NBS SPECIAL PUBLICATION 639

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

Fire Research and Safety

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Fire Research and Safety

Proceedings of the Fifth Joint Panel Meeting of the U.S.-Japan Cooperative Program in Natural Resources held October 15-24, 1980, at the National Bureau of Standards, Gaithersburg, MD

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ABSTRACT

The Fifth 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, MD, from October 15 through 24, 1980. The meeting consisted of in-depth technical sessions on arson and fire investigation, toxicity of combustion products, advances in sprinkler technology, and fire modeling. Progress reports briefly covered fire retardance, building design, smoke control, human behaviors in fires, and fire protection. Two days of informal sessions were held on toxicity, human behavior, detection and smoke properties, sprinklers, smoldering, and fire modeling. This meeting was held in conjunction with the Center for Fire Research's Annual Conference* which included United States presentations of related technical subjects. The proceedings include the technical papers presented at the UJNR meeting along with the ensuing discussion and the summary reports prepared by each session chairperson.

The first meeting of the UJNR Panel on Fire Research and Safety was held in Washington, DC, 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 resolved that the sixth meeting, to be held in Tokyo, would cover the following topics in-depth: (1) building systems and smoke control, (2) human behavior, (3) fire modeling, and (4) toxicity. Progress reports will be submitted in the areas of human behavior, fire modeling, toxicity, sprinklers, detectors, fire and smoke retardants, fire investigation techniques, and building systems and smoke control.

Key words: arson, building design, combustion products, fire investigation, fire modeling, fire protection, human behavior, smoke control, smoldering, sprinkler systems, toxicity.

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*Fourth Annual Conference on Fire Research, Martinez, I., Cherry, S., Editors, Nat. Bur. Std. (U.S.), NBSIR 80-2127-1, 1980.

AGENDA
THE FIFTH JOINT PANEL MEETING
UJNR Panel on Fire Research

October 15-24, 1980

Wednesday, October 15	Session Chairman - Dr. F. B. Clarke
9:00 a.m.	Opening Session Welcoming Remarks Selection of Chairmen and Recorders Introduction of Panel Members
10:15	Coffee and Tea Break
10:30	Progress Reports on: Fire Retardance Building Design Smoke Control Human Behaviors in Fires Fire Protection
12:30 p.m.	Lunch
1:30	Session Chairman - Mr. I. A. Benjamin
	Technical Session "Arson and Fire Investigation"
5:00	Adjournment
Thursday, October 16	Session Chairman - Prof. J. J. Bryan
9:00 a.m.	Technical Session "Toxicity of Combustion Products"
12:30 p.m.	Lunch
1:30	Session Chairman - Dr. T. Jin
	Technical Session "Advances in Sprinkler Technology"
5:00	Adjournment

Friday, October 17		
	9:00 a.m.	Session Chairman - Prof. T. Handa
		Technical Session - "Fire Modeling"
	12:30 p.m.	Lunch
	1:30	"Fire Modeling" continued.
		Session Chairman - Dr. R. Friedman
		Technical Session - "Smoldering"
	5:30	Adjournment
October 20 and 21		Informal Sessions
		Toxicity Human Behavior Detection and Smoke Properties Fire Modeling Smoldering Sprinklers
October 22, 23, 24		Center for Fire Research ANNUAL CONFERENCE
		Technical Sessions included:
		Human Response to Fire Detection Alarms Human Behaviors in Fire Building Design and Smoke Control Toxicity
Friday, October 24		Session Chairman - Dr. T. Wakamatsu
	1:00 p.m.	Closing Joint Session Reports of Technical Session Resolutions
	4:00 p.m.	Adjournment

LIST OF PARTICIPANTS

The Fifth Joint Panel Meeting
UJNR Panel on Fire Research

October 15-24, 1980

PANEL MEMBERS - Japan

Dr. Takao WAKAMATSU (Chairman)
Ministry of Construction

Dr. Fumiharu SAITO
Ministry of Construction

Mr. Yasaburo MORISHITA
Ministry of Construction

Mr. Yuji HASEMI
Ministry of Construction

Dr. Tadahisa JIN
Ministry of Home Affairs

Prof. Jun MIYAMA
Sophia University

Prof. Yoichi NISHIMARU
Yokohama City University

Prof. Takashi HANDA
Science University of Tokyo

Mr. Tetsuhiko KAWAMURA
Japanese Association of
Fire Science and Engineering

Mr. Juzo UNOKI
Japanese Association of
Fire Science and Engineering

Dr. Tadahiro ISHII (Technical Coordinator)
Science University of Tokyo

PANEL MEMBERS - U.S.

