (CdS) positioned on either side of the cage. If the gas is free from harmful components, then the number of rotations do not decline as shown in Figure 1.3. On the other hand, when the gas which the mouse has inhaled

contains harmful components, the mouse gradually loses her ability to ratate the cage by her own exertions. The author has defined the time required for a mouse to lose her ability to rotate the cage "ataxia time" and the time to respiration-stop "death time". Observation was made of the mice which had inhaled gas from which smoke particles had been filtered.

4) Experimental Results and Consideration

The results in the case where mice were exposed to combustion gas were recorded by two methods; observation and a photocell technique. A proportional relationship as shown in Figure 1.5 holds between the ataxia time which have been measured by observation in order to evaluate the dangerous level by the same standard of judgement. The mass smoke concentration was calculated from the weight of the smoke particles which adhered to the filter shown in Figure 1.1 and the rate of flow of smoke through a passage. Furthermore in Table 1.1, as one of indications of the toxicity there are shown the product $\Sigma CO \cdot t$ (%·min) of the lethal time, t (min), and the CO concentration (%) in the breathing air for each of the experimental mice and a comparison of the average value of the product is made between before and after the smoke particles are filtered.

The effect of smoke particles on the physiological action of the gas can be qualitatively determined by the difference in the death time between the mice on the upstream and downstream sides of the filter.

If the average values of the products of the time to death and the CO gas concentration in the presence and absence of smoke particles respectively are taken to be $\Sigma CO \cdot t_1$ and $\Sigma CO \cdot t_2$, then the relationship between them can be expressed by the following two equations:

$$COt_2 = \alpha_A + \Sigma COt_1 \quad \text{(Additive Joint Action)} \quad (1)$$

or

$$= \alpha_B \cdot \Sigma COt_1 \quad \text{(Synergystic Joint Action)} \quad (2)$$

The equation (1) applies in a case where smoke acts in a mode of additive action and the equation (2) in a case where smoke acts in a mode of synergistic action. It can be seen from the values of α_A and α_S shown in Table 1.1 that the kind of smoke varies very greatly with the kind of materials and combustion conditions. That is to say, the evaluation of the toxicity of the materials must be made in its relation to combustion conditions. Many chemical substances, however, can be regarded as a factor which causes chemical reactions with the trachea and pulmonary vesicles and thus causes the rupture of cells. Consequently it seems unlikely that the evaluation can be made simply by such short-time exposure tests as these present experiments. For that reason, it is necessary to breed the smoke-exposed mice for a long period of time after the exposure test to check whether there are any physiological problems.

If carbon monoxide alone determines the toxicity of a combustion product gas, then the values for $\Sigma CO \cdot t$ should be a fixed value. On the contrary, the results of the present experiments are considerably scattered and do not show a constant value. This shows that besides CO gas there exist gases which cause physiological impediments.

However, since the values for $\Sigma CO \cdot t_2$ and t_2 after filtering the smoke, in general, are always greater, it can be expected that smoke particles will accelerate the toxicity in the mode of a similar joint action or a synergistic joint action. The coefficient, M_T, which shows the rate of accelerating the gas toxicity of the smoke particles is obtained from the equations (1) and (2) as following:

In the mode of a similar joint action

$$\alpha_A = D_M \cdot M_T$$

$$\therefore M_T = \alpha_A / D_M \qquad (5)$$

In the mode of a synergistic joint acton

$$\alpha_S = D_M \cdot M_T'$$

$$\therefore M_T' = \alpha_S / D_M \qquad (6)$$

M_T and M_T' obtained from the above equations are the toxicity coefficients per unit of smoke (mg/m^3) when a law of either a similar joint action or a synergistic joint action is assumed to exist between the smoke and the gases.

2. Decrease in Oxygen Concentration

The concentration of oxygen in a combustion gas invariably shows lower values than that of atmospheric oxygen. As a general rule, when the concentration of atmospheric oxygen decreases, the rate of respiration will increase. In such a case, the presence of harmful gases in the air will also result in an increase in the volume of repiration unless these gases are especially irritative chemical substances. Consequently it can reasonably be expected that we will reach a dangerous level even when the concentration of the harmful gases is low. Experiments were carried out by placing four mice per experiment into a desiccator of 24 l in volume (Fig 1.1) and by supplying it with a gaseous mixture whose oxygen concentration had been lowered by mixing nitrogen with a mixed gas of oxygen and carbon monoxide. The experiments were run in triplicate, and the average value was calculated. The changes in the concentrations of oxygen and carbon monoxide in the desiccator at that time are shown in Figure 2.1.

As a criterion for evaluating toxicity, there has again been employed that product of the carbon monoxide concentration (%) until death time and the gas-breathing time which is represented by $\Sigma CO \cdot t$ (Fig 2.2).

It can be deduced from the Figures that a decrease in the concentration of oxygen in the air will cause people to run into danger even at a lower carbon monoxide concentration in a shorter period of time.

Because the only factor in the death of the mice is carbon monoxide, the quantity of CO-Hb in the blood of the mice ought to show roughly the same value, irrespective of O_2 and CO concentrations, although the author cannot conscientiously say this since he did not measure the quantity of CO-Hb in the blood.

Thus in evaluating the toxicity at a fire, both the toxicity of harmful gas-components and factors accelerating it must be taken into consideration. In other words, a synthetic evaluation of both the toxicity of gas components and the factors increasing the volume of respiration under a fire environment is required.

3. Increase in Temperature and Humidity

Since a fire is a phenomenon of the combustion of organic materials, defusement of combustion products to all parts of a building surely gives rise to the increases in temperature and humidity in the air in the building at the time of the fire. It may be expected that the increases in temperature and humidity cause the volume of respiration to increase, and it is thought that the physiological action of toxic gases is accelerated by an increase in the volume of respiration.

Accordingly, usning carbon monoxide as a toxic gas, experiments were performed on acceleration of the physiological action caused by temperature and humidity.

1) Effect of Temperature

As experimental animals, four-week old dd-male mice with a weight of about 20 g were used.
The mice were placed into a chamber as shown in Figure 3.1 which was maintained at a constant temperature. The chamber was supplied with CO gas, and the lethal time and $\Sigma CO \cdot t$ were calculated by a mice monitor. In these experiments, an improved mice monitor was used as shown in Fig 1.2 B). This monitor is different from a photocell-type monitor in that its cage weighs 55 g to the photocell-type's about 95 g and uses adjacent switches instead of a photocell.

It was expected that the mice would die of shock when suddenly exposed to a highly concentrated gas. Hence the CO concentration in the chamber was gradually raised as shown in Figure 3.2. In this case, $\Sigma CO \cdot t$ is determined by summing up the CO concentrations at regular one minute intervals.

The results of the experiments are shown in Figure 3.2. It can be said from the Figure that the rise of temperature obviously causes the toxicity of the gas to accelerate.

2) Combined Effect of Temperature and Humidity

Experiments were carried out in much the same way as the experiments on the effect of temperature described above, except that the temperature and the humidity respectively were set at 30°C, 40°C, and 50°C and at 70%, 80%, and 90%: that is, as setting conditions, there were adopted nine comined conditions of the three settings of temperature and the three settings of humidity. Temperature control in the chamber was made by means of a humidistat positioned in the bottom of the apparatus.

The rising curve of CO concentration in the chamber for each experiment is the same as that in Figure 3.2. Sixteen mice were used in each experiment and the experiments were run in triplicate. Table 3.1 and Figure 3.3 give a compilation of the average arithmetic values for triplicate runs.

The lethal time for the mice decreases with the rise of humidity even at the same temperature, and this trend become more pronounced with a rise in humidity. However, the amount of variations in the results increases as the humidity is raised.

Conclusion

The problem of toxicity in a building fire involves considerations of all the factors which occur during the fire. Despite the fact that experiments with gas toxicity using experimental animals influenced by temperature, humidity,smoke, etc., in addition to gases the results are frequently analyzed only from a point of view of gaseous component. As the present study has clarified, such environmental conditions as temperature, humidity, etc., are also important factors which cannot be neglected under their certain level-conditions.

In particular, the evaluation of toxicity in terms of gas-analysis values is the important subject for advancement in future study. Furthermore, in order to clarify the correlation between the toxicity expressed in terms of the analysis values and that obtained by animal experiments, the weight function of such physical factors as smoke, temperature, humidity, etc., as experimental conditions must be elucidated beforehand.

Although tendencies in each single factor such as smoke, oxygen, temperature, and humidity were only obtained in the present study because various mice and different mice monitors were used, a further carefully thought out study is required in order to clarify the correlation between each factor.

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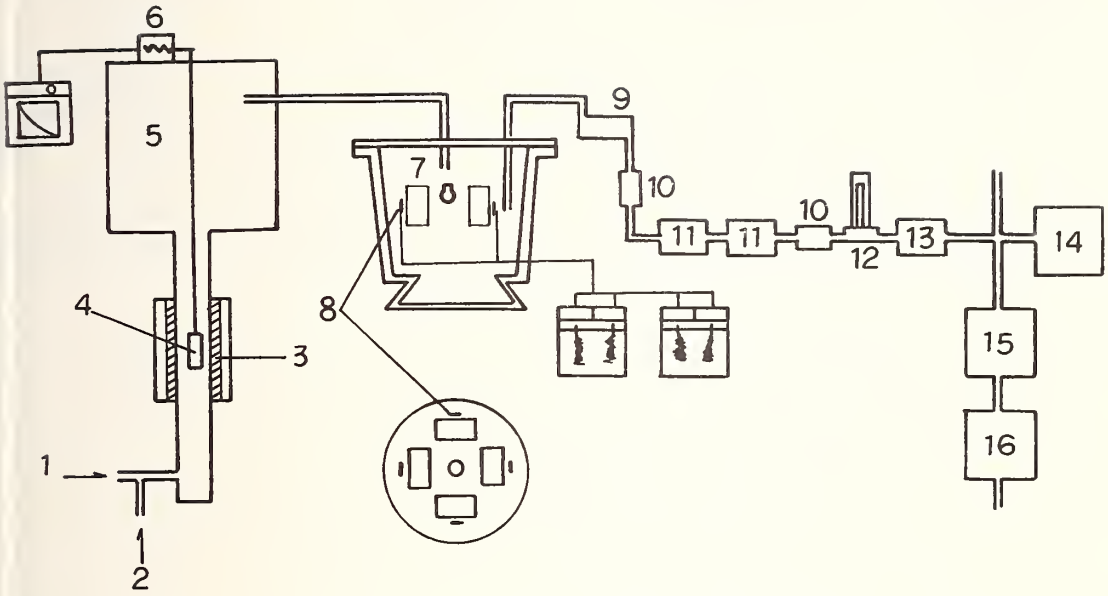
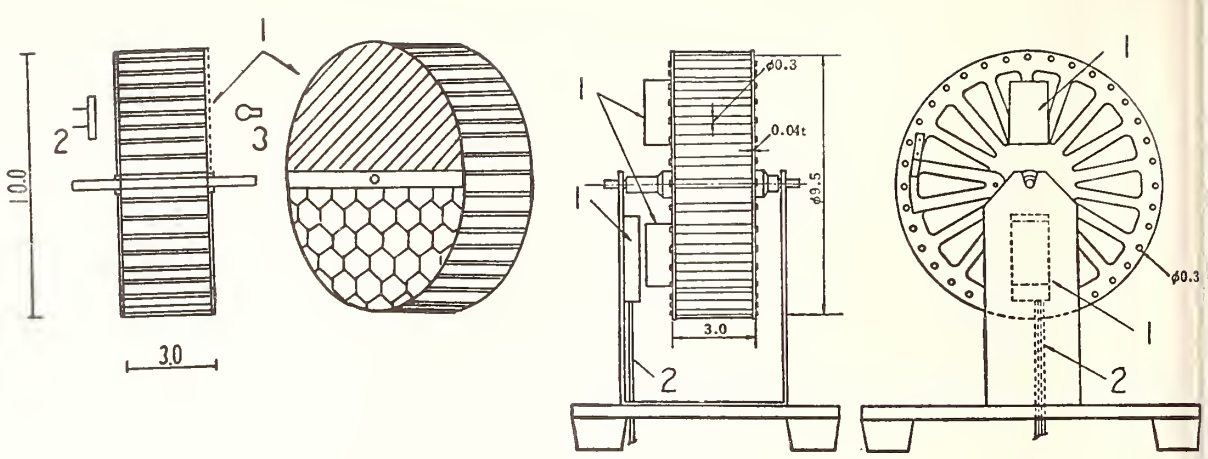


1	Air Supply	9	Smoke Meter (Path length: 50 cm)
2	N_2 Supply	10	Filter
3	Heater	11	Glass Tube
4	Sample	12	Flow Meter
5	Dilution Chamber (125ℓ)	13	Pump
6	Strain G	14	O_2 Analyzer
7	Decicater (24ℓ)	15	CO Gas Analyzer (Infrared)
8	Mice Cage	16	CO_2 Gas Analyzer (Infrared)

Fig. 1.1 Experimental Arrangement for Mice Test
(Influence of Smoke Particles on Gas Toxicity)



1) Black Paper
2) CdS Cell
3) Lamp

A) Photocell Type

1) Adjacent Switch (Magnet)
2) Lead Wire (to the recorder

B) Adjacent Switch Type

Fig 1.2 Type of Mice Monitor

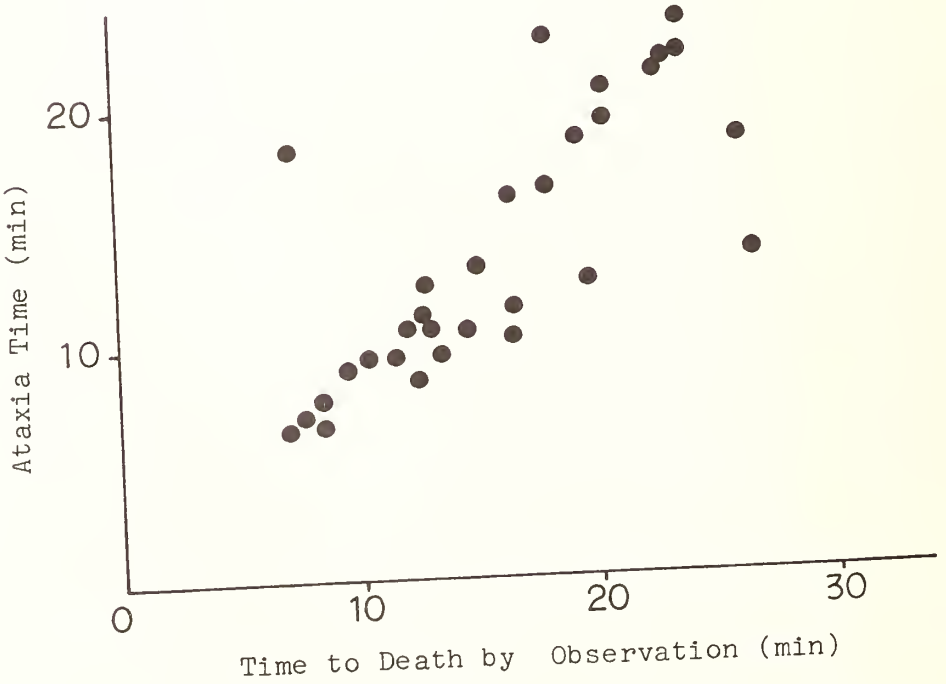


Fig. 1.5 Relation Between the Observation and Mice Monitor

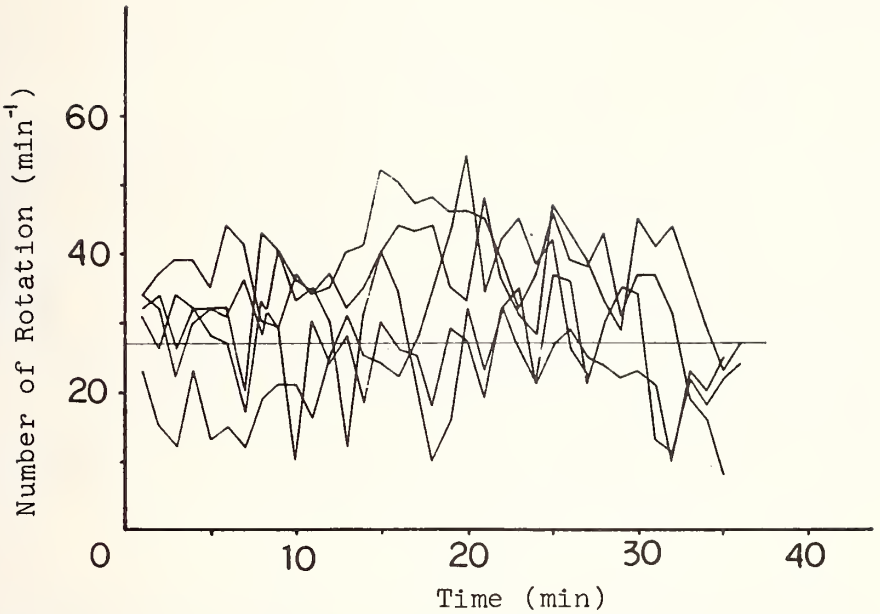


Fig. 1.4 Number of Rotation in the Air

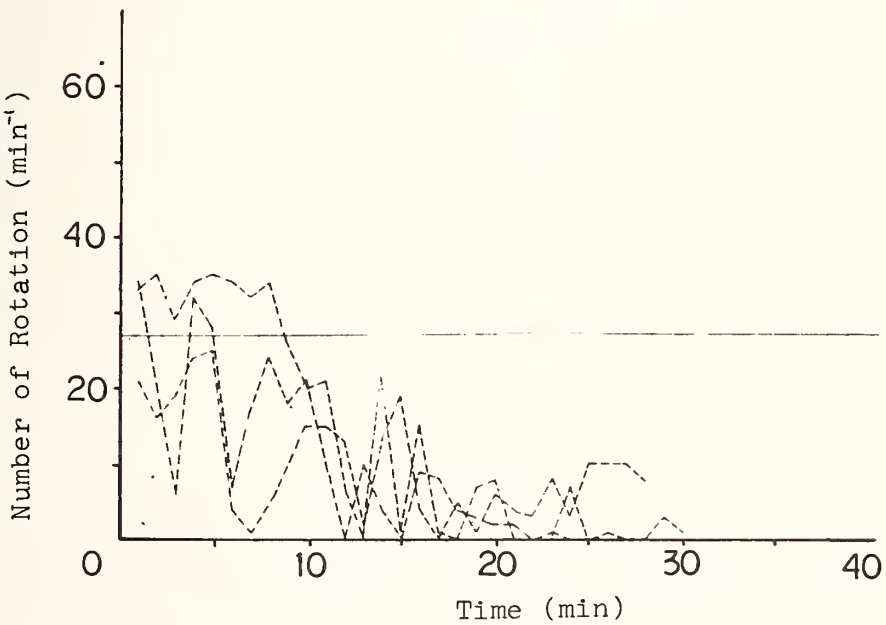


Fig. 1.5 Number of Rotation in the Air Contained CO Gas

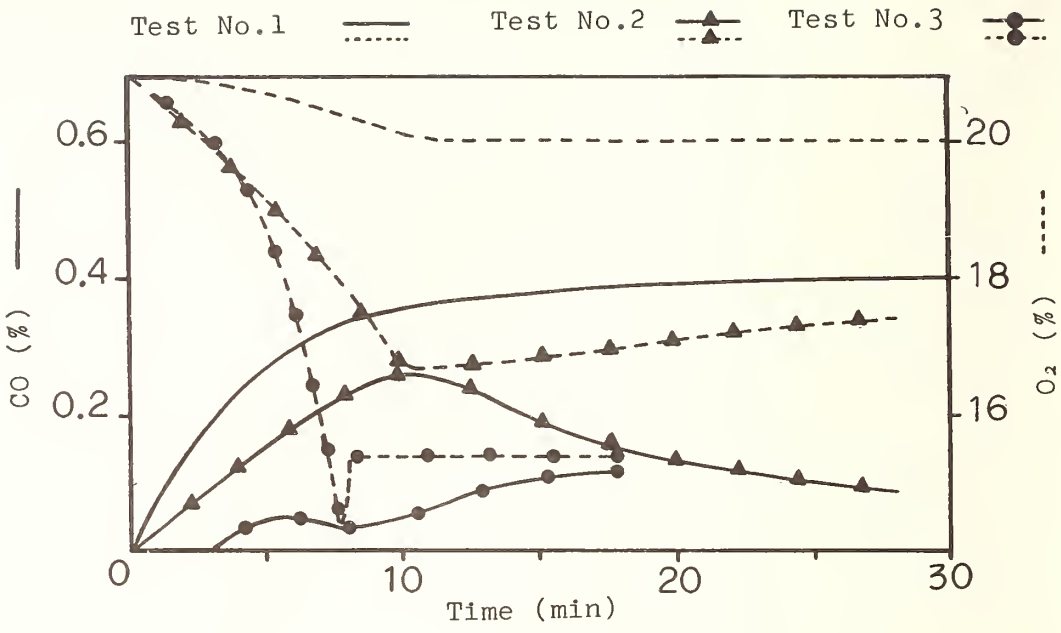


Fig. 2.1 CO and O_2 Concentration in Decicater

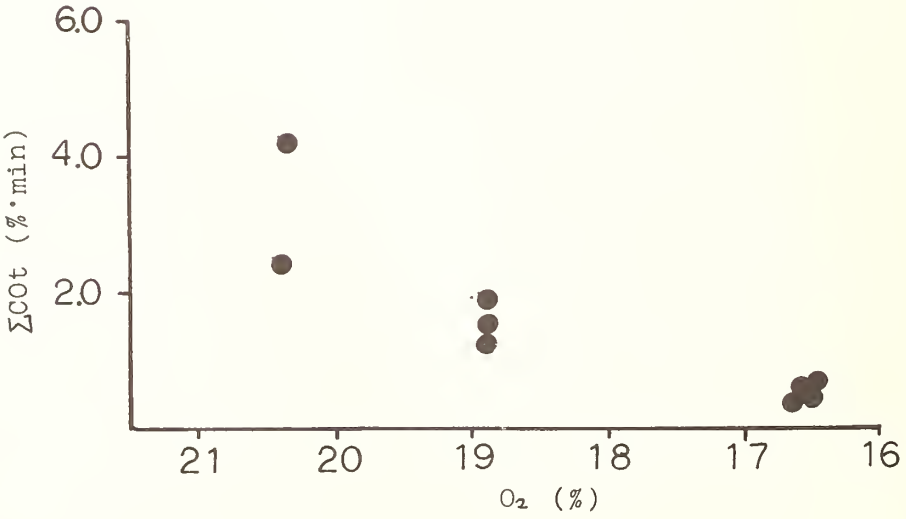
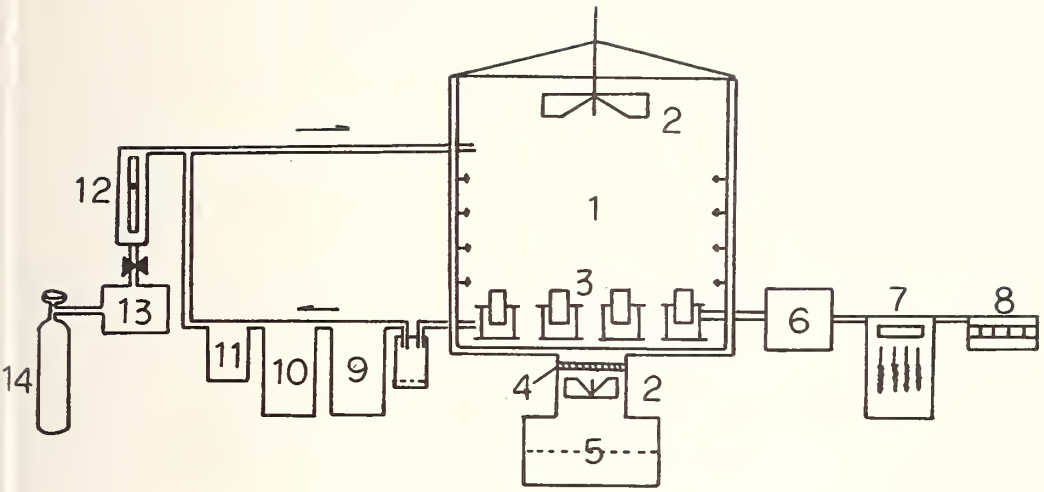


Fig. 2.2 Decrease of O_2 Concentration VS $\Sigma CO \cdot t$



1. Exposure Chamber
2. Aditater
3. Mice Cage
4. Heater
5. Humidity Generater
6. Amplifier
7. Mice Recorder
8. Rotation Counter
9. CO Analyzer
10. CO_2 Analyzer
11. O_2 Analyzer
12. Flow meter
13. Premix Box
14. Gas Bomb

Fig. 3.1 Experimental Arrangement for Mice Test (Influence of Temperature and Moisture)

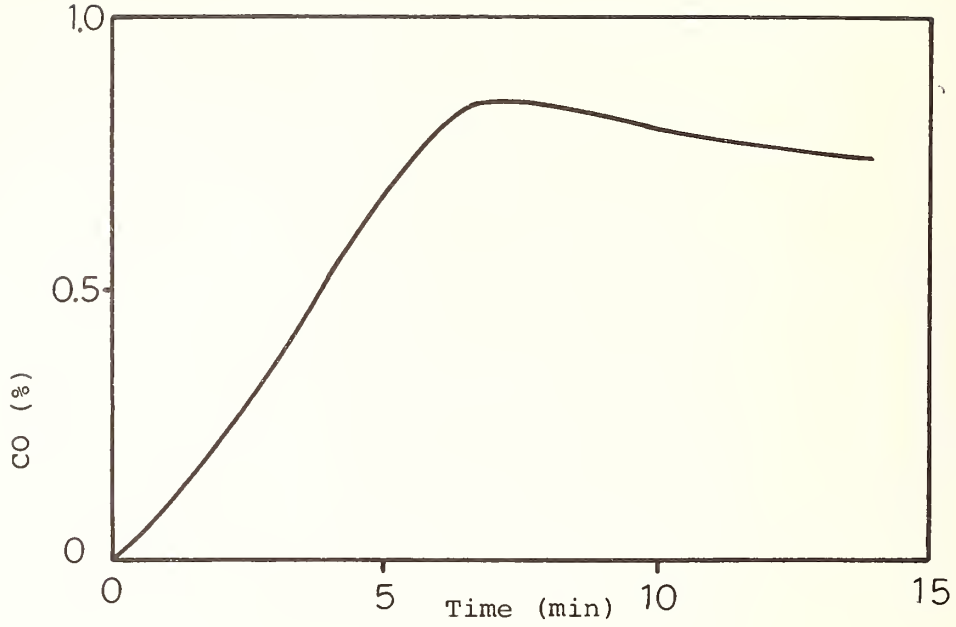


Fig. 3.2 Increase of CO Concentration (%) in Chamber

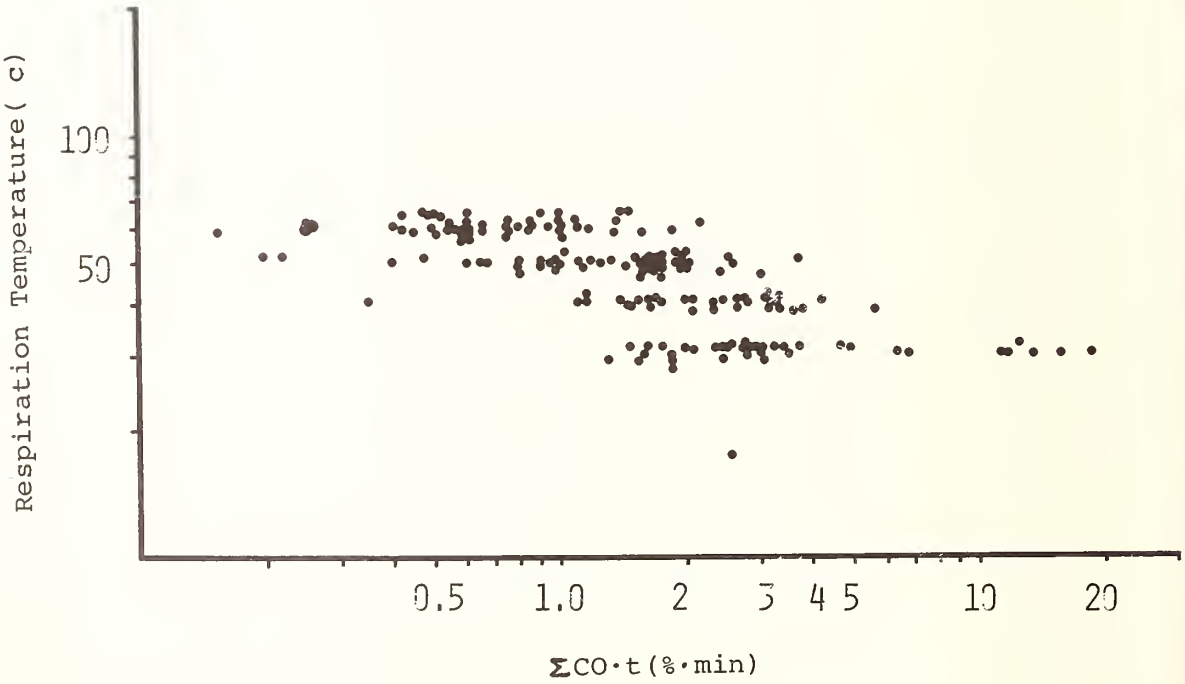


Fig. 3.3 Influence of the Temperature on ΣCO·t

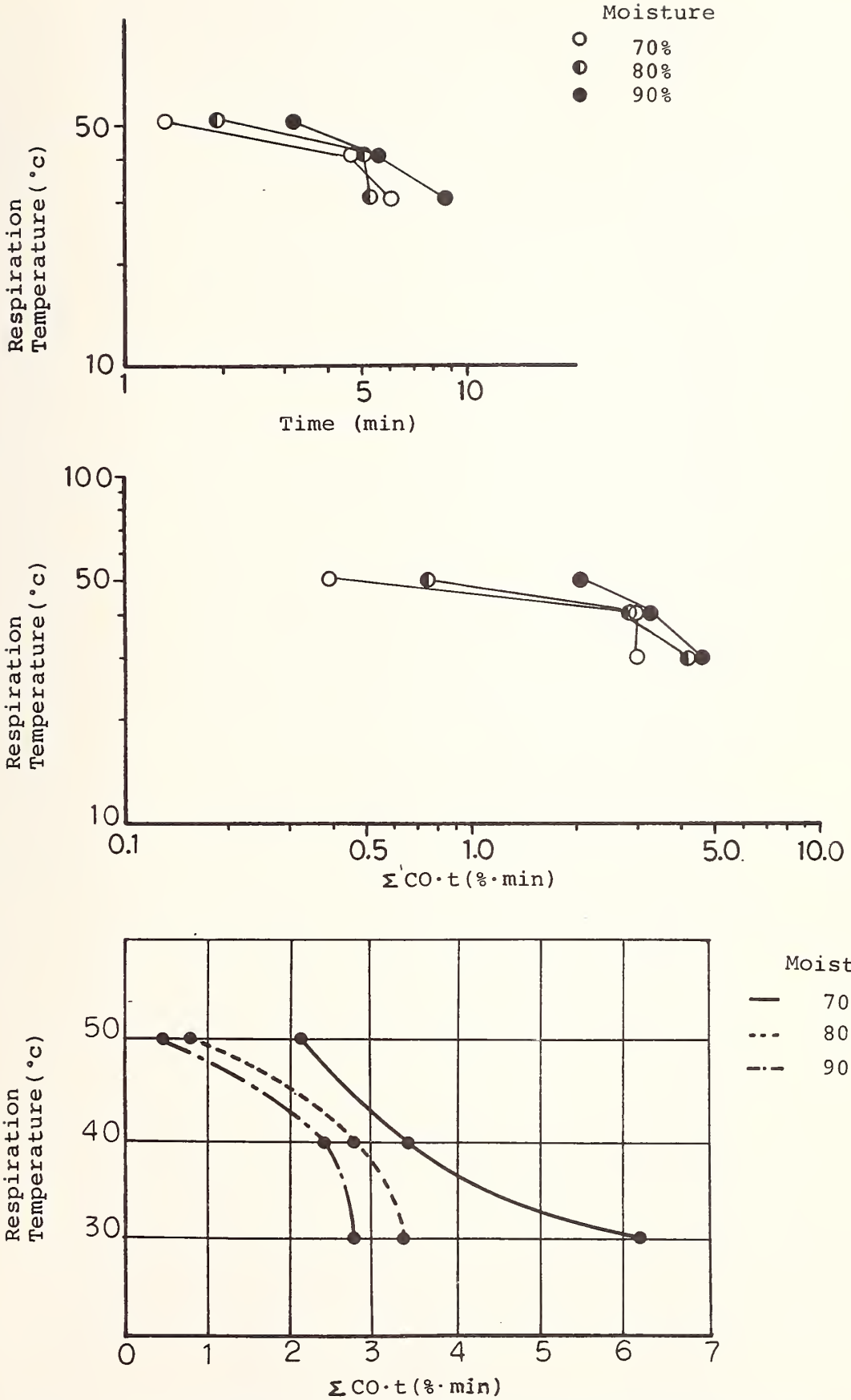


Fig. 3.4 Influence of Temperature and Moisture on ΣCO·t

Table 1 Example of Test Result

Material	θ (°C)	O_2 (%)	Wo (g)	ΔW (g)	C max	DM (mg/m)	CO (%)	O_2' (%)	t_1 (min)	t_2 (min)	ΣCOt_1 (%·min)	ΣCOt_2 (%·min)	α_A	α_B	MT $\times 10^{-4}$	MT' $\times 10^{-4}$
Japanese Cedar	400	21	31.4	31.4	4.83	787	0.12	19.67	20.93	22.0	2.15	2.34	0.23	1.11	2.92	14.10
"	600	21	28.9	28.3	6.75	750	0.18	19.1	15.36	17.18	3.28	4.17	0.89	1.27	11.87	16.93
"	400	15	30.1	24.7	2.97	270	0.19	19.4	27.5	28.46	4.3	5.2	0.9	1.21	33.33	44.81
"	600	15	27.5	25.9	5.87	597	0.43	19.4	15.12	17.44	3.38	4.98	1.6	1.47	26.80	24.62
"	500	21	31.6	30.8	4.63	560	0.13	19.7	17.60	20.58	1.59	2.09	0.5	1.31	8.93	23.39
Treated Plywood	400	21	34.2	24.8	1.59	190	-	-	L	L	L	L	L	L	-	-
"	600	21	34.3	33.5	4.40	337	0.15	20.3	15.31	21.67	3.12	4.35	1.23	1.36	36.50	40.36
"	400	15	34.0	18.9	1.92	273	-	-	L	L	L	L	L	-	-	-
"	600	15	33.7	29.4	4.10	293	0.16	20.0	16.03	17.31	2.75	3.43	0.68	1.25	23.21	42.66
Melamine	400	21	31.0	15.8	0.6	57	-	-	L	L	L	L	L	L	-	-
"	600	21	30.2	21.6	1.59	113	0.70	20.7	17.81	19.08	1.28	1.47	0.19	1.15	16.81	101.17
"	400	15	30.3	14.5	0.95	93	-	-	L	L	L	L	L	L	-	-
"	600	15	30.6	21.5	1.70	137	0.67	20.7	19.49	20.84	1.16	1.34	0.22	1.19	16.05	86.86

Continued to the next page

Material	θ (°C)	O_2 (%)	Wo (g)	ΔW (g)	C max	DM mg/m³	CO (%)	O_2' (%)	t_1 (min)	t_2 (min)	ΣCOt_1 (%·min)	ΣCOt_2 (%·min)	α_A	α_B	MT $\times 10^{-4}$	MT' $\times 10^{-4}$
P.M.M.A.	400	21	30.6	24.5	1.09	553	0.20	20.5	29.23	33.25	4.03	L	-	L	—	-
"	600	21	27.9	27.9	8.47	617	0.30	20.1	10.17	13.27	2.46	4.3	1.84	1.75	29.82	28.36
"	400	15	29.5	20.7	3.49	550	-	-	L	L	L	L	L	L	-	-
"	600	15	25.8	25.8	5.67	423	0.27	20.5	10.96	13.00	3.12	4.13	1.01	1.32	23.88	31.21
Acrylo-nirile	400	21	31.13	18.7	1.21	153	0.01	20.8	9.04	10.46	0.01	0.02	0.01	1.65	0.45	107.8
"	600	21	31.0	31.0	4.60	890	0.03	20.8	5.00	5.02	0.15	0.20	0.06	1.38	0.62	15.5
"	400	15	15.33	6.3	2.11	353	0.01	21.0	9.92	11.07	0.02	0.03	0.01	1.14	0.08	32.3
"	600	15	31.5	28.2	2.92	340	0.02	20.8	5.67	5.88	0.09	0.12	0.04	1.43	1.09	42.1

θ : Furnace temperature
O_2 : O_2(%) in the supplied air (premary air)
Wo: Weight of the sample (g)
ΔW: Weight loss (g)
DM: Mass smoke density in the test duration (mg/m³)
CO: Maximum concentration of the respirated air (%)
O_2': Minimum concentration of the respirated air (%)
t_1 : Time to death by observation with smoke (min)
t_2 : Time to death by observation without smoke (min)
α : Influence factor
MT: Toxic effect of smoke particles per unit weight (mg/m³)

Table 2 Influence of Temperature on the Σ COt

Temperature (°C)	Σ COt (%·min)				Ave.
	CO(%) 0.4	0.5	0.6	0.8	
30	6.60	1.92	-	2.94	3.82
40	2.82	-	-	2.17	2.50
50	1.53	-	1.31	1.42	1.42
60	0.70	0.77	0.71	0.79	0.74

Table 3 Influence of Temperature and Moisture on the Σ COt

Temperature (°C)		Moisture (%)	Σ CO t (%·min)		
			70	80	90
30	$\bar{x}$		6.23	3.38	2.67
	σ		3.13	1.56	0.89
40	$\bar{x}$		3.33	1.82	2.60
	σ		1.14	0.93	0.76
50	$\bar{x}$		2.13	0.75	0.39
	σ		0.47	0.26	0.14

BIOLOGICAL TESTING IN FIRE TOXICOLOGY

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I. INTRODUCTION

Two papers in the Proceedings of the Second Meeting of this Panel, held in Tokyo in 1976, deal extensively with the toxicology of fire (1,2), and we shall attempt to avoid a third presentation of the same type of material. However, the authors have been engaged in inhalation toxicology research for the past 7 years, and we thought this Panel might be interested in some of our experiences, a few of our findings, and in particular, our impressions of the current state-of-the-art and future directions for research in this area.

We entered the field of inhalation toxicology as a direct result of the Aviation Toxicology Laboratory's involvement in the forensic toxicology of aircraft accident investigation, which began in 1967. From the beginning of the program we had routinely looked for carboxyhemoglobin in the blood of accident victims because of its special implications for pilots at altitude and because of the clues it might give us as to the behavior and history of persons who fell victim to postcrash fires.

In 1970, following a spectacular accident at Anchorage, Alaska (3), we began to look for cyanide in addition to carbon monoxide in the blood of fire victims. We have described our findings in the victims of that accident elsewhere (4). Suffice it to say that we found both carboxyhemoglobin and cyanide at a variety of concentrations. On the basis of a long history of both experimental and accidental human exposures to CO, we might have speculated about the significance

of the observed carboxyhemoglobin concentrations, had they occurred alone. We knew much less about cyanide and could not interpret the meaning of combinations of the two. We therefore instituted a study of animal responses to CO and HCN, separately and combined, at a variety of concentrations.

II. STUDIES ON CO AND HCN

We began by exposing albino rats (Sprague-Dawley strain) to the approximate 5-minute LC_{50} concentrations of the two gases as determined in an earlier study (5) conducted cooperatively by FAA and the USAF at Wright-Patterson Air Force Base, Ohio. We decided that we must look first for the occurrence of psychomotor failure, or physical incapacitation, as our principal end-point, because this would signal the end of effective efforts toward unassisted escape from a fire environment in which the two gases were predominant. For this purpose we employed a motor-driven, rotating drum with mesh rim, in which the animal must walk or cling to avoid tumbling. This afforded a very precise, objective indication of incapacitation requiring no preexposure training or conditioning of the animals, and which was readily apparent to an untrained observer.

Because speed is the key to escape and survival in the case of rapidly developing fires, we decided not to count the numbers of animals incapacitated or killed in an arbitrary time period, but to measure the interval between the beginning of exposure and the occurrence of incapacitation (t_i) or death (t_d) for each of the individual animals, usually four in a group experiment. These initial

studies have been summarized elsewhere (6) and we shall mention only a few salient findings.

1. A concentration of CO (13,500 ppm) that killed 12 animals in a mean time of 5.8 min (SD $\pm$ 1.2) caused incapacitation in less than half that time, 2.4 (SD $\pm$ 0.3) min.
2. Rats died in a mean time of 12.9 ($\pm$ 2) min in an atmosphere of 450 ppm HCN, but were incapacitated in 4.1 ($\pm$ 0.7) min.
3. CO and HCN exerted definitely additive effects when combined at these concentrations; t_d 3.7, t_i 2.0.

Thus, the precision and value of measuring time to the occurrence of a toxicological end-point became apparent.

Unquestionably, however, the most important contribution to come from these studies was the discovery that by use of a formula based on the fact that pulmonary gas exchange is weight related, one can calculate the t_i's and t_d's for a human in the same environments with great accuracy (7). This capability was derived from an experimentally verified hypothesis that the measured biological response to those toxic gases whose mechanism of action was a stoichiometric reaction with critical tissue components would be directly proportional to total body mass--for any mammalian species. The most important of the combustion products that react in this fashion are CO, HCN, and H_2S.

When we began these CO-HCN experiments, our intentions were to quantitate the dose-response relationships that resulted from exposures to known atmospheric concentrations and to measure the resultant blood (and other tissue) concentrations of CO and HCN that were present at the time of the two biological end-points. We encountered many difficulties at all stages of our efforts to measure HCN.

Significant and variable losses of HCN occurred at every step in our early attempts to collect and transfer samples of the chamber atmosphere for analysis. Solution of these problems still left us with the need to measure blood HCN concentrations. The spectrophotometric, wet chemical procedure that was found acceptable, although inconveniently time consuming, for analysis of HCN in air proved to be totally inadequate for blood measurements. It lacked both the required sensitivity and specificity that we felt was necessary for our forensic work. Other analytical procedures that were investigated and found similarly unsatisfactory were selective-ion electrodes and fluorometric techniques.

We solved the problems of sensitivity and specificity, as well as that of prolonged assay time, by developing a gas chromatographic technique that for the first time utilized the alkali flame ionization detector (thermionic detector) for cyanide measurement. With this detector cyanide can be quantitated in amounts as small as a few picomoles. This system has been described in an earlier publication (6).

III. ASSAY OF TOXIC PRODUCTS BY DIRECT ANIMAL EXPOSURE AT CAMI

At this point in our investigations we were requested by our agency to attempt to assess the relative potential for toxicity of

a large number of aircraft interior materials by exposing animals to their thermal degradation (pyrolysis) products. The studies were to proceed in parallel with a program at the National Aviation Facilities Experimental Center (NAFEC) at Atlantic City, in which the same materials were to be pyrolyzed and the evolved mixtures analyzed chemically for nine of the more important constituents to be expected in such mixtures from the elemental makeup of the polymers involved.

Within the limitations imposed by a single stipulation, that the conditions of thermal degradation be very similar to those employed at NAFEC to permit a later attempt at chemical-biological correlations, we were free to design our own system. When we began to look about for features that we might incorporate--that were logical, realistic, and practical from physical, chemical, and toxicological points of view--we were dismayed at the lack of uniformity in the state-of-the-art of materials evaluation.

More recently, some principles and guidelines have begun to emerge, as the result of group efforts to introduce a degree of uniformity into materials-toxicity testing and to increase the comparability and utility of results from the several laboratories engaged in this activity. The deliberations of one such group have resulted in a report of great value (8). That report was, of course, not available to us when we began our planning, but it confirms our impressions at that time. The Committee document describes briefly the technology employed by 21 laboratories (including our own), presumably to accomplish the same purpose, but producing widely varied data.

The system that we developed has been described in great detail, as have the results of our tests of 75 aircraft interior materials in which the system was first employed (7). The results of the chemical study conducted at NAFEC have also been published (9).

With recent modifications, we believe the system being used at CAMI incorporates most--but not all--of the principles of biological assessment of the toxicity of pyrolysis/combustion products as set forth by the NRC/NAS Committee (8).

IV. IMPRESSIONS

A. Biological Assay. One frequently encounters an attitude, expressed or implied, among physicists, chemists, and engineers, that bioassay is an empirical, imprecise, quasi-scientific process. Those of us with extensive biomedical experience regard it differently. We can recall the days when the majority of our most potent therapeutic agents were standardized in this way. We realize better than most the reliance that medicine and industry must place on animal screening in order to establish the relative toxicity of pesticides, industrial chemicals, and drugs.

In our extensive testing of aircraft interior materials, we deliberately "loaded" the process to our disadvantage. We began with material number one and continued through the series, observing three animals per experiment. We then repeated the series, in the same order, a second and a third time. Thus, the individual tests of the same material were separated by at least a month--sometimes longer. We found that in the case of more than 60 percent of the

materials tested the variation of the t_i's and t_d's of the individual animals in a single experiment from their mean and from the mean of the nine involved in the cumulative tests was less than 5 percent. This is a goal that biochemists frequently must strive for in the analysis of chemical entities in biological specimens. The materials that did not yield such precision were, in general, composites such as laid-up panels or mixtures of nonuniform composition that offered sampling difficulties.

We were convinced of two things by these findings: first, that the bioassay process is capable of great precision; second, that the thermolytic process proceeded very uniformly in our system. It seems clear to us that if animals are "shown" the same mixture of toxic products on successive occasions, their answer will be the same. If it is not, the failure is likely to be one of physics and chemistry, not biology.

B. The Pyrolysis-Combustion Process. The literature of fire toxicology reveals wide variety in both the processes of thermal decomposition and the exposure of animals to the resulting products. Perhaps the greatest variability is in the first of these.

It would be impossible at this time to mention even a representative sampling of the methods for pyrolysis or combustion that have come into being over the years. Among the variables that have been combined in almost infinite variety are: mode of ignition or initial heat transfer; the temperature at which the decomposition is allowed--or forced--to proceed; isothermal or programed temperatures; the absence, or presence and relative abundance, of oxygen in the

environment of the specimen; static or dynamic systems; presence or absence of flame; sample size; and others.

It has been clear from the earliest animal exposures, and from both early and recent efforts at chemical analysis, that even minor variations in the manner in which these variables are combined can alter the composition of the product mix. In all probability the toxicity will vary also, but not necessarily in a predictable direction or degree. We know too little about the toxic properties of many of the individual gases that can be present in pyrolysis-combustion mixtures, and still less about their composite toxicity when combined. One usually expects to see an increase or decrease in toxicity as the composition of a gas mixture is altered; by fortuitous circumstance, however, depending on the interactions of components, appreciable changes could leave apparent toxicity relatively unchanged.

If it is true that the apparent toxic hazard of a polymer in a fire situation as revealed by animal tests depends primarily on the conditions of burning, then those familiar with fire dynamics must tell us what is and what is not realistic.

C. The Exposure System. The primary consideration in assessing the hazards of a burning material by animal assay is that the animal be exposed to the unchanged toxic mixture. We cannot possibly discuss all of the complications introduced by this requirement, and the NRC/NAS Committee (8) has dealt with them adequately. It has pointed out that if the burn is conducted outside the exposure chamber, the conduction pathway for the combustion mixture should be short. We believe that with the exception of HF, our system accomplishes

an essentially quantitative transfer from the tube furnace, but we are ready to admit that this is the most difficult of all of the desiderata to satisfy, regardless of the size, configuration, or design of an exposure system, when one is dealing with gases that adsorb on surfaces and/or are infinitely water soluble.

Recently, a somewhat different combustion-exposure system has been designed (10) that purports to minimize this difficulty. It does appear to present other problems, however, and only time and further testing will reveal whether it constitutes an improvement over other systems now in use. We refer specifically to the fact that the burn is conducted in a rather tall and narrow quartz receptacle, and oxygenation would appear to be precarious in such a furnace. The exposure chamber is also rather large, and mixing of the gases and their distribution to the animals is to be accomplished by convection only. In our experience, uniform composition of the gas mixture in a chamber of similar size is seldom accomplished early in the burn, when it should be of great importance, unless convection is supplemented.

Evidence of nonuniform distribution exists, in the form of high temperature gradients between furnace and other points in the chamber. We also question the practice of placing as many as seven large rats in a single cage. Rats huddle together and accentuate the problems of heat dissipation and adequate pulmonary ventilation. Temperatures in excess of 40° C near the animals have been reported at high fuel loadings ("concentration") at the upper end of multipoint dose-response curves that are employed to reveal differences among materials.

Translated into its equivalent of 104° F, this is a temperature that might compromise toxicological studies even in man, with his superior heat-dissipating capability.

D. Species, Exposure, and Objective Criteria of Toxicity. These three aspects of toxicity evaluation must be considered together, because they are interrelated.

The choice of an animal species depends on the special interests of the investigator and the types of observations he chooses to make. If he wishes to observe large numbers of animals en masse, with death as a single end-point, he might select mice. If he wants a highly active animal, or one that is especially sensitive to a specific property of a gas mixture such as irritant action on the pulmonary tract, he would probably choose the mouse. If, on the other hand, he can utilize fewer animals in a single test run; if his technique involves preexposure training or conditioning; if he intends to make behavioral or neurophysiological observations on individuals by means of implanted instrumentation or otherwise; or if he intends to make any considerable variety of biochemical measurements, he would almost certainly choose rats.

There has been much discussion of the use of other species, including primates. The days when the latter could be obtained in the numbers required for statistically valid studies in fire research are probably long gone, and it is an academic exercise to speculate about their possible superiority as test animals. In fact, when we are dealing primarily with irritants or systemic toxicants with essentially identical actions in all higher species, their presumed advantages may be more imaginary than real.

Kimmerle (11) has been a strong supporter of head-only exposure. It is true that a "purist" approach suggests that inhalation toxicants should be acquired by inhalation only. Alarie et al. (12) favor head-only exposure because it allows convenient observation of a biological response of special interest, namely, inhibition of respiratory rate by irritant gases.

We believe, perhaps naively, that if humans are almost certainly to be exposed in toto in a fire situation, our animals should be also when materials are tested. The cyanide ion, for instance, is readily absorbed through the skin, and there are other sensitive areas of the animal or human body in addition to the head and pulmonary tract. The stimulating, agitating effects of itching, burning skin areas should be considered also.

What signs of toxic action should be observed? Opinions vary. Death is certainly objective enough when either respiratory or cardiac arrest is positively established--and death has been the traditional toxicological observation.

There is a growing consensus, however, that the occurrence of functional impairment prior to death may be the more important determinant of potential for escape and eventual survival. Impairment may be detected in a variety of ways. The primary requirements are that the indication should be sharp and objective, not requiring arbitrary judgment on the part of an observer, and it should be reproducible.

We cannot discuss all of the various indicators that have been utilized. We have elected to use the rotating drum or cage as previously

described whenever circumstances permit because of its simplicity and its increased control of respiration rate.

Many of the devices and techniques employed must be testing approximately the same mode of neuromuscular impairment, even though the relative areas of cerebral involvement may differ, and it is unlikely that they would indicate a significantly differing order of apparent toxicity for a series of materials tested under otherwise identical conditions. The depression of respiration to 50 percent of its normal rate (12), however, may well be indicating a different type of phenomenon and probably belongs in a class by itself.

It is our opinion that a first-tier screen for materials toxicity might well stop with the observations of incapacitation and/or death, however these are accomplished. Certainly it is ultimately of importance to know the specific cause or causes of incapacitation or death. Certainly, there are many facets of basic toxicology that remain obscure. Therefore, each research team should perform as much chemical monitoring of gas mixtures, as much biochemistry on survivors or the dead, and as much pathology as their capabilities permit. The polymer manufacturer and the end user of such materials are more likely to want to know, from as simple a test as possible: Is product A more or less hazardous than product B in a similar and realistic fire simulation?

E. Towards Uniformity. Within the past few years, three different groups have been attempting to develop a standard screening method for rating the relative hazard of polymers in fires. The deliberations of one group are complete and their report has been issued (8).

This group did not describe any single test method in specific detail, but issued a set of principles that should be incorporated in the design and operation of a test facility. The approach was that of toxicologists who recognize the many compromises that must be made between the science of toxicology and the desires of engineers and others who are reluctant to realize that animals cannot simply be placed in the proximity of a roaring fire.

The toxicologist can live with these principles, and if they are observed, more comparable and more useful data should begin to emerge from materials testing.

The approach of the American Society for Testing and Materials and the National Bureau of Standards has been different. Each has assumed the burden of describing and prescribing a single, rigidly defined test method that could potentially become the toxicological and industrial standard. Industry might approve, but toxicology would suffer and innovation would be stifled.

ASTM has thus far reached no conclusions. It is rumored that NBS is nearing the issuance of a recommended technique. It has also been proposed that the "official" method, once described, be subjected to a "round robin" or referee testing program, presumably to establish its validity.

Many of us have been urging for years that such a referee program be instituted under the auspices of an agency such as NBS, in an attempt to identify the real reasons for the divergent results issuing from the principal laboratories engaged in fire research. It should be recognized by those in charge of any such program, as it is by

the majority of scientists, that referee testing of a single technique can only establish its precision, not its inherent accuracy.

Finally, as toxicologists convinced of the value of bioassay as an analytical tool, we would regret very much the prescription of a technique that would make the process seem mysterious, complicated, or more difficult than it really is--or needs to be to answer satisfactorily the specific question asked of it.

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Birky: I had a question about the PVC data and maybe you partly answered it. I noted the toxicity was very low. I wonder if that is because of the weight or is it because the animals are not incapacitated at that level but die later?

Yusa: I would say I have stated in my papers that the toxicity is low for PVC.

Birky: Well this table had a fairly high concentration before the animal was incapacitated.

Yusa: For one thing we did not use pure PVC. I do not know any other factors that might have contributed to that result.

Levine: Mr. Yusa chose dosages of the materials that cause incapacitation in a relatively short time, one and a half to six minutes. I wonder if you will tell us your philosophy of choosing these dosages.

Yusa: From the experiment we found out that if you don't use enough of the materials, we could not incapacitate the animals.

Levine: So suppose you decided to have an average incapacitation time of 20 minutes instead of two or three minutes?

Yusa: For instance if I take ten or twenty minutes, a longer period of time than I have used for experiments means we would have to change the evaluation methods perhaps.

Einhorn: Two comments briefly, one with regard to the question just asked. In Salt Lake City last year we had three fires involving PVC. In all of these fires we had a total of fifty firemen in the hospital. Not one of the fires had more than one pound of wire insulation burned, forty-five grams or less, and essentially in all cases the symptoms as reported by Yashi Washington was a drop in blood Ph, disorder, dizziness and a very low carboxyhemoglobin. Because there was little smoke the firemen went in without gas masks and your time of exposure was just a few seconds. Again let us consider in this case a polyurethane cushion. Let's consider that cushion on Mr. Bates' aircrafts, 600 m.p.h. 30,000 feet, the same cushion in my living room, a cushion in the subway, or in an airport or in a bus in a tunnel in Washington, all with the same ignition source. We have the same material burning and we have four different sets of conditions to assess. At some time we are going to have to learn to put a weighting factor on that phase as well. I don't think we know how to do that yet either.

Yusa: For instance the prognosis for the PVC, we should really observe the experimental animals one month later or two months later on. Perhaps it might be important to have that type of evaluation in order to see the prognosis of the exposure to the PVC.

Einhorn: We have looked at animals for six months after exposure and we have also looked at humans. All of the firemen in our case were released from the hospital in two days with no permanent effects that we could see. In the case of the animals, the concentration is high enough they loose the epithelium on the tracheal bronchial tree in about three days. When that comes back depending on dose we can see the development of a goblet cell hyperplasia which is abnormal cells. In the case of wood smoke we have seen the squamous metaplasia where it is lined with this type of material. That is the same as one seen in tobacco smokers. When the animals survived 30 minutes exposure to a vinyl which has incapacitated them within that period, we have never had a delayed death.

Watanabe: Thank you very much for your active discussion. If I was not the chairman I would have joined with you in discussing various aspects. This will not conclude the toxicity session. We will continue tomorrow at the Applied Physics Laboratory. Thank you so much for your kind participation.

TOXICITY SESSION HELD AT THE APPLIED PHYSICS LABORATORY,
JOHNS HOPKINS UNIVERSITY

US/Japan Panel for Fire Research

Berl Presentation

Berl: The Johns Hopkins University is to Baltimore what Washeda University is to Tokyo. Both are about one hundred years old. Both are institutions of higher learning. Since its founding in 1876, The Johns Hopkins University has pioneered in education of scientists and engineers at the graduate level. Its Medical School and Hospital rank among the best in the world.

In the early stages of the last war, The Applied Physics Laboratory was founded as a branch of this University. It is now more than a third of a century old and is flourishing.

During these thirty-five years studies have been done on naval topics above and below the ocean; scores of satellites were conceived, developed, built and flown, devoted to navigation, to the shape of the earth and to the understanding of the solar system. We are deeply engrossed in medical engineering problems, heart pace makers, pain killing and prosthetic devices. We are concerned with the siting of power plants in the State of Maryland. We have a large program on extracting power from the small temperature difference in the equatorial oceans.

We also have been concerned with fire research since 1971. Since this Laboratory of 2500 people is filled with chemists, physicists, mathmaticians, systems analysts, and with a Medical Institution nearby, it was a natural step to look at fires as an enemy that must be kept in check or, when loose, subdued quickly.

We were pleased in 1971 when the National Science Foundation made it possible for several institutions to carry out research on fires and to translate these findings into useful outputs.

We have concentrated on four areas in our activities. We have taken our University connections seriously in encouraging the teaching of the Fire Sciences throughout the United States and also in providing information resources of use to fire researchers and practitioners, in particular, making the Russian and Japanese information more widely available in this country than it has been in the past. Secondly, we have pursued combustion studies for many years, particularly ignition and extinction, where chemical parameters play a crucial role. Lately this work has been extended to the ignition of wires and cables. We have worked with fire departments in Washington and in Baltimore to provide command and control devices that would support the commander in his decision making on the fire ground. We are anxious to continue looking at fire department operations and supplying them with tools, and also to protect them against toxic gases. Finally, we have been deeply involved in the analyses of the causes and consequences of fires that lead to human death and are just beginning to extend this analysis to serious injuries as well, and to the potential benefits of the performance of fire detectors. We have been supported in this enterprise by the National Fire Prevention and Control Administration and by the Center for Fire Research of the National Bureau of Standards.

Hunter Presentation

Hunter: I would like to introduce you to three of the problems that are currently under study by the combustion section of the APL Fire Group. The first area is the measurement of heat transfer in fires. Heat is transferred by forced convection and by radiation, the forced convection being important at small scale and radiation at large scale. Measurements of heat transfer typically measure the sum of the two. We are interested in measuring the forced convection without any interference from the radiation. Conventionally, one uses a slug calorimeter of cylindrical shape immersed in the flame. Its rate of temperature rise is a measure of how much heat is being transferred to it. It responds to both kinds of heat: the flux is the sum of the radiated part, the convected part and reradiation.

The new method is very simple in concept. At a very small radius, the convective part of the heat transfer is enhanced because the heat transfer coefficient increases. The radiative flux does not change. By working at small radius, we can emphasize the convective part.

We checked out the method for premixed ethane-oxygen flames, and found that one can extract the forced convective coefficient in the presence of up to 5 watts per square centimeter of radiation. Our calorimeter is a 10-mil thermocouple acting as a calorimeter.

A second problem deals with cable tray fires. An experimental program on fires in trays of electrical cables is being undertaken by Sandia Laboratories and by Underwriters' Laboratories. We are developing theories which support that work, correlating it and explaining qualitatively what is happening.

Flames are propagated by fire balls fueled by flammable gases. There are two sources of this flammable gas. One is excess pyrolyzates from the first tray. When plastics burn, the combustion is seldom complete. Unburnt gas can flow around, accumulate and even flow right through the second tray. Another source of flammable gas is from out gassing of the second tray which is heated by the fire from below.

Another phenomenon is vertical propagation of a vertical tray of cables. If the cables are tied down securely, then the propagation is much like that over a solid wall of plastic. If the cables are not tied down, then during combustion they can warp or bow and air channels develop among the trays and one gets chimneys and ducts. This sets the pace for the propagation. The propagation is more rapid up these channels.

The remaining problem I would like to discuss is polymer combustion. Flames on a stationary polymer sample spread over the sample and move with time. This is a difficult system to measure. By moving the sample in the appropriate way one can arrange that the flame is stationary in laboratory coordinates. We have done this by coating the polymer on a wire and pulling the wire in the direction of its axis through the wake of a premixed flame. The wake provides everything for polymer ignition: hot gas to heat it up, excess oxygen to support the combustion and free radicals to initiate the combustion. This polymer flame is stationary in laboratory coordinates. A particle of polymer, as it moves along the wire, increases in temperature until it reaches the gasification point, which is the lowest temperature at which gas can evolve and therefore, flame can be supported.

There is another way to get stationary polymer combustion, the so-called opposed-flow diffusion flame technique. The polymer is moving one way and the oxygen is flowing the opposite way. The polymer is advanced at the rate it is consumed. The flame is also stationary in laboratory coordinates, but for a charring polymer, the char has to be consumed before the polymer can be advanced and the observations are those for carbon combustion.

In our case we have worked with charring polymers. As the coated wire is moved, the char is removed from the flame. We have been working with polyvinylchloride and have sampled the polymer flame by classical techniques of quartz microprobes and mass spectrometry. We have been interested in finding out what flammable gases evolve from the surface under combustion conditions. At one atmosphere pressure the polymer flame is so close to the surface of the polymer that we cannot get inside it with our probe and can only see the products of combustion. Another problem is the intense heat and sooty nature of this flame.

When oxygen is absent we find that benzene evolves at around 280°C. This is the same temperature at which ignition occurs when oxygen is present, marked by a temperature rise in the gas phase and a sudden drop in the oxygen level. At low pressure, the polymer flame is expanded. We can probe inside it and we confirmed that benzene does evolve under combustion conditions.

Kuvshinoff Presentation

Kuvshinoff: Since the beginning of our Fire Problems Program, fire information has been an important part of our work. We became concerned at an early date that fire safety, fire protection and suppression were problems that reached far beyond the Fire Service. Specialists from every science and technology had a role to play in their solutions. We soon discovered, however, that the specialist who could contribute to the solution of various fire

problems had no convenient means for understanding specialized fire terminology. Also, they had no medium for learning about each others' activities. To help resolve these difficulties, we undertook two projects. One of these is a Dictionary of Fire Science terminology and the other is a Fire Technology Abstracts Journal.

The Dictionary, published in 1977, contains about 10,000 words drawn from a wide variety of disciplines. Terms have been taken largely from fire practice but also from building construction, safety, education, physics, chemistry, medicine, toxicology, transportation and many other areas of technology.

The definitions are presented in a very simple fashion. Our purpose was to help educate technical people to understand papers written on subjects outside their own immediate specialties. Work on this Dictionary started in 1969. Since its publication in 1977, about 1,000 new words have been selected and many new definitions have been written. We hope to republish this as an improved and enlarged edition within the next three or four years.

While working on this Dictionary, we were also developing a plan for publishing a literature announcement journal, an abstract journal which would be an effective means for gathering fire related information and providing it conveniently and economically to those who could use it. One of our early ideas was to spread the cost among interested appropriate agencies in several countries who would contribute literature citations to a central point for incorporation into a regularly published fire abstract journal.

The only more or less extensive compilation of fire information in English was a publication prepared in the United Kingdom called "References to Literature on Fire". The scope of this announcement service, however, is restricted to building construction. Also in Great Britain, the Safety in Mines Research Establishment produces a journal "Safety in Mines Abstracts," but this is restricted narrowly to mines. In 1971, the Soviet Union began publishing a journal which is called "Fire Protection Abstracts."

With the advent of the National Fire Prevention and Control Administration, we proposed publication of Fire Technology Abstracts. The topical coverage of the journal was to be broad, encompassing thirteen major areas including physical and chemical aspects of fires, engineering and operational responses to fires, fire protection, fire service organization, psychological and medical problems, and social and economic matters related to fire prevention and safety. To insure quality and comprehensive coverage, we have organized an International Advisory Board that reviews our work. The Japanese representative of this Board is Mr. T. Wakamatsu of the Building Research Institute. Other boardmembers are representatives from Great Britain, Germany, U.S., Canada, Sweden and the Netherlands. This journal is now in its second year of publication, is issued six times a year, and contains author, subject, source and report number indexes. It cites books, journal articles, patents, meeting papers, and reports. 6% of our citations are to the Japanese literature. Of about 2400 abstracts included in Volume 1, there were 140 abstracts that came from 41 Japanese journals. Eleven Japanese patents were also cited.

We have noted the excellent Japanese literature dealing with railway fire protection, earthquake fire disasters, safety and also integrated fire detection alarms and fire protection systems. We no not have Japanese language capability. Therefore we rely on our agreement to share resources with the Soviet Union's "Fire Abstract Journal". Thus we have a fairly good coverage of the Japanese literature but we have no way of obtaining reports on conference papers. We would like very much to correct this deficiency.

Halpin Presentation

Halpin: In our fire casualty study, we are interested in trying to understand why people are dying when they have been exposed to the toxic atmosphere of the fire. People will be affected by the toxic products. They can become disoriented; they have a loss of judgment. Alcohol will cause some secondary problems as will heart disease. At APL we are coordinating the program. Post mortems, autopsies and pathological analyses done by the Maryland State Medical Examiner and at the Applied Physics Laboratory, and field investigation complete our understanding of the total problem. APL sends investigators to the site to gain an understanding of what has happened. Samples are taken to determine blood alcohol levels, blood CO levels, drugs and blood cyanide.

We had a program where we were taking lung samples, outgassing them to determine which gases were trapped in the lung tissue and lung cells. We have been getting scrapings of the soot deposition within the trachea of the victims and analyzing those scrapings for heavy metals.

We have covered 398 fires during the period from September '71 - December '77. In those fires 530 people died. Smoking or mishandling of smoking materials is the biggest factor for the cause of fires. 45% of the victims died in fires in which smoking was the cause. A listing of the initial items that were ignited shows that 30% of the fires were started in the mattress and bedding. Alcohol was found to be a significant factor. 40% of the 530 fire victims had positive blood alcohol levels. We are also looking at blood cyanide levels. In a normal sample the range of blood cyanide is 0.25 mg/cc. We believe the upper range is primarily from smokers. In our own study we are using a value of .25 mg/cc for the upper part of normalcy.

Through December 1977 we have looked at 272 fire fatalities for cyanide. 31% were considered to have a normal level; 69% had above normal levels. 10% of the cases had 2.01 mg/cc and above which is a highly toxic level. We are finding a fair number of cases where we have a combination of blood carboxyhemoglobin below lethality and cyanide in a level below lethality.

We found cadmium, lead, manganese, copper and zinc. We do not believe the heavy metals enter into the acute problem of fire death, but they may add to the chronic problem.

Our next step is to get an understanding of what is happening with survivors. We have a joint program with the Shock-Trauma Unit of the Maryland Institute of Emergency Medicine which has a hyperbaric chamber, so that the people who are exposed to smoke can be taken to this smoke inhalation center and be treated. The smoke inhalation victims will be treated at approximately 3 at. oxygen. Blood will be drawn at the fire scene,upon admission and during the time that fire victims are in the chamber.

Smith Presentation

Smith: If you got the impression from my presentation that it is more philosophical than factual, you could be right. If you have a distinct sense of deja vue, having been here before, then indeed you have. It will be a repetition, in part, of work that we have reported over the past few years. We have been engaged in inhalation toxicology for about seven years. We came into it for reasons rather closely related to the human factors studies being pursued here. Our specific interest was in the aircraft fire, few of which occurred in flight. But postcrash fires occur frequently.

In our forensic program we have always measured carboxyhemoglobin saturation as a matter of particular interest in the field of aviation. In 1970, we added the measurement of cyanide to our battery of tests. This came about because of an interesting accident at Anchorage, Alaska. The circumstances of the crash were of interest, but even more so was the fact that the passengers were military personnel fit for active duty and could be assumed to be in a normal state of health. Therefore, we could interpret carbon monoxide findings with little question that we would not be dealing with anemic, weak, the elderly and, hopefully, the intoxicated. However, when we measured cyanide in these victims we could not interpret the meaning of the combination of the two gases. And this caused us to enter the field of inhalation toxicology. We decided that we must study these combinations in greater detail and this was our first effort.

I will not go into great detail on information which is present in the printed text, but I will indulge in some asides, some additional ideas which are not clearly expressed in print. After testing many devices for the determination or the detection of some degree of physical impairment short of death, we adopted the rotating cage. This system also had insertable cages which allowed us to look at animals in the more customary way, simply observing from zero time to time of death, or if we chose, we could use the system at multiple doses with death as the traditional customary endpoint.

There are honest differences of opinion about the use of time as the measured variable rather than the number of dead at a fixed period. Time is of importance in our specific research context, escape from a burning aircraft, or from a burning structure. It is perhaps more so in the case of aircraft fires, frequently fuel-fed and developing with almost explosive rapidity. We were able to show in these experiments that time to incapacitation was important because time to incapacitation is a brief fraction in most instances, of the time to death. We were also able to show that CO and HCN exert additive effects, if each is present at a potentially lethal level. When you combine these two gases, at low concentrations, there is less, if any, evidence of additive action.

The important contribution to come from these studies was the demonstration that if one takes into account the fact that respiratory gas exchange is weight-related as shown by Autian in studies during the fifties and early sixties, one can extrapolate the results obtained in one species at least with these gases, to other species, including man. One can calculate a dose based on respiratory or pulmonary gas exchange, and one can make estimates of the survival time of man in the same gas atmospheres.

The rotating cage as a device for indicating incapacitation is useful because of the precision with which it can be observed as an endpoint. We had every intention of going forward with a series of experiments which would involve blood and tissue measurements of the two gases in an effort to solve the very problem that Mr. Halpin mentioned earlier, the meaning of these lower concentrations in combination. One of our other accomplishments was the development of the alkali flame gas chromatograph method for cyanide measurement which we have used with considerable satisfaction and others have found of value elsewhere.

We were asked by the Federal Aviation Administration to look at the toxic potential of a variety of aircraft materials in fire situations. We began to look about for a system that we might use for this purpose. There were certain prescribed aspects that we must incorporate. The means of burning must be comparable to that employed in a parallel study at the the Federal Aviation facility's experimental center in which nine or more of the more important combustion gases were to be analysed chemically in the emissions from the same materrials. We did not chose the temperature at which the combustion was to be conducted - it was set to be 600°C. Above all, the system, whatever its final form, must be capable of mass production of data in a rather short time.

We were dismayed when we surveyed the literature that there were no guidelines for the design of a suitable apparatus. We believe that a move to develop such guidelines has been long overdue. We think the report of the Committee working under the auspices of the National Academy of Sciences has produced a document of considerable value, and what they say was what we were thinking when we had to devise our apparatus.

We chose to keep the volume of our system small. One produces less heat and one stays in a more linear area of the thermalitic process. We looked at systems which diluted the gases to solve the problems of accumulating CO_2 and oxygen depletion. We did not like them, because the gas mixture from a burning polymer is not uniform throughout the burning process even though with small samples at 600°C, 0.5 - 0.75 grams burn completely in two to three minutes.

If one sweeps away the early product, which may be hydrochloric acid, many hydrocarbon fragments such as methane, ethane, ethylene or chlorinated fragments, one is missing a part of the toxicological picture. Many of these low molecular weight hydrocarbon fragments are central nervous depressants. We feel that the dilution or flow-through system distorts toxicology and so we went to a recycling or recirculating system. Its total volume was only 12.6 liters. It was big enough to fit our rotating cages inside the small box and it was easy to clean.

Gas circulation and mixing were accomplished so efficiently that temperatures never rose above 35°, and in the majority of instances stayed below 32°C throughout an exposure period. We monitored oxygen and replenished it to maintain it at 21%. It may disturb engineers that we insist so strongly that our animals be protected from heat and from hypoxia in an exposure system. Admittedly these are a part of a fire situation but if you are looking at the toxicity of the thermalitic mixture one must avoid these complications.

We anticipated some problems. What does temperature and what does recirculation do to the composition of the gas mixture? For the two gases which interested us most this is what happens. At 400° hydrogen cyanide production is low from a standard polymer (34% acrilonitrile 66% butadiene). At 500° cyanide is appreciably higher. At 600° it peaks and you will note that recycling through the hot zone does relatively little to its concentration. People who insist on 850° as a burn temperature must reconcile themselves to an almost explosive production of HCN and a fairly rapid conversion in gas phase reactions.

The time for production of gases to their peak is relatively short. In six minutes you have a highly lethal concentration of cyanide. This is in contrast with the NBS chamber that produced a rather slow rise to peak concentration of the gases. Carbonmonoxide behaves quite similarly. At 600° it peaks, with very little further conversion to CO_2. These mixtures change with the passage of time because cyanide, with this plastic and under these conditions, comes off early. Carbonmonoxide rises a little more gradually and peaks later. All of these things are part of the compromises necessary in a biological assay system.

A word about biological assay as a method. When I first began to have contacts with engineers, polymer chemists, fire dynamacists, everybody said or implied that animals are poor analytical tools. I believe that animals are an admirable analytical tool. We have always depended on them.

When we atarted our testing of 75 selected aircraft interior materials, we exposed three animals to the products of material A, then three more to B and so on through the series of 75. We then returned to A. After an interval of the better part of, or perhaps more than, a month, we did the same test a third time. The variance of nine animals involved in three tests at these intervals was less than 5% for more than 60% of the materials assayed. To find this reproducibility in animal exposure has surprised us. It showed that if you present animals with the same mixture on successive occasions, they will give the same answer. If they don't, something has gone wrong with chemistry and physics.

We chose to keep the exposure volume small. When we burned progressively larger samples in the tube furnace and measured CO and HCN from 0.25 grams, one sees that the emission of hydrogen cyanide is fairly linear up to 0.75 grams. But when one goes a quarter of a gram further, one begins to lose linearity. This is even more apparent with carbon monoxide.

Dr. Alarie prefers to work with mice because his primary interest has been sensory or pulmonary irritants. They are admirable for that purpose. Rats are more phlegmatic. They respond less readily to irritants but we see the same effects with some irritant gases. Hydrogen chloride is classic. When we burn vinyl materials, rats may become incapacitated early, perhaps from respiratory effects, but they revive later. Perhaps they become semicomatose and the CO_2 forces them to breathe again. Most of them live throughout a thirty minute period in spite of early incapacitation, and we have had no delayed deaths. With fluoride we have rapid deaths. So the choice of an animal and the choice of an endpoint are options that must not be made precisely uniform.

When one looks at the avoidance condition reflex or if one chooses to go to the time and trouble of the lever press reward type reflex or if one wishes to use some other index, its limitations should be recognized. The flexion reflex and incapacitation in the rotating cage are probably measuring much the same thing. RD50 measurement and the respiratory depression are measuring something else. And these differences should be taken into account. As far as the selection of the endpoint is concerned, we prefer the rotating cage for its simplicity. But if you are working in obscuration, you may wish to have an automated record or whatever endpoint you choose, and the avoidance reflex may be the logical choice. The one thing that I would urge is that whatever system is recommended for use by most of the laboratories, the inherent difficulties of bioassay and burning materials should not be made any worse than they must be.

Yamamoto: I would appreciate very much if you could give us your thinking on how you arrived at the additive effect of CO and cyanide?

Smith: I pointed out that the additive effect does not become pronounced until each is present in near lethal concentrations. In a preliminary series of studies done in cooperation by the FAA and the USAF at Wright-Patterson Air Force Base, it was found that if one

looks at the toxicity of hydrogen cyanide, the five minute LC50 for cyanide is practically identical whether it is given alone or in combination with a concentration of CO designed to produce a blood saturation of 50%. There was thus no evidence of additivity under these circumstances. However, if you add the approximate five minute LC50 for the two gases, then you get addition. The way we interpret this, and there could be differences of opinion, if you use a nonlethal concentration of carbon monoxide the tissues are being adequately oxygenated. Under these circumstances if you add cyanide you are essentially looking at the toxicity of cyanide alone. However, if you add a potentially lethal concentration of the two, oxygen deprivation plus the inhibition of the cytochrome system at the periphery begin to become additive.

Yamamoto: The levels where the CO and the level of where the HCN start working, would they be the same or different?

Smith: The toxicity of the two gases is amazingly dissimilar, 15,000 parts per million of CO is approximately equivalent to 470 parts per million of HCN, so far as five minute lethality is concerned.

Yamamoto: Perhaps I have not made myself clear. In the case of CO this was combined with the hemoglobin and this reduced the transmission of oxygen by the blood. On the other hand, HCN would inhibit the tissue from using the oxygen. And therefore these two had different influences on the body.

Smith: Let us assume that we have an inhibition of the cytochrome system at the periphery by HCN which is just short of that required to cause tissue incapacitation or death. This would show up first in the nervous system as we see it in incapacitation or in death. Now cyanide is peculiar in that it causes respiratory arrest and we have seen the heart continue beating for five minutes. If you are just short of the tissue lethality level of cyanide and the tissue is getting an adequate amount of oxygen, the animal lives. Now if you superimpose upon this system a blood picture which has vastly reduced quantity or carrying capacity, then one of the consequences as blood goes further and further toward the periphery is a drop in oxygen tension. The tissue cannot live with a critical stage of utilizing ability and a short supply of oxygen and this is when we believe the superposition becomes apparent.

Einhorn: We have shown the effects of the concentrations of the two gases. We likewise found what Dr. Smith has said, not only for five minutes but for thirty minutes. If one measures the partial pressure of the oxygen in the arterial systems and the venous system, as we increase the concentration of cyanide to a level of about 120 parts per million, we find we cannot transport the oxygen, and it returns to the venous system for essentially the same PO2, which shows the effect of the cytochrome system. Now if you have CO first and you are complexing some of the hemoglobin so that you are approaching anoxia and then superimpose HCN, you will see a more additive effect.

We heard how reproducible biological experimentation is. The big problem is the combustion aspect. Our studies with the tube furnace showed exactly what Dr. Smith has shown. We use a single tube furnace and we use two tube furnaces in series. The flow rate and the residence time of the combustion products will change. A third aspect we must look at is the rate of heating. If we take a material and the rate is two degrees or ten degrees or forty degrees C per minute, there is an entirely different biological response as is the distribution of products when we expose animals. We really have to determine how we are going to thermally combust or degrade a sample. Once we define that, the biological measurements will be a lot easier.

Nakamura Presentation

Nakamura: My talk today is about the toxicity of CO, CO_2, HCl and HCN which are combustion gases generated when materials burn. We evaluated the toxicity of these gases by using mice. At the same time we also evaluated the toxicity of O_2 deficiency. There are several methods for evaluation of toxicity such as the ones done by Dr. Einhorn and Dr. Smith which are the medical methods. There are other very simple engineering methods for the evaluation of toxicity. One of the simplest methods is by evaluating the amount of gas that is necessary and the time that is required to either collapse or lead an animal to death when these animals breathe toxic gases. What I will be talking about today are the results of this second method. In order to represent the amount of gas inhaled we used an exposure index. This exposure index is the product of the concentration of toxic gas times the time of absorption

or inhalation. As for the time required for inhalation if this makes the animal collapse, then we called this exposure index a collapse index, and if the animal should die because of inhalation of the toxic gas we called this kind of an exposure index the lethality index.

Collapse index is IC, Lethality Index is IL and Exposure Index is IE. Although these indexes may be different in their expressions I think that many researchers have already suggested this kind of a symbol. And what is important in this kind of thinking is that in the time of fire where there is a very high concentration of toxic gases and if that kind of gas is inhaled in a short time, we would want to know what kind of value these indexes will have. Also if there is a combination of more than two gases we would like to know what kind of an index these gases will have in the mixture. In the test that I conducted I used mice in a free environment where they can move around. When I say incapacitation or collapse it means the position or the situation when the mice are in a prostrate position and do not move. When I say death, it means the stoppage of the respiration.

The gas concentration inside the chamber was constant when this test was conducted. HCN was generated inside the chamber by combining KCN and H_2SO_4. HCl was generated by reacting NaCl and H_2SO_4 inside the exposure chamber. When the maximum concentration of CO is less than 1% then the lethality index has a tendency to increase. We see that the critical exposure index for HCl is approximately 2.0.

When we compare the LC of CO and HCN, we see that CO was 1.06% and HCN was 175 PPM. We can see that HCN is about 60 times stronger than CO in its toxicity. As for the collapse index or the death index, we also compared the two and we have seen similar results.

I would like to report to you about the results when more than two kinds of gases were used. We used the same kind of testing methods. The exposure index of a gaseous mixture of the death divided by the lethality index when that gas is used singly is called the index ratio. If toxicity is completely additive the sum of the index ratio should be one. We see that the sum of the index ratio of CO and HCN was on the average about 0.90.

We used a more complicated mixture of gases and there is quite a large O_2 deficiency effect in mixtures of toxic gases. Also in that case when there is less O_2 concentration, the effects of toxicity of CO or HCN becomes larger. For O_2 deficiency we were not able to get an index ratio or lethality ratio index. In that case, we would like to try to quantify the O_2 deficiency by using a lower lethality index or lower collapse index of other gases such as CO and HCN. CO, CO_2, HCN, and HCL were used as gaseous mixtures and we also noted the effect of O_2 deficiency.

Fristrom: I wonder if the author would comment on the relationship between Figure 4 and Figure 5 in the text which he distributed. What are the apparent ranges of error in Figure 5 and how they are related to the curves in Figure 4?

Nakamura: Let me explain Figure 4. Curve A is the rise of the CO concentration inside the exposure chamber. There are six dots on that line. In that kind of a rise in CO concentration this is the time when the mouse died, starting from the time of inhalation. The dots represent the times that the mice died. In this case the rise is very rapid and from the point of view of lethal index is the area which is surrounded by the Curve A and the time so different from a low concentration there is a vast variation at the time of deaths. And it depends on the lethality index. If you will refer to Figure 5, there is a great range. There is a white circle A here. For A, it is from the lethality index about 5 - 13, so that is a very wide range because there are five of them. You will see the vertical index is from about 5 - 13 so that you see the range is very wide.

Einhorn: As you expose an animal to two gases, carbon monoxide and hydrogen cyanide, we have the unique capability of studying dosage because you know the concentration the animals are being exposed to. You know the time of exposure and you can monitor the saturation carboxyhemoglobin and blood cyanide. You can measure the amount taken in and the amount given off within the rise. When you have mixed gases it is difficult to get the coefficient of absorption of individual gases. I wonder if you could go back to Figure 4 and now relate time and concentration and tell us about carboxyhemoglobin levels at these different concentrations. Were they the same? What ranges were there on the high and low curves?

Nakamura: Going back to Figure 4, let us take up Curve A first. The first mouse that died for Curve A, the CO was about 1.3 per cent, and the last mouse that died was at about 2.0 per cent CO concentration. You are asking whether there is a difference in the value of carboxyhemoglobin and I do not have the devices to measure it as a relative factor. If there is exposure to about 2% concentration, then the respiration rate of that mouse is very slow (about one in 30 seconds). However in this research the arrest of respiration is the time of death. I believe that at 1.3% CO concentration the carboxyhemoglobin of the first mouse and the carboxyhemoglobin of the last mouse that died, is about the same because saturation point had been reached and the amount is about the same.

Einhorn: I think it would be very important to have carboxyhemoglobin measured.

Smith: The approximate carboxyhemoglobin concentrations for each of these concentrations and at the given times could be calculated by the formula given in my paper based on the pulmonary exchange rate of the mouse relative to the rat. However, there is something rather interesting to us here. The arrival at death which occurs at the carboxyhemoglobin concentration, usually in the neighborhood of 70% or thereabouts for the rat, at 1500 parts per million is about five minutes which this graph indicates roughly. If I recall correctly, the 30 minute time to death as calculated by our formula is in the neighborhood of 7000, and so this graph and other toxicological studies seem to be in relatively good agreement.

Robertson: These same two curves, Figures 4 and 5 show lethalities for different mice. Were these mice subjected in a single experiment or was it just one mouse at a time?

Nakamura: The results of Figure 4 were achieved by using the chamber in Figure 2. For CO, instead of HCl, we put CO gas inside a pump and by adjusting it by a flow meter we put it inside the chamber. We put six mice simultaneously into the chamber.

Birky Presentation

Birky: The information that I would like to present is on our progress towards the development in the United States of a standard test method for evaluation of combustion products in terms of toxicity. As you have already heard, this exercise is going to be in the area of technical and scientific compromises.

Before I talk specifically about the test method we are developing, I would like to indicate some of the things that are going on in the International Standards Organization related to the development or the acceptance of a test method for combustion products toxicity. At the last meeting in Germany, the German toxicity test method was proposed as a possible test method. This test method is fairly well documented in the scientific literature. It is quite different from what we have used in the United States and what the Japanese are using right now. It uses rats and a dynamic system where new products are generated continuously and fed past the animals. It is similar in terms of technique to that which Dr. Alarie has used.

In the past three years the Center for Fire Research at the National Bureau of Standards has been working toward a test method, with the general objective of developing a recommended protocol for this assessment. After reviewing the state-of-the-art of what can and what cannot be done in combustion toxicology, we decided that one could not do a relative ranking of combustion products. By that I mean it would not be possible under the present state-of-the-art to say that material A should be used over material B because its toxicity is a little less. We set about, using the state-of-the-art, to develop a test method to sort materials into two categories, i.e. materials that have conventional toxicity, perhaps similar to cellulosics, and materials that would produce unusually toxic combustion products.

Any new system is going to have to meet certain criteria. It should be able to expose samples to various temperatures or heat fluxes similar to what the Japanese have reported. It should be able to handle a flaming mode of combustion and a non-flaming mode of combustion separately. No heat stress was to be applied to the animals, nor oxygen depletion. What we are looking for is a chemical toxicity test in the absence of heat and oxygen deprivation on the animals. We are using four rats at present, but the test method will require six. We are measuring time to an effect in terms of the hindleg flexure incapacitation model and are also looking at lethality. In the non-flaming mode, we are testing 15 degrees below the auto-ignition

point as defined in the combustion method. The maximum temperature is 800°. In the flaming mode we are talking 15 degrees above the auto-ignition point.

I will try to give the rationale why we chose these conditions. The combustion furnace was developed at Dow Chemical Company. It can be incorporated into the animal exposure chamber without producing heat effects on the animals. We are concerned about whether enough oxygen is supplied to the sample in the non-flaming mode as you would have in the fire environment. We are developing a radiant heat system but have not progressed enough to have successfully overcome the heat stress problems on the animals.

The exposure chamber is made of polymethyl methacrylate. We are not using teflon-coated stainless steel. The volume of the chamber is very close to 200 liters. The time of exposur is 30 minutes. Maximum temperature in the animal chamber is 35° and the initial chamber temperature should be 22° $\pm$ 2°C. Oxygen concentration is not to fall below 18%. The measurements that we are requiring in this test method is oxygen, CO, CO_2 and temperature. The biological measurements are time to incapacitation, time to death, blood CO hemoglobin at the time of incapacitation and percent mortality.

The method is a compromise trying to take into account the classical toxicologists' opinions that LC50 and dose response curves are the appropriate toxicological parameters. However, as has been well documented by a number of papers, time to produce an effect in terms of a fire environment can be a very important parameter. So we have both of those criteria in the test method at this time.

We have specified male rats but no specific species or strain. In the protocol six rats are required per test. One animal is to be sacrificed for blood and pathology if there are no deaths in the exposure and five would be observed for a total of fourteen days for post exposure lethality calculations. If an animal were cannulated by the Utah technique, we would not have to sacrifice that animal for blood chemistry.

There are a number of problems associated with any particular chamber configuration. Mixing time becomes an important characteristic when you have a short exposure such as 30 minutes. In addition the rate of generation of products becomes an important parameter. We have no fans in this chamber to accelerate mixing rate because of the difficulties of depositing particulates of combustion gases such as HCN, HCl, etc. on any surface that is introduced into the exposure chamber.

We have generated HCl in the Potts furnace and found no systematic concentration gradients. We have measured CO_2 in three positions as a function of time to determine if we have rapid mixing. The limitation of this particular system is the rate of generation of products and not mixing. We have also shown that, based on lethality and incapacitation, there is no preferential incapacitation or death of any animals as a function of location.

We are not happy with the rate of production of products from the furnace in a 30 minute exposure. If you load the furnace with wood up to 30 miligrams per liter, it takes a significant amount of the 30 minutes to generate the products. We are trying to do a comparison between the rotating cage technique and the hindleg flexure technique. We found that the rotating cage technique gave an earlier indication of incapacitation than the hindleg flexure technique. With the rotating cage we had difficulty seeing the animal when we decomposed materials that produce a large amount of dark smoke which led us to abandon this particular technique.

The system has been undergoing quite a few modifications, trying to incorporate the best features of combustion toxicity systems. There are many other techniques being developed in this country that are going to provide new insights to the effects of combustion products both from a lethality point of view as well as from behavioral modification points of view, and also information as to the cause of injury that may lead to perhaps new methods of treatment.

Handa: Instead of sampling a few test animals at one time, perhaps the test should be repeated by using three or four rats at a time and trying to get statistics by using three or four rats repetitively.

Birky: I agree. In this particular test method we will do dose response which will require more animals. We may even have to do repeats at a given fixed concentration to get the statistical analysis of the effects. You will note that I did not discuss what we meant by 'unusually' toxic. We are still looking at the data on materials that we consider to be in that classification. To be more specific, the CO hemoglobin measurement is not at this point falling into a criterion of toxicity. It is an indicator of other toxic species being present.

Handa: About two years ago at a conference on Fire Safety of Combustion Material in Edinburgh, Scotland, people from Borehamwood Research Station said that phosphate products were liberated from flexible polyurethane. Would you consider them unusually toxic?

Birky: There are some that will be toxic. We have only seen one case - the Utah case. I have not seen data on flexible polyurethanes that suggest unusually toxic combustion products.

Einhorn: Were you referring to the cyclophosphate ester? I would like to add one comment. This work was initially done at Utah and Dr. Birky was present as a visiting professor. When we found the unexpected formation of this material we were working with rigid urethane foams with a low molecular weight crosslink density of about 300, but not more than 500. In flexible polyurethane foams the crosslink density of TMPP-initiated polyols in the formulation would be about 4 - 5000. So there would be a substantial decrease in the production of the cyclophosphates in the presence of phosphorous fire retardants of any kind. In real fires or large scale tests, some of the cyclophosphate ester may get through. It is destroyed at the higher temperatures in the flame.

It is our feeling, based on studies as yet not published, that there is a progressive change in the nervous system given a single exposure. Industry, worldwide, has eliminated the combination of phosphorus-TMPP rigid foams. I do not believe they have eliminated the combination for flexible foam. And again while there is no information on injury available involving real fires, there may still be a hazard in the use of these materials.

Smith: I would like to ask Dr. Birky questions of a technical nature and some related to toxicology. You have now adopted a policy of selecting a furnace temperature of 15° below spontaneous auto-ignition and 15° above. In our experience, this is cutting it very close. When you aim for 15° below, and this may depend on the state of division of the sample, it will flame. 15° below the point of auto-ignition and 15° above is making it a very critical temperature range. I think a 25° margin was more reasonable.

I was interested in your experiments in which you compared our rotating cages with the flex reflex. I wished I could have heard you say that they were about equally precise. The rotating animal drops first. There are reasons for this. He is exercising. There are also other possibilities from the physiological point of view.

We believe that the exercise, in part, controls his physical state and makes him perhaps a more uniform animal than one who squirms and then relaxes, is tense and then relaxes. We believe that the rotating cage process actually contributes to precision. You cannot use it under all circumstances but it is a matter of configuration. I noticed that you put your rotating cages in a position where it was indeed difficult to see the animals in smoke. We have ours very close to the plastic wall of the cage and we found that an amber light decreases diffraction from the fog and allows us to observe the animals when it would otherwise be very difficult. But if you can't see them you have to go another route.

I am very much in favor of the principle that we use a few animals at a time and repeat again and again, because this is the essence of precision testing; not twelve animals at once and counting the dead one at a time, but four animals at a time three times repeated.

In your emphasis on separating material into those of ordinary toxicity and those of super toxicity, I would like to know your real reason for this. Why can't you say that A looks better than B and is preferred. Is this an industrial compromise?

Birky: I thoroughly agree that 15°C above and below auto-ignition is cutting it close. Based on our experience this may have to be modified. My first cut was 25°. Discussing this with other people who had experience, they felt that 15° was better in terms of picking out the worst toxicity cases. It was important to come as close as you could to the auto-ignition point for picking up the worst toxicity case.

Regarding the rotating wheel, we did not try to optimize having the wheels as close as possible to the wall. However, I think you still have the fundamental limitation of being unable to make observations on all materials and that was the reason for this compromise.

Super toxicity was not compromised at all. It was not made to pacify the industrial community. That compromise was based on my own judgment of what could and could not be done in combustion toxicity. If you look at the toxicity data, you will find that material A may indeed be a little bit less toxic than material B, but it will decompose at a different temperature, perhaps lower or higher. A material that is more toxic than B may have a greater thermal stability than the more toxic material. So one should not make a decision based simply on toxicity whether a material should or should not be used at this point.

Smith: Flammability and decomposition fragility are factors that must be woven into a hazard formula.

Watanabe: Perhaps we can form an ad hoc committee on smoke toxicity. I would like to know if there is such an ad hoc committee in the United States?

Birky: Yes, I have put together an ad hoc committee on fire toxicity in the United States for review of the test method. It involves universities, other government agencies and industry. It includes toxicologists, combustion scientists and behavioral scientists.

Watanabe: Such a committee should form some kind of philosophy on the danger of toxics. For example, if there were any apparatus that the Japanese side should be very interested in, would it be possible for you to give us a diagram of such an apparatus, or if there are evaluation methods in the United States and Japan, could we exchange such information? If we do not go ahead with this kind of exchange, we cannot come to a common understanding.

Saito: I am from the Architectural Research Institute. I have one comment and one question. You measure the behavior of the rat in the rotating cage, but because of the smoke generation it becomes difficult to see inside the cage. In Japan, we have a switch on the rotating cage. This is included as one of the suggestions in the reports from UJNR.

When you do testing of material toxicity should you do the tests all at once or should you do them one after the other? I don't think you can say that repetition of the test is a good thing, because there is a problem of reproducibility, because there is a question about whether the rats are in the same condition at all times. On the other hand, do we have uniform materials? There may be discrepancies because of the non-uniformity. We should also include the toxicity of the smoke as well.

Birky: In the Japanese techniques you have a freely running cage. The mouse drives the cage. The cage system that I have showed uses a motor driven cage. There is an effort at Carnegie-Mellon to look at the torque that the rat imposes on the motor driven cage so that you can look for incapacitation without seeing the animal.

Saito: In Japan, the rat is inside the rotating cage and the rat itself is moving the cage. The other method is a rat on a beam.

Chaiken: Not being too familiar with toxicology fire testing, I wonder why the decision was made in this test device to produce combustion gases at a specific temperature rather than some type of programmed heating that might more or less reflect some physical process which occurs in actual combustion, particularly where we have a priori knowledge as to when a specific material is going to give off something that is specifically toxic.

Alarie: I agree with the last speaker. For toxicity purposes the method which will produce the most toxic gases from a sample is to program the sample in the heater at a linear rate and let the sample degrade as it wants to degrade rather than putting all the sample at a particular fixed temperature.

Birky: There is one other temperature at which you can carry out these exposures, at 460°C, in addition to 15° below the auto-ignition temperature. The furnace could be used in that mod if you wanted to use it. The reason that a temperature was specified was based on experience with a number of materials. 15° below the auto-ignition was the worst condition in most cases It may not be so in all cases.

Saito Presentation

Saito: I would like to discuss factors affecting the gas toxicity in fire. First of all, I would like to touch upon how best we could use the data obtained from experiments in actual fire situations. I believe the applicability of the test results to the actual situation is very important. Even if we get very good results from the experiments, if these cannot be related to the building fire or the aircraft fire or even the fire in the residential area and if this cannot contribute to the reduction of the people dying from fire then the experiments are not useful. Because of this way of thinking I have decided to look at factors affecting gas toxicity in a fire from the building construction point of view. And therefore I would like to limit myself to those factors which contribute towards the better safety in the building.

Toxicity of combustion gases depends on the chemical makeup of the material itself as well as the environment which exists when the combustion takes place. Materials should be examined at the temperature where the worst toxicity is emitted. Rather than discussing the worst possible toxicity I will put more emphasis on the range of the temperature during which toxicity gases could be emitted.

There are two different types of toxicity - acute toxicity and chronic toxicity which might have an effect later on. The acute toxicity should be evaluated as to how fast the toxic gases could be emitted from the material. In the case of actual fires when the person is evacuated from the site and is still breathing, we talk about what medical science can do to help this individual. One of the reasons why we are looking at the short time toxicity is because it is difficult to conduct a long experiment.

At present, we look at various commercial products as well as building material in order to evaluate the toxicity of the various materials. The method we apply does not get an absolute value of the toxicity of each material. We divide them into different groups to eliminate or to find some of the most toxic materials.

The toxicity produced by gases has been obtained by the use of various animal experiments as well as other combustion experiments. When we are looking at the acute toxicity during a short time period, it is quite possible to predict the approximate toxicity of the material using experimental animals. However, as it has been pointed out by Dr. Einhorn, if the gas affects the nervous system, it would not suffice to conduct an experiment on animals only, but we should proceed with a chemical analysis.