Dr. Frederic CLARKE (Chairman)
National Bureau of Standards

Mr. Irwin BENJAMIN
National Bureau of Standards

Prof. Howard EMMONS
Harvard University

Prof. John BRYAN
University of Maryland

Dr. Raymond FRIEDMAN
Factory Mutual Research Corp.

Dr. Patrick PAGNI
University of California

Mr. Philip SCHAENMAN
U.S. Fire Administration

Dr. Takashi KASHIWAGI (Secretary)
National Bureau of Standards

Invited Speakers

Invited Speakers:

Dr. Hsiang-Cheng KUNG
Factory Mutual Research Corporation

Mr. Clifford KARCHMER
Battelle Institute

Dr. Merritt BIRKY
National Bureau of Standards

Dr. Thomas OHLEMILLER
National Bureau of Standards

Mr. John O'NEILL
National Bureau of Standards

Invited Guests:

Mr. H. KURIHARA
Science Counselor
Japanese Embassy

Dr. K. HEINRICH
Office of International Relations
National Bureau of Standards

Dr. J. LYONS
National Engineering Laboratory
National Bureau of Standards

Mr. A. GLEASON
Bureau of Alcohol, Tobacco and Firearms
Department of Treasury

Mr. R. CHAIKEN
Bureau of Mines
U.S. Department of Interior

Dr. R. MYERS
University of Maryland

Fifth UJNR Meeting

Minutes of the Opening Session:

Dr. Frederic B. Clarke, Chairman of the United States delegation, opened the joint session by welcoming the delegation to the National Bureau of Standards (NBS). He then introduced Dr. John W. Lyons, Director, National Engineering Laboratory, NBS (and former Chairman of the UJNR U.S. delegation). Dr. Lyons pointed to the great progress made by the Panel in the first four meetings, and voiced his belief that present and future sessions would also be fruitful.

There followed the selection of Chairmen and recorders for the sessions. The Panel voted unamiously to make the following individuals session chairmen:

F. Clarke (USA)	- Opening Session
I. Benjamin (USA)	- Arson and Fire Investigation Session
J. Bryan (USA)	- Toxicity of Combustion Products Session
T. Jin (Japan)	- Advances in Sprinkler Technology
T. Handa (Japan)	- Fire Modeling Session
R. Friedman (USA)	- Smoldering Session
T. Wakamatsu(Japan)	- Closing Session
H. Emmons (USA) F. Saito (Japan)	- Resolution Committee

Panel members were introduced. The minutes of the Fourth Joint Panel Meeting in Tokyo were approved and will be printed in Proceedings to be published by the Japan delegation.

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.

1. PROGRESS REPORTS

PROGRESS REPORT

Recent Development of Fire Retardance

by F. Saito

To decrease the probability of fire-outbreaks and prevent fires from developing are primarily important in the field of fire prevention technology. Compartmentation of fire, smoke control and evacuation are also important subjects to be studied.

In Japan, we have enforced the regulations so that interior materials, such as linings, curtains and carpets applied in public buildings or tall buildings, from which people will take a long time to evacuate, should be resistant enough to fire, having a certain level of flame retardancy or fire retardancy depending on the place where the material is applied. The methods for evaluating flame and fire retardancy of these materials have been already established.

Flame retardant materials:	char area, after flame (curtains, and carpets)
Fire retardant materials:	heat release, smoke generation, toxicity (linings)

The methods of flame and fire retardant treatment tc meet the standards prescribed in the regulations are being developed. In this paper, flame and fire retardant technology, their defects and profits are briefly discussed.