I would like to give some results of experiments where we have looked at temperature as well as humidity and smoke to see how these factors would influence the toxicity of the combustion gases. We tried to evaluate the toxicity of the smoke particles. There are three methods of evaluating smoke. One we have talked about is in connection with the sensitivity of detectors. Another method of evaluating smoke is the obscuration test. Thirdly, there are experiments in which we look at the physiological influence of the smoke. We have used particle size distribution as a parameter. For the second method we could use extinction coefficient. When it comes to a physiological property of the function of the smoke, both of these two methods should be used, because of the fact that it has a direct relationship with the weight of the smoke.

The apparatus is very simple. There is a rotating mouse cage inside the desicator. There are four cells and four animals are used for experiment. The smoke goes through a filter and mice are placed inside small glass tubes. We analyse the gas present; as for smoke we have to look into the weight as well as the particle distribution. Perhaps in that way we might be able to get more accurate results.

In fires, we also get high temperature as well as humidity. Because of the coexistence of high temperature as well as humidity, the toxicity appears to rise as the metabolic function of the human being increases. 16 - 24 animals are put into a rotating cage in the exposure chamber. When we vary the temperature as well as humidity, we are able to see the influence of those two factors on the animals. Depending on the type of gas the temperatures as well as the humidity effects will differ. As a representative of a toxic gas, we have used CO. Especially in high humidity environment it is difficult to observe effects microscopically and therefore I feel that this apparatus was very useful.

We have looked into the influence of high temperature. The temperature seems to have a great influence on high toxicity.

In Japan there was a large fire in a department store. The temperature at which deaths were reported was when the temperature reached 60 - 80°C.

The evaluation of the smoke should be done to quite a high temperature. The volume of the actual combustion as well as the size of the room has great influence on the result. When we look at the smoke test, if we know the toxic potential of the gas, then we might be able to predict the concentration of smoke at various points in the building. If we know the temperature then we would be able to design a building which might be safer.

Einhorn: We have had a discussion on how a material is exposed to heat or a combustion source and the nature of the products and concentration of the products resulting from this. This is an area which needs a great deal of further discussion. We have studied for the past several years natural materials, cellulosics, wood, polyurethanes, polycarbonates, and nylon, with or without fire retardants, at heating rates from half a degree to one hundred degrees Centigrade per minute with the type of techniques that Dr. Birky discussed, using the conductive heating tube or the types of tube furnaces that Dr. Smith talked about and the variable flux heaters in our NBS chambers. There is very close agreement between different laboratories using a similar method. However, there are major differences in the product distributions and we do not see the same biological effect when we expose materials to these different approaches.

Watanabe: Quite a number of people raised opinions regarding the method of heating. Perhaps we should discuss heating methods.

Alarie: It is important to discuss heating methods. However, I think it is also very important to discuss what we consider toxicity to be. Right now everybody is considering time for an effect to occur as being toxicity. Unfortunately, this is incorrect. Toxicity is not the time for an effect to occur. Toxicity is the amount that you need for an effect to occur. Therefore, we could have the best combustion system, but if we are using the approach of time for something to occur, we are not going to obtain the proper data classifying materials that are unusually toxic. An unusually toxic material would be a material that would kill either rats or humans when only a small amount of it is present. It is not the same thing as saying "super rapid effect". Also we should not confuse super toxic or unusuall toxic with what I would call 'dramatic' effects. When rats go into convulsions, it may be mos dramatic, but it has nothing to do with unusual toxicity. And so if we want to compare the toxicity of materials, we have to do it on the basis of the amount of material that will produce the effect, and not the time that it takes for the effect to come in. I would rather tha we have the discussion on the toxicity first rather than the combustion.

Japanese: Since I am an amateur in this field, I do not know whether what I am saying is correct or not. The toxicity could be obtained from the products of the concentration and time and perhaps we might be using a different terminology talking about the same thing.

Alarie: I have data that will show that you cannot determine a toxicity index by multiplying the concentration times the time.

Smith: We are in fundamental disagreement on this point. It is obvious and I agree with Dr. Alarie, that toxicity is related to amounts required to produce an effect. However, I am firmly convinced that one can arrive at an amount by suitably taking into account concentration and time.

Alarie: Unfortunately, nobody has done it. The problem is that we are all dominated by the time to get out of a fire. I agree that time is important, but toxicity is not time. Toxici is the amount. If you look at the amount of wood (Douglas fir) to kill 50% of the animals, it will take about 64 grams. If you take the amount of teflon to kill 50% of the animals, it will be about .6 grams. There is a factor of 100 between those two materials. And so teflon is unusually toxic compared to wood. Obviously the comparison is meaningless in the real world because teflon does not compete with wood, but that's the only way that you can compare toxicity - on the amount of material to produce an effect.

Chaiken: When I asked about the temperature condition for which you set up the standard test, I was not terribly concerned with toxicology or its definition but I was really concerned with a screening test which will indicate if there is a problem with a new material that is to be introduced for which there is interest in the toxicological hazard. If you have a system, a test that takes thirty minutes to kill a rat with an exposure to wood products as far as a rat is concerned, that is pretty toxic. But if you then put another material and employ the same exposure and the rat dies in one minute, I would be a little worried about using that material. I am talking about a screening test.

Birky: I am in between these opposing views. The point of difficulty that we are addressing here is the position that a strictly classical toxicologist takes versus the question of time to get out of the building and the questions of an animal model that is universally applicable to all types of combustion problems. For example, if you are going to use incapacitation as a criterion and time, there may be some materials that produce delayed effects which may show up at the beginning or early in the exposure. So, in one sense, both views are right. There are materials which may cause an effect in one minute. There are materials which will cause a rather long-delayed effect in which fatality will not show up for three days. And so I think the problem we are dealing with is trying to look at a multitude of toxic effects from one particular view point and it is not going to work.

Einhorn: If one uses the modified Potts chamber as we have done under an NBS program, we can show the effects in grams/m^3 producing incapacitation and 50% mortality in the flaming and non-flaming mode. There is a major difference when a sample is suddenly exposed to radiative flux. We find that in fire loss from flaming, we have high mortality, low blood pH.

Alarie: Toxicologists have always been concerned about differences between materials or chemicals. If something is four times worse than another, it is possible that in the real world you will see a difference. If there is a factor of ten between materials, then the difference is real and it will make a difference in the real world. If we are talking of difference of a hundred and a thousand, that will make a real difference. We are wasting our time looking at small differences which will make no difference in the real world.

Japanese: Perhaps if we could work on these two different ways of thinking, we might be able to present something for the next meeting. Could we possibly have a paper on combustibility or toxicity along the two different thinkings that were expressed today?

Levine Presentation

Levine: I will bring a different point of view, a more clinical point of view to the problem of toxicity. We are looking at both civilian casualties and the fire fighters themselves to determine clinically observable effects of exposure. I might also add several other compounding factors, which are host related, one of them being the condition of the person or firefighter in terms of cardiac reserve, his pulmonary functions, his psychological state, as well as the physical forms or mode of particular agent or substrates that we are talking about.

There are not only different endpoints in terms of death, disease, disability, pulmonary disfunction, but there are also different endpoints in terms of acute, chronic and long-term latent diseases. Much attention has been directed recently to diseases such as cancer and genetic defects which may not be related to a one-time exposure. With some additives, they may be more commonly related to repeated exposures of firefighters.

We have been working now for several years with the Applied Physics Laboratory Fire Project - a joint effort to uncover the effects of inadvertent occupational exposures to fire atmospheres. We looked at immediate effects of toxic atmospheres on civilians and on firefighters, particularly by carbon monoxide and cyanide. We have looked at chronic long-term consequences, particularly chronic lung and cardiovascular disease. In terms of firefighters in the City of Baltimore, we have investigated a thousand men. We have recorded pulmonary function data, EKG, blood pressure and extensive medical histories. We are now looking at changes that develop in their lung function, related smoking and age, in Baltimore, Maryland and the USA in general.

Some of the interesting things we have found are that the standards, which are published for pulmonary function are usually done in places where people do not have the exposure that we have in Baltimore. The standards are not really true comparison standards for fire fighters. We fortunately have another study ongoing that has looked at Baltimore people. We found also that if you concentrate on social and economic status, we have a difference.

We also have dosages in terms of soot absorbed in the lungs identified by black sputum being coughed up six to twelve hours after exposure. We are making a mortality study. We have analyzed over 500 deaths over a 14-year period. We see a significant change in cummulative effect, and a not quite so obvious change in long-term chronic exposures. One would expect people exposed to high levels of carbon monoxide over a working lifetime to develop similar cardiovascular changes, neurologic changes. They probably do, but whether or not they are sufficient to cause death is questionable.

In another study which was done before I joined the group, biopsies were done on civilian casualties, correlating levels of carbon monoxide (as carboxyhemoglobin) that caused death, and the state of the coronary artery circulation. Persons who were severely compromised would find exposure to CO much more toxic than some vigorous individuals.

We are comparing controls with firefighters who are exposed to the normal routine fighting of fires. We are purposely excluding firefighters who have had obvious immediate traumatic or medical problems. These are firefighters who felt healthy and vigorous in their work.

The general population of exposed firefighters have a significantly higher level of blood carbon monoxide than a group of firefighters who were not exposed to the fire. A very small percentage, maybe ten percent, have an exposure higher even than the highest controls, going up to about 18 - 20%. If you question these men carefully, 8% admit to headaches, 2% to nausea and vomiting and other symptoms. The mean level of carbon monoxide in the blood increases very significantly with smoking habits. Compared to nonsmokers there is an elevation in every smoking category. One of the major factors in the toxicity of the fire in terms of exposure to carbon monoxide depends upon the habits of the men in terms of smoking.

We try to see whether firefighters could decide for themselves if they were in a toxic environment, using subjective measures. Our firefighters commonly called a fire a bad fire depending on smoke density, the color of the smoke, or perhaps the heat. Firefighters using subjective evaluations, really cannot tell what type of exposure they are getting, nor are they able to pick up a colorless or odorless gas, or PVC decomposition product.

We looked at exposure by mask users and although you can show that continuous mask users were fairly well protected from exposure to carbon monoxide, non-users were significantly les well protected. People who use the mask intermittently were in worst shape. We take that to mean the the firefighters cannot judge the level of exposure they are being subjected to. Because they have an aversion to wearing masks and at certain times tend to take their masks off too soon, it appears that wearing the mask intermittently is as poor a form of protection as not wearing it at all.

A casualty study was done in a prospective manner. We took all victims who were identified as having been in a fire or involved with a fire. Of about 414 victims identified as such, w were able to follow 346 to conclusion. If we look at the cause of the fire which resulted in casualties or fatalities, smoking and children playing with matches were by far the most comm cause of fires. Flammable liquids and arson are not making as great a contribution as antici pated. 65% of fatalities were due to careless smoking. It again may relate to host factors whether the people were drinking or not.

We were able to follow most of the patients. There is a 7/1 ratio of casualties over fatalities. A large percentage of the persons were just treated and released. Of the 55 fire victims who did not survive, the largest number died of carbonmonoxide intoxication. All of them died within the first 24 hours. Many of them died before they reached the hospital.

We have instituted some emergency training and have changed mask wearing habits in Baltimore We also change resuscitation procedures so that patients get oxygen very quickly without any question about whether or not they need it. People who are young and old present a greater percentage of fatalities.

Einhorn: All of the members of the American group on the UJNR panel were very impressed that every Japanese fireman is personally fitted for a mask by a physician, and furthermore that those masks were apparently in very good repair. We have seen in our studies a number of people who have masks that do not fit properly or leaked. I wonder if that can be part of the problem of this intermediate group?

Levine: Not only the fit of the mask but other technical problems such as how long the compressed air supply lasts are important.

Einhorn: Are there any follow-ups after people have been released six months, a year or two years later?

Levine: We have not got that far along. Let me return to your original question. The difference between continuous mask users and intermittent mask users is probably not due to the lack of fit. But carboxyhemoglobin in mask users is higher than in controls and that may be due to the leakage. They are not getting as complete protection as we had hoped.

Einhorn: The New York Commissioner told me that there are certain fire departments in the Bronx and Queens where men go on fire calls in the morning and are busy all day. Do you see a higher level among those people?

Chaiken: One of the major objectives seems to be to study fire fighters and the amount of carboxyhemoglobin which presumably comes with the result of their work. Are there other professional groups who possibly get exposed to even more CO during their work? Miners I know get exposed to everything. If so, have you ever made cross-correlations with regard to whether they are worse off than fire fighters?

Levine: Most of the studies that I am familiar with have been done on tunnel workers. There has been one series of studies which was fairly extensive and looked at all sorts of parameters of blood enzymes and liver enzymes. They have a shift change every two hours and do other sorts of things because they are aware of the hazard. Fire fighting is unique in that one cannot approach that side of it. Neither can you measure the atmosphere. Nor can you control the situations, so it is somewhat unique. I do not know of anybody who has conducted the type of long-term studies that we are doing with the firefighters in any group regardless of where they are exposed.

Handa: Especially in the case of firemen do you have any tendency that they contract more cancer of the lung or do they have more tendency to have heart failure? For instance, when we look at the toxicity of various combustion products, perhaps we might take into consideration some of the elements which might cause that kind of side effect, for instance lung cancer or heart failure.

Levine: We are now looking at long-term chronic effects. This is complicated by the fact that we live in Baltimore which is a very heavily industrialized area. There has been a study done by the National Cancer Institute which relates cancer to geographic areas. The Baltimore-Washington area in general has a higher lung cancer rate than our national average. So it is extremely difficult to pull out how much of that is due to general pollution and how much is due to firefighters' exposure. We have just looked at pulmonary functions and find that if you take into account not only where people live, but their social economic status we can show a definite difference.

Einhorn: Is anybody familiar with Peabody's cardiac studies in San Diego? They had firefighters in a number of firehouses connected with portable cardiographs to see what happened when they were eating or when the fire alarm went off.

Levine: There are obviously cardio-vascular functions in addition to the gas exposure in the fire atmosphere. There are many deaths of firefighters due to cardio-vascular disease but I am not sure that it is statistically greater than one would expect in the general Baltimore population.

Yamamoto Presentation

Yamamoto: When we talk about toxicity, we will have to use gases, and the route by which those gases come into the body is through inhalation. The speaker confirmed this fact by using cyanide. Depending on the way that cyanide is administered there is a difference in blood concentration. One is by the oral method and one is by inhalation. The samples are taken from a rat right ventricular blood. There is a big difference between those that were administered by the oral method and those that were administered by the other method. Although the samples we used are rather small we see similar kinds of results using rabbits as well as rats.

When there is inhalation of HCN we have studied the data on the cyanide distribution inside the body. We do not have too many experimental data. Therefore, I decided to measure the concentration of cyanide in the blood in two or three places of the rabbit's body. We measured at the same time the blood PO_2 because it determines whether somebody dies because of acidification or not. Secondly, depending on the value of PO_2, we can see what kind of gas is involved and we can also see what kind of toxicity there was from that gas. The materials that were used were PAN, silk, wool and gauze. They were all about 1.5 centimeters square and everything except gauze weighed 20 grams. For gauze we used two kinds - one that weighed 20 grams and another that weighed 30 grams. The combustion apparatus that was used is included in Reference 7 of my paper. The material was put inside the metal wire basket and heated with an electric heater of 300 watts.

When we use rabbits in our experiments, they inhaled the combustion products through the non-breathing bulb and through the tracheal canule. In the HCN inhalation experiment we produced HCN by reacting sulfuric acid with sodium cyanide. The HCN that was generated was led through a plastic tube and a non-breathing bulb or through a tracheal canule into the experimental animal. The animal that was used for our experiment was a male rabbit of about 2 kilograms in weight. It was anesthetized by urethane.

In the combustion experiment, we used respiration stoppage as the ultimate index. If there was no arrest of respiration even after fifteen minutes, we ended the experiment and took a blood sample of the animal. In taking a sample of the blood we opened the chest, and first took the blood from the left ventricle, then the right ventricle, then the descending vena cava. We also measured carboxyhemoglobin with a spectrophotometer. Before exposure we took blood from the jugular vein and measured the COHb of each animal.

The results of this experiment have been reported in the Japan Forensic Medical Journal. We counted the respiration rate by the motion of the wall of the chest by the naked eye. For PAN, silk, and wool, all the animals died during exposure. The mean survival time was 14 minutes for PAN, for silk 16.7, and for wool 21.9 minutes. The survival times are statistically shorter for PAN compared with the other materials. The range in the difference of survival time is about 5 - 10 minutes.

Between silk and PAN we did not see a remarkable difference in survival times. If the amount of combustion gas inhaled becomes large, respiratory rate becomes faster too. Towards the end we see a gasping kind of respiration. The time of this gasping respiration or the intensity of such varied case by case.

In the gauze group three of the five animals died during exposure. These animals showed a very severe respiratory depression after 20 - 40 minutes of exposure. However, after that they seemed to recover.

Carboxyhemoglobin was 55-65% and for those that died during exposure, it was 85%. For PAN, silk and wool it was lower, and for silk, the maximum value was about 10%.

We observed the trachea with the naked eye. For PAN we did not see a very big difference. For silk, 6 out of 8 cases had some frothing. For wool, we saw both froth and soot. In the case of gauze, three out of five cases showed black particles. When we did a microscopic investigation, we looked into the lungs but did not see any big influences.

Considering that the survival time for PAN and silk is very low, these are considered more dangerous than wool or gauze. This is in accordance with the results in Reference 7. At the same sampling sites we saw quite a difference in both cyanide levels and PO_2 levels. Because there is a correlation between cyanide and PO_2 we think that there is quite a big influence during the past part of the exposure, especially on the influence on respiration. Towards the end there was heart failure or disturbance of heart function. Because of this disturbance of heart function, the transportation of cyanide becomes more and more difficult inside the body. In the left ventricle blood, we saw a remarkably high value of cyanide. We see that this is very similar to the theory of Gettler that cyanide concentration is high in the lung in those animals that inhaled HCN. We will have to look into respiration, the measurement of heart function during exposure and also we would have to measure blood pressure, ECG and ventilation.

In the silk groups we think that because of the gasping respiration that occurs and also because of an acute cardiac disturbance that takes place the cyanide is not transported into all parts of the body. Cyanide is different from CO in that it inhibits the utilization of O_2 of oxygen in the tissues. Thus, in the case of acute cyanide poisoning, there should be a higher level of PO_2 than in the case of acute CO poisoning. By using rats we see that the PO_2 level is very high. From these results we can see that for acute CO poisoning PO_2 values are low.

In the combustion experiments that we conducted, PO_2 of gauze was lower than others and we observe that it was not contrary to the results of CO poisoning. As for the wool, we could not identify the dangerous substances in the combustion products. We did not see an abnormality in the alveolus. What is the level of hydrogen sulfide in the case of wool? In my opinion we would have to compare cyanide poisoning and sulfide poisoning from the point of view of blood PO_2. I orally administered sodium sulfide to rabbits. The results of this are published in the Japanese Journal of Legal Medicine. PO_2 of sulfide poisoning has a lower value than cyanide poisoning but there is no big difference between the two. However, there is a difference in the manner of the experiment. One was administered orally and the other one was by inhalation. Therefore, we cannot supply the data directly to the combustion experiments. However, we cannot exclude H_2S as a toxic gas when we do this kind of experiment on combustion products.

Levine: Is there any relationship between the elapsed time between the blood drawing and the results that you get?

Yamamoto: When blood was sampled, it was put in ice. The time difference is only at the most 30 minutes.

Alarie: Very often, the cause of death is being explained by a particular blood level concentration. In my judgment, at least at the present time, carboxyhemoglobin levels would be much more reliable than the cyanide level. I would like to know if you agree with me on that particular point.

Yamamoto: As a tentative standard of criterion, the cyanide level of blood, if it is between 2 and 3 micrograms per miligram, can be given as a tentative criterion. I did include this discussion in Reference 1, so that you can look into it further.

Levine: We took a very cursory look at cyanide in dogs. We measured the amount of cyanide in samples of blood over a period of time and we found for a constant dose of potassium cyanide i.v. the measurable cyanide in the blood decreased so that after one half-hour, we could no longer detect any cyanide. Blood was drawn one half-hour after injection and the cyanide apparently was metabolized.

Halpin Presentation

Halpin: What we want to do in this particular project is to assess real fire incidents that we investigated and see whether there would have been an impact on fire losses by putting fire protection devices into residences and to see whether there would have been a different outcome in lives saved, casualties, injuries or property loss. I want to emphasize that this study was confined to fires in which we had at least one fatality.

Three fire protection devices were postulated. One would be a smoke detector, a second would be a smoke detector with a remote alarm capability directly to the fire department, a third would be a suppression device similar to a sprinkler. There are many assumptions that have to go into this particular type of study, but the two most important and very glaring assumptions are these. Operable equipment is properly installed. It must be properly maintained, so that the equipment is doing what it is supposed to be doing and what people say it will do. Secondly, upon alarm, people will act appropriately. An appropriate action means to leave, remove oneself from the residence, call the fire department from some other place.

We obtain data from the fire investigator to reconstruct what has happened. We also go to the fire scene and interrogate various people who know something about the fire. Through this set of interviews and the information above, we evaluate this information and data as to what happened in the fire from ignition to detection. We try to reconstruct what was happening at the fire. After we have evaluated this data, we will then make a judgment. If a detector had been placed in this residence where we had the fire that we investigated, the consequences are looked at case by case. The detector goes off and the people react. Would they have been saved? Would there have been casualties? Would there have been less property loss?

We had 73 fires in a one-year period. As to the cause of the fire, smoking again is very prevalent. Matches are a prevalent ignition source. The most common area of the house where the fire started is the living room with sofas and chairs, and the bedroom with beds. These are the areas in the United States where much smoking takes place. Fires occur across the clock with some peaking in the midnight hours to the early morning. This reflects the type of fire caused by smoking. A smoking type fire is smoldering, slow to break out into a flame. It is in a flaming stage when the humans do the detecting.

Let us assume that we decided to install some fire protection devices. The actual deaths that were found in these fires were 114 deaths together with 119 other casualties. On the basis of our judgment one can determine the numbers of people who would definitely have been saved with detectors. We can identify situations where these devices cannot help. As an upper bound the best that could be done would be about 90% saving in lives and casualties.

This is primarily due to time saving. The smoking caused fires, we believe, begin as a smoldering fire. Data that is available indicates that smoldering fires on an average take 90 minutes to two hours before they will break into flaming stage. We are assuming that a smoke detector will respond on the order of 25 - 30 minutes after smoldering starts.

The dollar damage does not take into account other economic factors such as the loss of income from the head of the household or the hospital costs for casualties. We have seen in one year 73 fires with 2.6 million dollars' worth of damage within the State of Maryland.

In eight cases there were detectors present at the time of the fire. It is not safe to conclude that the detectors did not do their job to prevent fatalities. As an example, in several cases the detector was in the house, but not installed. We had more than one case where batteries had deteriorated and were not replaced. In one case where the detector alarmed, the husband and wife had an argument whether they should leave the house. The husband won the argument. They left, but then he decided to go back in to call the fire department. He died due to the toxic atmosphere. In another case, the alarm went off. A young man looked out and saw a fire. There was a family discussion. Five people in the family were trying to decide what clothes to wear, what valuables to get and save. Finally they started to escape but their escape route was cut off by the fire. Another discussion ensued. Four persons jumped out of a third story window and were saved. The father decided he did not want to take this action and died in the toxic atmosphere.

Lyons: What kind of sensor did you assume would be used on the suppression system?

Halpin: On the suppression system I assumed a fixed temperature device would be installed according to NFPA Code 13-D.

Lyons: Your data suggests that many of these fires occur after midnight and were of a long time smoldering measure which would explain the peak of fires near 6:00 a.m. I do not understand how you can conclude such a large percentage of saves from a suppression system if indeed we have many hours of low temperature smoldering as the cause of toxic gas.

Halpin: The conclusion was primarily based on the fact that we know the fire was detected by the humans. 90% of the people were on the move. Many of these fires were also detected in a room other than where the people were actually affected. When the fire broke out, it got to a stage where the sprinkler would be actuated and knock down the fire and provide enough escape time. We also assumed that there was an alarm with the sprinkler system.

Lyons: You assume that there is a detector or some other alarm?

Halpin: There is an alarm tied to the sprinkler system. When the sprinkler goes off, there is also an alarm.

Benjamin: Obviously one has to have criteria in an exercise like this. It was that the people would react appropriately. I am wondering if this is a completely wrong assumption to start out with. In other words, if people were to react appropriately we might never have fires.

You show that within a few percentage points the number of people saved by smoke detection and suppression equipment were about equal. And yet in another graph we see that there was a rough relationship between the number of fatalities and the amounts of the house burned indicating that the fires were large when there were large fatalities.

Halpin: Multiple fatalities do not necessarily occur when the burned area is large. As far as the "area burned" is concerned it affects the property damage and contents more than life safety.

Benjamin: There are some assumptions that are not clear. With suppression you may not have had the large amount of damage to the house or multiple fatalities. The assumptions that you have made which gave you this mix bothers me because obviously one can get any mix they want and any numbers they want based on the criteria you start out with.

Halpin: One of the more important things I have found were the types of cases where nothing could be done to help. 10% of cases had to be written off.

Birky: I would like to present some data on CO and HCN in human victims. In the Columbia, Tennessee fire: This was a fire in which 42 victims were trapped in the jail. A cell padded with synthetic material caught on fire. The blood data we have on ten of the victims shows elevated COHb. We also have some fairly substantial blood cyanide levels (1.83 and 1.64 micrograms/cc). We also did soot scrapings from the trachea and bronchi. I would like to point out the very substantial levels of antimony. The question that was raised earlier about the significance of antimony in long-term toxicity data, that is, in terms of the recovery of the victims who have survived.

The materials we got from that padded cell were styrene-butadiene rubber, which had a very high concentration of zinc and a covering material of nylon over coated neoprene. The toxicity data suggested that there had to be at least one other material in that fire. We checked with the fire investigators who sent us these two materials: the antimony comes from the PVC that was treated with a fire retardant and chlorine also is derived from the PVC. The question that I am raising for your consideration is the significance of cyanide as compared to COHb.

Lyons: I heard today that at a level of about 50% COHb, one must expect fatalities much of the time. I was at a meeting in Arizona where I was argued out of that position. Some argued that it must be 70% COHb. Before we start talking about cyanide, we should agree what constitutes 95% probability of a fatality in terms of COHb.

Japanese: We were talking about toxicity of gases and the relation between time and concentration. Someone said that there is no relation there. I think that this is not an established fact at all times. However, in some limited areas it can be established. I say this because the objective of this Panel is to see what kind of gases are toxic in fires. This is different from the problem of air pollution. If there is a fire in a building, we have to get the poison gases out of that building. We have to think about toxicity over a very short period of time. According to what was on the blackboard it is only concentration that is the issue. Temperature and perhaps humidity can be a problem too. I think the time factor is, in a limited range, an important factor as well.

Alarie: I would agree that with a very limited range of concentration and time, the product would be a constant. But what most people have done is to extend the range much too far. In inhalation toxicity concentration is much more important than time. Concentration always dominates the picture, not time.

The way to get around the time problem is to fix the time. We should have a fire scenario which may be quite different for escape from an airplane, escape from a train, escape from a home, escape from a high-rise commercial building. We should say we want materials that if they burn, we want a probability that the individual can escape within one minute, three minutes, ten minutes, 30 minutes (whichever time you want to postulate). Then you test for the amount of smoke that you can tolerate within that fixed time. The way to rate the material is to fix the time and vary the concentration. What everybody is doing is to fix the concentration and then let time vary. This means that when they fix the concentration, they locate themselves somewhere in the fire because a fire will have a wide range of concentration from a very small amount of smoke to a huge amount of smoke. That is the wrong approach.

Einhorn: Commenting on Dr. Lyons' question, in 1963 Schulte reported 70% carboxyhemoglobin for death. Something we have seen in our animals and which Dr. Pettijohn has commented on is that there is an incapacitation level with CO and other materials. If you have a high concentration of CO in the lungs and breathing stops, there can still be a period of loading after "clinical death" which might be 50% or so and still continue to load carboxyhemoglobin because you still have a pulse rate. We have seen a few 70% COHb levels, but by and large 50-55% covers most of our deaths.

Berl: Many fire victims contain cyanide. Ingestion of CO alone is a very rare situation.

Einhorn: Unless you have a faulty furnace flue or a garage.

Chaiken: Can anybody say that fatalities or incapacitation in fires is due to CO + something else or can the findings be explained by CO alone?

Smith: I do not think they can be explained by CO alone. In the average fire death we may find 50, 55, 60% saturation. If you are thinking of pure CO, you had better think 75% COHb as death. There are other cooperating factors in the average house or vehicle fire death.

Chaiken: Is there anybody who can cite hard data for the fact that HCN can contribute to fire accidents and fire deaths?

Einhorn: From animal studies with pure CO, the COHb level at death was about $87 \pm 3 - 4\%$. In wood fires it was 65 - 67%. This is a significant difference. In pure CO, 65% COHb would not be the cause of death.

RECENT TEST RESULTS FROM THE FAA/NAFEC CABIN FIRE SAFETY PROGRAM

by

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It is believed that 15 - 20 percent of the fatalities in transport aircraft accidents die from fire. There is some evidence which suggests that in highly survivable impact accidents some of these victims may be dying from the hazards produced by burning cabin materials. The Federal Aviation Administration (FAA) has a major program in cabin fire safety, and it is now particularly attuned to the interior materials fire problem.

The FAA program is performed by three agency organizations: (1) the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, (2) the Civil Aeromedical Institute (CAMI) in Oklahoma City, and (3) the Systems Research and Development Service (SRDS), which is the Washington program office. About a year ago NAFEC and CAMI completed a cooperative study to evaluate the toxicity of 75 cabin materials. By testing a material under similar exposure conditions, toxicity was measured at CAMI by direct animal exposure and at NAFEC by chemical analysis of specific toxic gases collected in the combustion mixture. Presently, a study is underway to determine the correlation between the analytical and animal toxicity data. Another important study which was recently undertaken is the development of a combined hazard index (CHI) for cabin materials. This is a major contract awarded by SRDS to the Douglas Aircraft Co.. The goal of this study is to develop a methodology for ranking materials according to their total fire hazard, weighing the relative importance of flammability, smoke and toxicity in a single index.

The preceding very briefly describes only some of the CAMI and SRDS contributions to the FAA cabin fire safety program. The subject of this paper is recent experimental results from the NAFEC portion of the program.

First, an example of the problem - Figure 1 is the interior of a TWA 707. A sister ship of this aircraft suffered a low-impact, nose-hard landing and resulting cabin fire at Los Angeles International Airport on January 16, 1974. A photograph of the accident aircraft is shown in Figure 2. There was no fuel spillage in this accident yet the entire interior was gutted. The fire started at the collapsed nose wheel and initially consisted of burning hydraulic fuel and rubber. It then penetrated thru the floor into the cabin. Fortunately, there were no fatalities because the passenger loading was less than 50 percent and evacuation was rapid, estimated at less than 50 seconds. Note the much-more severe damage at the ceiling than at the floor. In the rear of the cabin, the vinyl coating at the ceiling is disintegrated

while the carpet is practically undamaged. Recent full-scale cabin fire test data described subsequently in this paper also indicates the significant differences in temperature between the floor and ceiling. The NAFEC program ultimately seeks to improve our understanding of the various events which occur in a postcrash cabin fire, and to develop fire tests for cabin materials that will allow confident selection of the safest materials.

The NAFEC FY-78 Cabin Fire Safety Program (Figure 3) is divided into four major efforts: the development of new or the improvement of available small-scale material fire tests for flammability, smoke and toxic gas emissions; the initiation and conducting of physical fire modeling studies; the measurement of full-scale cabin fire hazards in a wide body aircraft under realistic postcrash conditions; and the correlation of data from small-scale and large-scale material fire tests. The first three efforts are currently active while the lab/large-scale correlation effort is planned for next year.

In the area of laboratory fire testing of cabin materials, the greatest activity by far is in toxicity. The development of the combustion tube furnace is continuing. This is a pyrolysis test which was used to evaluate 75 cabin materials in the recent cooperative study with CAMI. The combustion tube furnace is being adapted to test composite samples and to study its feasibility for testing materials under flaming-combustion conditions. Concurrently, toxic gas sampling and chemical analysis methods and an animal exposure system for utilization in the C-133 full-scale tests are under development.

There are relatively modest efforts in flammability and smoke. In flammability, 20 inservice cabin materials are being evaluated by five popular test methods: the vertical Bunsen burner test, the E-162 Radiant Panel Test, thermogravimetric analysis and the rate of heat release apparatus. We are searching for the "next generation" flammability test that could conceivably someday supplement or perhaps replace the current vertical Bunsen burner method.

In the smoke area, several modifications have been made to the NBS smoke chamber, including installation of a variable radiant heater (capable of 10 Btu/ft.^{2}-sec), a laser transmissometer and a load cell for continually monitoring sample weight loss. The 20 materials mentioned above are currently under evaluation in the modified smoke chamber.

The second major effort of the NAFEC program is physical fire modeling. Work was begun in this area in the Summer of 1977. A modest contract was awarded to the Factory Mutual Research Corporation to evaluate the feasibility of pressure modeling vertical specimens, and to fire test at elevated pressures the previously mentioned cabin materials. At NAFEC, geometrically scaled modeling tests are in progress to study thermal radiation, flame penetration, and smoke and heat accumulation inside a cabin arising from an external fuel fire adjacent to a fuselage opening. This work is not Froude modeling per se, but is instead very exploratory scaling experiments in search of gross trends in support of full-scale tests.

The third major effort is the C-133 full-scale, wide body cabin fire test facility. The C-133 was created because there is an urgent need for full-scale fire testing, not just of aircraft cabins but of other environments as well. How else are we to learn what occurs in a real fire to enable us to propose fire safety improvements or solutions?

The C-133 effort is divided into three phases. The first phase is in progress and consists of determining the cabin fire hazards arising from an external fuel fire adjacent to an open door in an intact fuselage. We hope to understand from this work, for example, the relative importance in a fuel-dominant fire of heat, smoke, and toxic gases, or what bearing external winds have on the rate of cabin hazard buildup. The second phase, which is scheduled for the Summer, consists of determining for the same scenario the involvement and contribution of interior materials to the overall cabin fire hazard. The third phase consists of fire testing large samples as part of the lab/large-scale correlation studies. During the 1st and 2nd. phase tests in the C-133, the visibility of inservice and advanced emergency lighting systems will be studied under the realistic smoke conditions generated inside the C-133.

This summarizes the NAFEC FY-78 Cabin Fire Safety Program. Compared to past work in this area, a greater emphasis has been placed on full-scale testing and ultimately on the relationship of these results to laboratory tests. The remainder of the paper will describe some recent work and data.

In the lab test area, one of the flammability test methods under evaluation is the Ohio State Rate-of-Heat-Release Apparatus (Figure 4). A specimen is subjected to controlled, simulated fire exposure conditions and the combustion products are transported by a carrier

air stream up through a stack. Usually the temperature of the exhaust stream is measured to determine rate of heat evolution, although smoke and toxic gas emission measurements can also be taken. This test has a number of attractive features; namely, (1) capability of vertical and horizontal specimen orientation, (2) selection of incident heat flux from a range of values, (3) determination of release rate values, and (4) display of rate changes with time.

Figure 5 is a heat release rate history graph obtained for a wide body honeycomb ceiling panel tested in the Rate-of-Heat-Release Apparatus. Data is shown at two incident heat flux levels - 2.5 and 4.9 watts/cm^2. The discrete peaks indicate the involvement initially, of the decorative laminate or, later, the resin-impregnated fiberglas facing and honeycomb core. For the decorative laminate, the heat release rate curve is similar at both the high and low incident heat levels. For the fiberglas facing and honeycomb core, there is a gradually increasing but minimal production of heat at the low heat level. However, at the high heat level the facing and core ignite at about 30 seconds and release significant quantities of heat, in excess of that produced by the decorative laminate.

One of the major changes made at NAFEC to the NBS smoke chamber is the installation of a Mellon furnace capable of 10 Btu/ft .^{2}-sec. Figure 6 shows the heater in a calibration position. Since sample weight loss is also monitored using a load cell attached beneath the floor, the sample remains stationary during a test. A test begins by hydraulically sliding the heater, which is supported by two rods, in front of the sample holder. A shield prevents any heating of the sample during warmup and calibration of the furnace. Figure 7 is a photograph showing the heater positioned as during a test, except that the specimen holder was removed to allow observation of the heating coils. The heat shield is withdrawn at the initiation of a test simutaneously with the movement in place of the heater. The heat flux transducer for heater calibration is mounted on the back wall of the smoke chamber.

The following discussion describes preliminary data on four materials tested in the modified smoke chamber at different incident heat flux levels. Figure 8 is a plot of specific optical density or D_s versus time for a honeycomb sidewall panel at 2.2, 5, 7.5 and 10 Btu/ft .^{2}-sec. large increases in smoke production occur between 2.2 and 5 Btu/ft.^{2}-sec. or between 5 and 7.5 Btu/ft.^{2}-sec.. The smoke profiles are fairly close at 7.5 and 10 Btu/ft.^{2}-sec. The inflection points in the curves correspond to ignition of the specimen. Thus, for a honeycomb panel smoke production increases monotonically with incident heat flux.

Figure 9 is a similar plot for a urethane foam seat cushion. The results are opposite to those previously shown for a honeycomb panel. Smoke production decreases with incident heat flux for the urethane foam. However, the results are misleading because what happens during a test is that the foam melts and drips from the vertical specimen holder into a trough. The higher the incident heat, the faster the foam melts and the less time it is exposed to the high-flux radiant heat. Figure 10 describes the behavior of wool. In this case, the peak smoke production was attained at 5 Btu/ft.^{2}-sec.. The smoke produced at the two highest heat flux levels, 7.5 and 10 Btu/ft.^{2}-sec., was similar to each other (as was the case for the honeycomb panel), but was positioned between the 2.2 and 5 Btu/ft.^{2}-sec. values. Polysulfone, a fire-resistant thermoplastic which is under evaluation for use in aircraft, is similar to the honeycomb panel in that smoke production increases monotonically with incident heat. The increase in smoke production at the higher heat levels, compared to the "standard" NBS value of 2.2 Btu/ft.^{2}-sec., was clearly greatest for the polysulfone as compared to the previous materials. One possible reason is that polysulfone intumesces more at the higher heat flux levels, exposing the char to even higher heat flux levels which, of course, exist closer to the heater. Figure 12 is a bargraph which summarizes the previous smoke data. At 2.2 and 5 Btu/ft.^{2}-sec., the smokiest material was urethane foam, and the least-smokiest was polysulfone. However, at 7.5 and 10 Btu/ft.^{2}-sec. a complete reversal occurs in that polysulfone becomes the smokiest material. The least smokiest at 7.5 and 10 Btu/ft.^{2}-sec. is wool. Thus, smoke production clearly depends on the incident heat flux level, and this relationship depends on the nature of the material.

A photograph of the combustion tube furnace used for toxic gas emission testing is shown in Figure 13. It is a flow-through type of test and consists essentially of an annular furnace and temperature control module, a quartz combustion tube for accommodating the sample, a vacuum pump for drawing air through the system, a manifold for dividing and passing the combustion effluent into four fritted bubblers containing appropriate collection liquids, and a series of downstream rotameters and a single upstream rotameter for controlling air and effluent flow rates, respectively. The following test conditions are usually employed: Furnace temperature of 600^{o}C, sample weight of 250 milligrams, airflow rate of 2 liters/min. and test duration of 5 minutes.

Figure 14 contains the yields of carbon monoxide (CO) and hydrogen cyanide (HCN) for a series of aircraft cabin materials tested in the

tube furnace under the above conditions. The materials are arranged within each usage category in the order of decreasing toxicity, as measured at CAMI. For the fabrics, the highest CO yield was obtained from material No. 130, a cotton rayon blend, while the second and third highest CO yields were produced by cotton, No. 93, and rayon, No. 95, respectively. The modacrylic drape (No. 127) produced the highest yield of HCN of any of the materials tested. The wool (No. 88) and wool/nylon blends, Nos. 142 and 70, also produced high yields of HCN, second to the modacrylic in overall ranking. Note how the toxicity of the wools, Nos. 88, 140, 70, 82, and 96, decrease with decreasing HCN yield. The coated fabrics produced only CO and hydrogen chloride (HCR), in significant quantities, and the yields of these gases were inversely related. A direct relationship was apparent between toxicity and yield of CO. The flooring materials that produced the highest yields of CO were the structural floors constructed of Nomex honeycomb cores. The yields of HCN were greatest for the wool carpets, Nos. 33 and 34, although these were significantly lower than the wool upholstery fabrics. For the thermoplastics, the polycarbonates (Nos. 32, 116, and 113) produced the highest yields of CO of any of the materials, significant yields of hydrogen bromide (HBr) but no HCN. They were the most toxic thermoplastics. The ABS/PVC materials, Nos. 100, 107, and 85, produced much lower CO yields, high HCl yields, and relatively low HCN yields. The CO yields of the cargo liners varied from moderate to low, with only the polyester, No. 10, producing HCN. The toxicity was directly related to the yield of CO. For the transparencies, polycarbonate, No. 111, again produced the highest CO yield. Although the two polymethylmethacrylates produced much lower CO yields, the fire retardant material, No. 108, produced more than four times as much CO as the untreated material, No. 109. However, the untreated material produced an exceptionally high yield of formaldehyde.

Physical fire modeling tests are performed inside a building in order to obtain control over the fire and good test repeatability (Figure 15). Simulated ambient winds are produced by operating two large building exhaust fans which draw air through a slightly opened overhead door. Ducts of 4, 3, 2, and 1 foot diameters were tested to study the thermal radiation from an external fuel fire into a cabin opening. Figure 16 shows a fire test with a 4-foot duct. The fire is observed to attach to the duct and neck down to a size smaller than that of the pan. A 4-foot-square pan was necessary to completely mask the door from visual observation. Under quiescent wind conditions, the radiant heat flux at the duct symmetry plane was invariant for the four sizes

tested at a rough value of 1.7 Btu/ft.^{2}-sec.. For the 4-foot-square pan, the heat flux on the surface of the duct adjacent to the fire was about 12 Btu/ft.^{2}-sec.. A photograph of the inside of the 4-foot duct during a test under quiescent conditions is shown in Figure 17. The mechanical device provides remote traversing of a heat flux transducer at the symmetry plane. Very little flame penetration was observed, as shown, in tests without simulated ambient wind and with open-ended ducts.

The C-133 sencario consists of an airplane involved in a low-impact, highly-survivable crash resulting in an external fuel spill fire adjacent to an open door in an intact fuselage. Figure 18 is a photograph of a typical test. In order to control the degree of flame penetration into the cabin, a wooden barrier was erected to negate the effect of random ambient winds and a fan provides adjustable simulated wind. As shown in the photograph, even a fuel fire of moderate size (4 foot square in this instance) produces high flames and thick smoke, and would appear to be overwhelming. Larger and more realistic fires corresponding to much greater fuel spills would be even more imposing. However, based on other experiments and accident experiences, it appears that ambient wind velocity and opening area are more critical factors than the size of the fuel fire.

A drawing of the C-133 wide-body cabin fire test article is shown in Figure 19. The fuselage diameter of a C-133 is 200 inches, which is slightly smaller than that of a DC-10 (216 inches). Since the cargo deck is located much closer to the belly than in a commercial transport, an aluminum covered wooden floor was installed about 3 feet above the cargo floor in order to provide a wide-body type of contour. The installed floor extends from the cockpit bulkhead to the rear cargo ramp, a distance of about 76 feet. An 8-foot ceiling was also installed along the length of the installed floor. The calculated volume of the interior air space is 13,200 ft.^{3}, making the C-133 by far the largest test bed ever used for the study of cabin fires. Two standard wide-body type "A" door openings about 60 feet apart were cut along one side of the fuselage. During present testing, an external fuel fire has been placed adjacent to the forward door while the aft door allows for smoke and gases to exhaust into the atmosphere. In order to assure use of the test article for numerous fire tests, the aircraft interior was stripped of all combustible materials, covered with a noncombustible liner, and protected with a CO_2 fire suppression system, along with steel sheeting atop the fuselage skin surrounding the fire door, has provided a very durable test article. Almost 50 fuel fire tests have been conducted

without any significant damage except for extensive soot deposits.

The major emphasis of the present work is to attain repeatable results from replicate fire tests. This is a prerequisite for performing tests with a furnished interior in order to establish the hazards solely from the fire involvement of interior materials. Figure 20 is a temperature-time plot for five replicate tests at a cabin symmetry plane location 35 feet aft of the fire and 3.5 feet above the floor. The fan was set to produce an average simulated wind velocity at the fire door of about 6 mph. Two family of curves are evident in Figure 20. On one family, the flames continuously penetrated into the cabin, resulting in an ever increasing cabin temperature; however, for the other family, the flames penetrated for about a minute at the beginning of the test but later receded and the resulting cabin temperature leveled off. The two-family behavior was probably related to the ambient conditions, possibly in combination with the steel-covered wind barrier. However, no correlation could be made with measurements taken during each test of ambient wind speed and direction, temperature, and relative humidity. For this reason, the wind barrier and fan have been removed and testing is now underway with larger fires to determine if predictable and repeatable results are attainable with existing ambient winds. Nevertheless, the data obtained with the wind barrier and fan presented in this report provides useful information about the characteristics of a cabin fire.

There was significant stratification of heat, smoke, and gases in the cabin. A temperature-time plot at three symmetry plane elevations located 35 feet aft of the fire door is shown in Figure 21. At 5 feet 6 inches, near the head of a standing person, the temperature was considerably higher than at the lower levels, 3 feet 6 inches and 1 foot, closer to the head of a crawling person. For example, a temperature of 200°F was reached in 30 seconds at 5 feet 6 inches versus 2-1/2 minutes for the same temperature at 3 feet 6 inches. The cooler region near the floor is extensive, as evidenced by the two lower-level curves which are practically coincident over the first several minutes. This qualitative behavior appears to prevail through the cabin.

A better indication of the amount of heat stratification is provided by a vertical temperature profile. Such a symmetry plane profile at a station 35 feet aft of the fire is found in Figure 22 at various times into the test. At this station the hot ceiling gas layer extended at least 2-1/2 feet below the ceiling for the first 2 minutes of the test.

By 3 minutes the hot gases were clearly extending closer to the floor (note profile change at height of 3 feet and 6 inches between 2 and 3 minutes). Although only four data points were available to construct each profile, to some degree it appears as if the cabin environment is divided into two regions - a hot zone extending downward from the ceiling and a cool zone near the floor. To a first approximation, a two-zone model may be a good way of mathematically treating a cabin fire.

Figure 23 shows the carbon dioxide (CO_2) concentration history at 2 symmetry plane elevations located 35 feet aft of the fire. The CO_2 concentration is slightly higher at 7 feet 11 inches (1 inch below ceiling) than at 5 feet 6 inches. However, the degree of stratification of CO was far more significant at this station. The maximum CO concentration at the ceiling sampling location was approximately 0. 5 percent (or 5000 ppm). But at 5 feet and 6 inches CO was not detectable instrumentally with our gas analyzer (Beckman IR analyzer, Model 864) which has a threshold detection limit of less than 100 ppm. Thus, it appears that the degree of stratification of gases may be strongly related to molecular weight. The amount of oxygen (O_2) depletion at this station was found to be insignificant. As expected, the lowest O_2 concentration was detected near the ceiling, but never dropped below about 18 percent.

The previous discussion has concentrated on the changes in cabin environmental conditions with time or with vertical distance (stratification). However, in a realistic, full-scale fire test article such as the C-133, one expects and measures severe environmental changes along the path from the fire to the point of ventilation into the atmosphere. Figure 24 is a symmetry plane plot of the ceiling air temperature against distance from the fire, at various times into the test. Tremendous thermal gradients are evident with the greatest change occurring near the fire. Two characteristics of the thermal gradients are noteworthy. First, at any point in time during the test, the ceiling temperature at the fire is about 500 - 700°F higher than at the exhaust door. Secondly, the ceiling anywhere along the instrumented path is being exposed to air temperatures increasing at a rate on the order of about 100°F per minute.

For the fuel fire scenario studied, there are three important preliminary findings with regard to the cabin hazard characteristics:

(1) Significant stratification of heat, smoke, and toxic gases occur during a cabin fire.

(2) Heat and smoke individually are more hazardous than carbon monoxide in a cabin fire dominated by burning fuel.

(3) Oxygen depletion is insignificant if the cabin is ventilated.