1. Production of flame retardant chemicals

   Table 1 shows a statistical data of the amounts of the retardant chemicals used.

2. Technology for flame retardant treatment

   It is needless to say that chemicals and treatment methods have to be selected according to a material and performance level for fire protection required.

LOI method has been adopted in many research laboratories because this method is easy to be applied and gives accurate values for evaluating efficiency and synergistic action of chemicals.

A defect of this method, however, lies in the difficulty in correlation between LOI values and the ones obtained by our national standard method. Therefore it is difficult to decide the type and the proper amount of chemicals to be used by LOI method.

Flame retardant: Cellulose-type curtains concerned, additive type flame retardant in which phosphoric ester are dominant, are mainly used and small amount of inorganic type chemicals, in spite of their poor light durability but owing to their inexpensiveness, are also found in market. As cleaning test is now enforced to evaluate curtains, which are usually washed, after treatment is studied to pass the test.

Fire retardant: As legal regulations of fire protective materials in Japan are considerably strict, it is very rare that organic materials are made noncombustible only by the treatment of fire retardant chemicals. Adding large amount of inorganics or treating surface material is a common method to be taken in Japan. Fire retardant is often added in adhesives, in case of bonding organic lamination on inorganic base layer.

For example, in case of wallpapers, a fire protective material should be used as a base material. Wallpaper whose weight is designated according to the classified fire protection properties required should be applied on base material, using adhesive which contains fire retardant from 1 to 3% in dry weight content.

In this case the weight of phosphoric ester to be used should be a dry weight of 10 to 20% of the weight against the original wallpaper.

3. Future work

1) Plastic foams

In 1978, a lot of firemen were wounded in a fire of warehouse whose insulation was made of poly-urethane foam. The backfire caused by poly-urethane insulation was a main reason for such unfortunate injury. The material was classified as a self-extinguish type by ASTM test method.

The cause of the fire-outbreak is considered that high temperature droplet of welding penetrated into the insulation layer and combustion was taken place inside the plastic foam.

In this case, thermal insulating property of this material acted as a negative factor. Backfire occured when the firemen opened the door of the warehouse, because the building, which has little opening, accumulated large amount of smoke and combustible gases.

After that, a method of evaluating plastic foams in view of such danger has been established, but other insulation materials which will be used in near future should be also studied.

2) Evaluation for fire retardant chemicals

The type and the proper quantity of fire retardant to be applied depend on what kind of testing method is taken for evaluation.

The world-wide standard for evaluating fire retardant has not yet been established. And how to apply the values obtained from a test to a real fire has not been clarified.

There are so many ignition sources such as cigarettes, waste baskets, electric appliances, and stoves in circumstance. From the view-point of fire protection, probability of turning such substances into primary ignition sources should be kept as low as possible.

However, intensity of thermal load that a material receives from these various ignition sources has not been clarified.

As shown in Figs 1 to 3, thermal load that a material receives from an ignition source depends on the size of the ignition source and the distance from it. Therefore, it is necessary to know the extent of fire retardant effectiveness expected, according to the size of the ignition source and the distance from it.

To extinguish a fire on their way of developing, prevent a flash-over or at least delay a flash-over; these are most important in preventing building fires. Duration from a fire-outbreak to a flashover is not always proportional to the size of the ignition source, even if the materials are the same as shown in Figs 4 and 5. Although, researchers in other fields may give a fruitful solution, researchers of fire retardant should be eager to solve these problems.

3. Durability of fire retardant materials

Materials, according to their end-use, are used under various circumstances.

It is needless to say that materials have to possess various properties depending on their purposes. Besides that, fire protective materials should possess fire protection properties.

It means that their own general characteristics should not be degraded due to the treatment of chemicals and the fire protection properties should not be reduced with time. At present, however, there are few testing methods which require long lasting durability of fire protecting efficiency. A proper method for evaluating such durability should be developed.

At present, basic researches for evaluating durability are being promoted in Japan, in such a manner that a material is exposed to light under glass, or immerced in water.