Fig. 1 B 707 Cabin Interior

Fig. 2. Accident Aircraft Interior

NAFEC FY-78 CABIN FIRE SAFETY PROGRAM

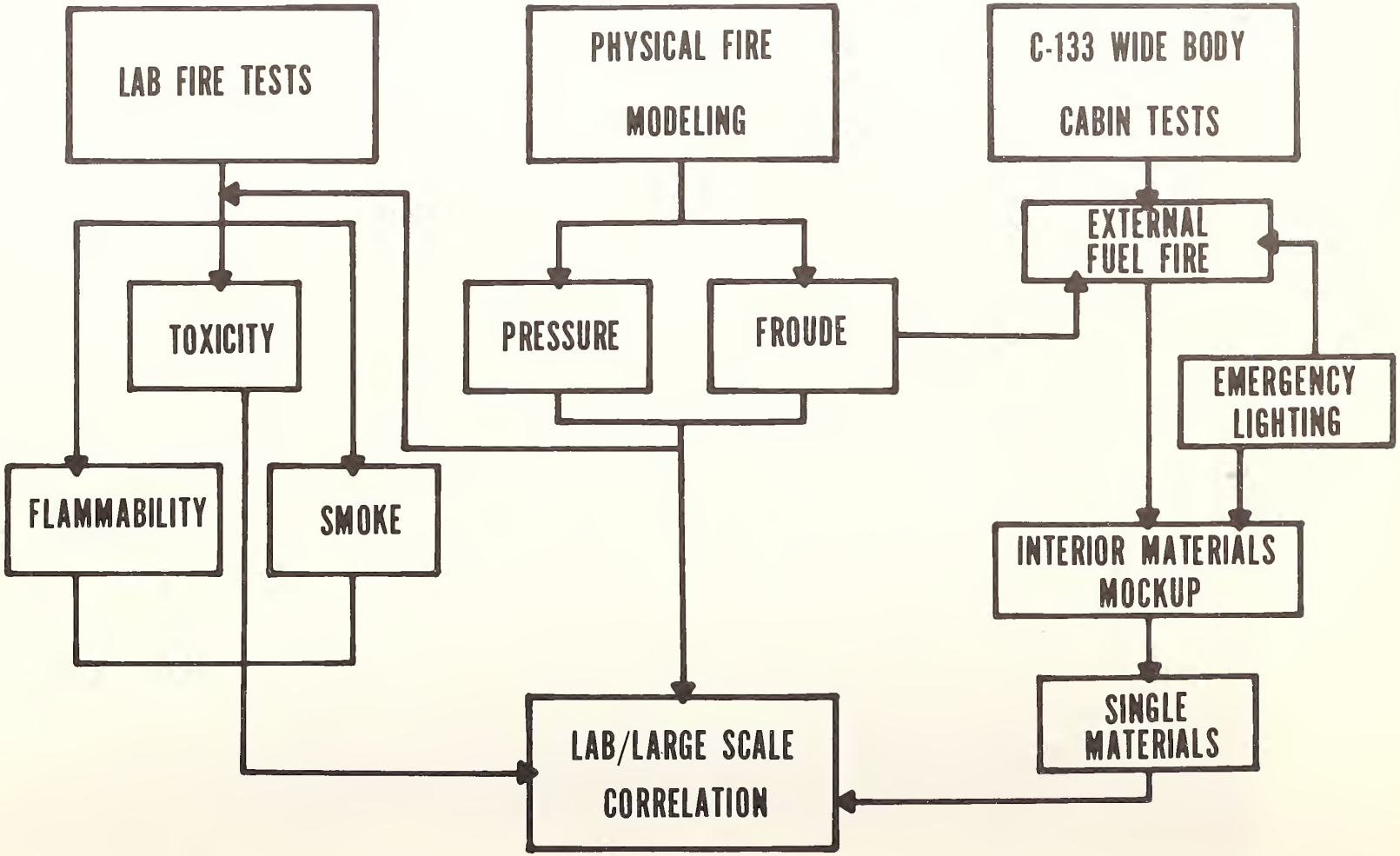
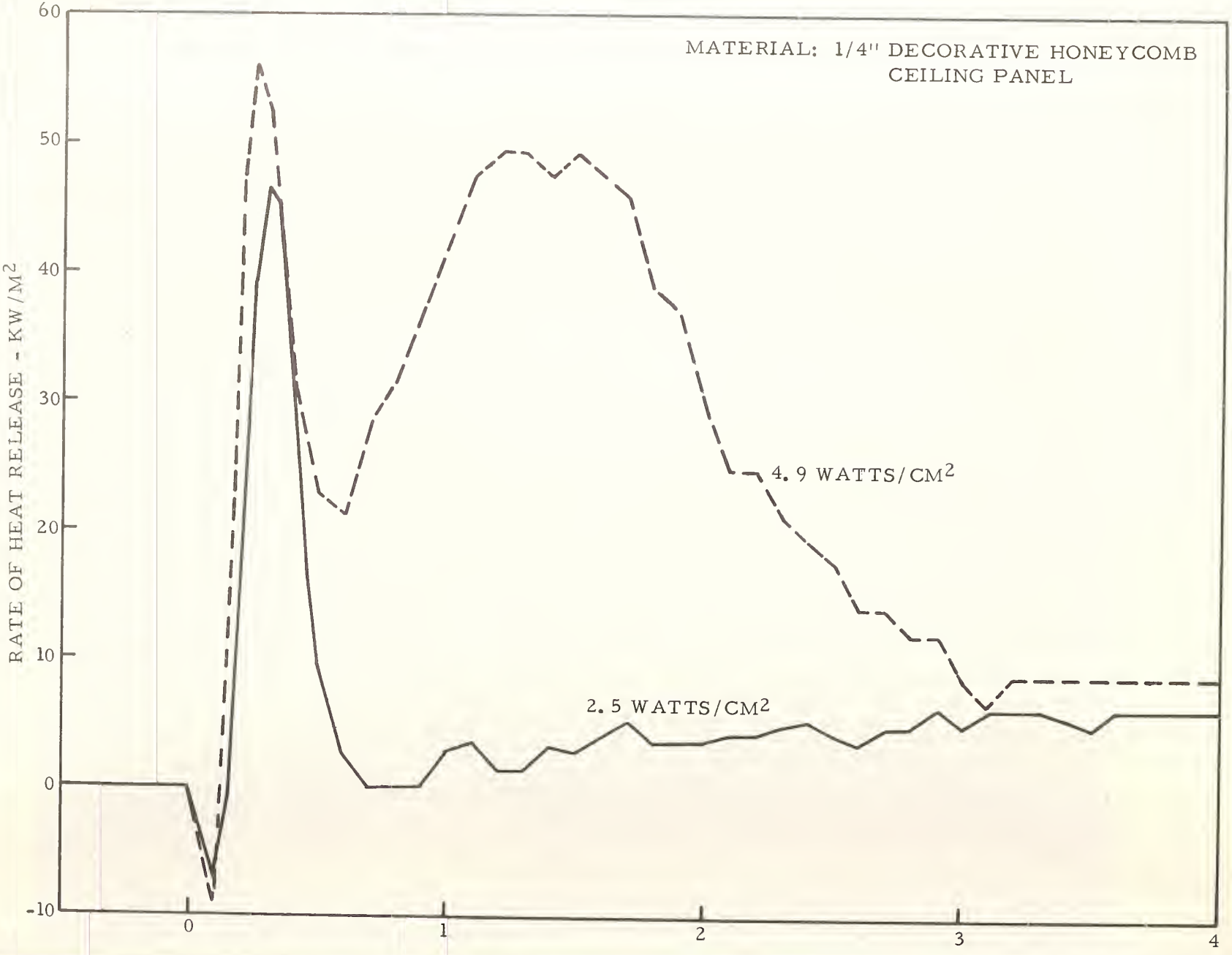


Fig. 3

Fig. 4. Ohio State Rate of Heat Release Apparatus


MATERIAL: 1/4" DECORATIVE HONEYCOMB CEILING PANEL
RATE OF HEAT RELEASE - KW/M2
60
50
40
30
20
10
0
-10
0
1
2
3
4
4.9 WATTS/CM2
2.5 WATTS/CM2

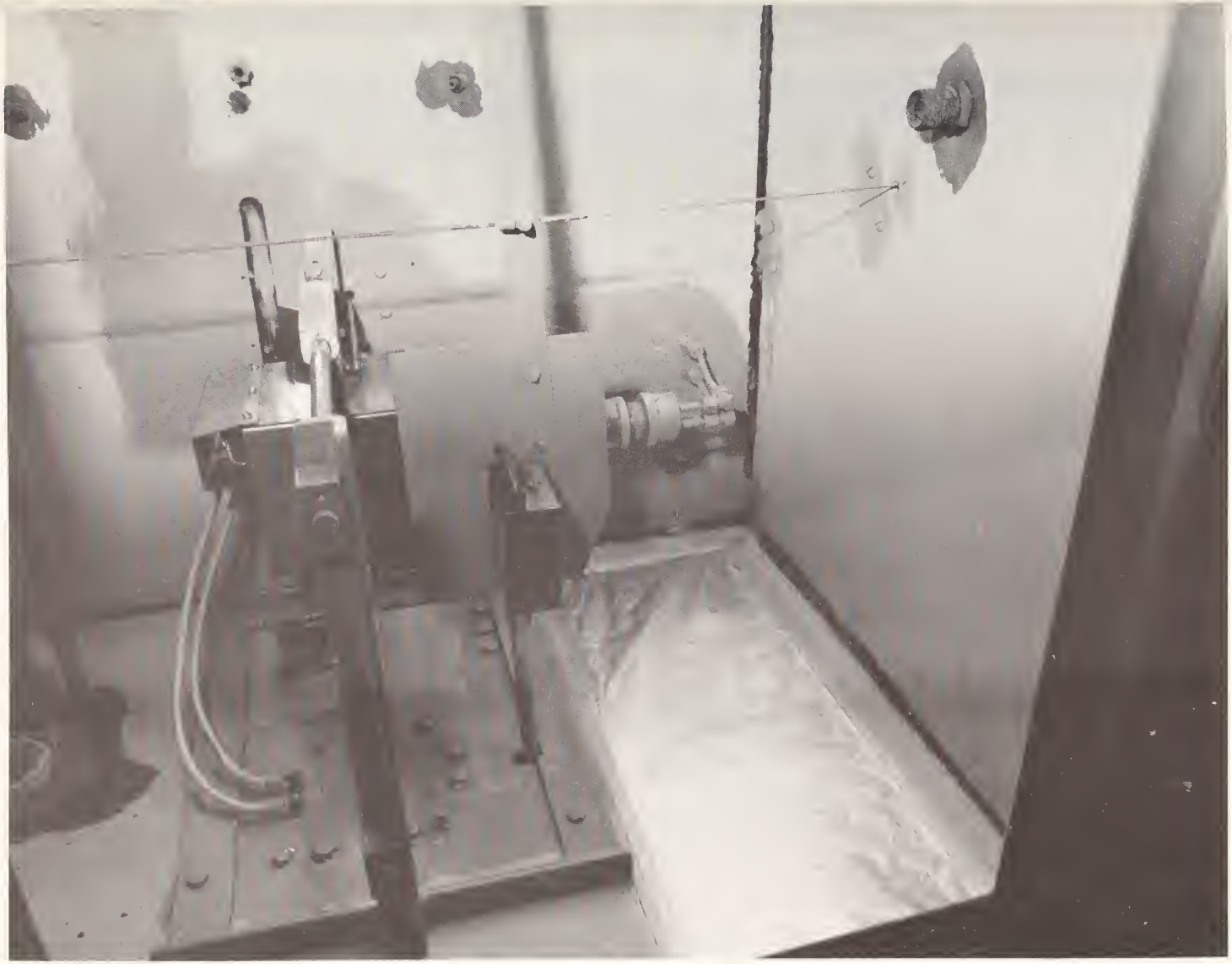


Fig. 6. Modified Smoke Chamber with Heater in Calibration Position

Fig. 7. Modified Smoke Chamber with Heater in Test Position

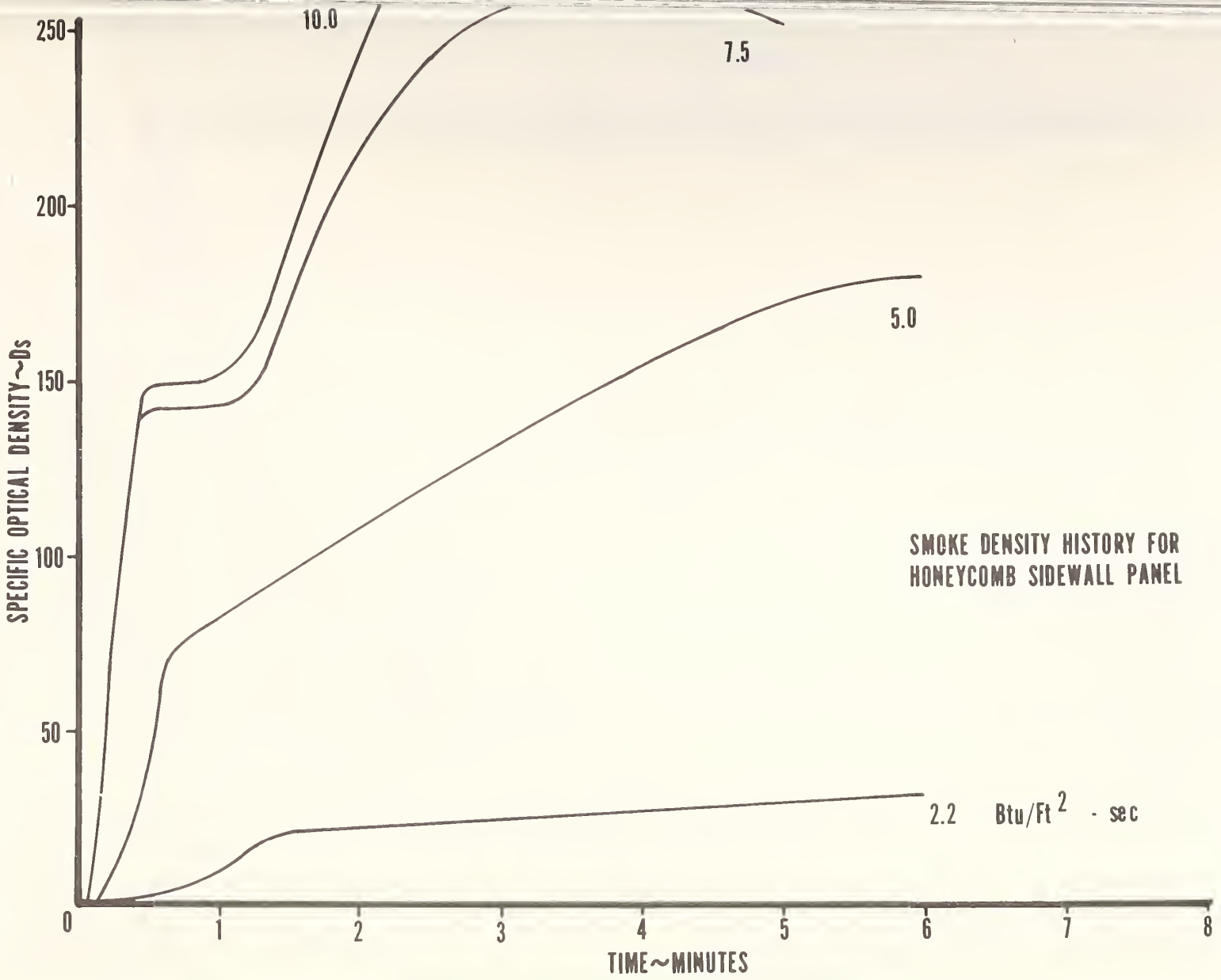
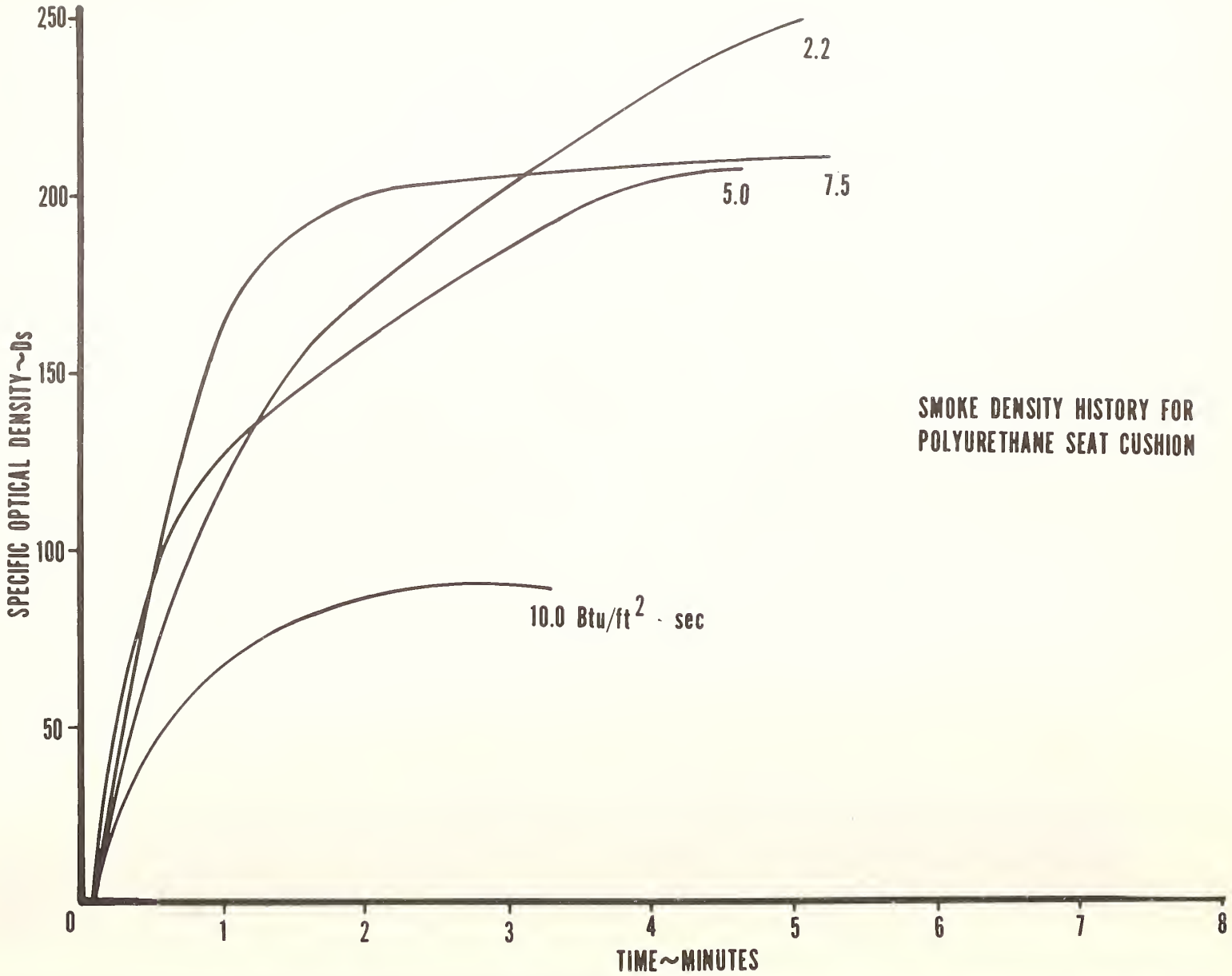

10.0
7.5
5.0
2.2 Btu/Ft 2 - sec
SMOKE DENSITY HISTORY FOR
HONEYCOMB SIDEWALL PANEL
SPECIFIC OPTICAL DENSITY~Ds
250
200
150
100
50
0
1
2
3
4
5
6
7
8
TIME~MINUTES

Fig. 8



SMOKE DENSITY HISTORY FOR
POLYURETHANE SEAT CUSHION

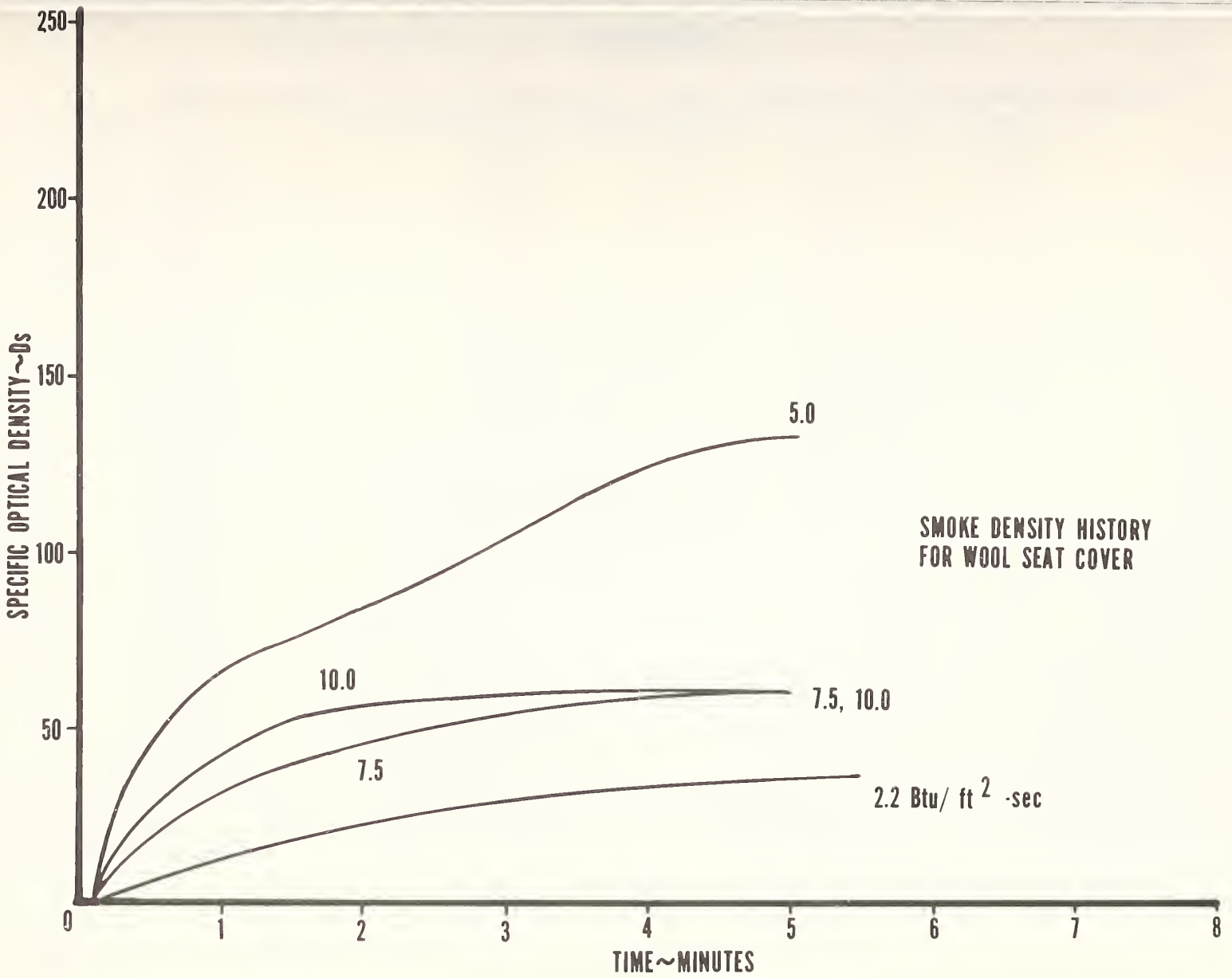
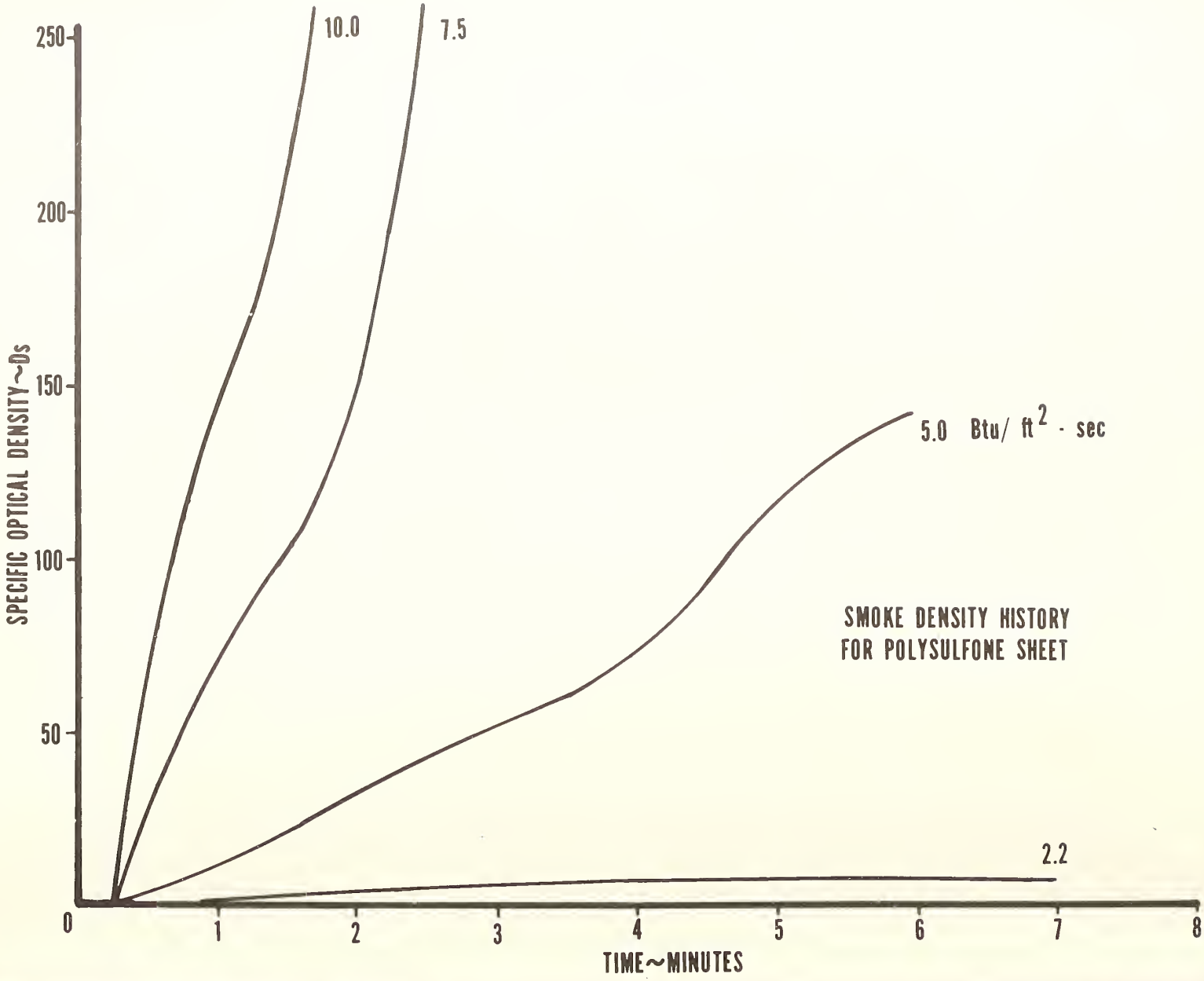

SPECIFIC OPTICAL DENSITY~Ds
250
200
150
100
50
0
1
2
3
4
5
6
7
8
TIME~MINUTES
5.0
10.0
7.5, 10.0
7.5
2.2 Btu/ ft 2 -sec
SMOKE DENSITY HISTORY
FOR WOOL SEAT COVER

Fig. 10


250
200
150
100
50
0
SPECIFIC OPTICAL DENSITY~Ds
10.0
7.5
5.0 Btu/ ft 2 - sec
2.2
SMOKE DENSITY HISTORY
FOR POLYSULFONE SHEET
1
2
3
4
5
6
7
8
TIME~MINUTES

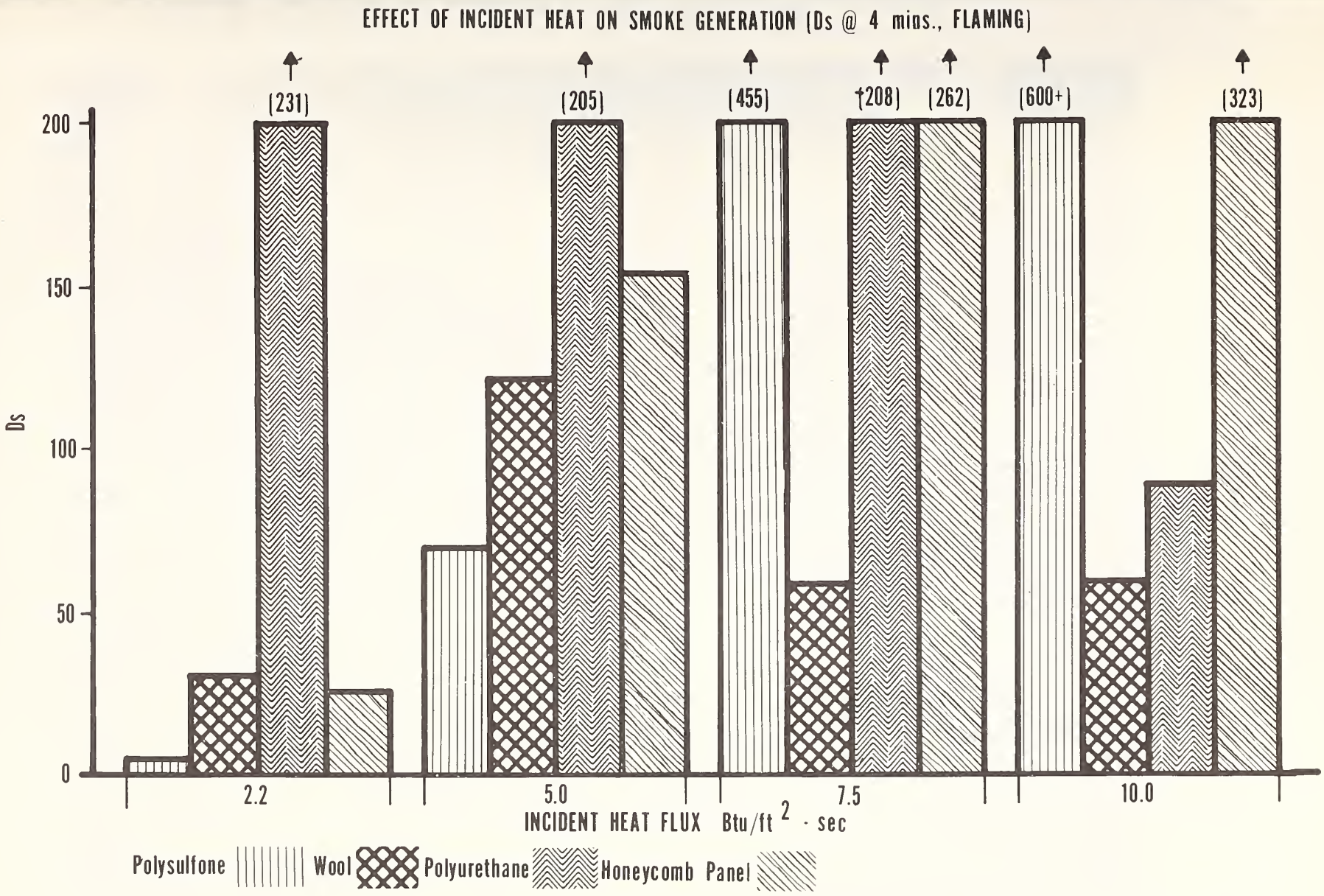

EFFECT OF INCIDENT HEAT ON SMOKE GENERATION (Ds @ 4 mins., FLAMING)
(231)
(205)
(455)
†208)
(262)
(600+)
(323)
200
150
100
50
0
Ds
2.2
5.0
7.5
10.0
INCIDENT HEAT FLUX Btu/ft 2 · sec
Polysulfone
Wool
Polyurethane
Honeycomb Panel

Fig. 12

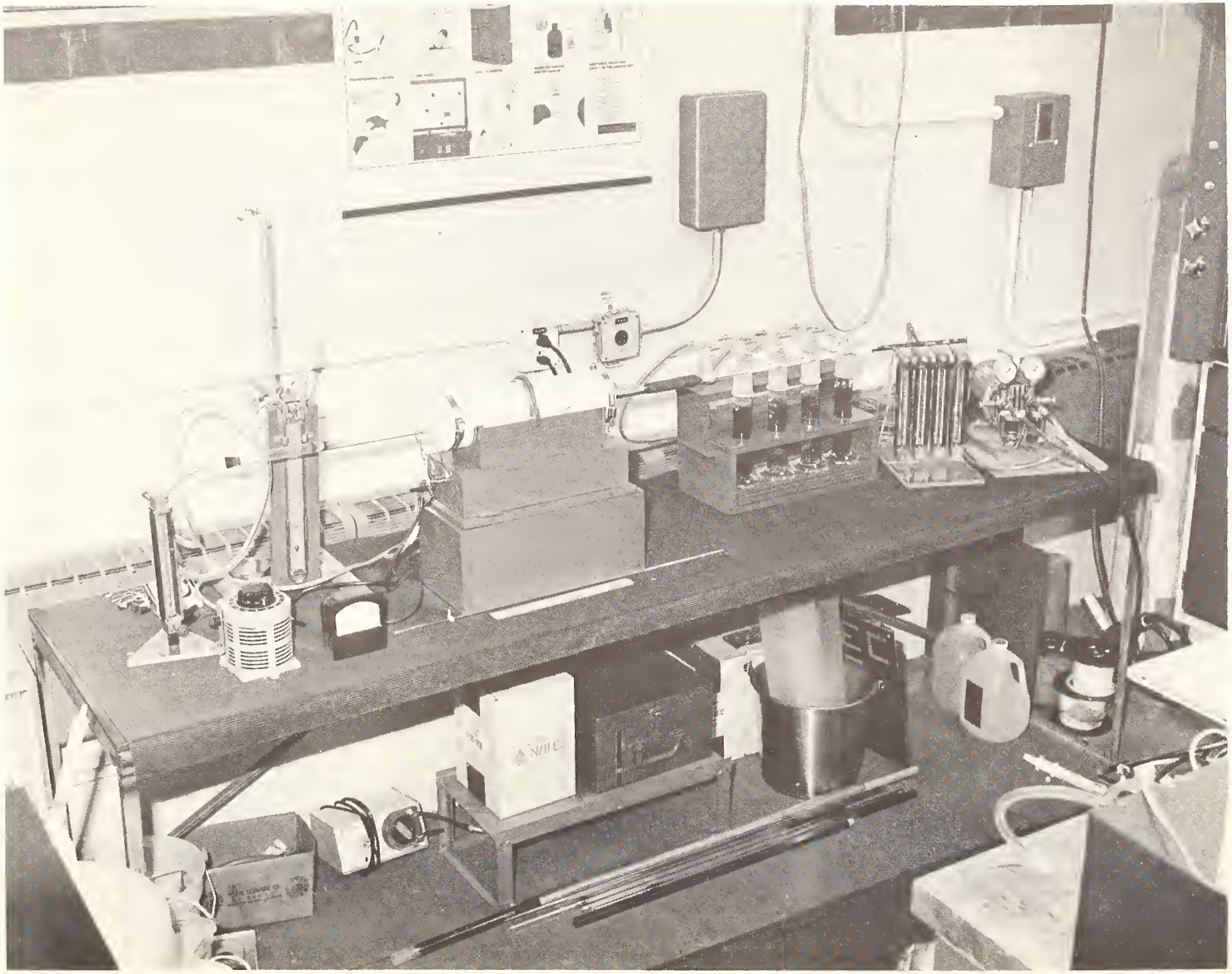


Fig. 13. Combustion Tube Furnace Test for Generation Toxic Gas Emissions

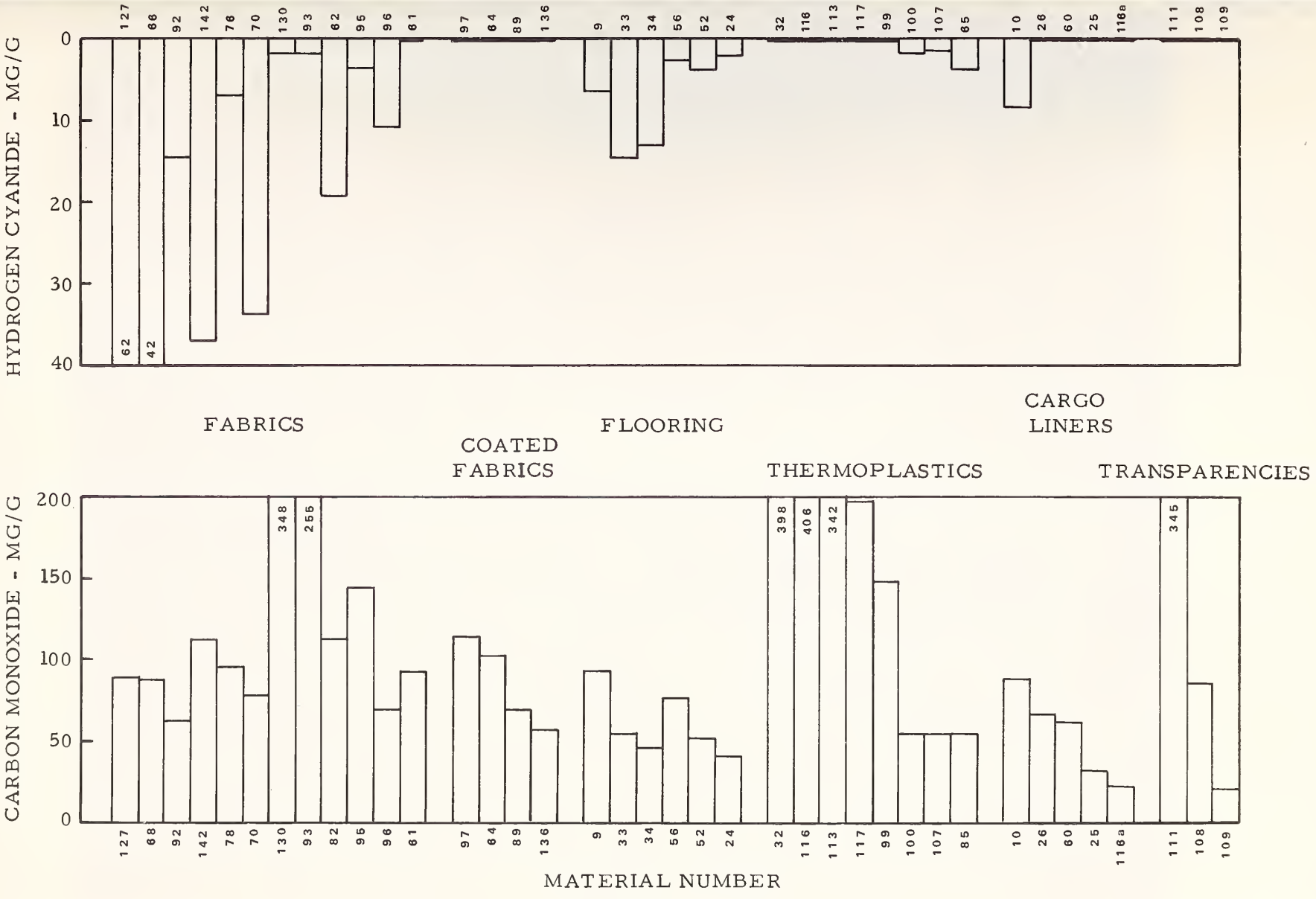

HYDROGEN CYANIDE - MG/G
0
10
20
30
40
127 66 92 142 78 70 130 93 82 95 96 61 97 64 89 136 9 33 34 56 52 24 32 116 113 117 99 100 107 85 10 26 60 25 116a 111 108 109
62
42
FABRICS
COATED FABRICS
FLOORING
CARGO LINERS
THERMOPLASTICS
TRANSPARENCIES
CARBON MONOXIDE - MG/G
200
150
100
50
0
348
255
398
406
342
345
MATERIAL NUMBER

Fig. 14

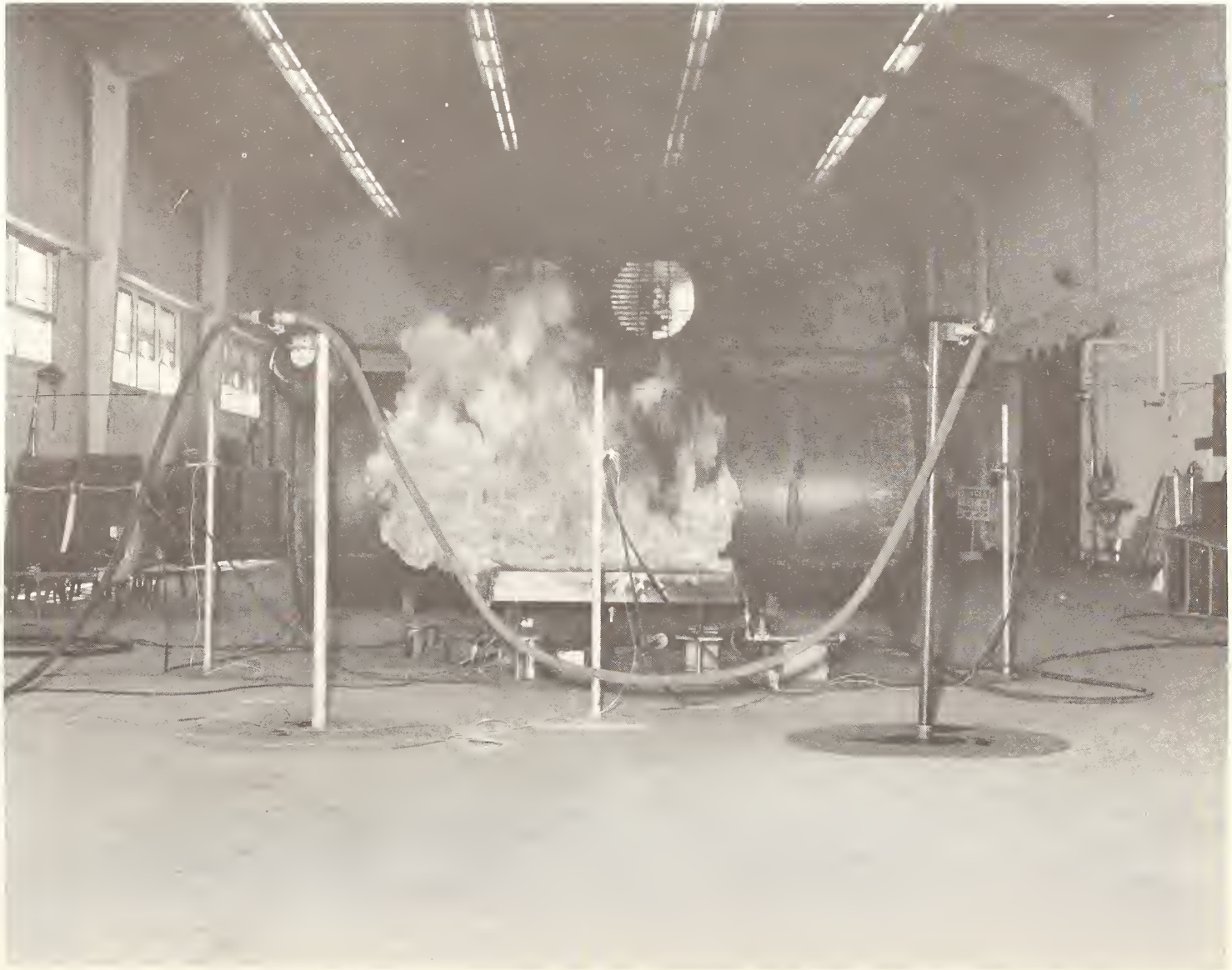


Fig. 15. Physical Fire Modeling Test Building

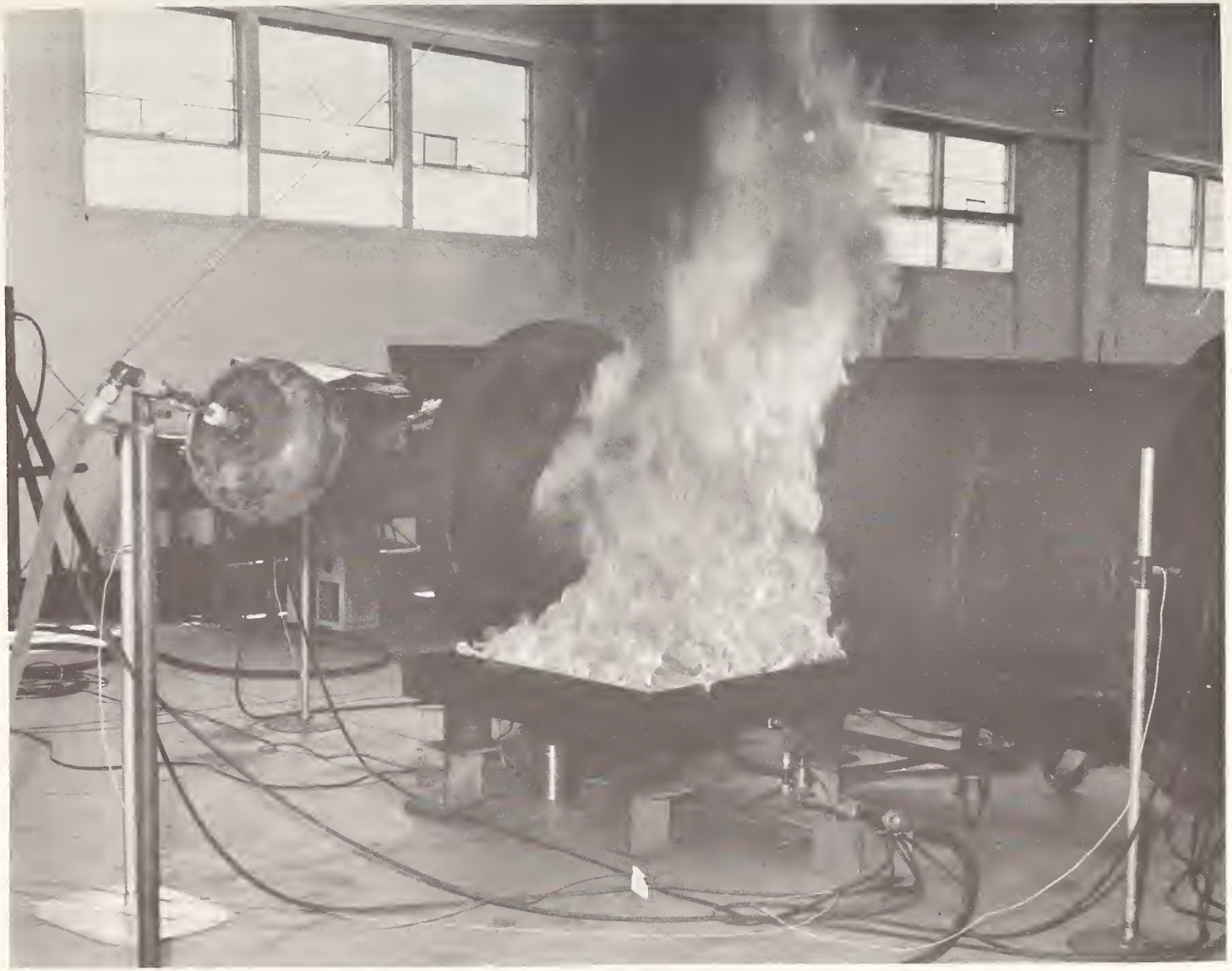


Fig. 16. Typical Modeling Fire Test without Wind

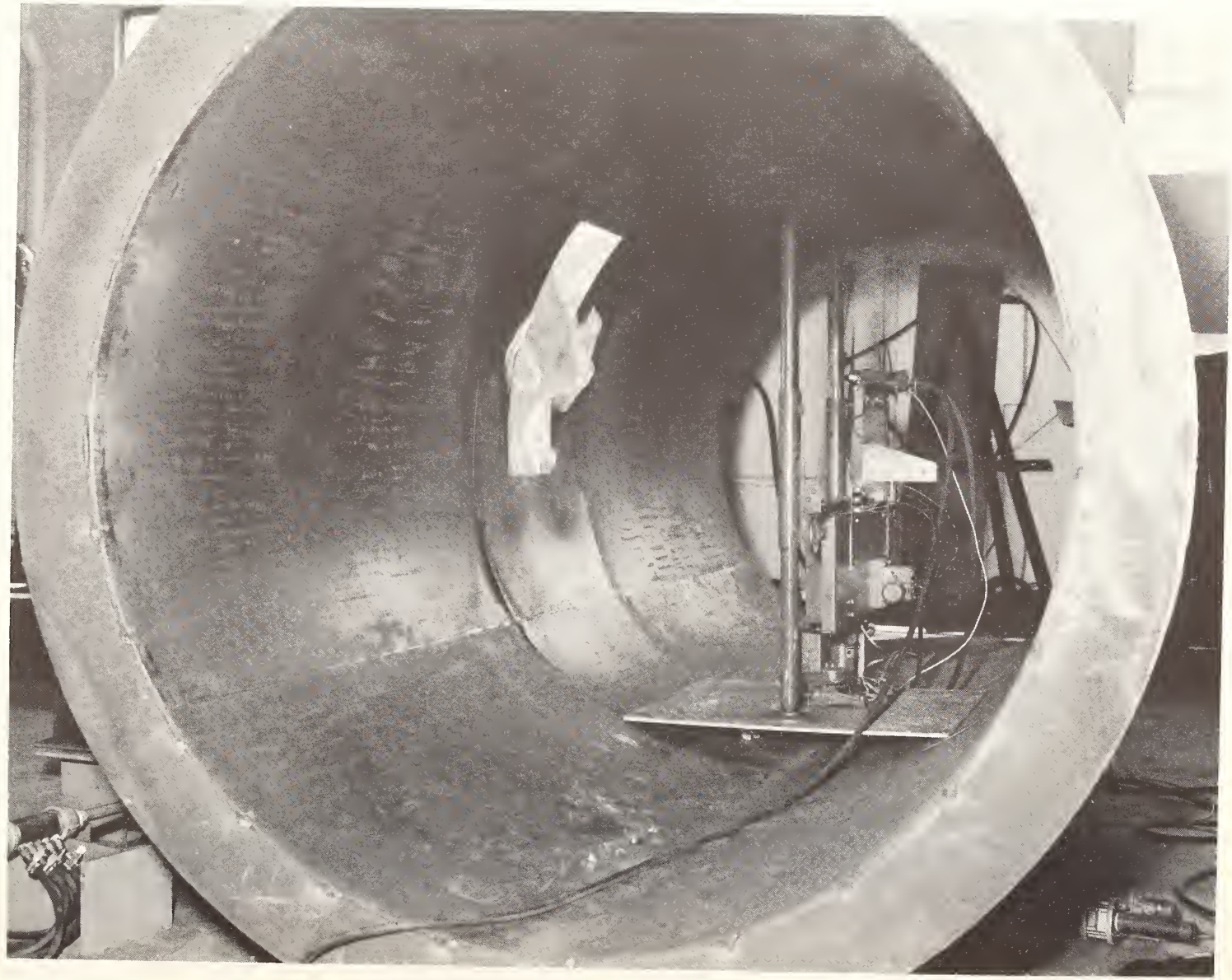


Fig. 17. Interior View of Duct During Typical Test without Wind

Fig. 18. C-133 Wide Body Cabin Fire Test

C-133 WIDE BODY CABIN FIRE TEST ARTICLE

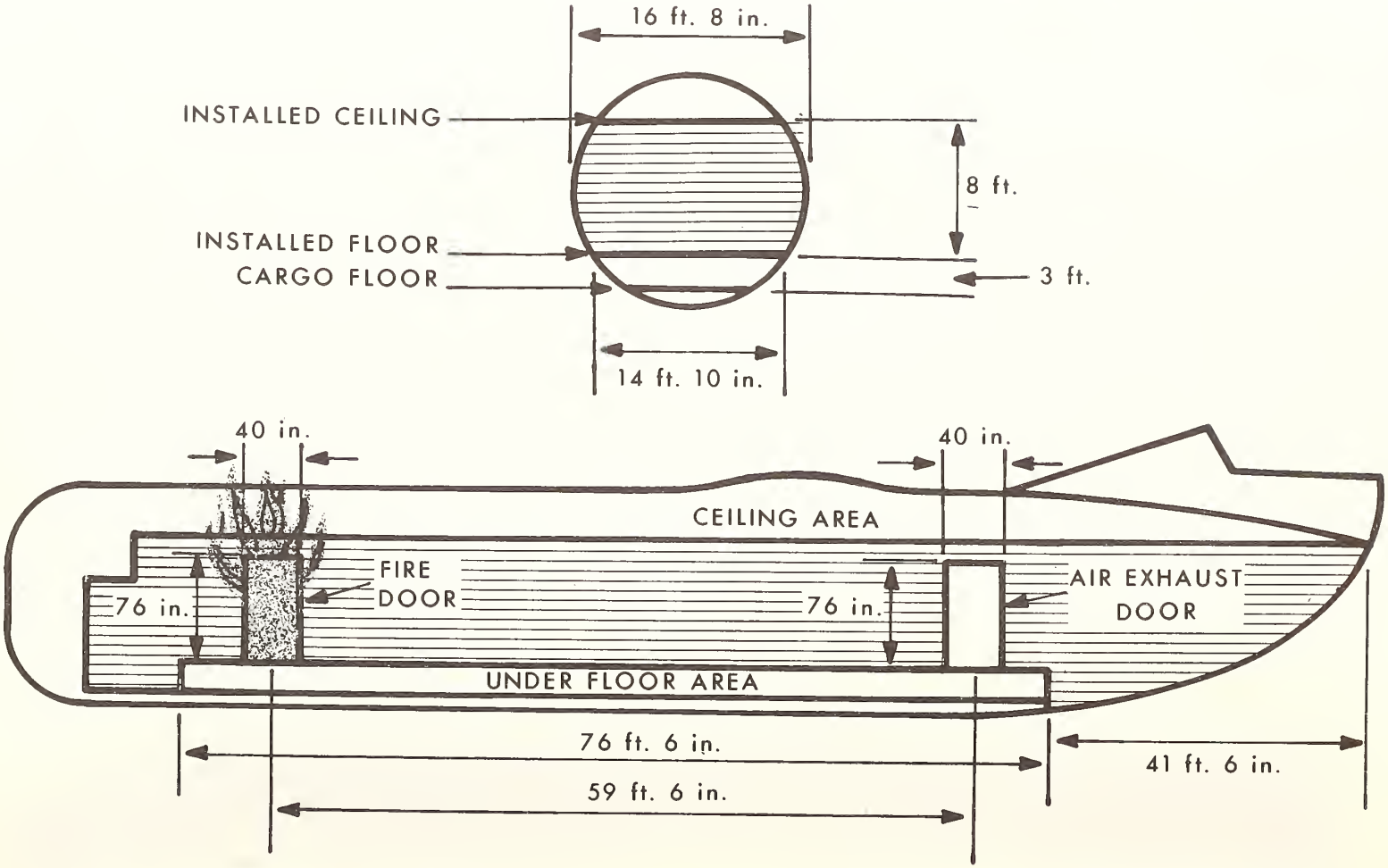


Fig. 19.

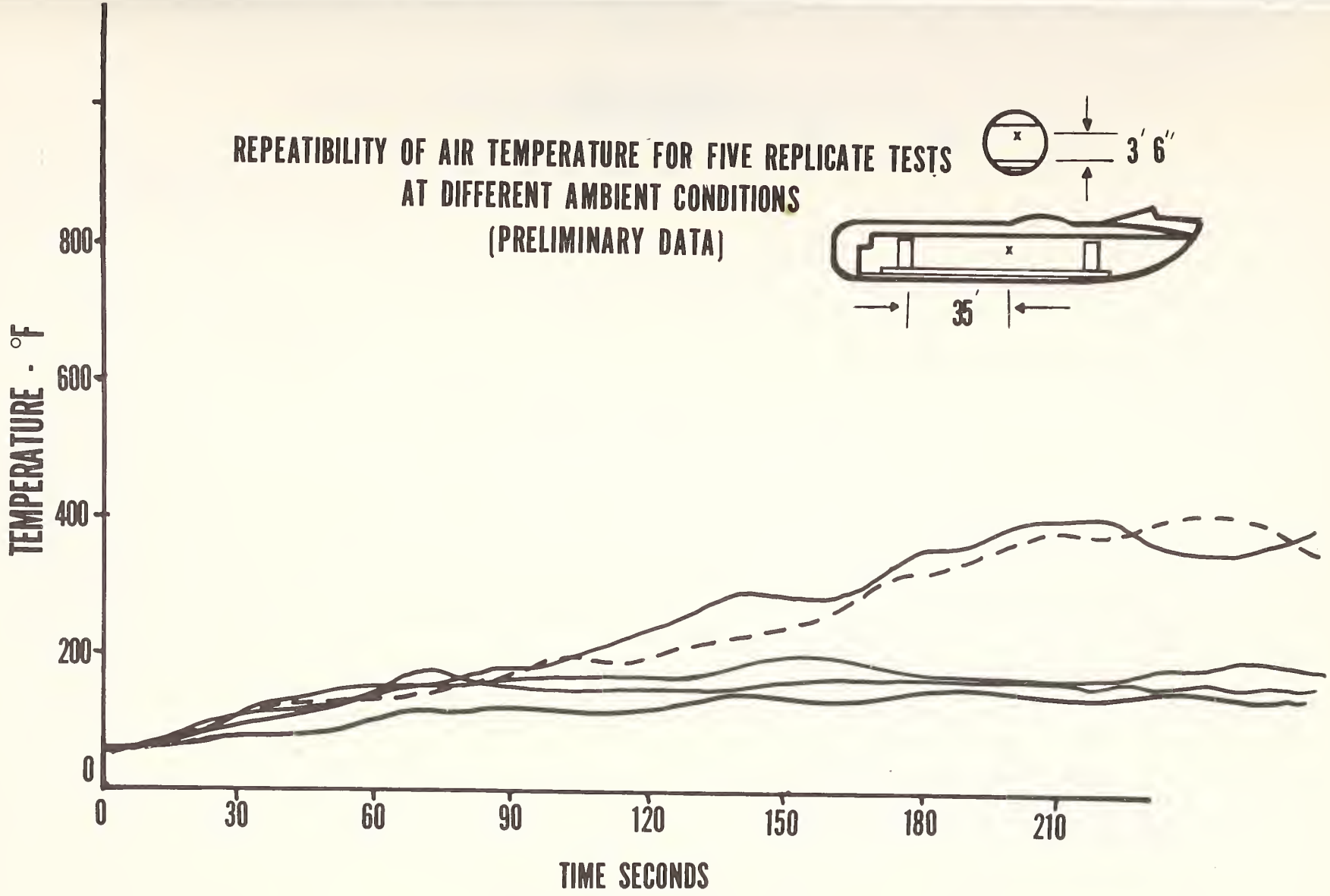

REPEATABILITY OF AIR TEMPERATURE FOR FIVE REPLICATE TESTS
AT DIFFERENT AMBIENT CONDITIONS
(PRELIMINARY DATA)
3' 6"
35'
TEMPERATURE - °F
800
600
400
200
0
0
30
60
90
120
150
180
210
TIME SECONDS

Fig. 20

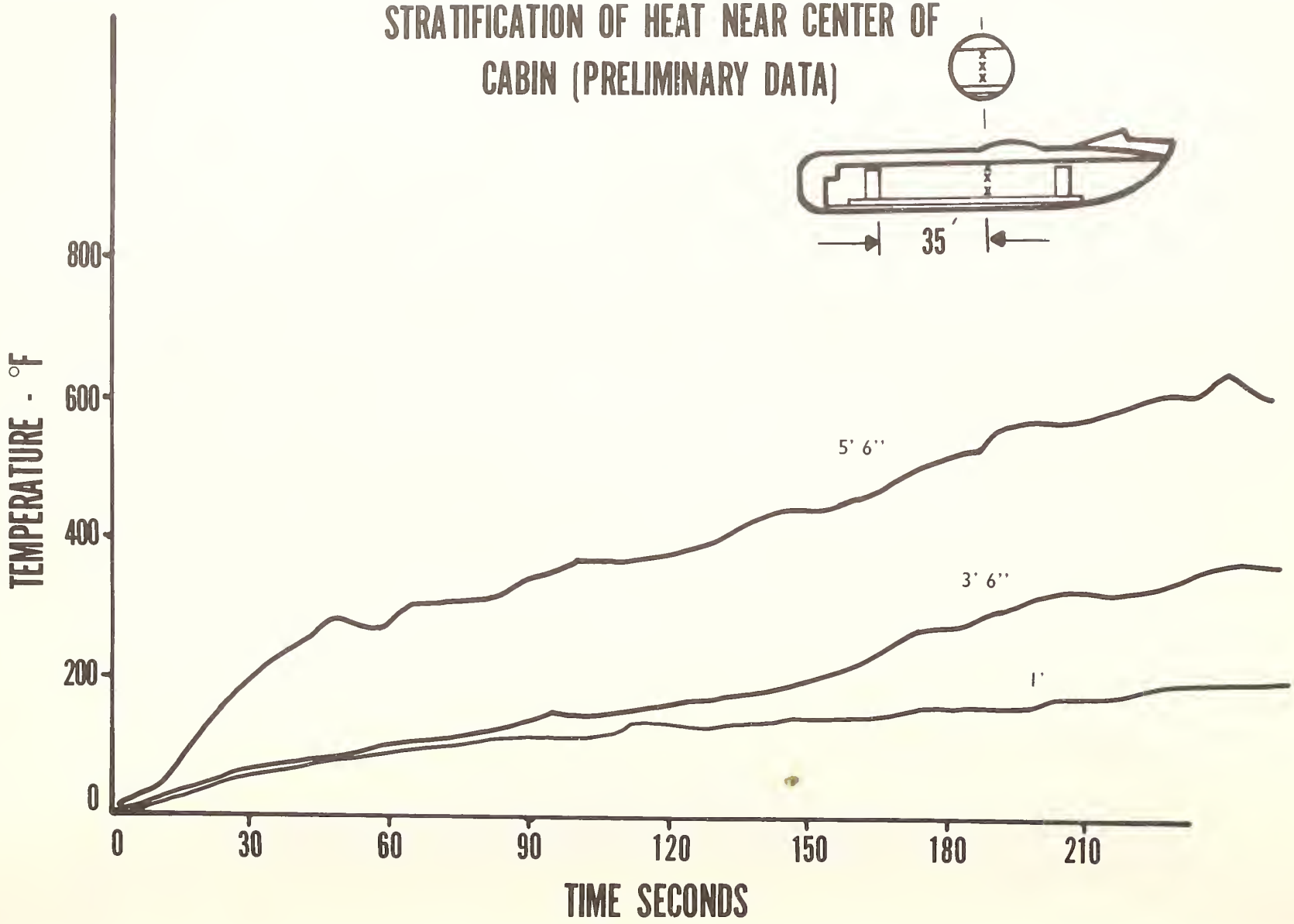

STRATIFICATION OF HEAT NEAR CENTER OF CABIN (PRELIMINARY DATA)
35'
TEMPERATURE - °F
800
600
400
200
0
5' 6"
3' 6"
1'
0
30
60
90
120
150
180
210
TIME SECONDS

Fig. 21

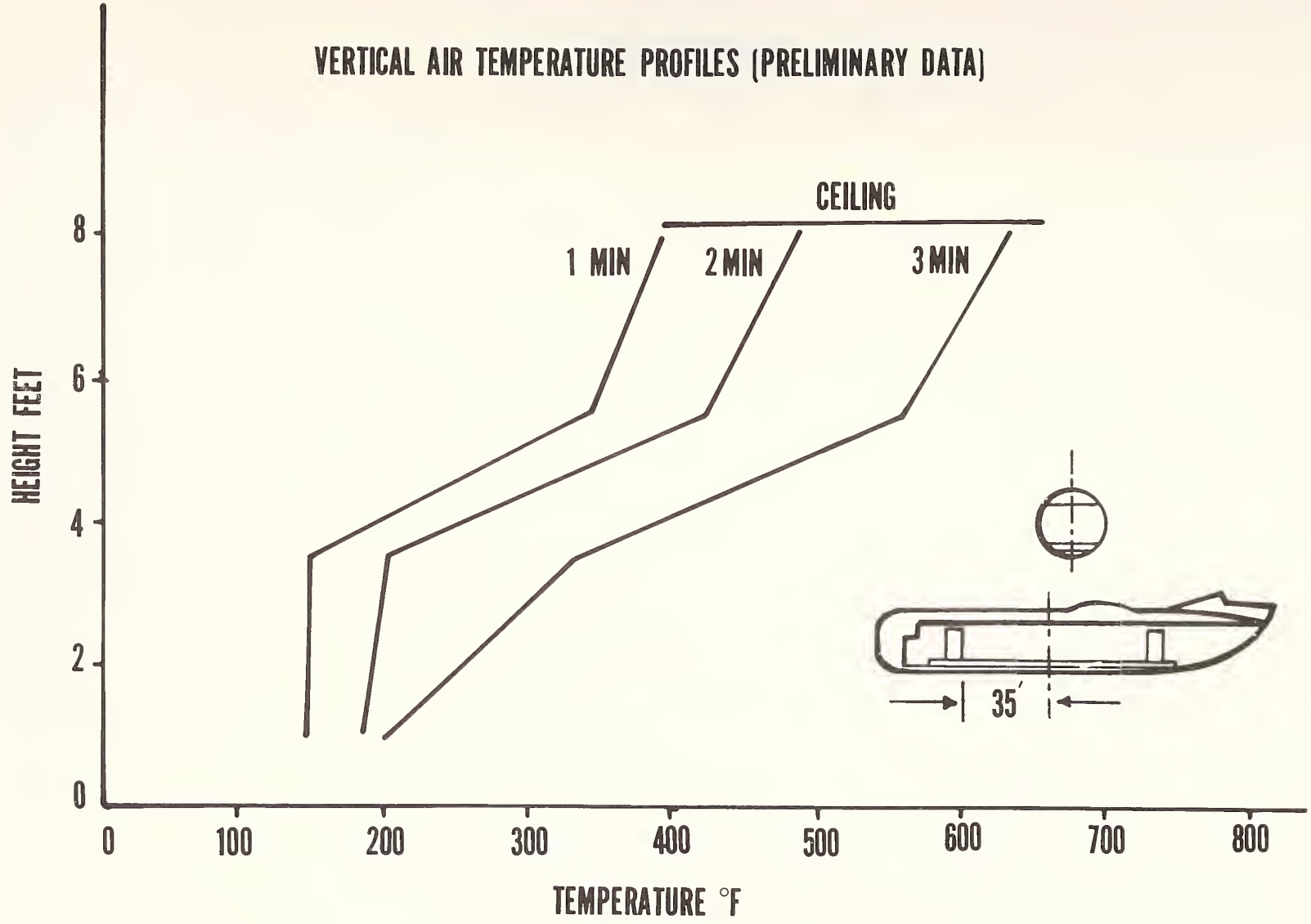

VERTICAL AIR TEMPERATURE PROFILES (PRELIMINARY DATA)
CEILING
1 MIN
2 MIN
3 MIN
HEIGHT FEET
0
2
4
6
8
0
100
200
300
400
500
600
700
800
TEMPERATURE °F
35'

Fig. 22

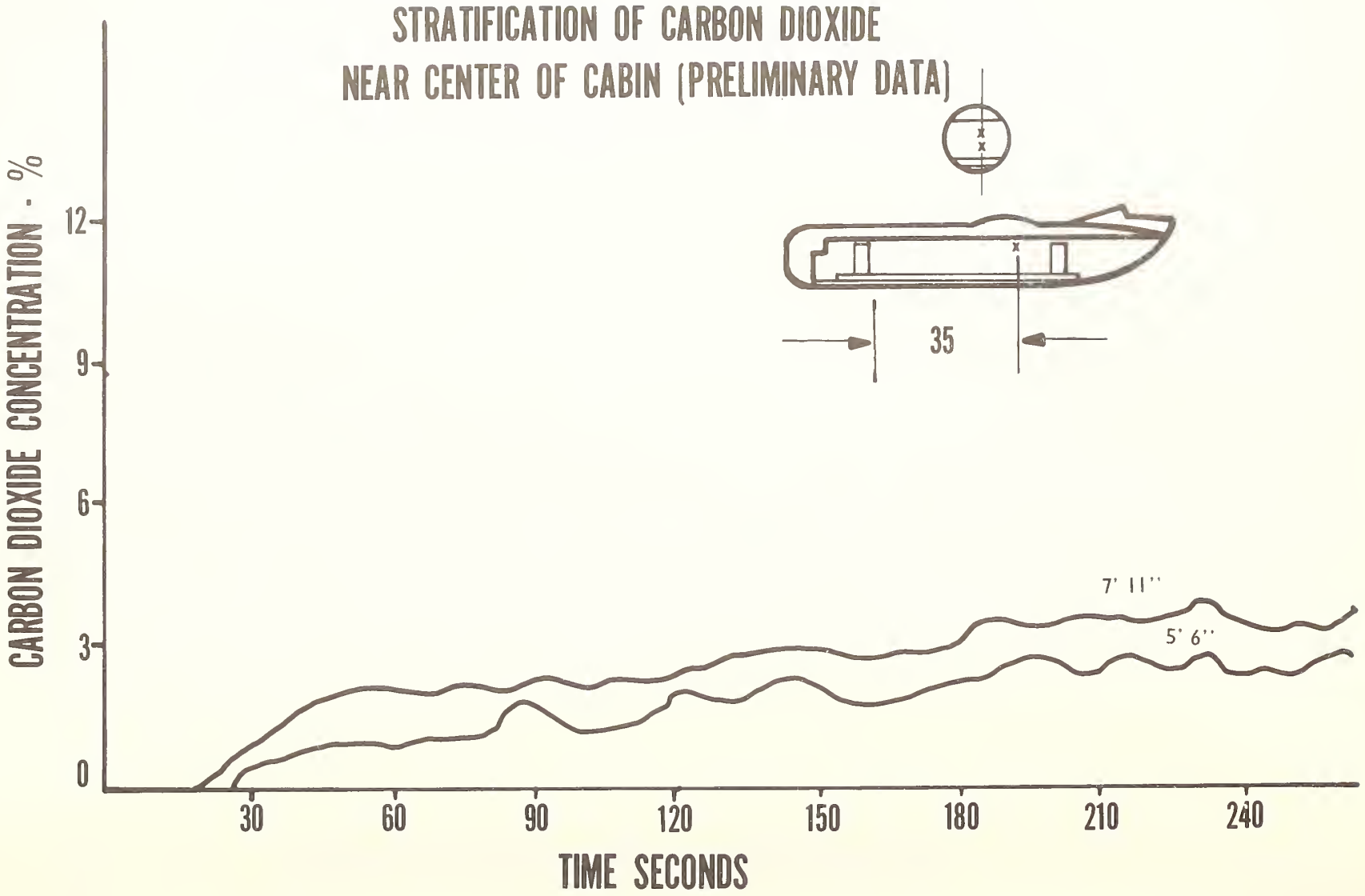

STRATIFICATION OF CARBON DIOXIDE
NEAR CENTER OF CABIN (PRELIMINARY DATA)
CARBON DIOXIDE CONCENTRATION - %
12
9
6
3
0
35
7' 11''
5' 6''
30
60
90
120
150
180
210
240
TIME SECONDS

Fig. 23

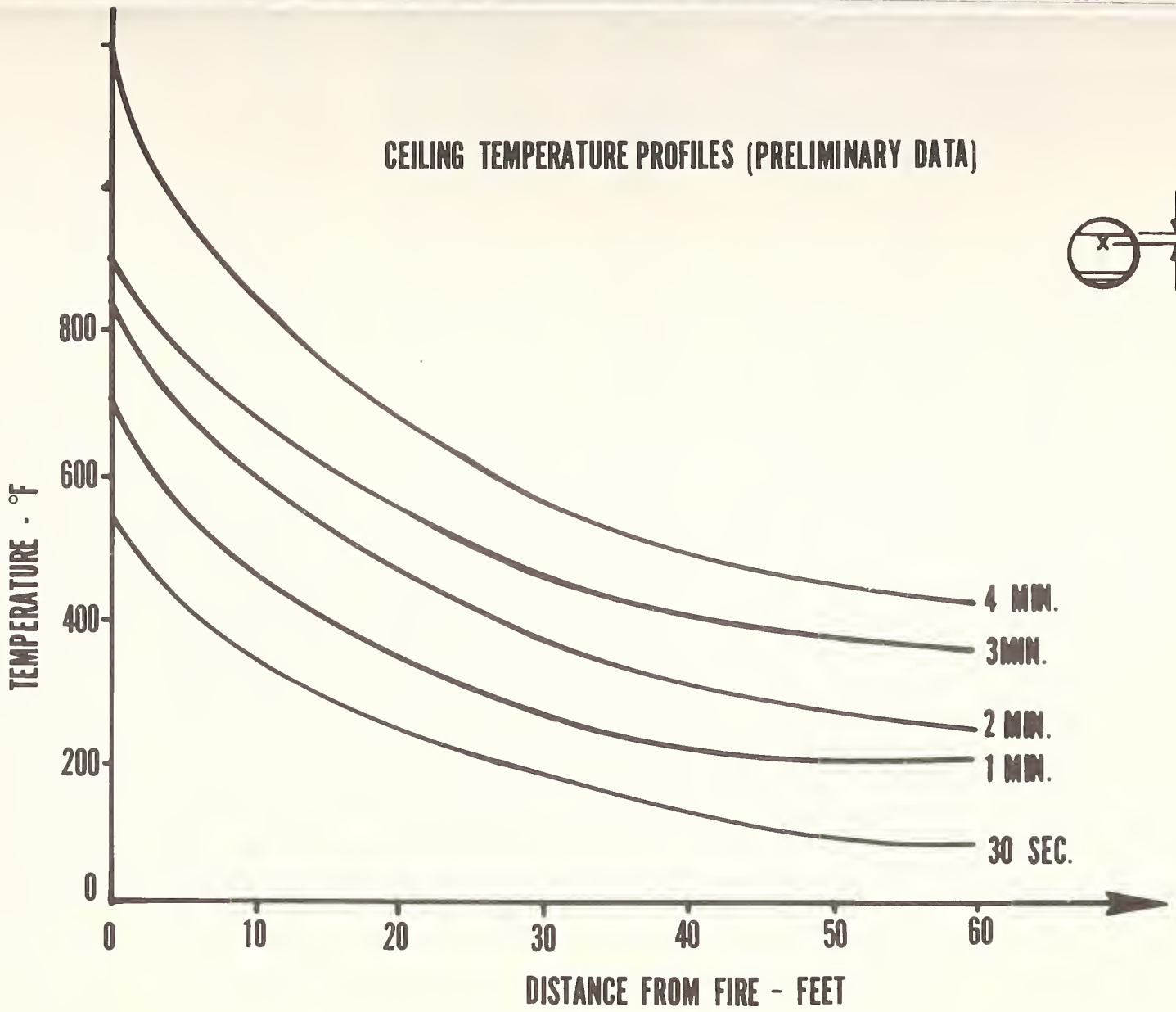

CEILING TEMPERATURE PROFILES (PRELIMINARY DATA)
TEMPERATURE - °F
800
600
400
200
0
0
10
20
30
40
50
60
DISTANCE FROM FIRE - FEET
4 MIN.
3MIN.
2 MIN.
1 MIN.
30 SEC.
X
1"

Fig. 24

BRIEF COMMENTS ON FIRE RESEARCH AT THE U. S. BUREAU OF MINES

by

Robert F. Chaiken

Pittsburgh Mining and Safety Research Center
Bureau of Mines, U. S. Department of the Interior
Pittsburgh, Pennsylvania

Fire represents one of the two most probable causes of major mine disasters (defined by five or more fatalities) in underground mining in the United States. Fortunately, the incidence of reportable mine fires has declined since 1970; however, the potential for a major mine fire disaster is ever present, as evidenced by the Sunshine silver mine fire in 1972 where 91 miners perished. In addition to the potential hazards to underground personnel, fire represents significant production and financial loss, even today, due to the required sealing of working sections or even the entire mine.

With the advent of the Coal Mine Health and Safety Act of 1969, the U. S. Bureau of Mines has greatly expanded their research and development activities to improve overall mine safety with fire and explosion prevention being just one aspect of this work. In the fire safety area our objectives can be categorized in terms of:

1. Regulatory Criteria - Working with the Mine Safety and Health Administration (MSHA), we evaluate available detection and extinguishment hardware; evaluate and improve flammability tests for approval and certification purposes; evaluate inspection dust sampling techniques, fill gaps in existing data; demonstrate the feasibility of applying state-of-the-art fire protection systems to mining; and provide technical backup to MSHA during accident investigations.

2. Improved Safety Techniques - We search for new methodologies for detecting flames and incipient fires, seek to develop and justify small-scale flammability tests by observations of small and full-scale fire tests; develop flameproofing systems and nonflammable materials; develop remote sealing techniques and criteria for safe re-opening of a mine after a fire; and seek new extinguishing agents for underground use.

3. Systems Analysis - Determine basic parameters such as quenching diameter for coal dust-air flames, which determines the applicability of pneumatic transport of coal; the spontaneous combustion of eastern and western coals, which relates to the development of mining methods and ventilation plans for these future coal mines; the combustibility and toxicity hazards of mine materials, which relates to the entire spectrum of fire scaling; the influence of ventilation on mine fires, which relates to the development of improved analyses of ventilation networks and escape plans.

It is well beyond the scope of this brief presentation to discuss all of these fire related R&D activities, but it should be noted that some of our current research into fire ignition,detection, propagation and extinguishment should have direct application to the fire problem in large office buildings. In many ways an office building does resemble an underground mine with its interconnected system of ventilated rooms and corridors - generally single level in the case of a coal mine and multilevel in the case of a metal and non-metal mine. The mine fire hazards may be somewhat more severe due to the industrial activity that takes place along with heavy fuel loadings (e.g., timber, oil, plastics and coal itself) and long and tortuous escape routes. In most instances major fire fighting techniques can only be mounted from the surface.

The early detection of fires is believed to be extremely important, particularly the detection of incipient fire conditions associated with spontaneous combustion ignitions. The measurement of low levels of CO and submicron particles combined with multi-tube bundle gas sampling techniques appears to be a very useful approach in this regard.

The concept of ventilation control of mine fires is also under investigation; however, the propagating mine fire, its spread rate, its heat and fume production and its effect on mine ventilation is extremely complex. Combined theoretical and experimental studies of fires in wood and coal lined tunnels ranging from 1 ft^2 to 64 ft^2 cross-section are currently being carried out to identify and quantify the various fire hazards, as well as to develop appropriate scaling laws for predicting the influence of mine fires on mine ventilation networks.

A significant aspect of all this fire research is a thorough understanding of the material properties (as distinguished from environmental factors) that determine the materials' combustibility. To this end, the pyrolysis of various woods and coals is being investigated under fire-level surface heat flux (i.e., 1 to 3 cal/cm^2-sec) using a laser heating technique. Pertinent parameters such as the rate of gaseous fuel generation as a function of incident and absorbed heat flux are determined directly. Such studies already have given us insight into how to improve the fire resistance of wood surfaces.

The progress which has been made in the above fire research is well documented in the more than 30 publications which have been prepared by Bureau investigators since 1969. The reader is cordially invited to contact the Pittsburgh Mining and Safety Research Center for further details on our past and current fire research program.

INSTRUMENTATION FOR THE SIZE DETERMINATION OF SUBMICRON PARTICULATES SYSTEMS BY SIDEWAY LIGHT SCATTERING METHOD AND THE CHARACTERISTICS OF SMOKES FROM POLYMERIZED MATERIALS IN FIRE.

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ABSTRACT

The handy submicron level particle counter using low output He-Ne laser (unpolarized, 8mW) has been designed for in situ measurements on the basis of the response calculations and the experimental checks on factors governing the signal to noise ratio level. The sideway light scattering system at right angle is the most available optical system in excluding the miscellaneous contributions to noise level and the primary component in enhancing the noise level comes from the carrier gas. However, the present instrument with 9-steps for channel isolation is so aligned to minimize the noise level primarily by reducing the sensing volume in terms of squeezing the beam diameter and the slit width. When necessary, it can detect the particulate down to 0.07 μm by controling the nozzle. Finally, the instrument can actually cover the correct size distribution from 0.1 to 10 μm without detectable coincidence loss under the environmental particulate concentration up to 5×10^4 particulates per cm^3.

The high concentration measurement can be acheived up to 1×10^{13} particulates/m^3 on the basis of a derived equation for the first order correction of the coincidence loss and cross-channel sensitivity due to the counting loss, while the critical concentration of the instrument with a few coincidence loss can ordinarily reach 5×10^{10} particulates/m^3. When applied to the measurement of polypropylene's smoke, a good coincidence was obtained between the scattering cross sections from the observed turbidities and those calculated from the size distribution in terms of the correction of the coincidence loss and etc. On this basis, the turbidities of several smokes and their stepwise coagulation are characterized by the change in their size distributions.

INTRODUCTION

Light scattering have provided available informations in determining particle size and particle number concentration for various aerosols and particularily its utility is characterized in situ measurement of the objective systems continuously and automatically on real time basis. Generally, the performance of the instrument or the experimental apparatus is governed by the following three characteristics: (1) The resolution power on particle size and high precision in the resolution. (2) The critical concentration in excluding the coincidence loss. (3) The minimum detectable particle size.

Recently, we are enforced to live or work under dust-polluted environments and those dust within particle size ranging from 0.05 to 5 μm are generally believed to interact with our lung organs.[1] Besides the study in the hygienic field, it seems likely that the study on the size distribution of aerosols has become the topics in many fields for the solution of the problems induced by particulates. To satisfy such requisition, the handy instrument available for in situ measurements and of high resolution power with minimum detectable particle size of at least 0.1 μm is now demanded. The minimum detectable size of the commercially available particle counters remains presently at 0.3 μm[2,3] and therefore, they are insuf-

ficient to satisfy the minimum limit of the aforesaid need for the measurement on the size distribution of particulates ranging from 0.1 to 5 μm. The minimum detectable size by light scattering method reported in the literature up to 1975 is 0.176 μm.[1,4,5]

For the detection of particulates with their size below 0.176 μm, Schiel had pointed out the possibility in detecting the particle of polystyrene latex particle down to 0.109 μm by his apparatus.[3] Gravatt had also suggested the possibility in detecting particles with diameter ranging from 0.05 to 0.2 μm by attaching his special device to the apparatus.[1] However, in reality, there is no indication of any literatures reporting the actual detection of very fine particulates of 0.1 μm diameter by light scattering method, in so far as my literature survey is concerned. In 1976, Roth et al. succeded in detecting the very fine particulates of diameter down to 0.07 μm by their light scattering particle counter using Ar^+ laser with high power output of 2 W.[6] However, it seems likely that the state of the art of the apparatus with Ar^+ laser of such highpowered output must be not portable and handy. Therefore, the measurement by using such apparatus intrinsically meet much difficulties for the in situ measurements of fine particulates in the actual environments of the fields.

Part I THE INSTRUMENTATION OF THE OPTICAL COUNTER FOR SUBMICRON SIZE PARTICULATES.

The purpose of the present research is firstly to explore the possibility in the development of the techinique for the portable and handy light scattering particulates counter which is available for the in situ measurement on the size distribution of particulates in the actual environments in every field. Secondaly, to pursue the properties of combustion dusts from chimney, automotive engine, fire and etc.

The new particle sizing instrument satisfying the said requisition is composed on the light source with multimode, unpolarized He-Ne laser of 8 mW output, the especially designed scattering cell connected to the flow system for the sampling, detecting system, and signal processing system with nine channels for the illustration of the size-distribution. The minimum detectable size of this counter is presently set to achieve submicron size detection down to 0.1 μm and to illustrate the size distribution of particulates covering 0.1 to 10 μm in diam. Therefore, the present counter is available for determining the size distribution of particulates in situ and their monitoring in the actual environments covering every fields such as the monitoring of dusts in semiconductor factory, computer room, air pollution by engine dust or by fall-out from factory chimney, the smokes in the earlier stage of the fire in the building and tunnels where the behaviours of small particulates are concerned.

The present investigation is pursued by taking steps

of the following four phases of studies: (1) Theoretical consideration regarding the evaluation on the magnitude of factors contributing to S/N ratio in the light scattering particle sizing instrument, (2) Improvements on the promotion of S/N ratio, (3) Instrumentation and the experimental check on the precision in the performance of the instrument by using standard uniform latex particles, (4) In situ measurements on the size distribution of combustion dusts of various relative refractive indices in different actual environments of the fields and the evaluation on their precisions.

I. THEORETICAL CONSIDERATIONS

A. Numerical Computation

The scattering intensities from single spherical particles of diameter ranging from 0.1 to 10 μm are computed on the basis of the Mie theory for various refractive indices m.[7,8] The scattering intensity $I(r, \theta, \phi)$ at observation point $P(r, \theta, \phi)$ from single spherical particles with m by linearly polarized plane wave in x-direction and with wave vector in z-direction is given by

$$I = I_o[\alpha,m,\theta)\sin^2\phi + i_2(\alpha,m,\theta)\cos^2\phi] \ /kr^2 \qquad (1)$$

where, I_o, α, D_p, λ, k, i_1, and i_2, is the intensity of the incident light, the size parameter ($= \pi D_p/\lambda$), the particle diameter, the wavelength of the incident light, the

wave number ($=2\pi/\lambda$), and the dimensionless intensity function composed of spherical Bessel and associated Legendre functions and their first derivatives, respectively. The ratio I/I_o means the differential scattering cross section and its normalized function F is represented by

$$F(\alpha,m,\theta,\phi) \equiv i_1(\alpha,m,\theta)\sin^2\phi + i_2(\alpha,m,\theta)\cos^2\phi. \qquad (2)$$

The numerical computation on the function F is pursued regarding the following two items for various m; (1) angular dependence of F, (2) particle size dependence of F. The computed results regarding item (1) is illustrated in Fig. 1 (a) and (b) taking m and D_P as parameters at λ of 0.6328 μm and ϕ of 0°, 90°, respectively. Those results regarding item (2) is illustrated in Fig. 2, taking θ, ϕ, and m as parameters at λ of 0.6328 μm.

B. Signal To Noise Ratio

The most important characteristics governing the performance of particulates counter by single particle light scattering method is its minimum detectable particle size and the signal to noise ratio is deeply concerned with the improvement in this precision of the instrument. It is generally believed that the first factor governing S/N ratio is one on the detector which transforms the scattered light from particulates to electric signal. As the

scattered light from small particulate is generally very feeble, it is recommended to select the photomultiplier tube (PMT) preferentially among many kinds of photoelectric detector. When the preamplifier with equivalent resistance R_{eq} is connected to the anode of PMT, the power of S/N ratio at the anode of PMT is given by the following equation taking the reduced noise the preamplifier at the input into consideration;

$$(S/N)_p = \frac{(\eta_\lambda \lambda e P_{is}/hc)^2}{2eF_p\left\{\frac{\eta_\lambda \lambda e}{hc}\left(P_{is}+P_B+P_R\right)+I_d\right\}+\frac{F_A k_B T_R}{\mu^2 R_{eq}}} \cdot \frac{1}{\Delta B} \quad (3)$$

where h, c, e, k_B, P_{is}, P_B, P_R, η_λ, μ, I_d, F_p, F_A, T_R, and ΔB is the planck constant, the light velocity, the elementary charge, the Boltzmann constant, the intensity component incident to PMT for the scattered light from the single particle, the intensity component as the background, the intensity component incident to PMT among the Rayleigh scattered light from air molecules in the scattered volume, the quantum efficiency at the surface of the cathode vs incident light with wave length of λ, the current amplication, the average dark current from the surface of cathode, the noise figure of PMT, the noise figure of preamplifier (PA), the temperature at the equivalent resistance, the overall bandwidth at the anode of PMT. The intensity of the scattered light incident to

PMT or P_{is} in Eq. (3) is given by

$$P_{is} = \int_{\Omega} I(r,\theta,\phi)d\omega \qquad (4)$$

where the integration is pursued around the region as determined by the solid angle Ω of the collecting optical system of the scattered light. Similar integrations are pursued for P_B and P_R. As the minimum detectable size of the particle is given by the one of the particle which can provide P_{is} with S/N ratio as equal to 1, we have to enlarge signal components in the numerator of the quotient in Eq. (3) as well as to reduce the magnitude of the sum of each contributions of the noise in the denominator for the purpose of obtaining the least minimum detectable size of the instrument.

C. Signal Components

As the signal component in the denominator of the quotient in left hand side of Eq. (3) is given as the product of P_{is} multiplied by $\eta\lambda$, we have to enlarge the contribution of both term simultaneously for the deduction of S/N ratio. The elevation in the magnitude of P_{is} is concerned with following improvements; (1) The use of the high output light source. (2) Squeezing of light beam to obtain high illuminating intensity. (3) Reduction of the attenuation of the intensity due to the optical system. (4) Collection of the strong forwards scattered light. (5) Widening of

the solid angle for the collection of the scattered light.

To satisfy the said requisitions item (1) and (2), He-Ne laser of 8 mW output is used by squeezing the beam diameter to 100 μm, which will provide ca. 10 W/cm^2 as the intensity of the incident light. The use of the high output laser is not necessarily recommended for the present objective in making the instrument portable for the in situ measurement of particulate system in the actual environments of the fields, in so far as the required lower limit for the measurements of the objective system remains above 0.07 μm. For the present objective, the forwards light scattering system is also not necessarily recommended except the case where the refractive indices of particulate possess the greater contribution from the imaginary part. The details will be referred to in the succeeding discussions. The requisition regarding items (3) and (5) should be sufficed generally. The second term in promoting the level of the signal component is which will be deeply concerned with the gain in the photo response of the material used in the cathode of PMT vs the wavelength of the light incident to PMT. The preferable cathode material of PMT for He-Ne laser light source is given by the litarature.[9]

D. Noise Components

The noise compornents constituting the denominator in

the quotient in Eq. (3) are classified into the following three, taking those from PMT and its PA as the primary ones for the criteria of S/N ratio: (1) The noise component issued by the fluctuations of incident light to PMT, (2) The noise component issued intrinsically from PA.

The noise in (1) is constituted by the following ones; (a) The fluctuations in the signal light incident to PMT [the first term in the denominator of the quotient in the Eq. (3)]. (b) Those in the stray light (the second term). (c) Those in Rayleigh scattered light from air molecules (the third term).

The noise in (2) are composed of the following ones; (d) The fluctuation in the primary electron emission from photo cathode in PMT. (e) The fluctuation in the emission of the secondary electrons by avalanche at dynodes of PMT. (f) The fluctuation in the dark current (the fourth term).

The noise in (1) includes intrinsically the contributions by (d) and (e), and the noise in (f) is superimposed doubly by the contribution by (e).

So far there was no indication of any literature explicitly referring to the analysis on the cause of S/N ratio for particulates counter particularily on the contributions as far as possible. The details in each contribution from (c) item which will govern the magnitude of S/N ratio ultimately after excluding other contributions

as far as possible. The details in each contribution to S/N ratio are discussed in the followings:

The first term based on P_{is}: This comes from the fluctuation in the signal light among other noises in the incident lights to PMT and hence can not be eliminated intrinsically any other external means.

The second term based on P_B: This term is particularily concerned with the merit in the improvements on the S/N ratio of the actual instrument. The stray light incident to PMT is analyzed to be composed of each element in the next equation:

$$P_B = P_o + P_L + P_{op} + P_e + P_t \qquad (5)$$

where P_o comes from the contribution of the external light into the system, P_L comes from the scattered light from the window of the light source, P_{op} comes from the diffracted and reflected portion of the incident light and deflected of incident light by refraction depending on the configuration of each elements composing the optical system and sometimes due to the rough alignment of the optical system causing small deflection of the optical path, P_e comes from the scattered light of each optical element, P_t comes from the reflected light from the optical traps and is depending on the configuration of the traps in the system and their shape. Therefore, the overall P_B at PMT is governed by the mode of incidence of each elementary

light to PMT which depends on the selection of light source, utilized scattering angle, configuration of each optical elements in the illuminating system, the cell and collecting system of scattered light including the light source in the alignment, particularily on the composition and geometrical structure of cell system.

The result from the analysis of factors governing the overall contribution of stray lights will suggest the possibility in reducing P_B to its minimum by introducing new devices to each optical elements and the new alignment of the optical system.

As the exclusion of noises from the external stray light by light chopping method can not be principally applicable for the optical particle counter, the external light rejection of PMT housing box is pursued so as to make the rejection state obsecure to the photoresponse curve of PMT. This is achieved feasibly by constructing the completely closed housing system enveloping the cell adjoined to PMT housing which reject the penetration of any light except the incident window for the incident light by blackened outer surface without any gap.

P_L and P_e are primarily due to the scattered light from the glass itself of the optical elements in the system including the one from the window of the light source and also due to the scattered light from the dusts adhered to

their surface. The former can not be reduced intrinsically, while the latter can be eliminated by cleaning though temporarily. Consequently, some cautions should be taken for the construction of device to minimize the latter contribution and particularily, for the cell system to exclude the adhesion of the flowing particulates system to the inner wall of the cell. The aforementioned completely closed housing enveloping the optical system for the rejection of external light will also work to exclude the intrusion of dust inside the said housing and thus prevent the adhesion of dust on the surface of each element except the cell and the inlet window. For the prevention of the adhesion of particulates flowing inside the cell, air curtain by the filtered circulating air is employed to insulate the inner wall from the flowing particulates.

For the detection of P_{op}, the elaborate cautions have been taken especially for the alignment of optical system to minimize the contribution of the reflected light from each element particularly from the wall of cell confronting the incident beam when a laser is used as the light source.

P_t comes from the reflected light from the light trap confronting the incident beam by the insufficient absorption due to the inadequate configuration and structure of the trap in the optical sytem. The most preferable location

and structure of the optical trap depends generally on the design of the optical alignment, utilized scattering angle, and the structure of measuring cell. Rayleigh horn per attached to the cell is concluded to be very effective for laser light source.

The third term P_R: P_R is concerned with the scattered light from illuminated air molecules in the sensing volume and is proportional to the product of the integrated Rayleigh scattering cross section σ_R of a single air molecule by the number of air molecules N in the sensing volume V_s. The integrated Rayleigh scattering cross section of air molecules with respect to ω_c, λ_{Rt} in V_s is given by

$$\sigma_{Rt} = \sigma_R N = \sigma_R p V_s / k_B T, \qquad (6)$$

where p is the cell pressure, k_B is the Boltzmann constant, T is the temperature of air molecules within the cell, and ω_c is the light collecting solid angle, respectively.

The mumerical value of σ_{Rt} is given by 4×10^{-13} cm^2, taking V_s as 1.13×10^{-3} cm^2, p as 1.013 x 105 Pa, T as 273 K, and σ_{Rt} as 1.4×10^{-29} $cm^2/0.5$ str. for nitrogen gas.[10]

The theoretical integrated scattering cross section σ_s at ω_c corresponding to Ω is illustrated in Fig. 3 as a function of the particulate diameter D_p where the case

A is concerned with the forwards scattering, B and C are concerned with the sideway scattering around right angle with the same collecting solid angle. The linearly polarized laser light is presumed regarding incident light for case C, where ω_c is taken as 0.5 str. equally and the numerical value of σ_{Rt} in the aforesaid estimation is marked laterally by the dotted line as a reference level in Fig. 3. On the above conditions, the numerical value of σ_s is given to be smaller than the numerical value of σ_{Rt}. This means theoretically that the signal light from the particulate of 0.1 μm diameter is covered underneath the Rayleigh scattered light of the environmental air molecules regarding the larger V_s of the instrument, even if other components of P_B can be excluded completely. Therefore, to attain the minimum detectable diameter of 0.1 μm or below 0.1 μm, following condition $\sigma_{Rt} < \sigma_s$ should be realized for the optical system of the instrument.

To achieve the deduction of $_{Rt}$ on the basis of Eq. (6), following methods are pursued; (1) the reduction of pressure within the cell by evacuation, (2) the reduction of sensing volume V_s by minimizing the width of the slit placed in front of PMT and by squeezing the diameter of the incident beam by the objective lens per attached to the light source, (3) the simultaneous use of both methods. The details in the preferential choice of the method

among them will be referred to in the succeeding section regarding the test results.

On this point of view, the possibility in detecting the particulate diameter smaller than 0.1 μm is examined regarding the present He-Ne laser light source of 8 mW output. As results, the minimum detectable size is obtained to be 0.07 μm with S/N ratio of ca. 3 by squeezing the beam diameter to 25 μm (1.6×10^3 W/cm^2), the slit width to 50 μm and by setting the sampling flow rate as 33.3 cm^3/sec.

The fourth term I_D: In so far as we presume S/N ratio to be sim[illegible] concerned with the selection of PMT, and therefore represent the noise component coming from PMT as solely contributing to the S/N ratio of the system, $(S/N)_p$ in Eq.(3) where $F_p = \delta/(\delta - 1)$ and δ means the average secondary electron emission ratio per dynode. Consequently, the preferable feature of PMT required for the present system remains good enough only to posses the higher value of δ and the lower value of I_D where the latter can be achieved by narrowing the area of the cathode exposed bv the incident light. For example, the area of the cathode of the presently available PMT remains to be within 8 cm x 5 cm.

The fifth term: This contribution comes from the noise in PA. Its magnitude measured at the output of PA is redu-

ced to the one at the input and finally represented by the reduced value as coming from the cathode of PMT. As the current amplification of PMT amounts generally up to the order of 10^6, the contribution of this term is usually very small and therefore can be neglected.

E. Selection of the Scattering Method

The location of the light collecting system in the instrument governs the S/N ratio of the system, and therefore the selection of the scattering method is also one of the important factors which are concerned with the level of the minimum detectable diameter of the particulate for the instrument. Particularly, in the case of laser light source where the contribution of P_e and P_t to the S/N ratio of the system are enhanced, the levels of their magnitudes are governed by the selection of the scattering method for the system concerned. The available locations of the light collecting system in the particle counter are usually classified into the following three; the forwards type, sideway one, and backwards one.

Criteria on the level of stray light contributing the S/N ratio of the system are pursued by the comparison on the level of the noises, the signal light, and the variant range of σ_s characteristics to each scattering method for the measurement of particulate distribution from 0.1

to 10 μm regarding each scattering method. Particularily, the detailed check are pursued between the forwards and the sideway collecting angle from 0.5^{o} to 25.5^{o} and $90^{o} \pm 25^{o}$. The evaluation on the preference in reducing P_e and P_t levels is pursued between both methods as the first criterion relating to S/N ratio of the instrument which governs the level of the minimum detectable particulate size. The situation of the stray light in the forwards scattering method is as follows; (1) The intergrated intensity of scattered lights from miscellaneous dusts adhered to the surface of each element in the optical system is strongest in the propagating direction of the incident laser beam, (2) Their components incident to PMT depend on another soild angle which is determined by the peep angle of PMT and the geometrical configuration of the optical system, (3) The setting of the effective optical trap is technically difficult due to the geometrical position of light collecting lens system vs the direction of incident beam.