Table 1.
Products of Fire Retardant Chemicals for Plastics (Building Materials)

type	amount of use (ton/year)
Cl system	6
Br system	439
alkyl-phosphate	2323
phosphoric acid-urea	280
total	3048

Table 2. Products of Fire Retardant Chemicals for Fabrics

type	number of manufacturers	ratio(%)
inorganic compounds	26	35
complex inorganic compounds	24	32
organic mono or dis alkyl phosphoric acid	8	11
other	16	24

Table 3. Smoke Generation from Fire Retardant Poly-Urethane Foam

weight (g) (22x22x0.5cm)	chemicals	smoke generation per unit area	L.O.I
5.83	———	33	17.0
6.76	additive type	54	22.0
5.82	additive + reaction type	40.5	21.5
5.43	reaction type	22.5	23.0
6.74	M D I	22.5	20.0
6.66	M D I	16.8	20.5

Table 4. Gas generation from Poly-urethane Foam (ml/g)

	CO	CO_2	HCN	$NO + NO_2$
PVC-laten	130	270	0.24	0.08
additive+reaction type	47	74	0.33	0.12
reaction type	26	66	0.35	--
control	63	71	0.43	0.07

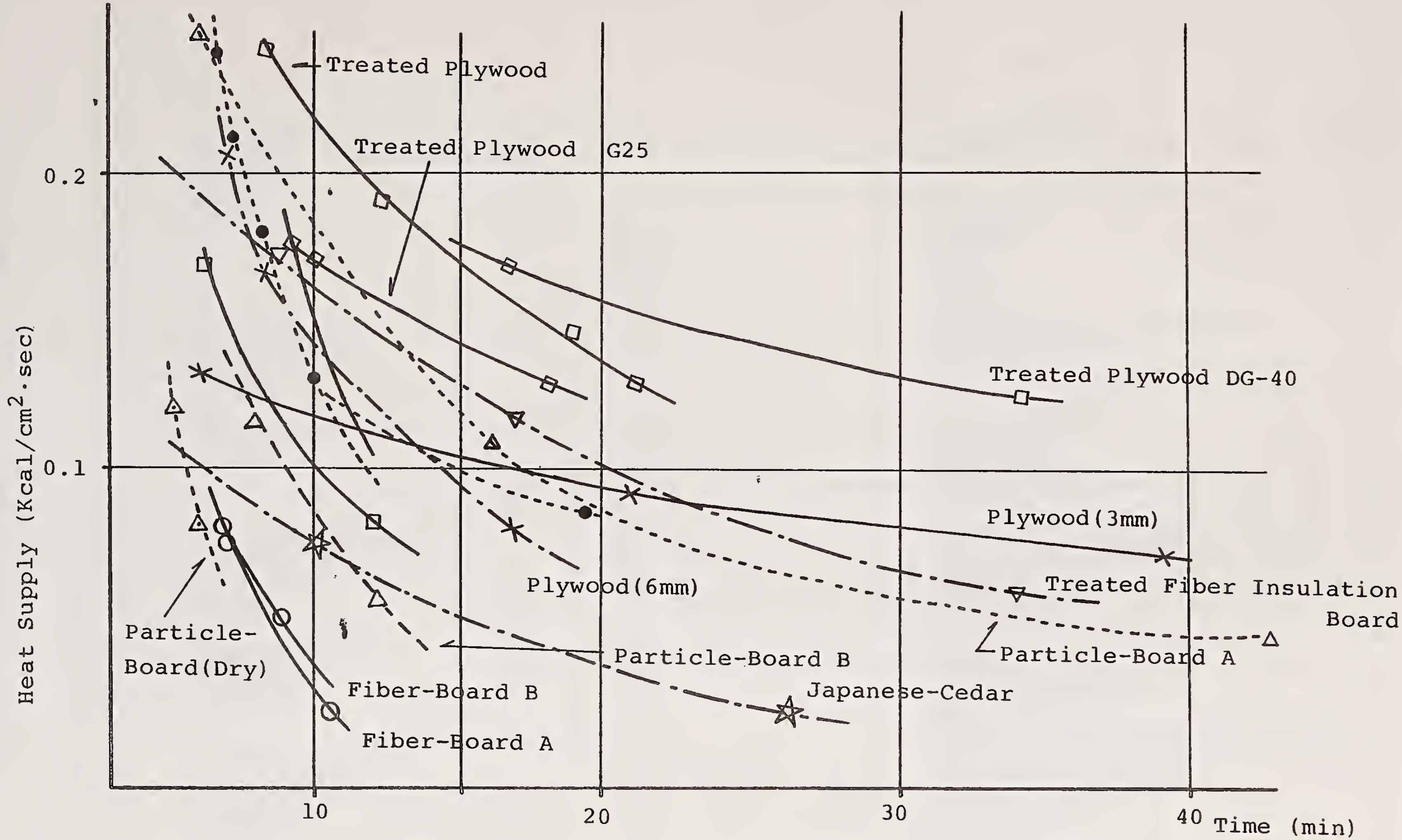


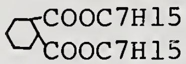
Fig. 1. Relationship Between Flash-Over Time and Heat-Supply

Table 5. Smoke Generation from PVC (Ministry of Construction Method)

PVC film	chemicals		
thick (mm)	type	PHR	C.A
0.2	-	-	45.0-60.0
0.25	epoxy	3	55
0.25	D O P	20	58.5
0.21	D O P	30	31.5
0.19	D O P	40	33.0
0.19	D H P	20	54.0
0.22	D I D P	20	49.0
0.24	Sb_2O_3	5	72.0
0.25	Sb_2O_3	10	75.0
0.2	CaCO3	10	39.3
0.25	CaCO3	30	63.0
0.25	CaCO3	30	
	Sb2O3	5	53.4
0.24	asbestos	20	73.5
0.23	Sb2O3	5	
	asbestos	20	51.0

D O P :Dioctyl phthalate C6H4(COOC8H17)2

D H P :Diheptyl phthalate



D I D P :Diiasdecyl phthalate (CH2)4(COOC10H21)2

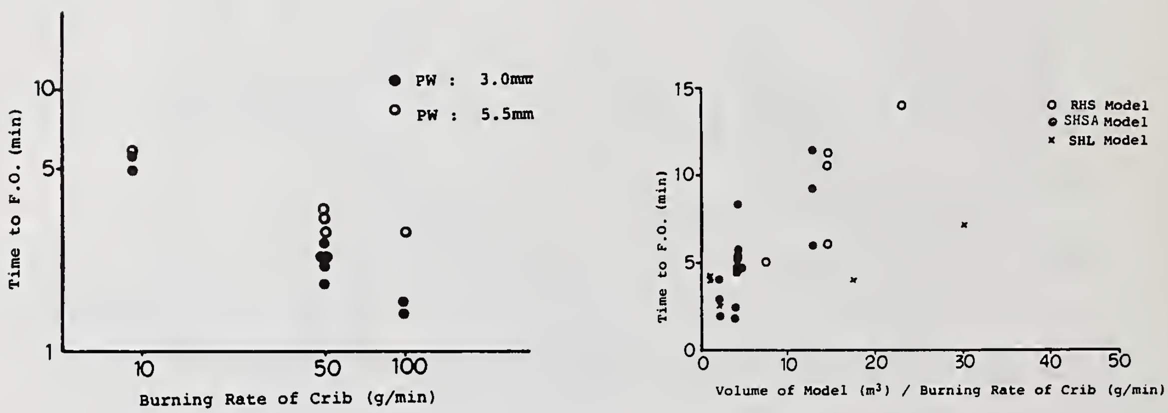


Fig. 2 Relation Between the time to reach F.O. and the Burning Rate of Ignition Source

Fig. 3. Flame Profile VS Distance from Corner

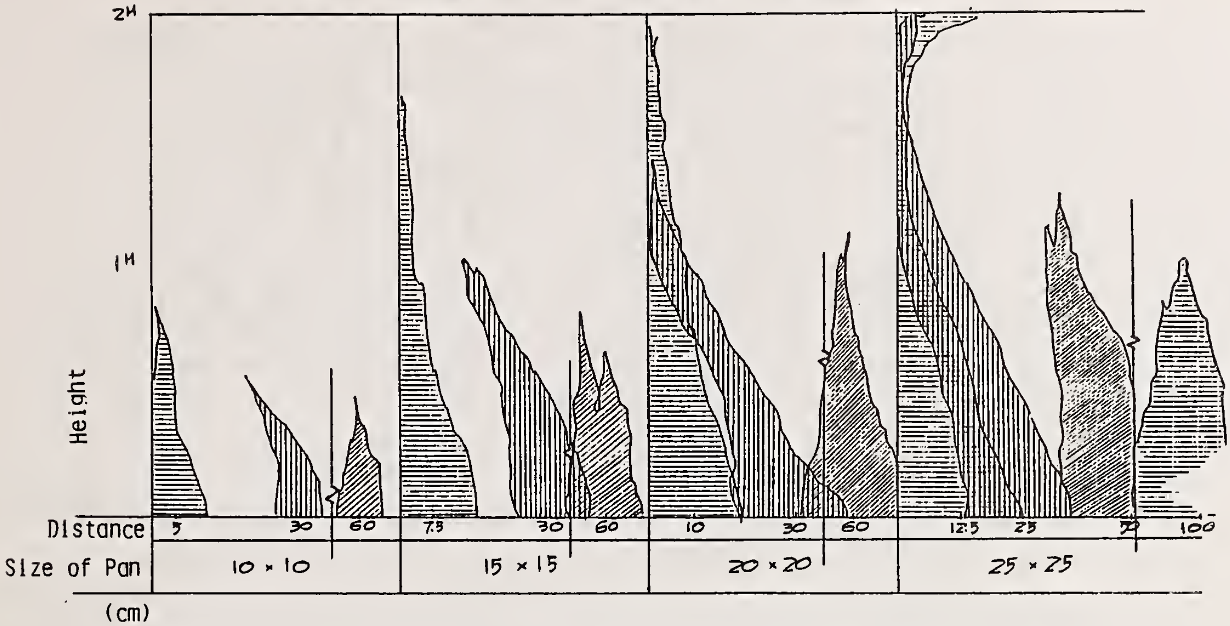
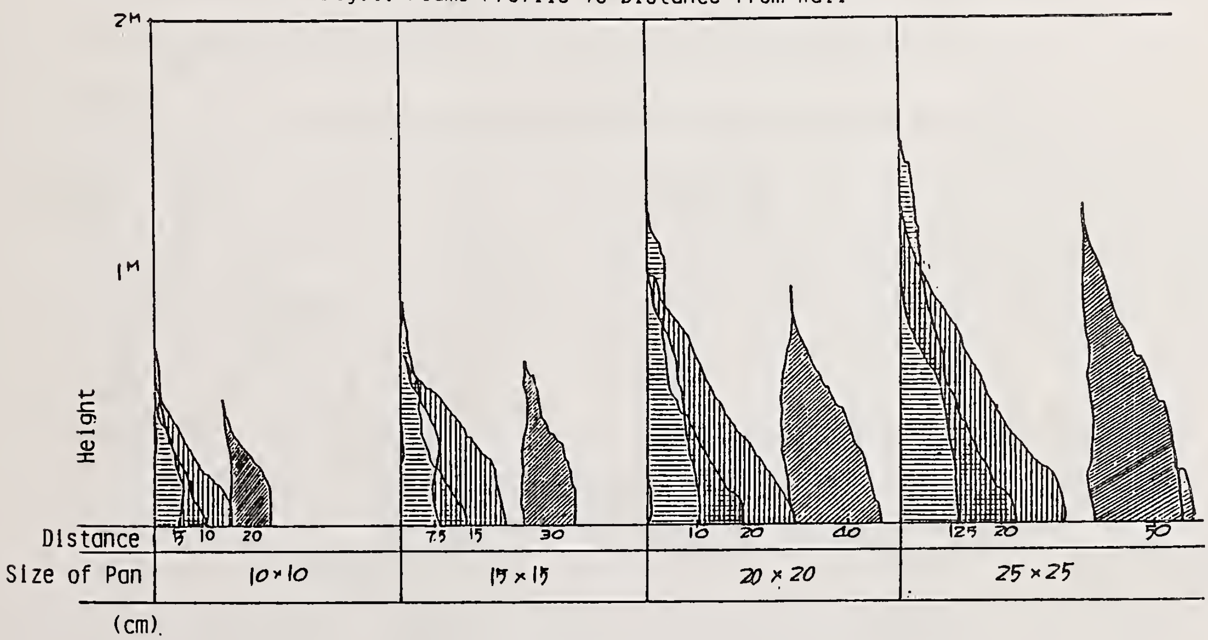