As for the situation of stray light in the sideway scattering method, the angular distributions of the intensity of scattered lights from the dusts adhered to each element composing the optical system are suggested

by those as illustrated in Fig. 1. Therefore, following situations are presumed for the noises caused by miscellaneous stray light; (1) The noise component incident to PMT is expected to be small vs the level of stray light from the dust as in the case of forwards scattering method. (2) As the light collecting system is placed at right angle to the direction of incident light, the technique in setting the good optical trap for the incident beam is geometrically very feasible when compared to the former method. (3) Provided that some higher level of stray light is still expected in the cell by the back reflection of the strong incident beam from the Rayleigh horn which is attached to the cell confronting the direction of incident beam, the opportunity of its direct incidence to PMT is very few for this method. Furthermore, another optical trap can be placed to the cell additionally confronting the location of light collecting system for the elimination of the background level caused by multiple stray light. Therefore, the considerable lowering of P_e level and particularily the extreme deduction of P_t level can be expected by latter method when the strong incident beam is provided by laser light source.

The difference between the modes in the D_p de-

pendence of σ_s of both methods is pursued as the second criterion on the selection of the scattering method. On the basis of the computed results of the numerical values of σ_s in Fig. 3, it seems likely that there is no indication of any remarkable difference between the change of σ_s vs D_p for the forwards scattering method and the one for the sideway one regarding the particulate diameter below 0.2 μm. This means no indication of any superiority between P_{is} of the former and the one of the latter method for the detection of small particulate of diameter below 0.2 μm. The third criterion on the selection of scattering method is concerned with the superiority in the precision of determining the size distribution of particulate system with particulate diameter ranging from 0.1 to 10 μm where the greatly variant range of the order for the change of σ_s expected. Excluding the cases where the refractive indices of particles possess the greater contribution from the imaginary part, the range of the order of the numerically computed values of σ_s is from 10^{-6} to 10^{-13} in the former method corresponding to the range of particle diameter from 0.1 μm to 10 μm, while the said range of σ_s in the latter method remains within the comparatively smaller range from 10^{-9} to 10^{-14}.

As the variant range of σ_s needs the corresponding width in the dynamic range of PA the lower the objective level of the minimum diameter is,

the higher preamplification is needed for the instrumentation. Although the use of logarithmic amplifier seems likely to settle the trouble in the amplification electrotechnically, this results in the lowering of the resolving power for the precise detection of small particulate in aerosol system with the wide range of distribution for the particulate diameter. Therefore, the scattering method with narrower variation range of σ_s vs the size distribution of particulate system is intrinsically preferable for the detection of small particulate distributed among the bigger ones.

F. Theoretical Requisitions

Finally, on the basis of the conclusions of each item of the theoretical consideration, following conditions should be taken into consideration for the instrumentation of the submicron size particle counter;

(1) The noise level due to P_B should be below the one coming from the dark current of PMT or at least should remain within the same order of the level.

(2) Provided that the condition (1) is satisfied, σ_s should be larger than σ_{Rt} for the detection of the small particulate with diameter of 0.1 μm or below 0.1 μm.

(3) Sideway scattering method is at most preferable

to suffice the condition (1) and (2). Hence, it is better for the detection of small particulates with their diameter below 0.1 μm among the distribution of other bigger particulates in the environmental system.

II. INSTRUMENT

A. Target of the Instrumentation

Following items are the targets regarding the performance of the actually operating portable submicron size particulate counter; (1) Detection of small particulate with diameter of 0.1 μm, (2) High resolution in the detection of particle diameter covering the wide range from 0.1 to 10 μm. (3) High precision in particle counting in each divided region of particle system. The development of the technique to attain the first target has been made possible along the guideline in the theoretical consideration. Before entering into the approach for the means to attain the second and the third target of the instrumentation, the overall explanation on the composition of the instrument will be introduced for the feasible understanding of the problems concerned there.

B. Composition

The actually operating instrument has been constructed by taking those results from the theoretical survey

into consideration. The outline of the state of the art and the performance of the present instrument are summarized in Table I. The overall composition of the instrument is illustrated by the block diagram in Fig. 4. The cross sectional view of the light scattering cell is illustrated in Fig. 5. He-Ne laser SP-model 078-1 with its state the art in Table I is used as the light source. The scattering method is the sideway one at 90° objective lens in the illuminating system and adjusted so as to posses 100 μm diameter at the center of the cell. The light collecting system is composed of two mutually facing camera lenses, one narrow slit with its width of 100 μm and PMT in the housing tightly per attached to the cell. Each element in the system is so aligned with center of yz-cross section of the sensing volume and with the other focal point on xz-plane including the aperture of the slit by taking the z-axis to the propagating direction of the incident beam and the aperture of the slit exactly to x-direction. The realized solid angle of light collection is 0.5 str. with semi angle of 25°. The material of photoelectric cathode of PMT is S-20. The type of the optical trap per attached to the cell is the glass Rayleigh horn with high reflective inner surface by cleaning and with black coated outer surface by high light absorptive paint. The output pulse height at the PA

is displayed digitally after the treatment via the signal processing circuit.

The sampling is pursued by the collection of the objective aerosol through the inlet of the flow system to the cell. After the size measurement within the cell, the sample is send back to the environment by the air suction pump after passing by the reservoir 1, the filter, and the flowmetwe 1. However, ca. 60% of the suctioned volume is introduced to the reservoir 2 and feeded back to the cell again after passing by the flowmeter 2. The particulates in the feedback flow to the cell are filtered off completely and the clean up flow functions as an air curtain to prevent the contact of the introduced flow to the inner wall by sorrounding the flow of the new sample from the nozzle marked as 9 in Fig. 5 and thus reject the stain of the inner wall of the cell. The function of the small conical hood marked as 8 in Fig. 5 and per attached to the incident window 1 of the cell is to perturb the inflow of the suctioned sample there by pressure difference and thus effectively exclude the stain of incident window 1.

By these particular design and attachment, the stain of the inner surface of the cell is effectively rejected vs the higher concentration of particulates in the samples from the polluted environments.

The attenuation in the transmittance at the incident window and exit window of the signal light is reduced by the coating of anti-reflecting film on their surfaces vs the wave length of 0.6328 μm of He-Ne laser light.

C. Rejection State of Stray Lights

The situation in the rejection of miscellaneous stray lights is as follows; The rejection of purely external light P_L is pursued by enclosing the whole optical system with the blackened housing box tightly. The contribution of stray light from laser tube P_e to PMT is rejected by the nozzle 9 in Fig. 5 and so are for P_e from each element composing optical system. The contribution from the reflection of the incident beam is almost eliminated by the Rayleigh horn 1 marked as 3 in Fig. 5 and the rejection of the reflected light from Rayleigh horn 1 is attained by the hood marked as 10 in Fig. 5, even though the contribution of that component is weak. Rayleigh horn 2 marked by 5 in Fig. 5 will work to eliminate the multiple scattered light. The noise level of each stray light by this composition of optical system will be referred to in the succeeding section regarding the test results.

D. Electronics

The approach to the second target for the realization of the actually available instrument of the said performance is achieved by the following three means on the basis of the fundamental mechanism of the counter; (1) Bisection of the covering range of particulate diameter from 0.1 to 10 μm into Range I (0.1 to 0.5 μm) and Range II (0.5 to 10 μm) at particulate diameter of 0.5 μm corresponding to the allowable dynamic range of PA in determining the particulate diameter with high resolution. (2) The squeezing of beam diameter by the lens in the illuminating system for the size determination of particulates in Range I and recovering the original beam diameter by taking off the lens from the illuminating system for the size determination of particulate in Range II. (3) Alternative measurements on each diameter of particulate and their number in the objective system by the switch of the channels belonging to Range I and Range II at a constant interval of time usually taking 60 sec. for the dilute concentration of particulate.

The rightness in the bisection of the range of particulate at 0.5 μm is justified by the situation in the change of σ_s vs D_p in curve C of Fig. 3. The optical bisection of ca. six figures range of σ_s into each three figures at σ_s of 0.5 μm fits the allowed dynamic range of PA within three figures in the corresponding bisection

of six figures dynamic range of PA on the electronic circuit side.

Even though the use of logarithmic PA seems likely to be effective for this objective superficially, this loses the accuracy in the resolution of particulate liameter among their wide distribution and hence is not available for the present objective. It should be mentioned that this bisection of the range of particulate diameter is only possible for the side way scattering method where the covering range of σ_s stays within six figures corresponding to the size distribution from 0.1 to 10 μm. This type of bisection is not applicable for forwards scattering method on the basis of the reason that the figures of the coresponding dynamic range of PA exceeds three figures and can not stay within the allowed dynamic range of PA. Therefore, high order section more than trisection is needed for this type of scattering method to maintain the same accuracy in the resolution of particulate diameter.

The requisition on the bisectional measurement of size for particulate system with a wide distribution of their sizes is also issued by the following reason; As the number concentration of bigger particulate in Range II is generally much lower than the one of smaller particulate in Range I,a greater counting error is expected to

be inevitable for particulates in Range II, unless the sensing volume is not enlarged by expanding the beam diameter of the incident light. Hence, the present mechanism is designed so as to remove the lens system for the measurement of particulate in Range II during the alternative measurements of those in range I and Range II separately at a constant time interval and the electronic circuits per attached to the system are provided to satisfy the requisition.

As the third target, to realize the instrumentation available for the in situ determination of the size distribution, channel isolation of the range of particulate diameter is pursued by dividing the objective range from 0.1 to 10 m into the appropriate number of sections depending on the need for the precision of the results. The principle of the present channel isolation is illustrated in Fig. 6 regarding the designation of signal pulses into a channel corresponding to a given range of particulate diameter. The actual circuit is composed of n_c number of EX OR elements forthe selective picking up of the signal pulses by EX OR in the neighboring comparators among n_c number of parallely connected ones and as mentioned above, the number of n_c can be given preferably, depending on the need for the precision. In reality, nine

channels are employed for the present instrumentation alloting four channels for Range I and five channels for Range II, respectively where four figures digital display is supplied for each channel. Counting time is exchangable by eight steps from 1 to 600 sec, depending on the number concentration of the particulates corresponding to each range in the objective systems and synchronized with the switching between Range I and Range II. The electronic circuits for this purpose are so designed to exclude those contributions from the extraordinary bigger particles with diameters larger than the programmed upper limit of particle diameter, presently 10 μm. It is also designed to close the channels for the unneeded ranges and to allot these resting channels to the needed ranges, if necessary.

After eliminating the contribution of P_B by means of the methods mentioned previously, the primary component governing the S/N ratio of this instrument comes from the noise induced by Rayleigh scattering of the carrier gases. This has been expected by the theoretical survey in the foregoing section and will be certified by the experimental results in the succeeding section. This noise component based on the Rayleigh scattered light is issued as the random pulses from the output of PA. The order of contribution of this pulse is estimated to be 3 nA as

the average current reduced at the anode of PMT, as will be referred to in the test results of the succeeding section. Including this background level, the S/N ratio defined by the mean pulse height illustrated very low value of 1.5 regarding the signal light of polystyrene latices with diameter of 0.109 μm. To exclude the noise from P_R, the noise pulse rejection circuit is employed in the present instrument. As P_R induced by Rayleigh scattered light incident to PMT is presumed to be induced by Poisson process, the interval, the width, and the height of this noise pulse is random and is on the average ca. 200 nsec., 1 μsec., and 30 mV, respectively. The average current of this noise is of 3 nA. On the other hand, the width and height of the signal pulse from polystyrene latices of 0.109 μm diameter is 40 μsec. (constant) and 45 mV, respectively. Obvious difference is recognized between the quality of the pulse from the carrier gas and the one from the particulate. Taking advantage of the difference in the pulse width particularily, the noise pulse can be eliminated by the circuit in Fig. 7, where the noise pulse of analogous nature is transformed to digital one by comparater and then eliminated by logic circuit.

E. Method of Error Reduction

The criteria here are primarily concerned with the error in the counting of signal pulses from the authentically ideal particulates system without any size distribution. Hence, the error concerned here is presumed to be basically caused by the fluctuation in the height of the signal pulse coming from the ideal particulates of a given diameter. As the result of the experimental checks, it is clarified that among many causes of the fluctuation in the pulse height, the non-uniformity in the special distribution of the illuminating beam is remarkably concerned with the problem. The mentioned uniformity is particularly requested for the present case where the diameter of the illuminating beam is designed to be extremely narrower than the one of the coaxially flowing aerosol flux. For the confrontation of this cause, the unpolarized multimode laser with uniform spatcial distribution of light intensity is employed instead of the single mode one. The second cause of the fluctuation in the pulse height of the signal light is the non-uniformity in the areal sensitivity of PMT. The confrontation of the cause is achieved by receiving the scattered light fully on the light receiving surface even to its periphery. The reason why the unpolarized laser is preferably employed is due to the following: The variation width of the theoretically fluctuating

σ_s becomes different depending on whether the incident light is polarized or unpolarized above the particle diameter of 1 μm and the smaller variation width is given for unpolarized light as illustrated in Fig. 3.

Since the multivalued dismeter of the corresponing particles D_p is presumed theoretically for a given value of σ_s, it seems likely that some error will be imposed principally on the counting by the selection of the nine channel corresponding to a given height of the signal pulse regarding the size determination for those particulates with diameters bigger than 1.0 μm. However, it should be mentioned that σ_s changes vs D_p in Fig. 3 illustrating the repeated small fluctuation in its slowly promoting level with a short interval vs the promotion of D_p in the range above 1 μm and the present channel isolation by nine steps in total is adjusted to possess a considerably wide range for each channel in the sectioning of bigger particle diameter from 1 to 10 μm by four steps. Therefore, equal opportunity is almostly endowed between the counting of the pulse height from particles of smaller diameters erroneously as belonging to the bigger diameter channel and the one of the larger diameter as belong to the smaller one regarding the case where the actual pulse height lays close to the oritical one on the border, say 4 μm in the sectioning of the channel.

In reality, the results can represent sufficiently the true patterns in the distribution of sizes of artificially composed aerosol systems or can reflect the actual size distribution of aerosols in the environmental system.

F. Coincidence

The coincidence effect can be described generally by the expression $c = c_o \exp(-y)$, where c_o is the true number concentration of aerosol systems and c the measured one. The dimensionless variable y is given by $y = c_o V_s$.[6] On the basis of these relations, the true number concentration c_o is obtained by taking the first order coincidence losses correction;

$c_o = -(1/V_s) \cdot \ln (1-\eta_l)$, where η_l the coincidence loss.

For example, provided that V_s and η_l is given as 7.85×10^{-7} cm^3, 1% respectively for Range I and 7.85×10^{-5} cm^3, 1% respectively for Range II, c_o is given as 1.35×10^5 cm^{-3} for the former and 1.3×10^3 cm^{-3} for the latter range, respectively. The attainable c_o of the instrument is ca. 2×10^6 cm^{-3} and 1×10^4 cm^{-3} for each range respectively using second order coincidence loss calculation. The said c_o level is the highest particulates concentration level of the environmental pollutants so far obtained, as will be illustrated in Fig. 14 of the succeeding section.

III TEST RESULTS

A. Reduction Method of σ_{Rt}

The possibility in the reduction of P_R was dicussed by three different approaches in the previous section.

Hence, the selection of the actually available method with the least σ_{Rt} has been pursued on the basis of experimental checks on the predictions in the foregoing disscussions.

Firstly, following experimental checks is pursued on the possibility by the reduction of cell pressure. The situations of the generation of pulses from the polystyrene latices are observed in terms of the change of the output at PA by varying the cell pressure from 6.67×10^2 to 2.67×10^3 Pa. Although the uniformity should be expected intrinsically in the height and width of the generated pulse from these ideal-like particles, very extreme non-uniformity in the pulse height is observed by the reduction of cell pressure, in reality.

This is presumably due to the following reasons: The velocity of the particulate stream from the narrow nozzle in the cell is extremely accelerated and exceeds 100 m/sec by the reduction of cell pressure, when keeping the same sampling rate of 60 l/hr as before at ordinary pressure. Hence, the reduction of cell pressure makes the flow of particulates turbulent and unstable besides the accumulation of dissipated particulates in the adjoined vortex flow within the cell. The former causes the irregularity in the narrowing of the width and the lower-

ing of height of the signal pulses detected at PMT, in so far as the same time constant as those at ordinary cell pressure is maintained for the resolution of the signal. Besides, those particulates in the adjoined flow causes the stain of the cell wall which increases P_{op}.

The reforming of the time constant needs the multiplication of electric circuits and this makes the instrument not portable and hence not available for the in situ measurement of aerosols in various environments of the actual fields.

The photograph in Fig. 8 is an example illustrating the horizontally visualized flow of incense smoke within the evacuated cell in terms of the tomb by the extremely thin and flattened laser beam ellipticitized through the cylindrical lenses. The highly concentrated flow of illuminating smokes along the center of the blackened back ground of jet flow and the layered smoke motion along the adjoined vortex within the cell are observed there.

It is concluded that, neverthless the reduction of cell pressure is intrinsically preferable for the detection of very fine particulates, this method is not applicable to the present objective with the minimum detectable size of 0.1 μm but it should be followed up for the development of the instrument with the objective minimum detectable size less than 0.07 μm.

Hence, the next possibility of the second approach by minimizing the sensing volume V_s is explored at ordinary cell pressure. As results, 7.85×10^{-7} cm^3 is obtained for V_s by squeezing both the beam diameter and the slit width to 100 μm. This value of V_s is three figures smaller than the usual ones cited in the literatures[1] and provides the good uniformity in the height of the signal pulse issued by the standard aerosol from Dow polystyrene latices (0.109 μm).

The mentioned difficulty in the first approach can not be avoided in the third approach in terms of the combination of the former method by the reduction of cell pressure with the latter method and therefore, the third one is abandoned presently. Hence, it is concluded that the available method among the aforesaid three ones is presently the second one in terms of minimizing the sensing volume at ordinary cell pressure.

B. Noise Level by P_B and P_R

The actual noise level of the present instrument is measured. The average level of the total shot noise current I_t collected at anode of PMT is expressed as $I_t = I_{DA} + I_S + I_R$, where I_{DA} is the average level of the dark current, I_S and I_R is the level of the shot noise current by the background light P_B, and by the Rayleigh

scattered light P_R, respectively. I_R and I_S is intrinsically constant vs the change in cell presure p, but I_R is considered to be strongly dependent on p by Eq. (6). The linear promotion in the level of I_t vs the change of p in the range from 0 to 1.33×10^3 Pa is illustrated in Fig. 9. Therefore, the cut on the ordinate by the straight line is considered to be equal to $I_{DA} + I_S$ and I_R is linearly proportional to p. Regarding the evaluation of these by the separate experiment with another PMT and with the sensing volume as much smaller than the one in Fig. 9, I_{DA} is obtained as 0.04 nA while I_t is obtained as 3.04 nA and 0.14 nA at 1.013×10^5 Pa and 3.33×10^3 Pa respectively. Particularily, a smaller slope is obtained for the increase of I_R vs p. Therefore, the smaller the sensing volume, the smaller I_R is obtained. At ordinary cell pressure, I_R, I_{DA}, and I_S is obtained as 3.0 nA, 0.04nA and 1.4×10^{-3} nA respectively. Therefore, very small noise level of P_B is realized vs the level of I_{DA} where I_{DA} is small enough for I_R even if I_R is reduced by squeezing the sensing volume for the present instrument.

C. Correspondence among Theoretical and Observed Values

The precision in the detection of particulate diameter is pursued by the exactness in the coincidence of

the theoretical behaviors of σ_s vs D_p with the experimental one on the basis of the change in the pulse height vs D_p where the pulse heights of aerosols from various polystyrene latices are reduced to the integrated cross sections by taking both the signal height and the theoretical integrated cross section of polystyrene latices of 0.481 μm diameter as standards for the normalization.

A fair coincidence is obtained between both behaviors as illustrate in Fig. 10 where ten kinds of polystyrene latices with particle diameter of 0.081, 0.109, 0.124 μm etc. are used as the samples. Those latics are each suspended in the superpurified water in the beaker, dispersed by ultrasonic stirring, atomized in the purified nitrogen atmosphere and then introduced into the measuring cell. The penetration of fine dust into the system is prevented by the cautions cleaning of the walls of the experimental equipment and by the preliminary purge of the environment using purified nitrogen gas after filtration.

Then, the deviation in the diameter of each aerosols from various polystyrene latices are checked by the pulse height analyser (PHA) regarding the modes in their count and pulse height. The peak value and the half width value of each aerosol is checked from these size spectra as are illustrated in Fig. 11. Regarding the details of

the normalization in Fig. 10, those pulse heights are normalized by the one from polystyrene latices of 0.481 μm diameter and reduced to the integrated cross section by taking the theoretical σ_s corresponding to 0.481 μm diameter as standard.

D. Detection of 0.1 μm Diameter

Even though the broad size spectrum is observed for polystyrene latices with 0.109 μm diameter, the rightness of the present signal processing circuit based on the pulse height of each polystyrene latics in synchroscope including the one of 0.109 μm diameter is established by the relation in Fig. 10 and it is also experimentally verified by the check on the linear decrease of the count number of polystyrene particulates with 0.109 μm vs each dilution by half amount in Fig. 12. where the curve 1 and curve 2 represents the count number in channel 1 (0.1$\sim$0.2 μm) and channel 2 (0.2$\sim$0.3 μm) respectively. The count in channel 2 for polystyrene particulate of 0.109 μm is considered to come from the coagulated particles which is caused by the duplicate presence of the particles in the comparatively larger mist droplets from the atomizer.

If necessary, the fine isolation of channel in the particulate diameter range from 0.1 to 0.2 μm by the

precision of present dynamic range of PA on the basis of the standardization using polystyrene latices of 0.109, 0.124, 0.176 μm diam. The isolation of channel down to 0.07 μm diameter is also possible with S/N ratio of 3 by making a small improvement on the nozzle within the cell and also by minimizing the sensing volume on the basis of the standardization using polystyrene latices of 0.081 μm diameter. The minimum detectable size of particulates is estimated to be 0.065 μm for the present instrument, if necessary.

E. Cross Check Test.

To confirm the performance of the present counter, several cross checks are pursued on the observed data vs those of other counters which are obtained by the simultaneous measurement. The examples of the cross checks tests vs Royco Model 220 counter and another optical one with tungsten lamp light source are illustrated in Fig. 13 regarding the results of two different environments. Those results in Fig. 13 (a) are concerned with simultaneous measurement on the size distributions of the dusts in the company building by Royco Model 220 counter and the present counter. Curve 1 is the one by the former and Curve 2 is the one by the latter regarding the atmosphere late in the afternoon. Curve 3 is the one by the latter regarding the change in the number and

the size distribution pattern by the perturbed atmosphere due to the traffic of many office persons going home 30 minutes after the measurement on Curve 1 and Curve 2.

Those results in Fig. 13 (b) are concerned with the results of the simultaneous measurement on the size distribution of welding humes by this counter (Curve 4) and the ordinary optical counter with tungsten lamp as the light source (Curve 5). Both measurements are pursued on those by 100 time dilution of the environmental sample. Good coincidence is observed between both results regarding the size distribution above 0.3 μm diameter.

Part II. APPLICATION OF THE OPTICAL COUNTER TO THE DETERMINATION OF THE SIZE DISTRIBUTION OF THE COMBUSTION DUSTS.

As the objective in developing the counter was originally to measure the engine dust from automobiles in the metropolitan environments, the minimum detectable size of the present counter is arranged to achieve the submicron size detection down to 0.07 μm in diameter under the particulates concentration range up to $10^{10}/m^3$ without any correction of the coincidence loss and the cross channel sensitivity.

1. Engine Dusts:

As the application of the present counter, the measurements are pursured on the miscellaneous urban environmental particulates which are considered to come primarily from the authomobile pollutants. The measurement are conducted under various conditions and environments sueh as passing through high way tunnel on the moving test car, downtown street in rainy weather, factorial area and residential area. Neverthless, the results can reflect the actual size distribution and particulates concentration there when compared to the data by other measurements and will be more dependable provided that the correction on the relative refractive index

is conducted on the results. Those results are summarized in Fig. 14.

2. Smoke in Fire:

Anyhow, some method on the correction of the coincidence loss and counting loss should be taken up for the measurement of the particle size of the highly concentrationed smoke particulates in the actual fire. The aforesaid difficulty have been settled by derving an equation for the feasible correction in the first order approximation, even though leaving some doubt on its accuracy.

On this basis, the following items have been pursued for the study on smokes in fire by laboratory scale;

(1) Analysis of the optical densities or the turbidities of smokes on the basis of the scattering cross section as calculated from the size distribution of the actual smokes.

(2) Characterization on the difference in the size distribution between smokes from smoldering and those from flaming combustion.

(3) Model experiments for the clarification of the thickening of smokes in an enclosure fire which is primarily due to the growth of bigger particulates in the distribution by the lowering of oxygen partial presure and secondly by the stepwise coagulation among the aged particulates and the nacent ones with a sise distribution of the smaller diameters.

Because of the high concentration of particulates as expected in smokes generated from organic polymers in fire,

the correction should be made on the count number for coincidence loss and cross-channel sensitivity due to the loss counting. R.Jaenicke reportedon the rigorous correction of the coincidence loss.[13] Although his equation satisfies the need in the theoretical rigidity for low concentration, it seems likely, it does not work for the correction of the in situ measurement of such thick particulates system as the nacent smokes in fire. Therefore, we derived an improved formula for the correction of the coincidence loss in the first order approximation on the basis of the total number of particulates in the sensing volume. Then, in terms of the theoretical curve representing the relation on the true concentration of particulates and the count number of total particulates, we pursued conventionally the coincidence loss correction on the count number of each channel by assuming the proportionality between the ratio of the count number of a channel to its critical one and the ratio of the total count number to the theoretically derived critical concentration of total particulates in the sensing volume. The statistial treatment of the coincidence loss as follows;

K is the number of particulates in the volume V, and V is much larger than the sensing volume v. Assuming the K particles are randomly distributed, the probability of giving i particles in v simultaneously is given by the binomial distribution.

$$P_i = \binom{K}{i} \left(\frac{v}{V}\right)^i \left(\frac{V - v}{V}\right)^{K-i}$$

retical curve representing the relation between Nc and Co from Eq.(2) illustrates a different pattern above the maximal Nc which works in the coincidence loss correction better, as compared to the former.

Therefore, the true number Co can be estimated in the first order approximation from the displayed counts and thus the instrument predicts the particulate number up to ca. $1 \times 10^{13} / m^3$ on the basis of the above correction.

Smoke Generation ; The generation of smokes have been carried out in a vertical electric test furnace at the hot bath temperature of 400°C, 500°C and 600°C, respectively. The particle concentration in the ascending hot current of the combustion product have been measured by intaking the current into the counter close to the sample plate in the furnace. The concentration of the accumulated smokes and their aging have been measured by turbido-meters in the smoke box (50 x 50 x 50 cm) placed above the vent end also by intaking a portion of smokes into the said counter at a rate of 2 liters per minute, simultaneously. The smoke concentration in the box is estimated as the average of the cross sections from the turbidities at 15 cm, 30 cm and 45 cm apart from the bottom of the box, respectively, and the intake of smoke to the optical counter is carried out at 30 cm apart from the bottom and right up the vent end of the furnace.

For $v/V < 0.1$ and $K \to \infty$, the poisson approximation can be applied and the probability of vacant P_o is described as follws.

$$P_o = e^{-\frac{v}{V}K}$$

A count is established only when the sensitive volume v is empty before a particle enters it. The number of particles counted is

$$Nc = \frac{s}{W} v \cdot Co \, e^{-Co \cdot v} \qquad \text{(1)}$$

where Co is the true concentration of particulates, W is the slit-width and s is the aerosol velocity from the nozzle.

As stated previously, we pursued the conventinal correction on the coincidence of the count in a channel (i) by assuming the following relation;

$$\frac{Nci}{Nc} = \frac{Nci^{max}}{Nc^{max}} = ki$$

Nci is the count number of channel i, Nc is the total count number of all channels. Nci^{max} is the critical count number of channel i which can be given experimentally at the decay of the count number vs. the increase of particulates during the smoke generation, while Nc^{max} is the critical count number of total particulates of all channels which is given either by theoretical equation (1) or its modified one (2).

$$Nc = [\, 1 - (\, 1 - \frac{v}{V}\,)^{Co}][\, 1 + \frac{s}{W}\,(\, 1 - \frac{v}{V}\,)^{Co}] \qquad \text{(2)}$$

The latter seems to give better corrections. The theo-

Samples ; The samples used for the experiment are as follws; (1) polypropylene (2) polyvinylchloride PVC (3) wood where 100 mg, 300 mg and 1.00 gr. of samples are used for the test of each specimen. The smoke generation has been varried out at the hot bath temperature of 400°C, 500°C and 600°C, respectively.

As has been refered to in the statement of the problem, the concentration dependency of the size distribution of smokes was investigated first for the smokes from polypropylene at a hot bath temperature of 400°C as are illustrated in Fig.15. The presence of the iso-particulate concentration point is recognized between the size distribution of smokes from 100 mg of polypropylene and 1.00 gr. of polypropylene sample where the growth of lager diameter particulates is suggested in compensation with the decrease in the number of smaller particulates due to coagulation. The size distribution of the smokes directly from the hot ascending current through the furnace is illustrated in Fig.16 below the size distributions of cooled smokes accumulated in the environment of smoke box. The growth of lager particulates more than 3 μm in diameter is recognized for the latter due to aging. To confirm the validity of coincidence loss and cross-channel corrections as mentioned in the previous section, the counter check has been carried out on the time-dependent change of the cross sections of

polypropylene smokes per 1.00 gr. of sample $m^2/gr.$ between those obtained frome the turbidities in the smoke box and those calculated theoretically on the basis of the size distribution of particulates in the smoke box varying the scattering coefficient (k) for each relative refractive indices (m). As are illustrated in Fig.17, it is not too far saying that the good coincidence has been obtained between them in so far as the precision in the channel isolation of the counter, the rightness on the correction of coincidence loss and the cross-channel sensitivity due to counting loss are concerned. Remembering the approximately of the simulation in replacing the complex refractive indices of the actual smokes smoldering by m = 1.6, and not taking the complexity in the change of cross sections from both turbidities.

The size distribution of particulates do not necessarily illustrate the proportional increase with the weight of samples linealy at higher concentration of smokes, as are shown in Fig.17. The lowering is suggested to be caused by the aging of smokes due to coagulation which will give lower values of the scattering coefficient k close to 2 again and partly by the reduction of particle number due to the dissipation of grown particulates onto the walls of the box or due to their precipitation down to the floor. The observed coincidence between the scattering cross section from turbido-meter and the one from the size distri-

bution at thin concentration is much deviated at high concentration of smokes. This will suggest that the excess calibration on the number of particulates has been carried out particularily at larger diameter on one hand. On the other hand, the mean specific gravity of smokes at such high concentration as the ratio of the weight of the collected smokes particles by filteration vs. the calculated volume of particulates from particle counter is also evaluated to remain unexpectedly to be within ca. 0.3 - 0.4 μm. Even after correction as illustrated in Fig.18 , the result will indicate still further shortage in the weight of particulates, in so far as the estimation on the basis of the weight of the collected smokes on the filter is concerned.

Hence, it is suggested that the surface of the white smokes issued from the smoldering at comparatively lower temperature (T = 400°C) will be covered possibly by the very tiny droplets of the condensed dew of the mixture of water and irritant volatiles, while the body is composed of oil soluble volatiles and fragments of polypropylene as illustrated in Fig.19. The former must be removed by evaporation from the particulates on the filter during the collection. The vaporization of these volatile fractions will cause the reduction of density with other losses of the recovering.

The most important factor governing the size distribution of smokes is the combustion temperature. The typical

examples illustrating the remarkable contrast are the mutually opposing change of the size distributions between smokes from wood and those PVC at the elevated temperature of the hot bath from 400°C, 500°C to 600°C. As illustrated in Fig. 20 and Fig. 21, an obvious decrease in the number of larger particulates above the particulate's diameter 3 μm is observed vs. the elevation of hot bath temperature for beech wood, while the remarkable growth of the number of larger particulates is observed vs. the elevation of hot bath temperature regarding the size distribution of PVC smokes as observed both at furnace and smoke box. Generally, organic materials emit thick smokes in smoldering combustion and their smokes are reduced when they flame. However, PVC is the exceptional sample which emit much thicker smokes in flaming combustion than in smoldering combustion. The results will suggest that the flaming or the high temperature combustion must cause the change-induced coagulation or carboneons smokes as in the case of the soot formation.

When the organic materials burn in as enclosure, the oxygen partial pressure lowers reversely vs. the growth of fire where they emit usually heavier smokes than they do in an open environment under enough oxygen supply. The effect of oxygen partial pressure on the size distribution of particulates in smokes is shown in Fig. 22 for polypropylene at the hot bath temperature of 400°C. The increase in the number of large particles in the range above the particle size of 5 μm has been recognized

specifically corresponding to the lowering of oxygen partial pressure, and therefore, the aforesaid increase in the turbidity will be suggested to be primarily due to the contribution of these particles.

Finally, the mode in the so-called aging of smokes has been pursued on the basis of the variations in the size distribution of particulates in smokes relatively . As shown in Fig.23, the growth in the size of smokes accumulated in the smoke box has been recognized by means of the time-increment of particulates in a stepwise change of their number at a diameter of 0.5 μm and ca. 5 μm, respectively. As shown in Fig. 24 the size distribution of particulates in the in-flowing hot current consists primarily of the smaller ones lacking the larger diameter ones, while the size distribution of those accumulated in the smoke box possesses the larger diameter portion and the critical concentration exists at around ca. 10^{14} for the number of particulates accumulated in the smoke box regardless of the number of particulates in the inflowing flux. This is presumably due to the coagulation between the aged smokes and the fresh ones which produces the bigger particulates and the increase in the turbidity of smokes in the box vs. time during the generation of smoke is suggested to be primarily caused by this mechanism. Consequently, it is suggested that the smoking behaviours of organic materials in fire can not be represented exactly by the one in laboratory scale and the cross check on the basis of the middle scale

experiment will be necessary for the description of smoking behaviours in terms of the one in laboratory scale. The increase in the volume-surface diameter vs. time is illustrated in Fig. 16 for the accumulated smokes of polypropylene in the smoke box during the generation.

Table I. The specifications of the instrument

Term	Range I	Range II
Light source	Laser (He-Ne, 8 mW, Multimode, Random)	
Beam diameter	100 μm	1.2 mm
Sensitive volume	7.85×10^{-7} cm^3	1.13×10^{-4} cm^3
Sizing particle range	0.1 - 0.5 μm	0.5 - 10.0 μm
Channel numbers	4	5
Sizing particle range in each channel[a)] in μm	0.1 - 0.2	0.5 - 1.0
	0.2 - 0.3	1.0 - 2.0
	0.3 - 0.4	2.0 - 4.0
	0.4 - 0.5	4.0 - 6.0
	———	6.0 - 10.0
Measurable maximum concentrations	5.0×10^4 cm^{-3}	3.3×10^2 cm^{-3}
Counting time	1,5,10,50,60,100,500,600 each seconds	
Flow rate of aerosol	0.6 l/min or 1.2 l/min etc.	
Display method	Digital (four digit/channel)	
Calibration	Uniform latex particles (Dow Chemical)	

a) Sizing range can be variable when necessary.

FIGURE CAPTIONS

Fig. 1(a) An example of the calculated results. On the differential scattering cross section. Angular dependence of function F in Eq. (2). The parameter is particle diameter D_p.

Fig. 1(b) An example of the calculated results. On the differential scattering cross section. Angular dependence of function F in Eq. (2). The parameters are the angle ϕ and particle diameter D_p.

Fig. 2 Particle size dependence of function F in Eq. (2). The parameter is the scattering angle θ.

Fig. 3 Comparison between the integrated scattering cross section of the instrument by forward and right angle light scattering method with collecting semi-angle 25°. The level of the integrated Rayleigh scattering cross section σ_{Rt} of air molecules in the sensing zone is by a lateral dotted line regarding the values of ordinary sensing volume V_s ($= 1.13 \times 10^{-3}$ cm^3).

Fig. 4 Block diagram for the outline of the present instrumental system.

Fig. 5 Cross sectional view of the present light scattering cell. ①; incident window, ②; sensing zone, ③; light trap 1 (Rayleigh horn which serves

a suction nozzle for the outlet of the aerosol), ④; exit window, ⑤; light trap 2 (Rayleigh horn), ⑥; guide pipe for the inlet of the aerosol, ⑦; guide pipe of the clean air, ⑧; protection hood for the stain of the inner surface of the incident window, ⑨; aerosol nozzle, ⑩; outlet pipe of the aerosol.

Fig. 6 The principle of the channel isolation shown by a time chart.

Fig. 7 The principle of the noise pulse rejection shown by a time chart.

Fig. 8 A photograph of the cross-section tomb of the aerosol flow within the light scattering cell under the reduced pressure, at $p \simeq 1.33 \times 10^2$ Pa.

Fig. 9 Pressure dependence of PMT shot noise current (average values) issued from the illuminated sensing zone. The results on the plot were those under the reduced cell pressure by 7 steps.

Fig. 10 The correspondence between the theoretical and experimental values. The experimentally obtained pulse height values were reduced to σ_s by the standardization on the basis of the normalization of pulse height by the one of polystyrene particle of 0.481 μm diam and the theoretical cross section of that particle.

Fig. 11 Size spectra of polystylene latex particles by pulse height analyzer (PHA).

Fig. 12 Count numbers vs. the relative particle concentrations of 0.109 μm polystylene latex particle represented by the dilution ratio.

Fig. 13 Results of the cross check tests. Royco Model 220 counter and an ordinary optical counter with tungsten lamp light source were used.

Fig. 14 Size distribution of particle concentration of particulates primarily dusts and automobile pollutants in miscellaneous environments.

Fig. 15 The concentration dependency of the size distributions of smokes from polypropylene at hot bath temperature of 400°C.

Fig. 16 The size distribution of the smoke from polypropylene measured at 8 cm above a sample boat in the furnace.

Fig. 17 Relation between the scattering vross section estimated from optical smoke density (Cs) and those from particle in terms of the number of particles and geometrical cross-section for each size fractions and the scattering coefficient (K) corresponding to their relative refractive indices (m).

Fig. 18 Relation between the weight of sample and total volume of smoke particles from polypropylene.

Fig. 19 Infrared spectral pattern of smoke from polypro-

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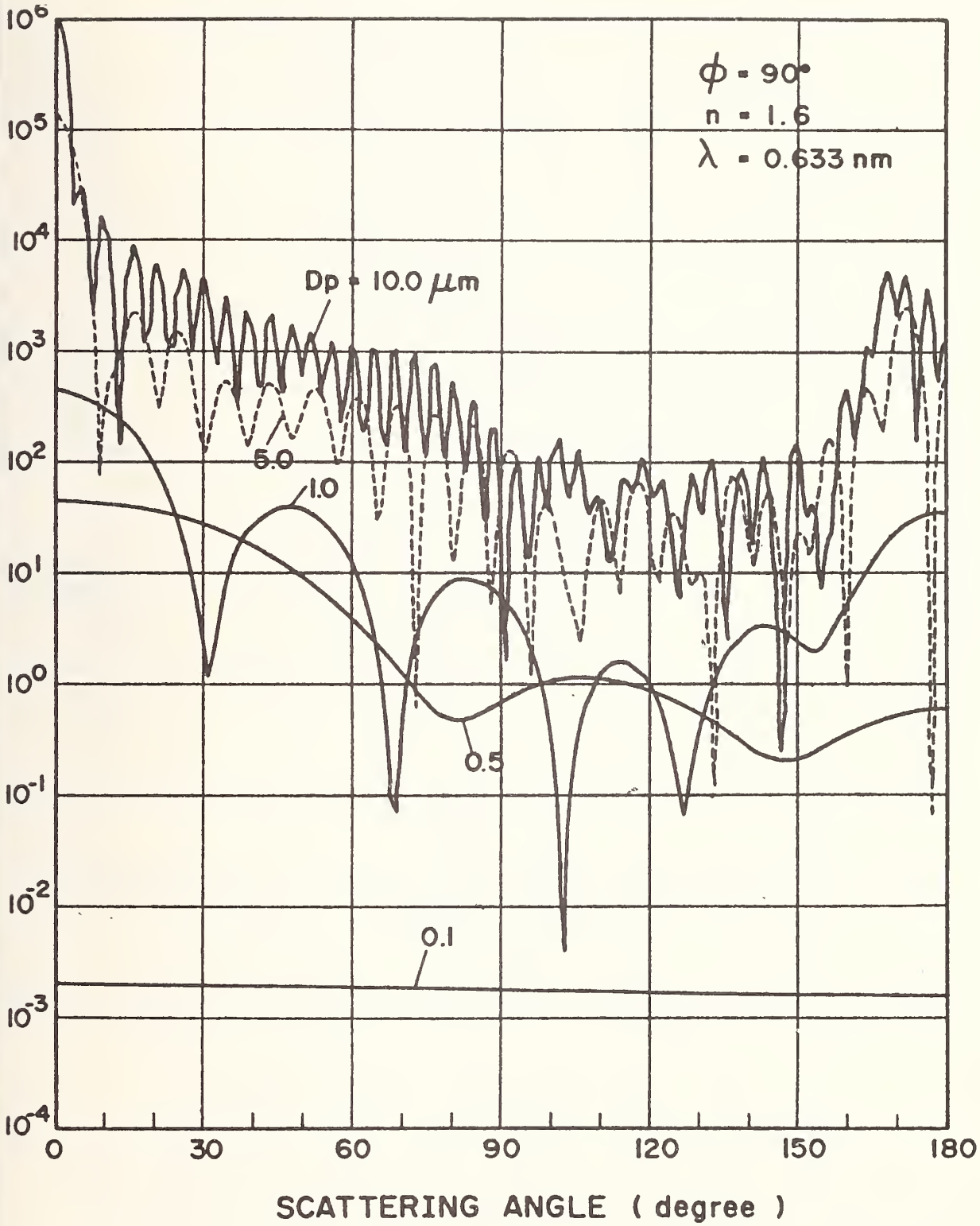
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n = 1.6
λ = 0.633 nm
Dp = 10.0 μm
5.0
1.0
0.5
0.1
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
30
60
90
120
150
180
SCATTERING ANGLE (degree)

Figure 1 (a)

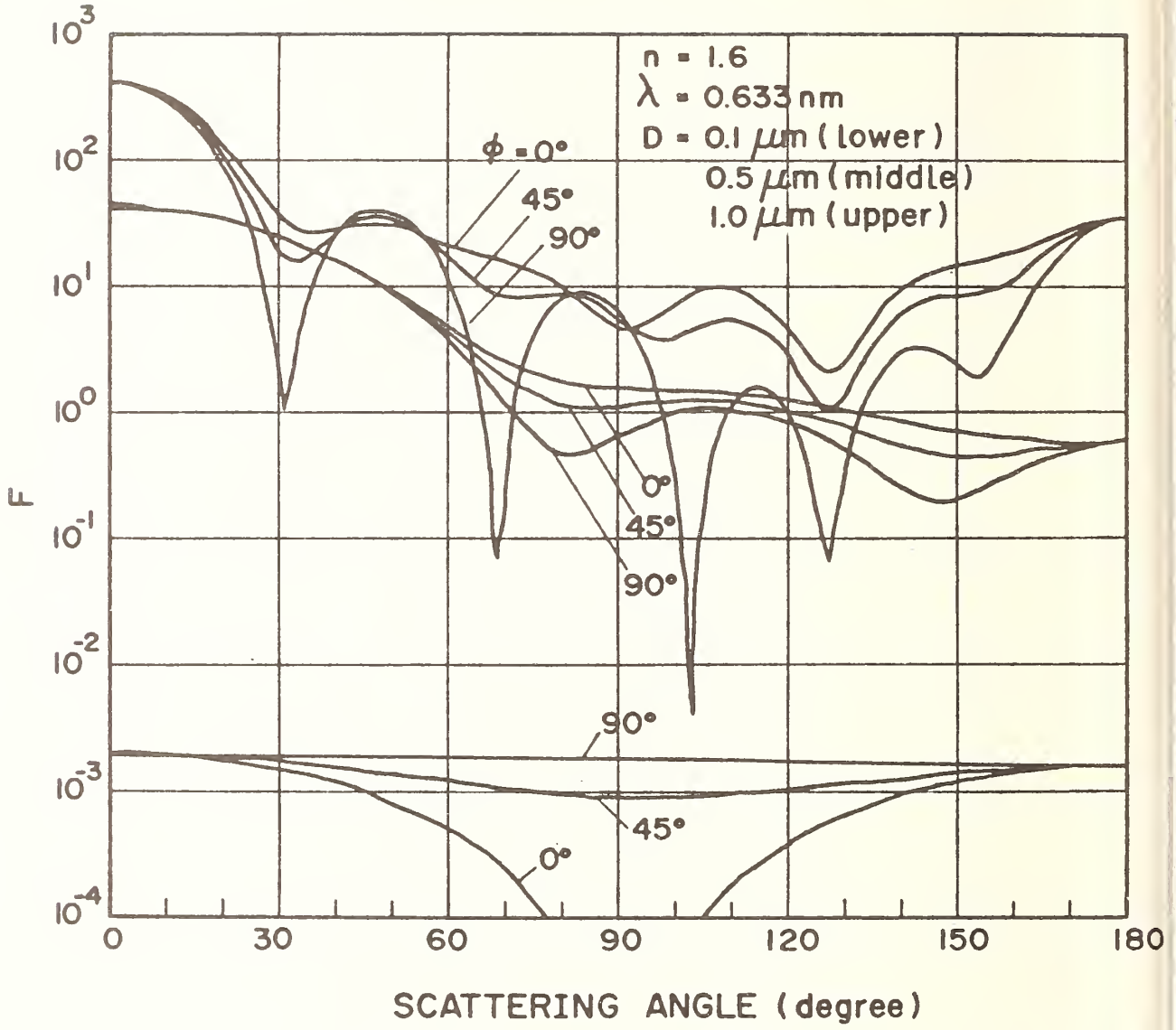

n = 1.6
λ = 0.633 nm
D = 0.1 μm (lower)
0.5 μm (middle)
1.0 μm (upper)
φ = 0°
45°
90°
0°
45°
90°
90°
45°
0°
F
SCATTERING ANGLE (degree)
0
30
60
90
120
150
180

Figure 1 (b)

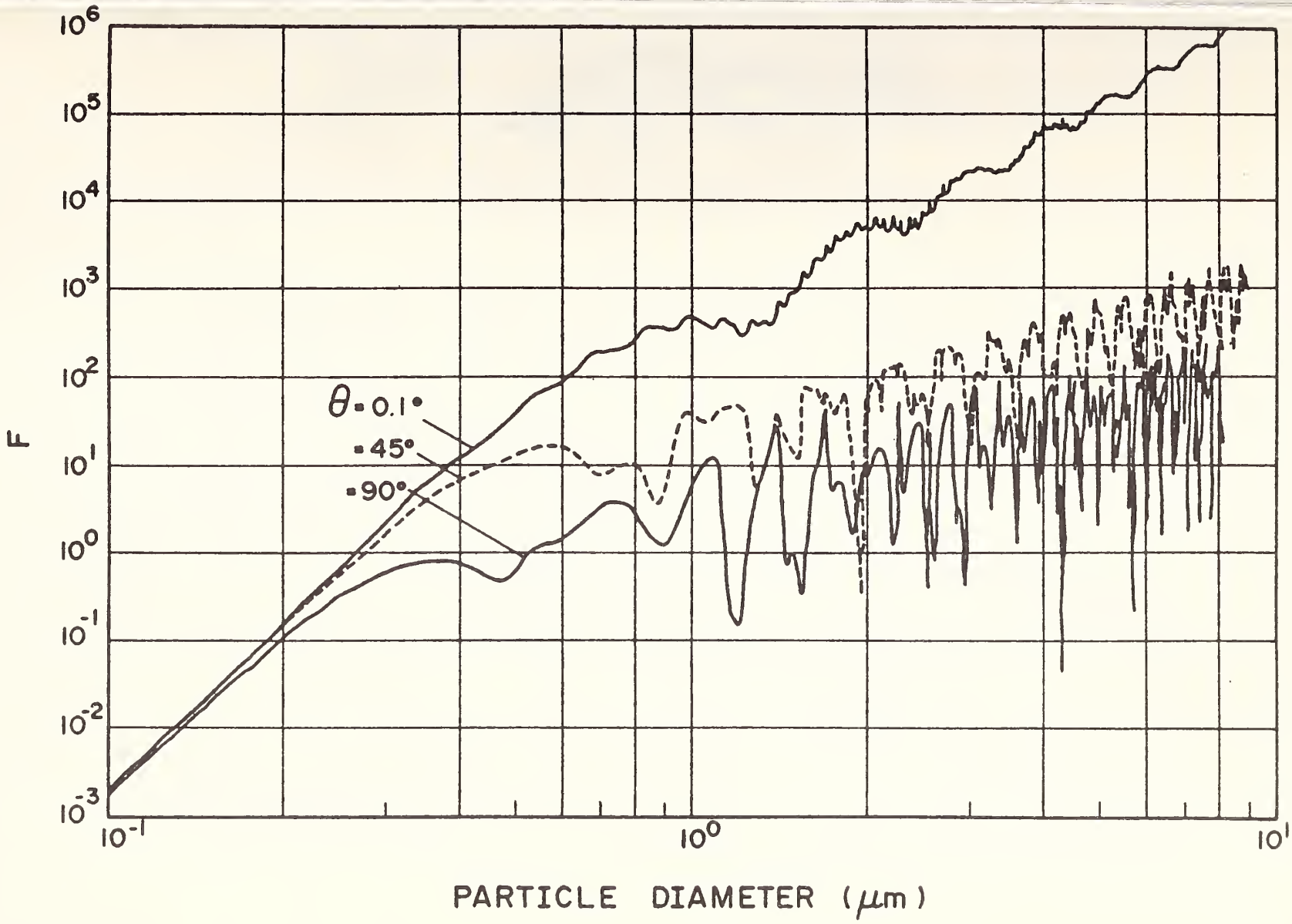

F
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
θ = 0.1°
= 45°
= 90°
10^{-1}
10^0
10^1
PARTICLE DIAMETER (μm)

Figure 2

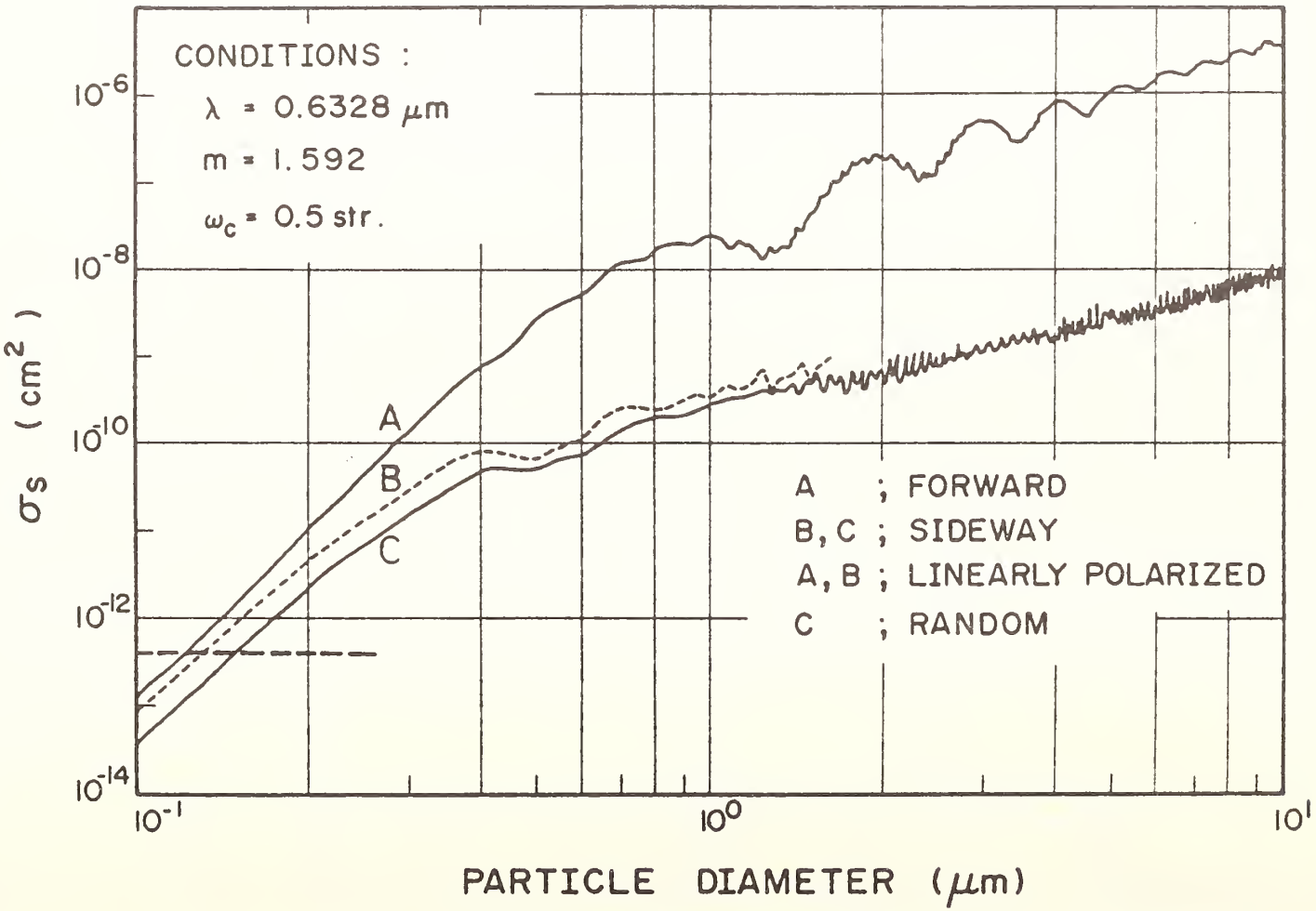

CONDITIONS :
λ = 0.6328 μm
m = 1.592
ω_c = 0.5 str.
A ; FORWARD
B, C ; SIDEWAY
A, B ; LINEARLY POLARIZED
C ; RANDOM
A
B
C
10^-6
10^-8
10^-10
10^-12
10^-14
σ_s (cm^2)
10^-1
10^0
10^1
PARTICLE DIAMETER (μm)

Figure 3

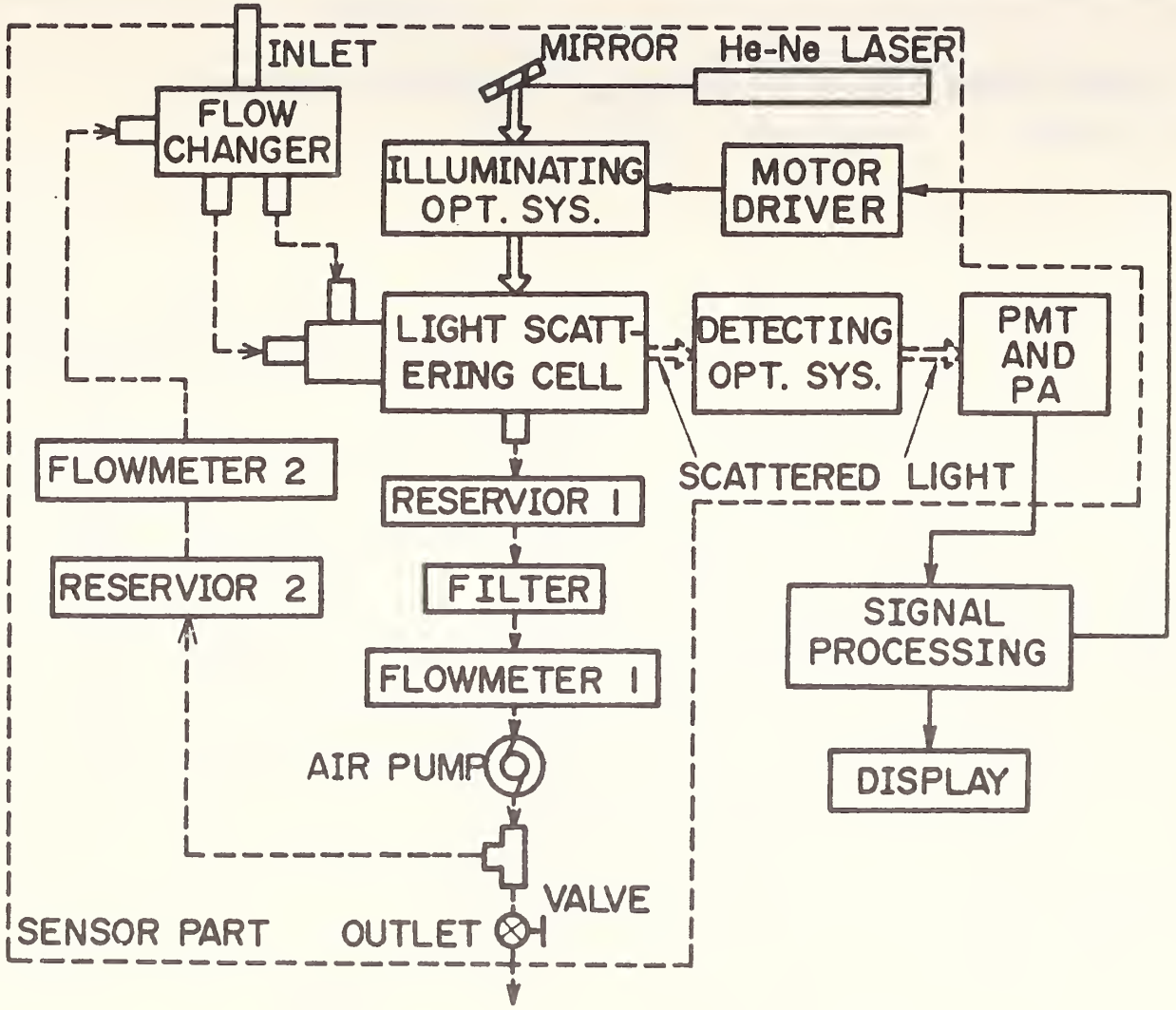
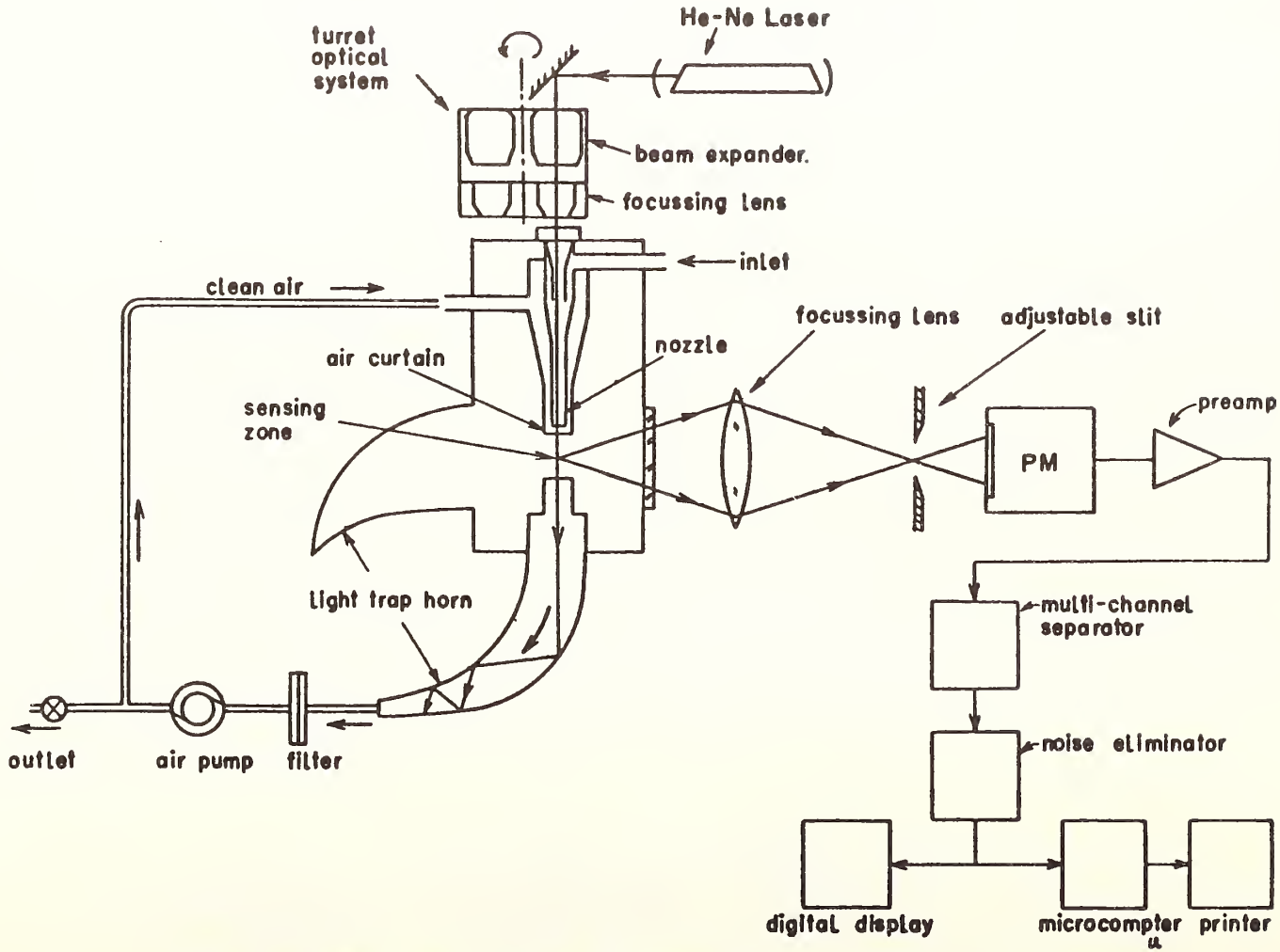
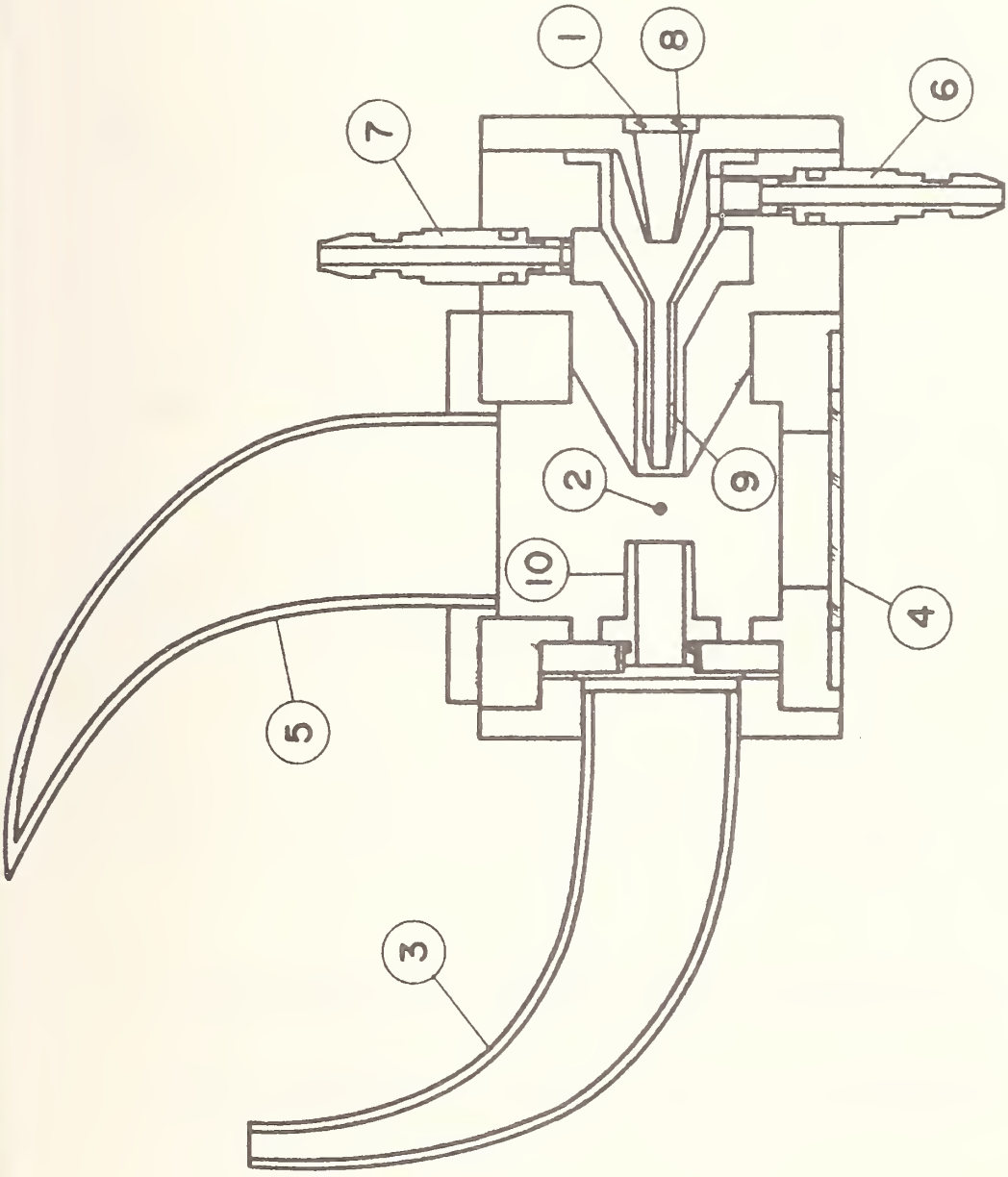
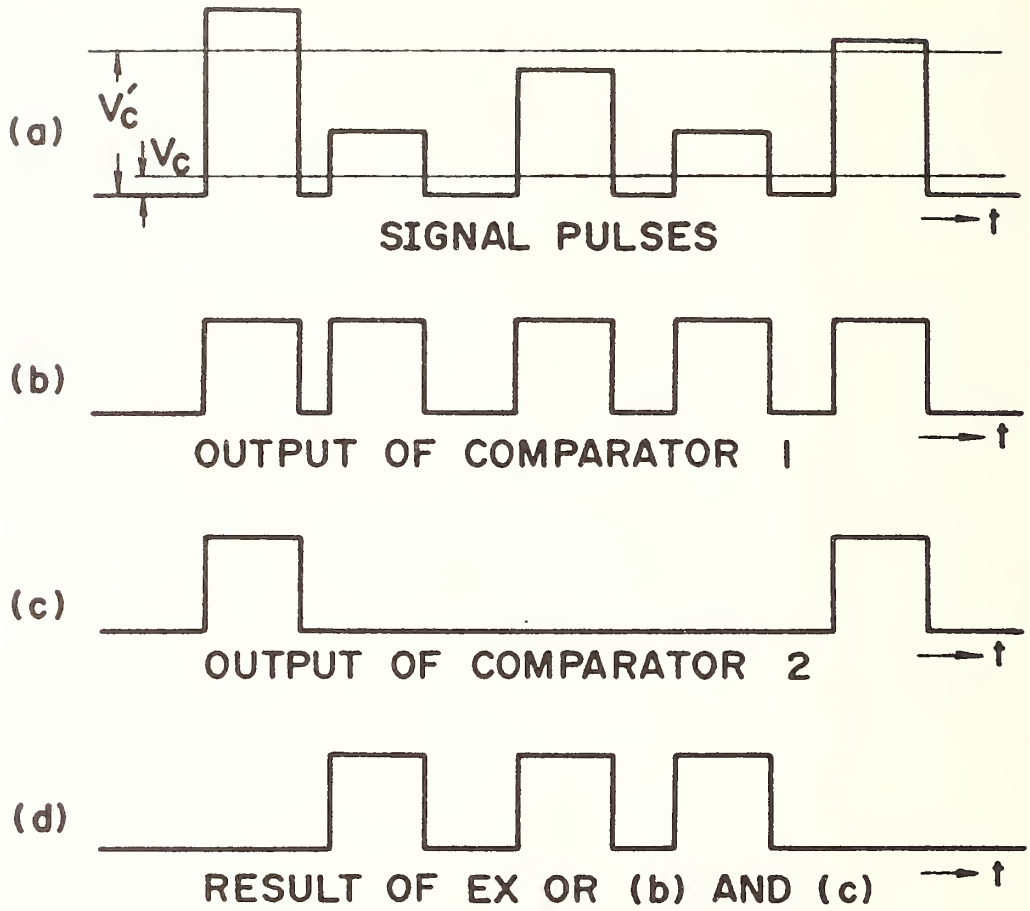

INLET
MIRROR
He-Ne LASER
FLOW CHANGER
ILLUMINATING OPT. SYS.
MOTOR DRIVER
LIGHT SCATTERING CELL
DETECTING OPT. SYS.
PMT AND PA
FLOWMETER 2
RESERVIOR 1
SCATTERED LIGHT
RESERVIOR 2
FILTER
SIGNAL PROCESSING
FLOWMETER 1
AIR PUMP
DISPLAY
VALVE
SENSOR PART
OUTLET

Figure 4



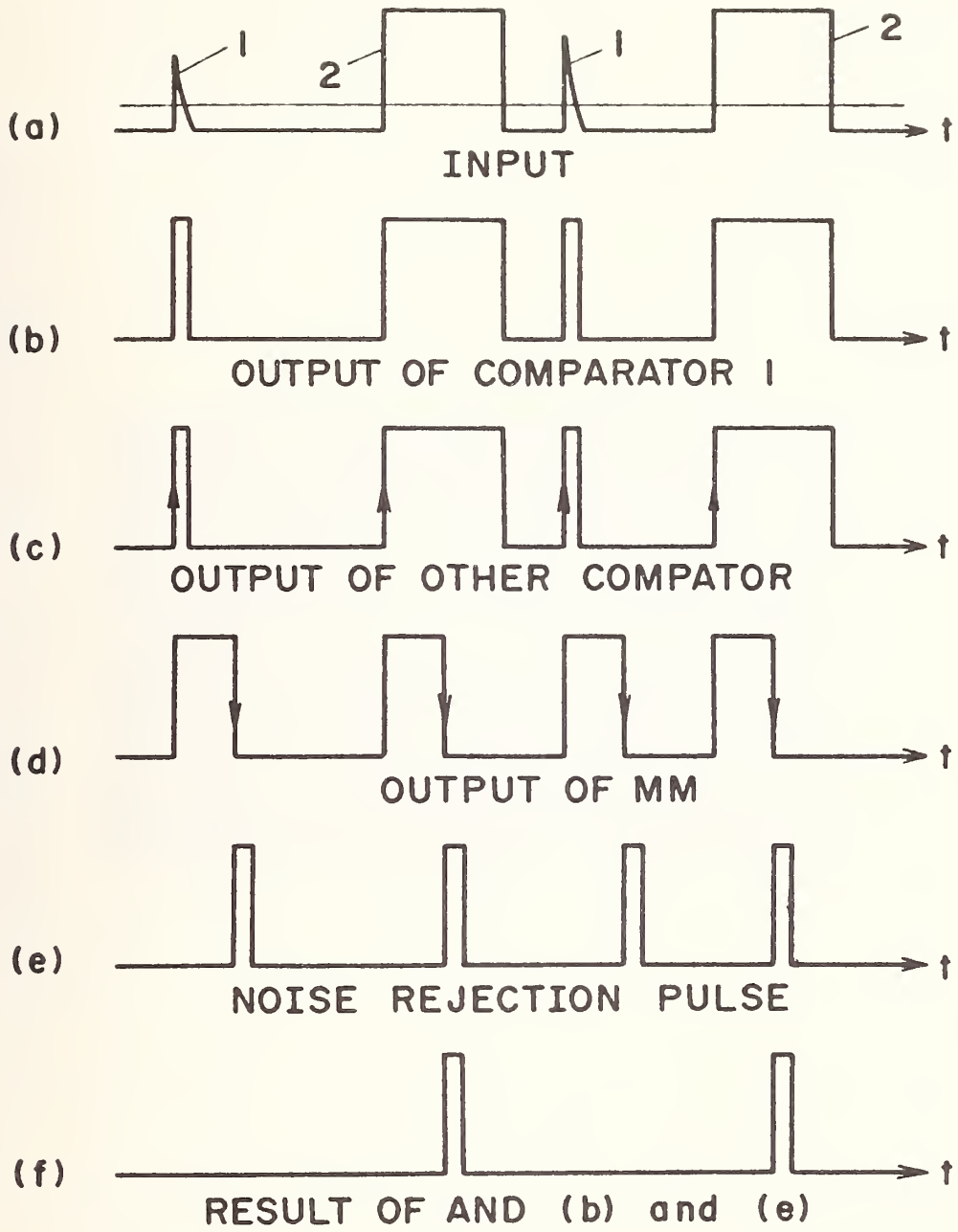
Fundamental construction of submicron particle spectrometer


1
8
6
7
2
9
10
4
5
3



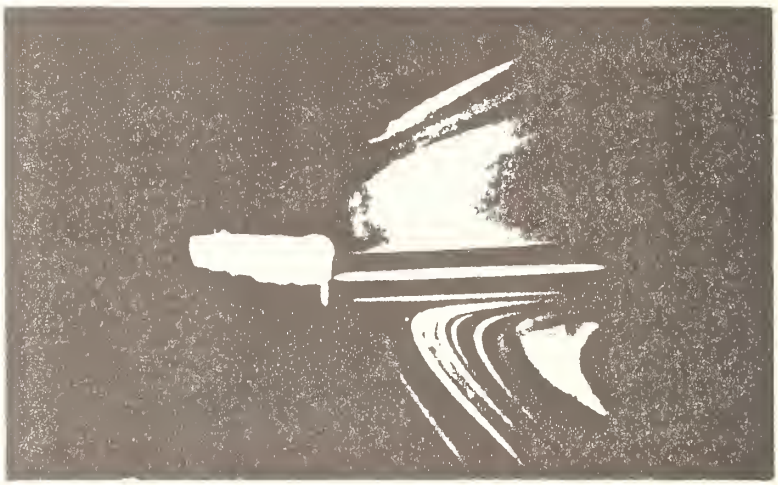
V_C : Comparate Level of the Comparator 1

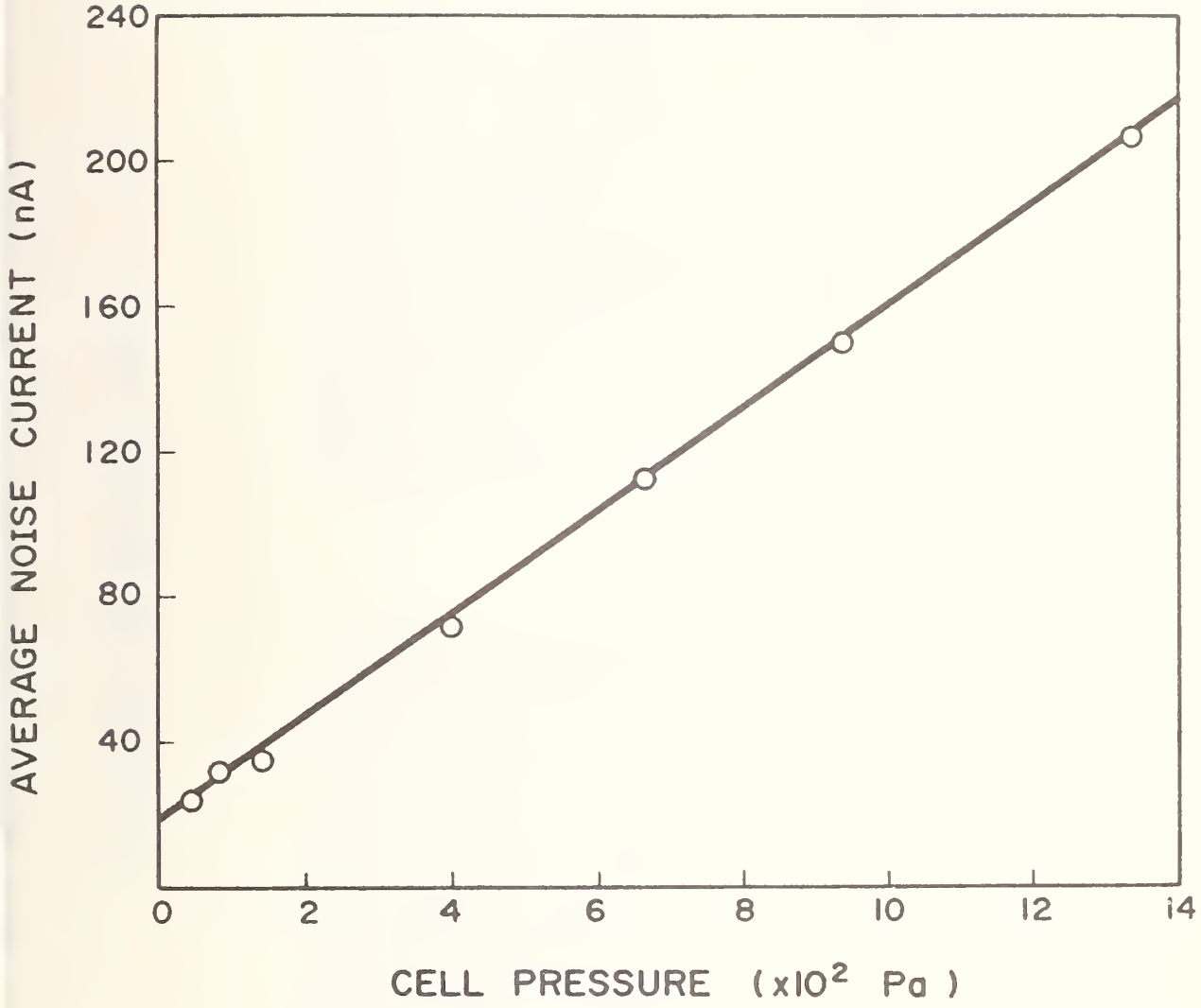
V_C' : Comparate Level of the Comparator 2

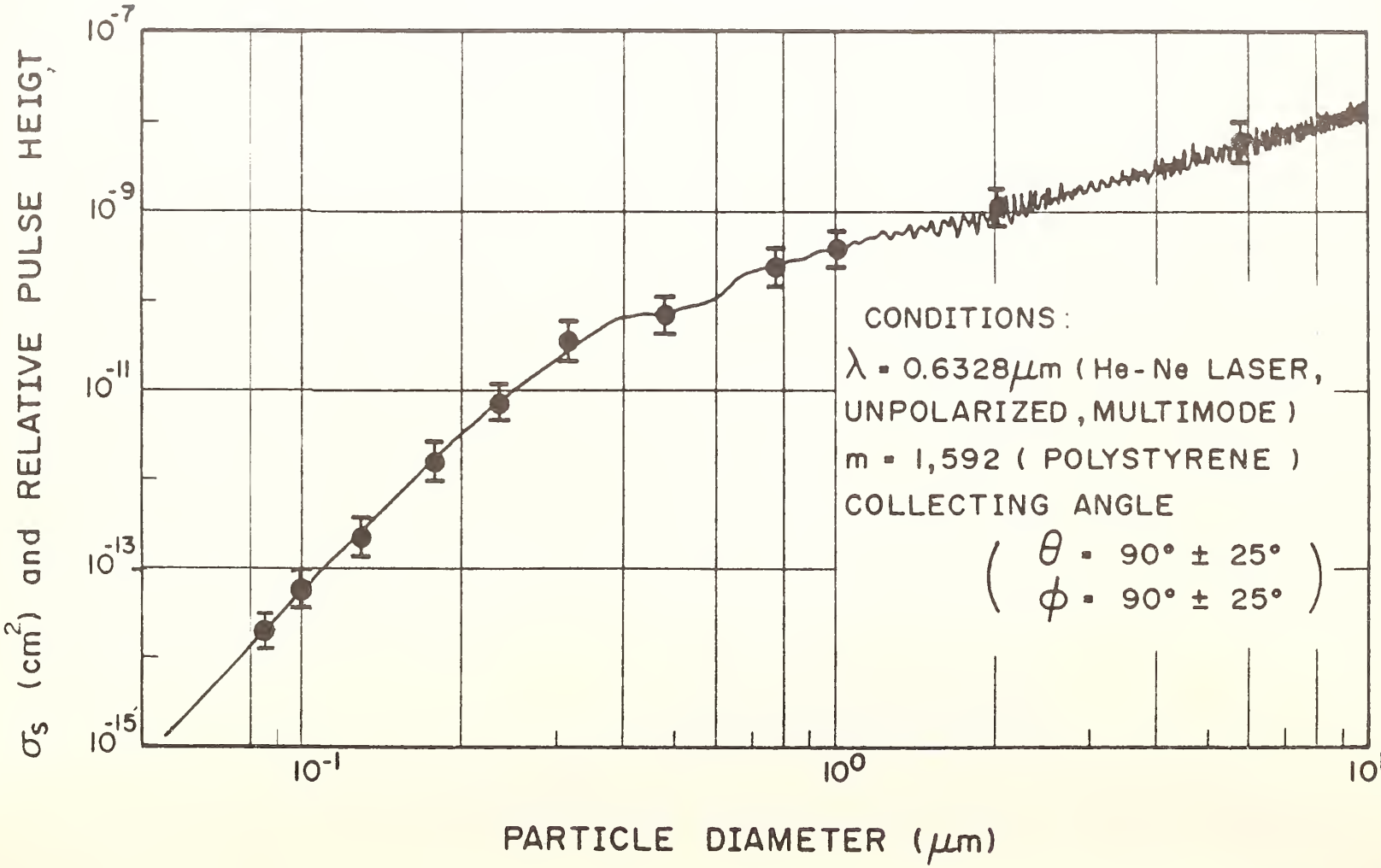


1 : Noise Pulse, 2 : Signal Pulse,

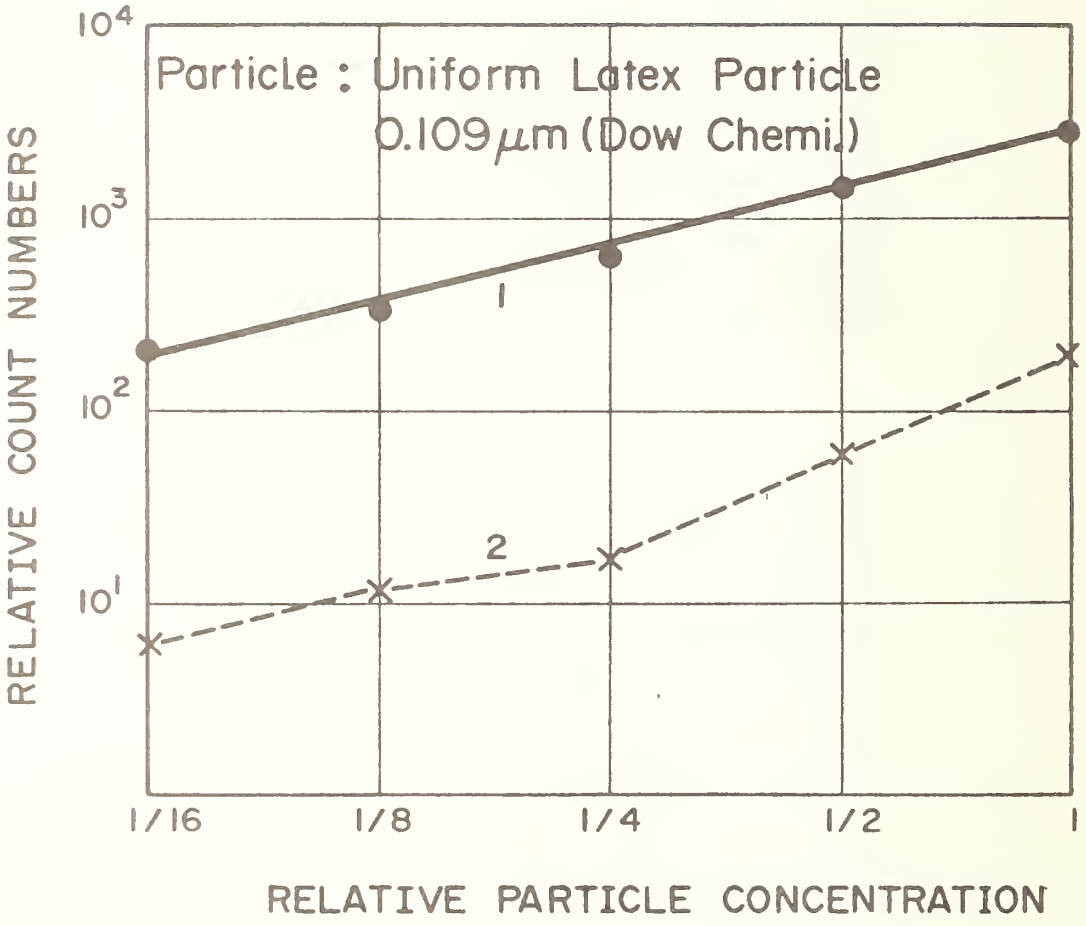
MM : Monostable Multivibrator.

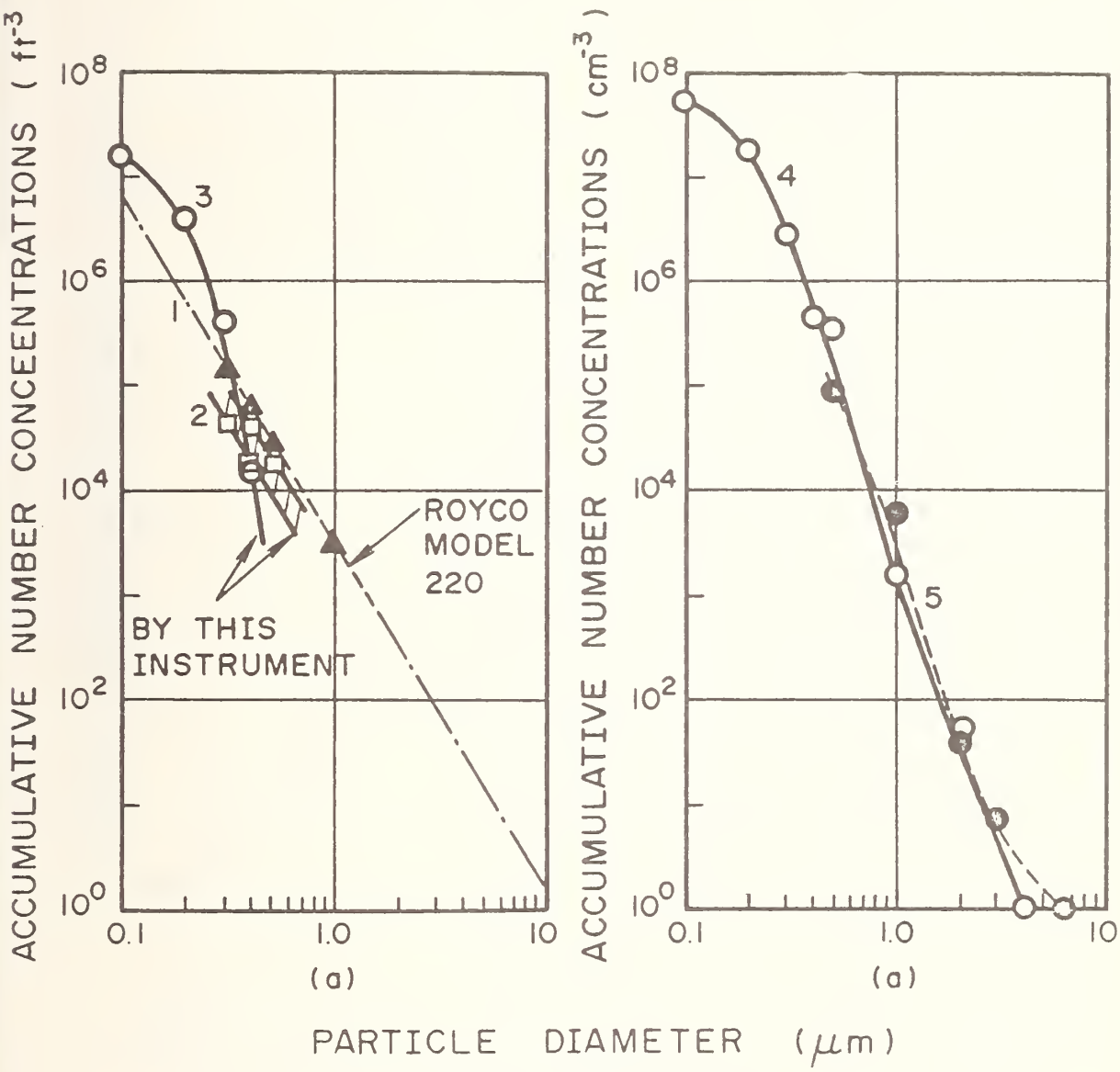


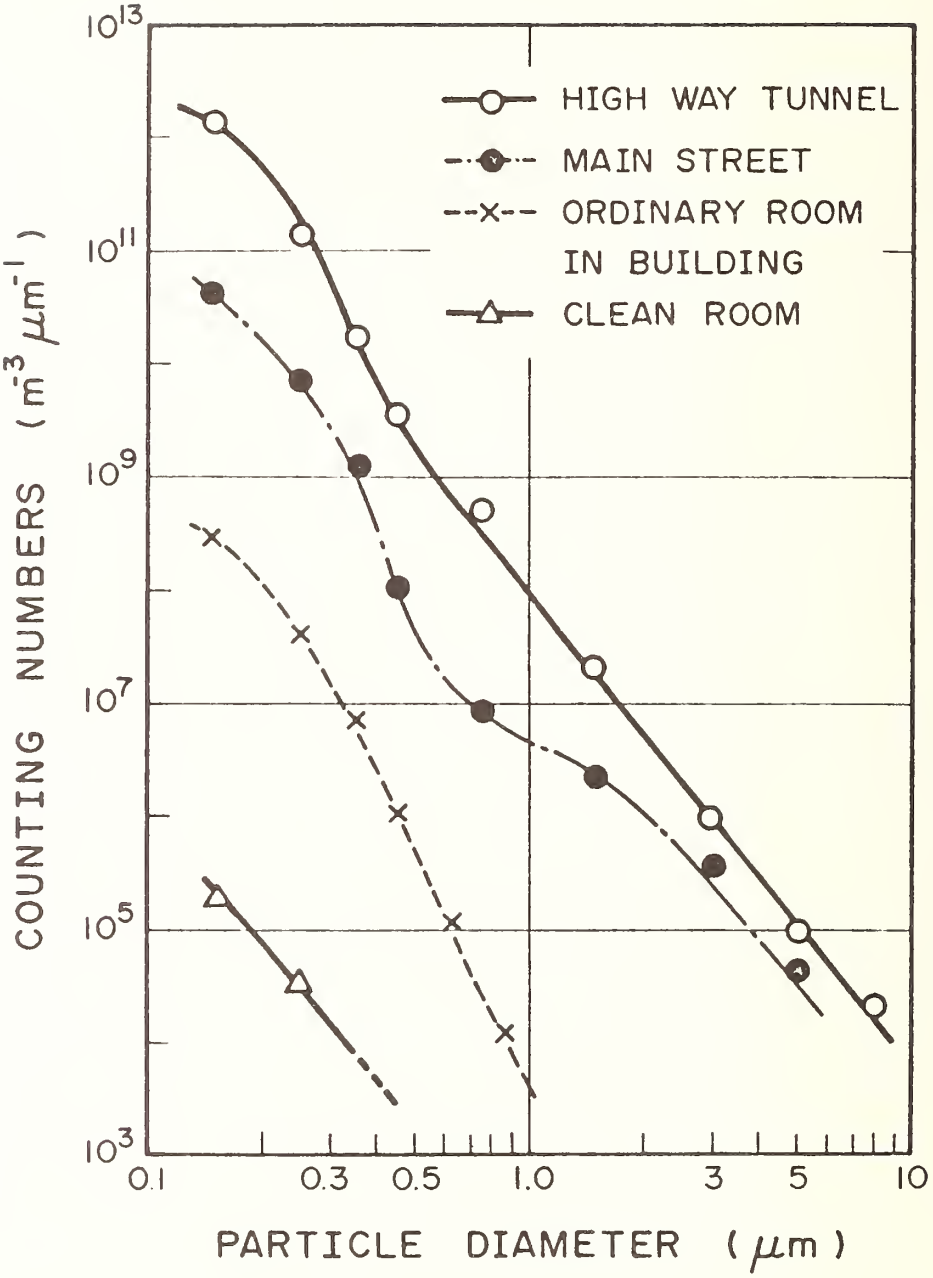

240
200
160
120
80
40
AVERAGE NOISE CURRENT (nA)
0
2
4
6
8
10
12
14
CELL PRESSURE (x10² Pa)

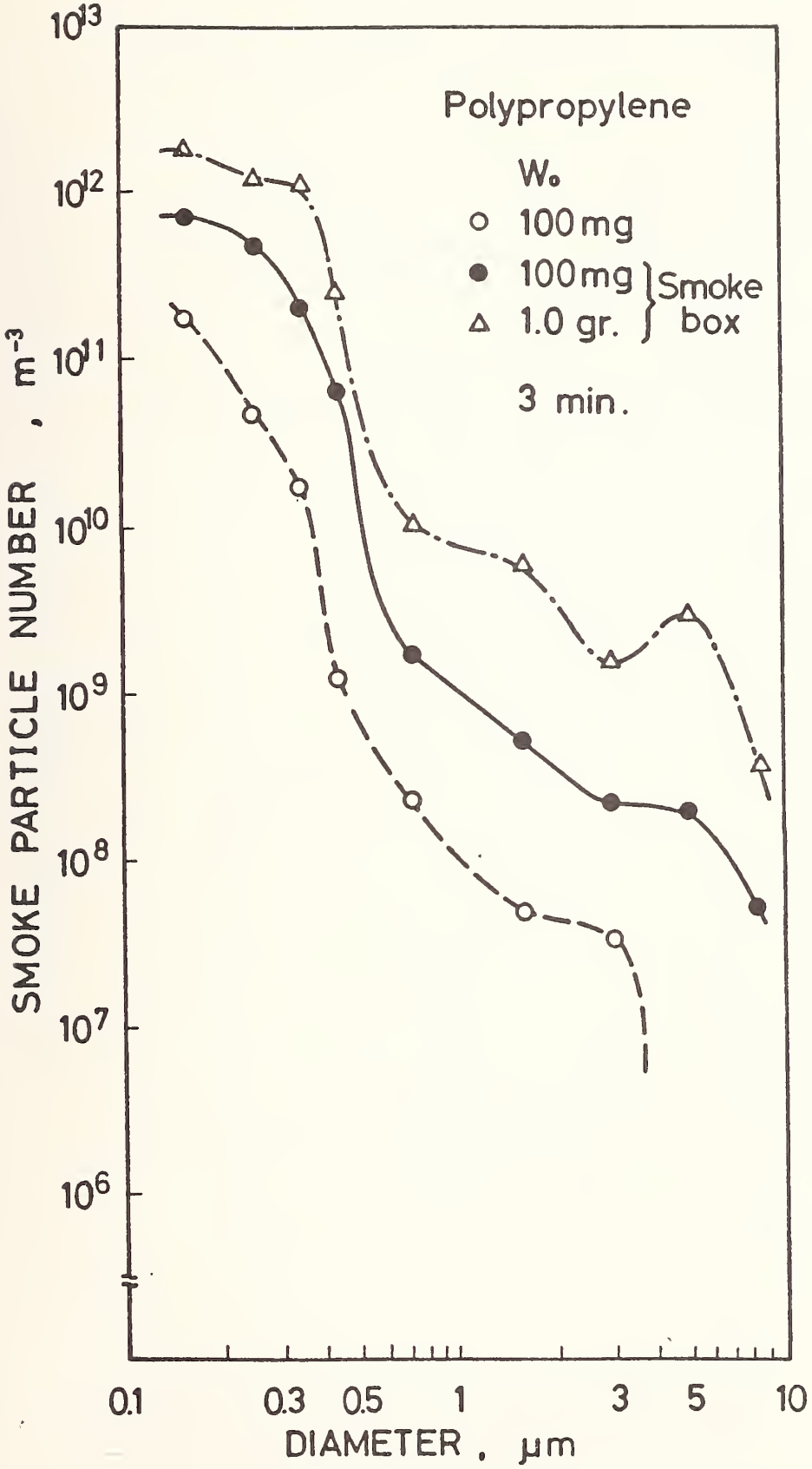

σ_s (cm^2) and RELATIVE PULSE HEIGT
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-1}
10^{0}
10^{1}
PARTICLE DIAMETER (μm)
CONDITIONS:
λ = 0.6328μm (He-Ne LASER, UNPOLARIZED, MULTIMODE)
m = 1,592 (POLYSTYRENE)
COLLECTING ANGLE
(θ = 90° ± 25°
ϕ = 90° ± 25°)

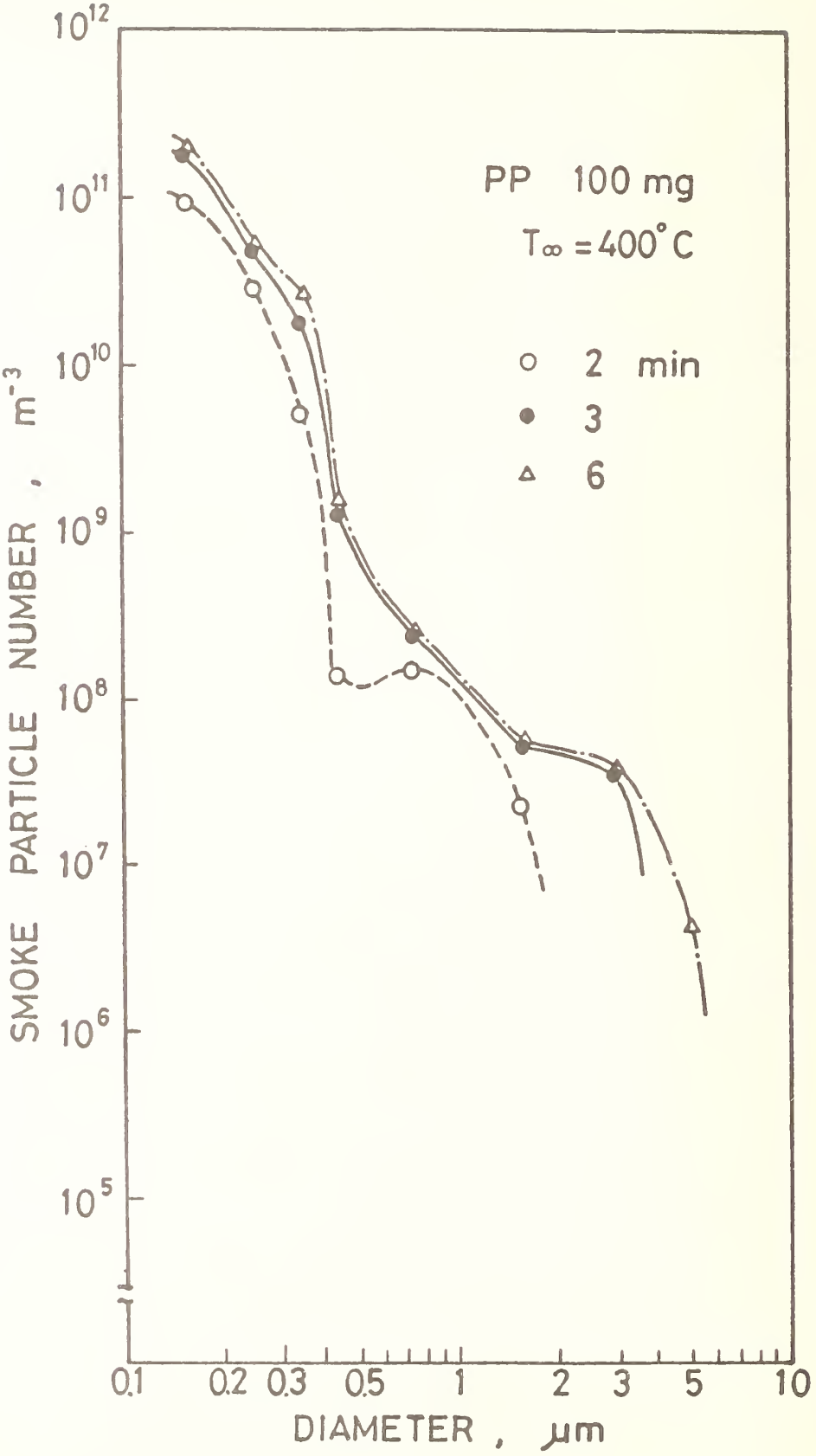
COUNT NUMBERS
CHANNEL
(a) 0.176 μm
CHANNEL
(b) 0.481 μm

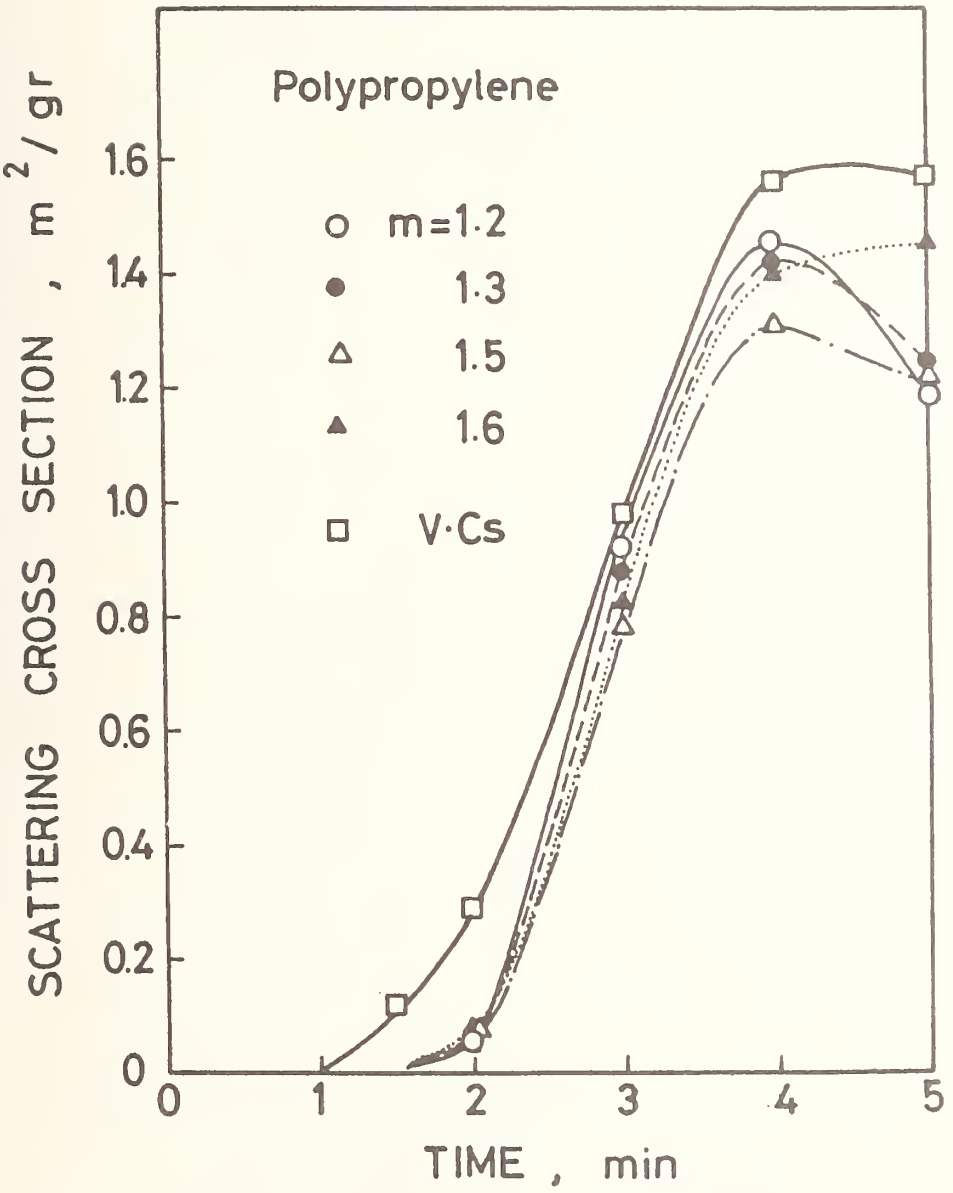

Particle : Uniform Latex Particle
0.109μm (Dow Chemi.)
RELATIVE COUNT NUMBERS
10⁴
10³
10²
10¹
1
2
1/16
1/8
1/4
1/2
1
RELATIVE PARTICLE CONCENTRATION

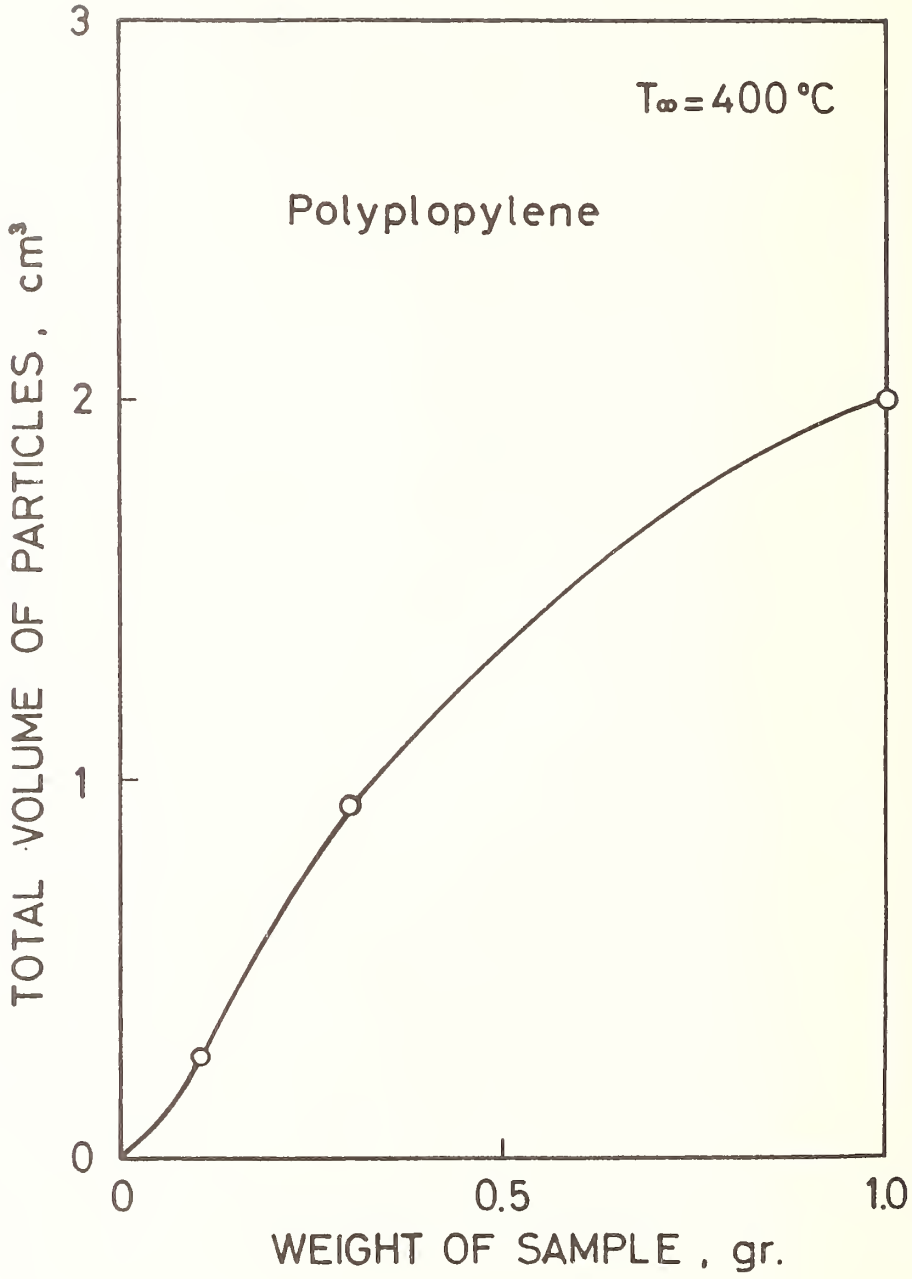

ACCUMULATIVE NUMBER CONCEENTRATIONS (ft-3)
ACCUMULATIVE NUMBER CONCENTRATIONS (cm-3)
10^8
10^6
10^4
10^2
10^0
0.1
1.0
10
(a)
(a)
1
2
3
4
5
ROYCO MODEL 220
BY THIS INSTRUMENT
PARTICLE DIAMETER (μm)


HIGH WAY TUNNEL
MAIN STREET
ORDINARY ROOM IN BUILDING
CLEAN ROOM
COUNTING NUMBERS ($m^{-3}\mu m^{-1}$)
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
0.1
0.3
0.5
1.0
3
5
10
PARTICLE DIAMETER (μm)

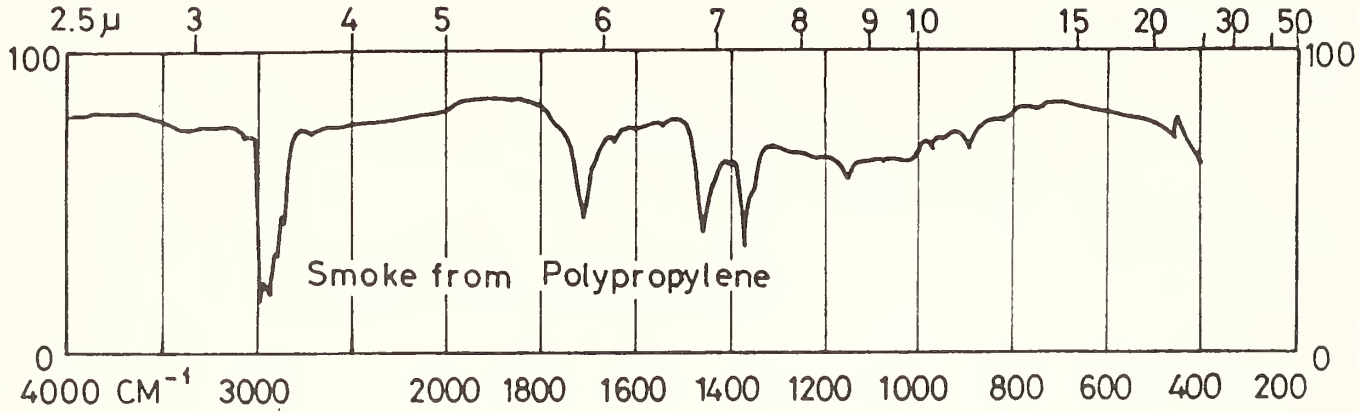

Polypropylene
W₀
100 mg
100 mg
1.0 gr.
Smoke box
3 min.
SMOKE PARTICLE NUMBER , m⁻³
10¹³
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
0.1
0.3
0.5
1
3
5
10
DIAMETER , µm

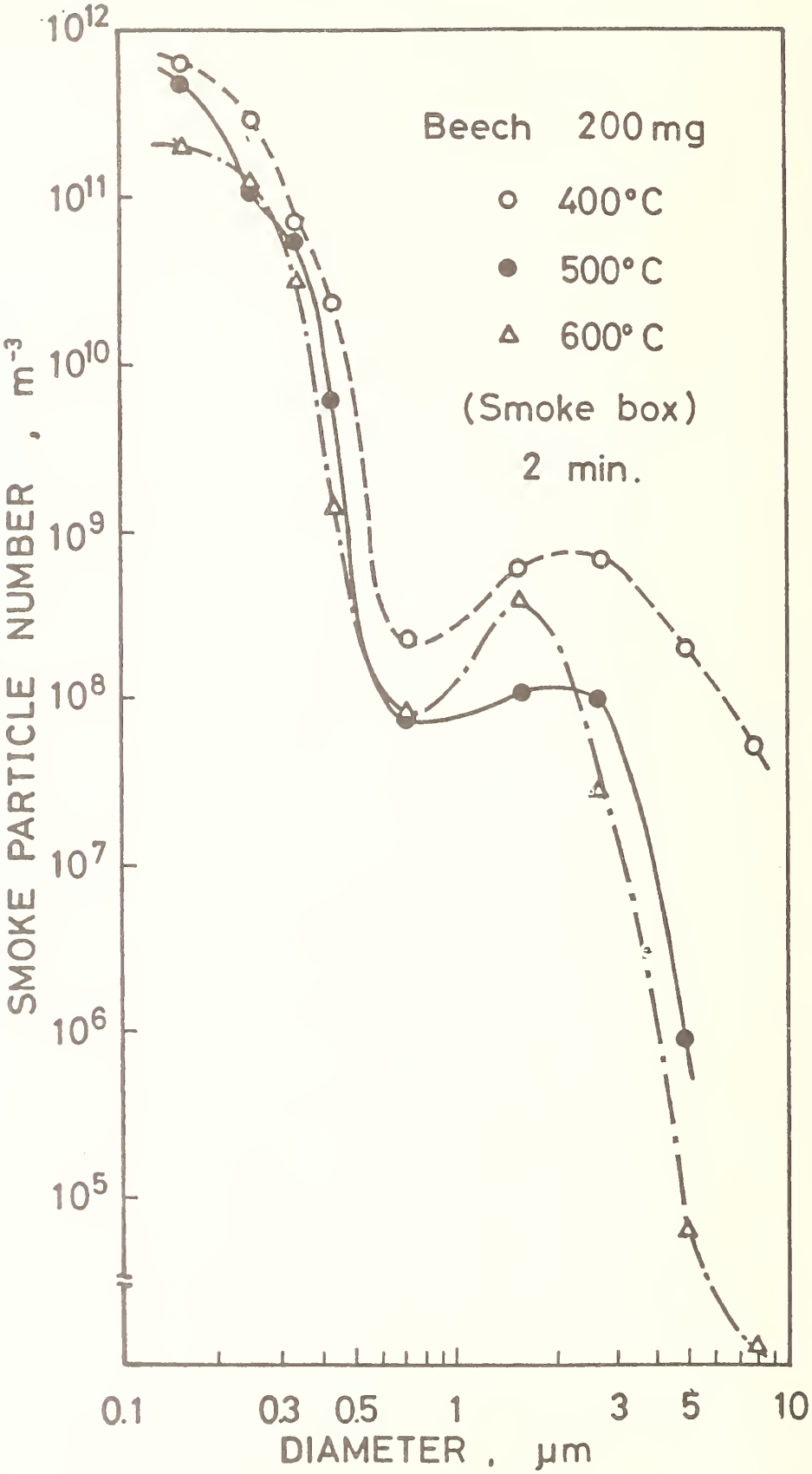

PP 100 mg
T∞ = 400°C
2 min
3
6
SMOKE PARTICLE NUMBER , m⁻³
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
0.1
0.2
0.3
0.5
1
2
3
5
10
DIAMETER , μm

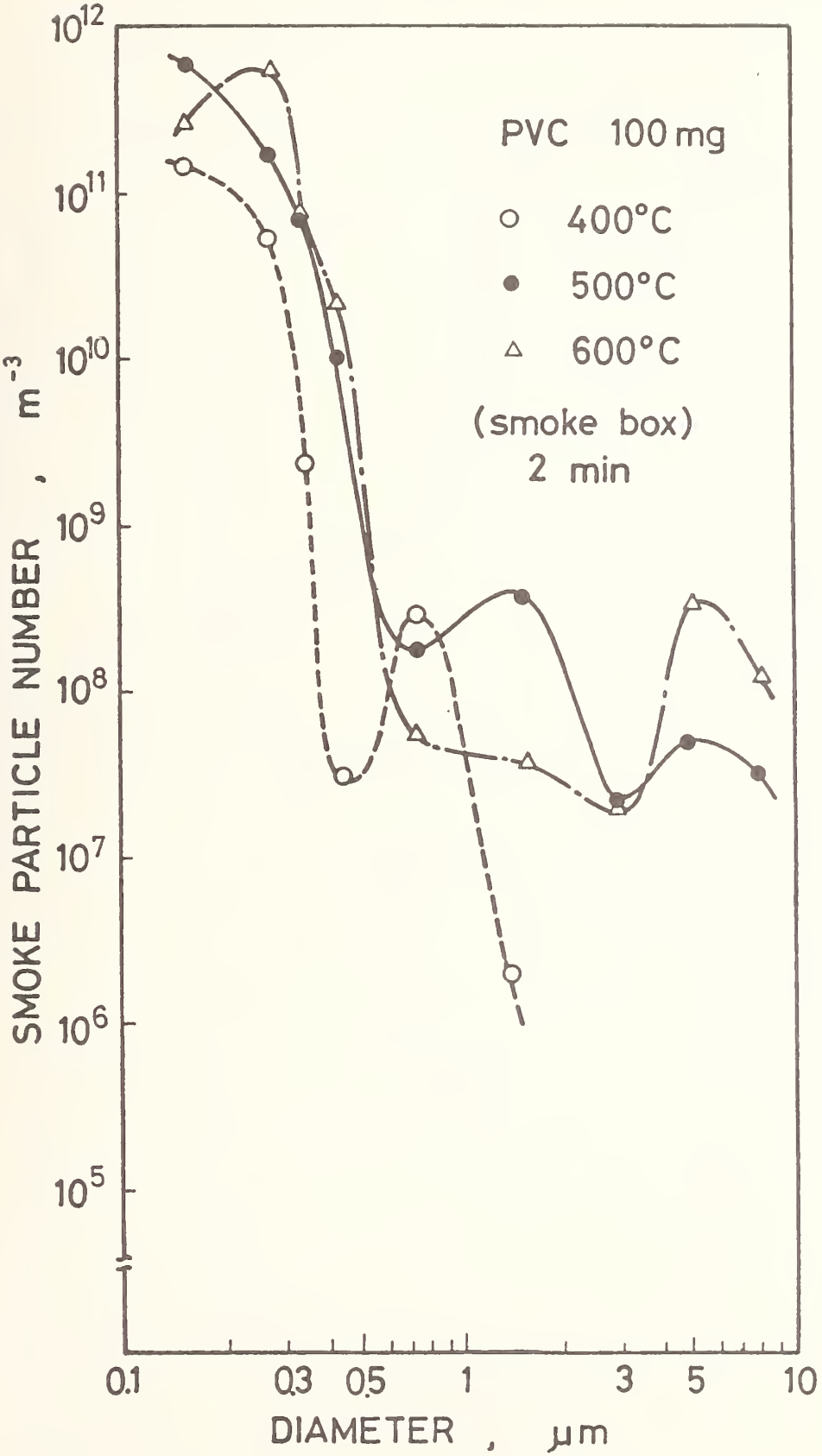

Polypropylene
m=1.2
1.3
1.5
1.6
V·Cs
SCATTERING CROSS SECTION , m²/gr
TIME , min
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
1
2
3
4
5

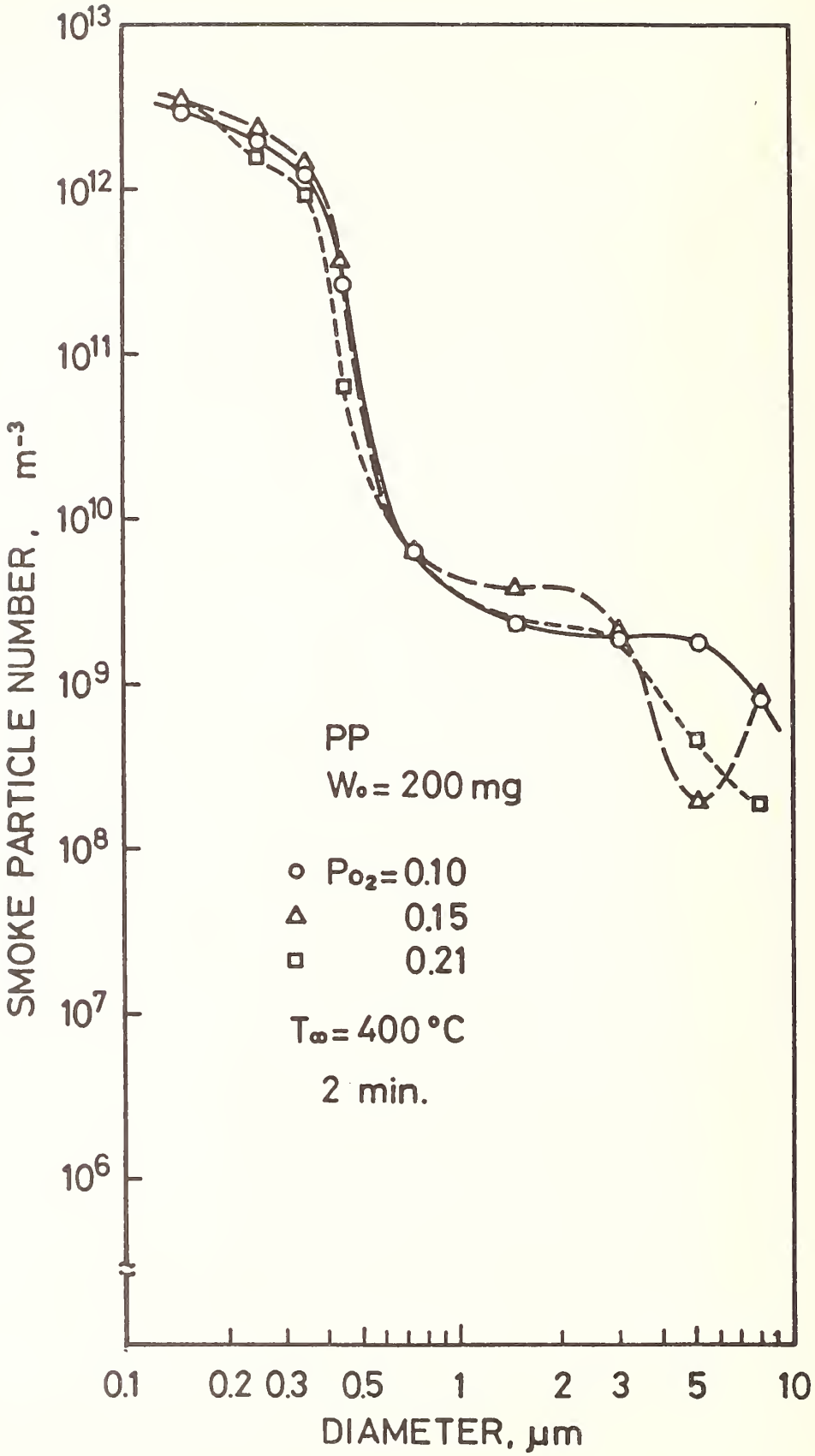

3
2
1
0
$T_\infty = 400\,°C$
Polyplopylene
TOTAL VOLUME OF PARTICLES , cm^3
0
0.5
1.0
WEIGHT OF SAMPLE , gr.

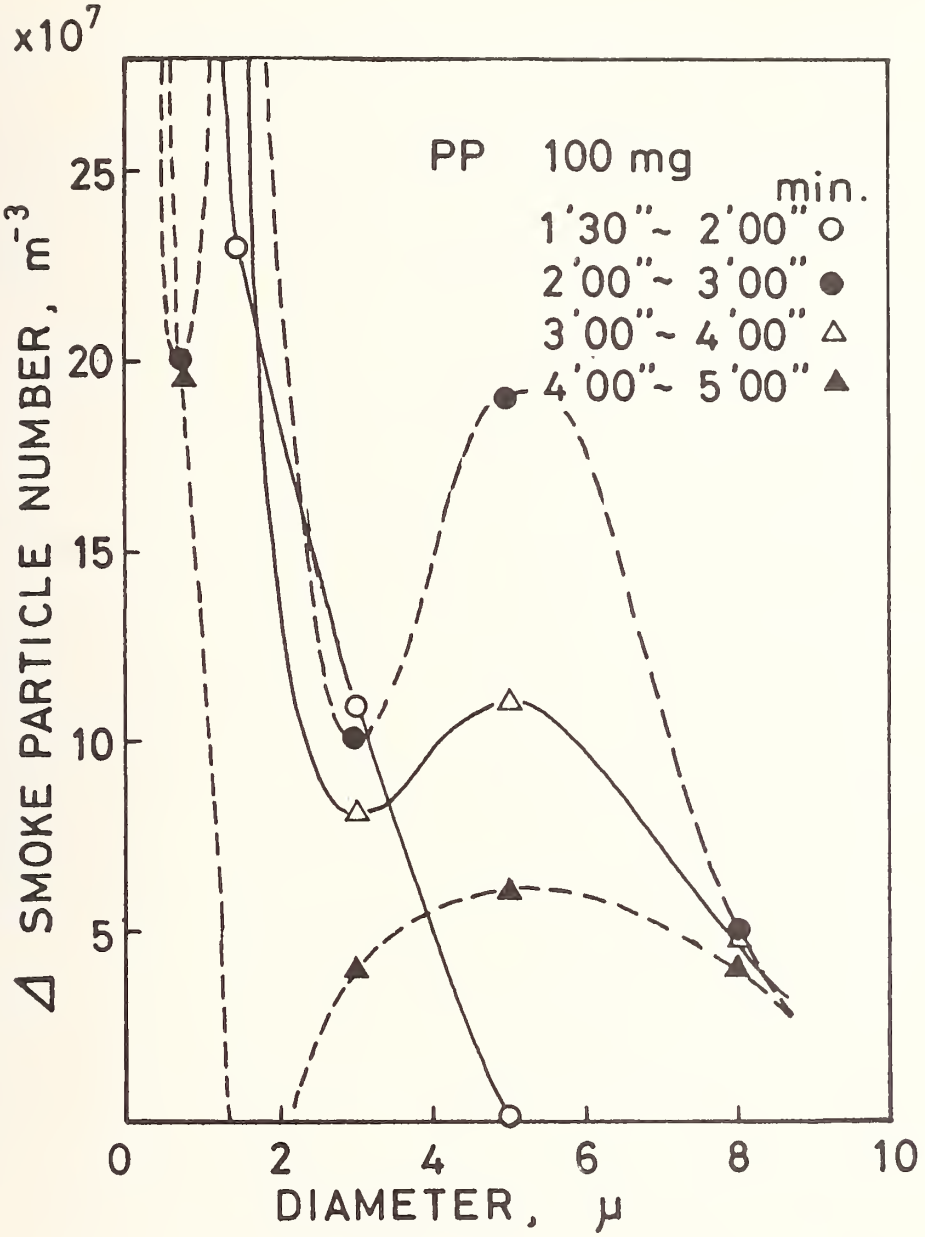
INFRARED SPECTRAL PATTERN




Beech 200 mg
400°C
500°C
600°C
(Smoke box)
2 min.
SMOKE PARTICLE NUMBER , m⁻³
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
0.1
0.3
0.5
1
3
5
10
DIAMETER , µm


PVC 100 mg
400°C
500°C
600°C
(smoke box)
2 min
SMOKE PARTICLE NUMBER , m-3
DIAMETER , µm
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
0.1
0.3
0.5
1
3
5
10


SMOKE PARTICLE NUMBER, m⁻³
10¹³
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
PP
W₀ = 200 mg
○ Po₂ = 0.10
△ 0.15
□ 0.21
T∞ = 400 °C
2 min.
0.1
0.2
0.3
0.5
1
2
3
5
10
DIAMETER, μm


x10^7
Δ SMOKE PARTICLE NUMBER, m^-3
25
20
15
10
5
0
2
4
6
8
10
DIAMETER, μ
PP 100 mg
min.
1'30"~ 2'00"
2'00"~ 3'00"
3'00"~ 4'00"
4'00"~ 5'00"

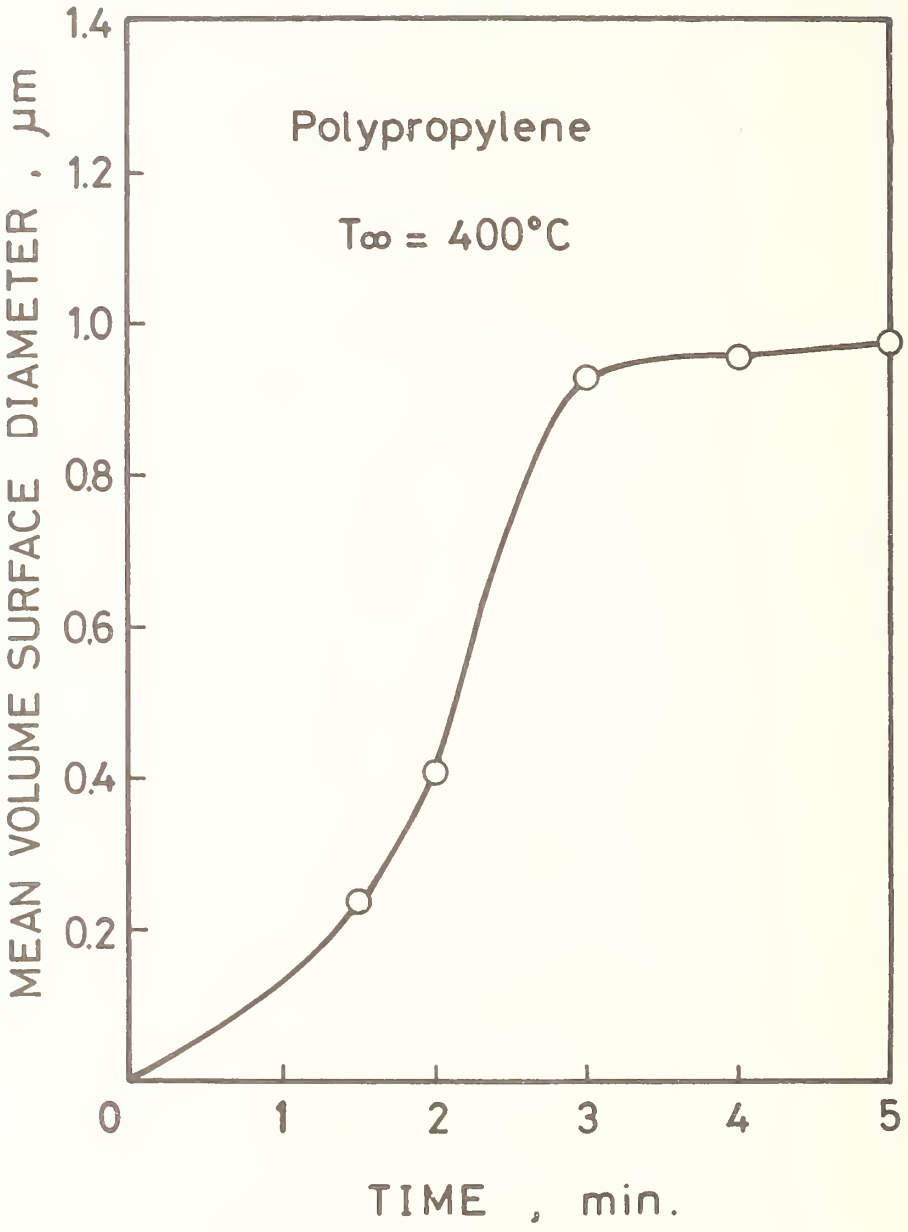

Polypropylene
T∞ = 400°C
MEAN VOLUME SURFACE DIAMETER , μm
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
5
TIME , min.

Table 1. State of the Art

Term	LMD	Roth
Laser	He-Ne	Ar^+, He-Ne
power	8 mW	2 W, 7 mW
λ	0.6328 μm	0.5145 μm, 0.6328 μm
beam diameter	(0.1 mm) 25 μm	elliptical 150 × 20 μm
intensity	(102 W/cm^2), $1.63 \times 10^3 W/cm^2$	4×10^4 W/cm^2
Particle Size Resolution	0.07 μm	0.07 μm
Slit Width	50 μm	400,200,100,40 μm
Sensing Zone Volume	2.5×10^{-8} cm^{-3}	1.2×10^{-8} cm^3
Pulse Duration Time	5.3 nsec.	250 nsec.
Concentration	4×10^5 cm^{-3}	1×10^6 cm^{-3}
Velocity	4.7 $msec^{-1}$	80 $msec^{-1}$
Aerosol Flow Rate	33.3 $cm^3 min^{-1}$	4 $cm^3 min^{-1}$
Aerosol Nozzle Diameter	3 mm	0.2 mm
Illumination	Coaxial	Perpendicular
Mean Scattering Angle	90°	40°
Collecting semi Angle	about 25°	20°
In Situ Measurement	O	Δ , ×
Dimenssion	Body: 600×400×150 Twin - Type (Travel Trank Size)	?

Sarkos Presentation

Saito: I think the treatment of that material or the cover of the material is important. What kind of treatment did you do for that kind of cover? And also I would like to know what kind of conditions are necessary if you are to apply these material testings to real cases.

Sarkos: O.K. A small sample is placed in a boat and the material is exposed to heat on all sides. We are trying to modify this so that we obtain what you might call one dimensional heating, which you would expect for a material on the surface in a cabin. I don't think we know what conditions we should test the materials under to simulate a real fire. For the moment we are developing test methods that will allow us to use a complete range of settings. In that matter when we do obtain large scale results we will be able to try a different setting to see which produces the best arrangement of heat.

Einhorn: Gus, does this possibly indicate that maybe what one ought to do along the fuselage is have occasional rows of seats out, and a door at floor level for exit and systems with your 90 second egress time so people can get closer to the lower level rather than having to stand up into the fumes and temperature at the higher area.

Sarkos: I still believe that the most important thing is to get out of the cabin as fast as possible. If you're trapped it's certainly beneficial to drop closer to the floor or safer as the NFPA has been telling us for years on their posters. I think what the data does indicate is that we should concern ourselves more with the ceiling materials which apparently will become more and more involved with the fire than those lower to the floor. We've seen this in accurate aircraft accident investigations before we completed studies, but I think now we'll get a better quantitative indication of the relative importance of location.

Handa Presentation

Mulholland: First of all I would like to comment that we would very much enjoy having an instrument like the one you described. It has the capability of measuring two orders of magnitudes higher concentration than our optical particle counter, and of measuring particles five times smaller in diameter than our instrument can detect. I would appreciate your defining the ordinate in your graph, which was called the number concentration. I wondered if this refers to the number of particles per increment of diameter or the number of particles per log increment of diameter.

Yesterday I did a little calculation as a result of some comments concerning the effects of particle charge on the coagulation rate. This also concerns your observation that at larger particle size, the Smoluchowski theory of coagulation doesn't apply because of particle charge. Using Fuch's equation for the effect of particle charge, it would appear that very small particles are more affected by the particle charge than the large ones. If we have two one micrometer particles one with a positive and one with a negative charge, I estimate a 2 or 3% enhancement of the coagulation rate as compared to the rate for uncharged particles. Maybe the explanation is that your particles have hundreds of charges and that would give you a much larger effect.

Rockett: If you estimated dosage of a particle that enhances with a very small coke volume I may be wrong but if you had focused the laser in this volume...I made very crude estimates because I don't know of your instrument but I thought perhaps some of the small particles might be getting a thermal dosage as high as 100 volts per gram. I wondered if you had estimated this.

Handa: I agree with you completely.

REPORT OF TECHNICAL SESSION ON DETECTION AND SMOKE PROPERTIES

J. Miyama, Chairman

The session commenced at 9:00 a.m. on March 14, 1978. Without delay Mr. R. W. Bukowski and Dr. G. W. Mulholland in turn presented a report titled "Detection and Smoke Properties." Recent developments in smoke detector technology were outlined and programs to determine the performance and reliability of detectors were discussed. Measurements were described of size distributions, mass and number concentration and coagulation frequency of smokes using the electrical aerosol analyzer, an optical counter and a monodisperse aerosol generator. An instrument for determining the sensitivity of installed smoke detectors was described in detail. This will be appreciated as an excellent replacement for the conventional punk stick smoke method.

Mr. A. Watanabe of Fire Research Institute presented a general report titled "False Alarm of Smoke Detectors" in collaboration with Jun Miyama of Sophia University. He summarized the requirements for smoke detectors in Japan and statistics on false alarms. Technical standards for smoke detectors have been revised by the Fire Defense Agency in order to avoid false alarms. A dust test, transient voltage test and humidity test have been added for smoke detectors.

Concerning the report presented by Smoke and Toxicity Load Committee (Japanese Association of Fire Science and Engineering), Mr. Saito especially emphasized:

1) the relationship between the generation rate of smoke and optical smoke density for fire-retarded materials.

2) the heavy influence of ventilation factors on smoke generation for compartment fires.

On each presentation we had so much active discussion that we could scarcely finish our session on time.

REPORT OF PROGRESS REPORT SESSION ON HUMAN BEHAVIOR, BUILDING SYSTEMS AND SMOKE CONTROL

G. Bates, Jr., Chairman

The chairman introduced these sessions by noting that the three (3) subjects had been covered in depth at the meeting in Toyko, October 1976, and that only summaries of recent work in Japan and the U.S. are to be presented at this meeting.

Human Behavior:

Professor John Bryan of the University of Maryland called the Panel's attention to the Bibliography on Human Behavior in Fires that he had prepared and distributed to all present. He then gave a verbal report with pictures of a major fire that killed 166 people at the Beverly Hills Supper Club in Southgate, Kentucky, in May 1977. This fire is covered in detail in a report "Reconstruction of a Tragedy" by the National Fire Protection Association, 470 Atlantic Avenue, Boston, Massachusetts, 02210.

This large supper club which contained over 2500 people was destroyed by fire. The deaths were from 1200 people in one room - and were caused mostly by heat and smoke. Fire fighting equipment was called and arrived promptly - but was not able to control the fire. The pictures presented by Professor Bryan were most graphic. This fire has received a great amount of study by many fire experts - with over 630 survivors being interviewed. There was no evidence of panic - the people were rapidly evacuated by the staff - but too late for many. Professor Bryan suggested that those interested in human behavior under severe fire conditions should study the details of this fire.

Dr. Tadahisa Jin, of the Fire Defense Institute of the Ministry of Home Affairs, discussed work in Japan on human behavior. He divided this work into three areas:

1) Experience in Real Fires
2) Computing Simulation of Dynamic Evacuation of a Building.
3) Experiments in Human Behavior during Evacuation.

He noted the need to increase levels of efforts in all areas, to increase the flow of information between the areas, and the need to find a way to obtain human data without live, dangerous experiments. Dr. Jin did note that in Japan the building designer is the person making use of data on human behavior in deciding how to design the next building. Some recent papers from Japan on human behavior are listed in the report from Dr. Jin.

Human behavior under fire stress is an inexact science - but must be considered in the design of fire protection of any system.

Building Systems:

Mr. H. Nelson of the NBS gave a paper on system design concepts by which the probability of and problems of a building fire could be studied. He proposed a decision tree approach which considered fire modeling, fire control, and people movement among other factors. He also presented a grid approach covering questions of technical assessment, total building control, flexibility and cost, and retrofit versus who makes decisions and how they are made. He noted that the problems of the systems concept are proofing/validation of in-put data, and understanding the results.

Mr. Tekeyoshi Tanaka of the Building Research Institute of the Ministry of Construction discussed the work by the committee of Fire Safety Systems. This committee is responsible for research programs to develop technique for fire safety performance evaluation of a facility. This committee divides its work into the following subgroups: Compartment Fire Groups, Smoke Control Group, Detection and Extinguishment Group, and Evacuation Systems Group. These groups examine subsystems concepts. A Total Systems Group and a Maintenance Systems Group work on the composites systems concepts. Mr. Tanaka also reported on the research by the Committee of Fire Safety Performance of Houses. This committee is making an analysis of 1000 home fires and expects to have a good model of how a fire develops in a home.

Systems is an area in strong need of application of knowledge and technologies used in other fields.

Smoke Control:

Mr. Irwin Benjamin of NBS and Mr. Tekeyoski Tanaka of the Ministry of Construction discussed smoke control. The concepts of pressurized stairways and compartmentized buildings for smoke control were outlined and examples of both types of construction were identified. There is interest in total pressurization as an outgrowth of energy conservation environmental controls in modern buildings. One use of such systems is to pressurize all floors except the fire floor and to exhaust from that floor. Mr. Tanaka mentioned the problems in calculating smoke movements in a building and the necessity to check all possibilities.

This subject is one wherein much experimentation and model development are still required. The concept of smoke control by limiting/controlling the nature of materials which might be subjected to a fire is also a goal of the aviation industry - and may be of value to others.

REPORT OF TECHNICAL SESSION ON FIRE MODELING

H. Emmons, Chairman

Mr. J. DeRis and Mr. C. McArthur discussed the U.S. work on fire modeling. A number of people are working the mathematical modeling of two aspects of fire.

1. The analysis of component problems such as the rate of growth of a fire, the radiation from a flame to a wall, etc.

2. The complete history of the fire from ignition to flashover, eventually to complete involvement of a large building.

There are two methods of treatment of fires and fire components:

A) Field Methods - the solution of the general partial differential equations. At present, this is essential to research on fire components but computing machines are far from large enough to solve a whole room fire.

B) Zone Models - which considers a fire as made up of distinguishable components and their interactions.

A National U.S. Mathematical Modeling Committee has been formed by NBS and includes Modelers, Users, and Fire Research Sponsors. This committee has discussed all current models and has listed fire component research needs and placed them in order of priority. As we might expect, Fire Spread and Burning Rate as effected by feedback radiation and vitiated air effects were of top priority.

Fire specific models were mentioned:

1. Quintiere, NBS Model
2. RFIRE - Pape at IITRI
3. DACFIR - McArthur & Reese - University of Dayton
4. Computer Fire Code III - H. Emmons & H. Mitler, Harvard
5. UNDSAFE - Notre Dame University

In Japan, several models conceived independently but which are very similar to the above are being developed. Mr. Tanaka presented the first three of the following reports: 1) SEMI has tried to identify all fire components and their interactions. He prepared a chart showing the level at which the various components and interactions are understood. This chart is an indication of what basic research is still essential. 2) Mr. Tanaka has concentrated his recent fire modeling efforts on the flow of fire gases through connected rooms. He uses a simplified fire in a room of fire origin and analyzes the flow through a succession of rooms and in a building of three stories. This is the first attempt to make a multiple room fire gas flow study and appears to be very successful. 3) Morishita has attempted to develop a quantitative statistical fire model. The fire records in Tokyo appear to be much more complete with respect to details of fire progress than in the U.S. and permits the quantitative evaluation of the probability of fire growth from one phase to another. The data is procured by a person trained for the purpose of data collection. This is a valuable addition to a statistical analysis since it attempts to make the predictions quantitatively. 4) Saito presented the experimental results obtained using medium size models. He pointed out that the burning rate in the early stage of fire is high when the internal materials are combustible. He also suggested that in addition to A H, the surface area of the combustibles and the volume of the compartment should be applied as controlling factors of the bufning rate in the compartment in the early stage of fire. Furthermore, he presented an experimental formula using these factors and experimentally proved that this formula is available for semi-nature fire tests and model fire tests (the volume of the compartment: 0.13 - 27 m^3).

REPORT OF TECHNICAL SESSION ON TOXICITY

A. Watanabe, Chairman

The session on toxicity was held from 1530 to 1630 on 15 March 1978 at the National Bureau of Standards, and from 1000 to 1715 on 16 March 1978 at the Applied Physics Laboratory/The Johns Hopkins University.

From the Japanese side, Mr. Yusa, Tokyo University, proposed the relative degree of toxic hazard in the animal test. Mr. K. Nakamura, BRI, reported the collapse or death index, and 50% lethal concentration for CO, CO_2, HCL, HCN and their combinations obtained through an animal test using mice.

Mr. Saito, BRI, introduced the Japanese method for toxicity evaluation, and showed the problems in measurements. Dr. K. Yamamoto pointed out that for postmortem diagnosis of HCN intoxication, the sample should be collected for as many parts of the animal bodies as possible.

From the American side, Prof. Einhorn suggested his philosophy of toxicity evaluation, and referred to recent work. Dr. P. Smith, formerly with the Federal Aviation Administration, and now a consultant reported inhalation toxicology research data obtained during the past seven years. He suggested that the effect of co-existence of CO and HCN on humans becomes additive only when one of the compounds is present at a nearly critical level.

Dr. M. Birky, NBS, introduced a proposed test method for toxic combustion products which is based on a 30 minute exposure for rats.

Dr. M. Levine, Johns Hopkins University School of Hygiene and Public Health, stated that firemen are exposed to low levels of CO and HCN and that intermittent use of face masks does not adequately protect men.

Mr. B. Halpin, APL/JHU discussed, on the basis of the Maryland fire casualty study, the predicted effect of fire detectors on life loss.

After hearing the honest opinions of those with first-hand experience, the members entered into lively discussions.

Philosophies of evaluation of toxic hazard differ, and this problem will be discussed once more on a progress report at the next panel meeting.

RESOLUTIONS

The members of the UJNR Panel on Fire Research and Safety wish to express their satisfaction with the successful 3rd Joint Panel Meeting held in the U.S.A., March 13-17, 1978. The formal and informal presentations and the discussions on fire toxicology, on smoke properties and detection, and on fire modeling were stimulating, instructive, and well received. Excellent arrangements for the meeting had been made by the Center for Fire Research/NBS and the Applied Physics Laboratory, Johns Hopkins University.

The Panel Members herewith resolve:

1. That the next (4th) meeting of the UJNR Panel on Fire Research and Safety be held in Tokyo in February 1979.

2. That the following topics be discussed in-depth:

   (a) human behavior in fires, (b) building systems and smoke control, (c) fire and smoke retardants, and (d) fire investigation techniques.

3. That progress reports be submitted in the areas of toxicity, of detection and smoke properties, and of fire modeling.

4. That the general format used during the 3rd Joint Panel Meeting be retained.

5. That Panel Members be encouraged to exchange information of mutual interest through the respective chairmen.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The Third Joint Panel Meeting of the United States - Japan Panel on Natural Resources (UJNR), Fire Research and Safety, was held at the National Bureau of Standards in Gaithersburg, Maryland, from March 13-17, 1978. The meeting consisted of in-depth technical sessions on detection and smoke properties, modeling of fire, and toxicity of fire gas. Progress reports briefly covered human behavior, building systems, and smoke control. This proceedings includes the technical papers presented at the meeting along with the ensuing discussion and the summary reports prepared by each session chairman.

The first meeting of UJNR Panel on Fire Research and Safety was held in Washington, D.C. from April 7-8, 1976, where the current activities in the United States and Japan on fire research and safety were introduced. After this exchange, the following 6 topics were selected for initial cooperation: toxicity, building systems, human behavior, smoke control, detection and smoke properties, and modeling of fire.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Building fires, conferences, fire detection, fire investigations, fire models, fire research, fire retardants, flame retardants, human behavior, smoke, toxic gases, toxicity.

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