Fig.4. Flame Profile VS Distance from Wall



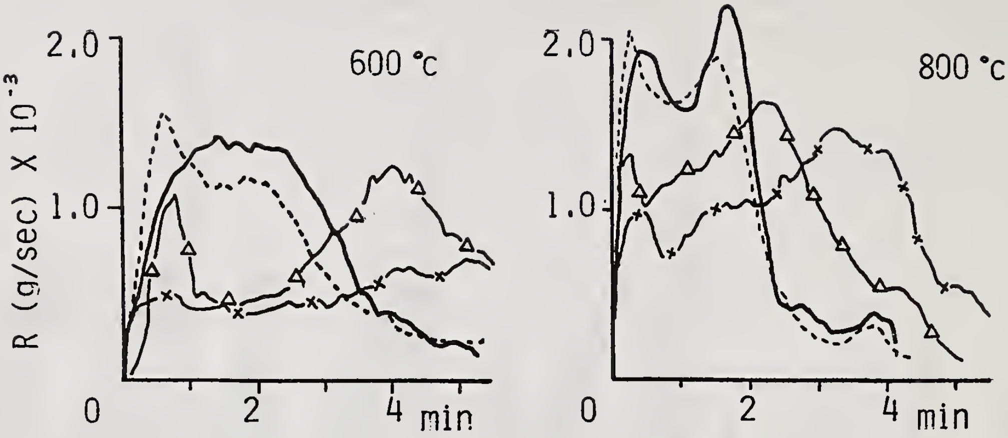


Fig 5 Burning Rate VS Time

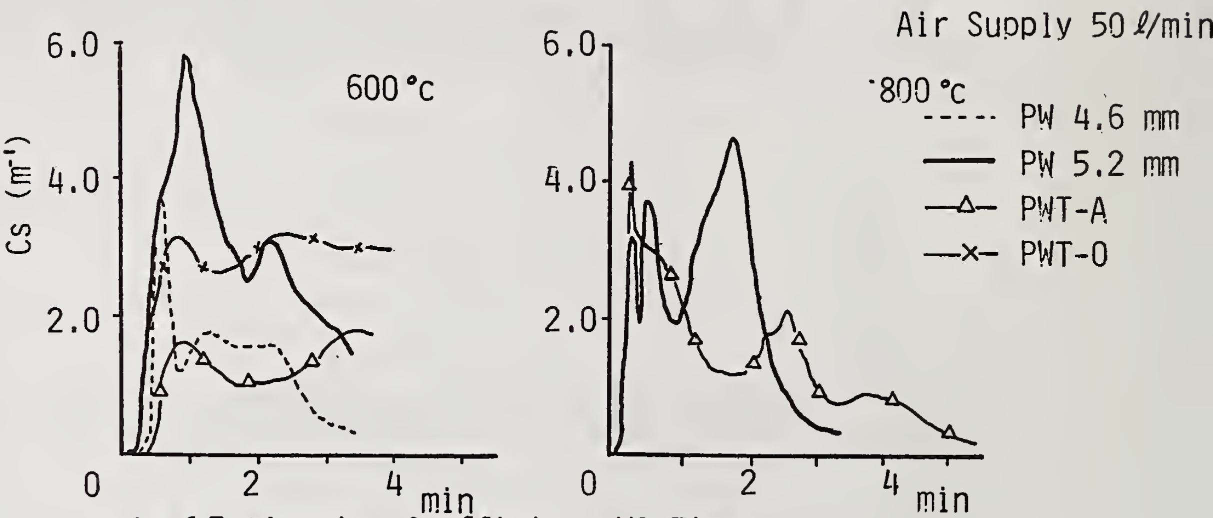


Fig 6 Extinction Coefficient VS Time

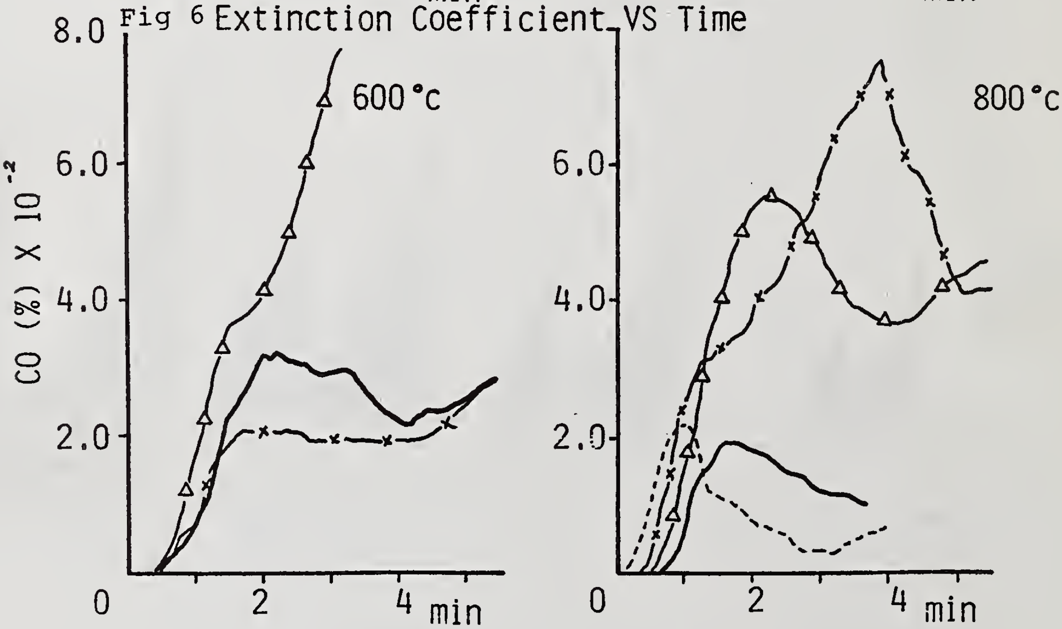


Fig 7 CO Gas Concentration VS Time

PROGRESS REPORT

RECENT ADVANCES IN FLAME RETARDANCE RESEARCH

By Frederic B. Clarke

The purpose of this update is to comment upon some of the significant developments in this field which have taken place since the last UJNR Panel meeting.

At that time, we surveyed some of the newly-emerging techniques which dealt directly with the condensed fuel phase and the earliest stages of flame chemistry. The past 18 months have shown that several of these continue a great deal of promise for the elucidation of fire retardance.

1. <u>New Instrumentation</u>

A. Opposed-Flow Diffusion Flame

It has been shown that the opposed flow diffusion flame is a useful tool for the better understanding of polymer combustion.

Sawyer and co-workers have studied the burning characteristics and the flame structure of poly(ethylene) in an opposed flow diffusion flame near extinction conditions. Using appropriately designed burners, sampling perturbations can be minimized. Compositions and temperature profiles can be made similar in the radial direction, which confirms predictions and simplifies the modeling of the opposed flow diffusion flame.

Oxygen was found on the fuel side of the diffusion flame, and carbon monoxide levels at the flame are above equilibrium. It means a departure from collapsed flame model. Oxygen transport to the surface is important because it can result in exothermic surface oxidation reactions and increases the fuel pyrolysis. The difference between oxygen diffusion rate to the surface and the rate at which oxygen is transported away from the surface by the pyrolyzing polymer was calculated. The result of the energy release calculation estimated that the surface oxidation could provide at most twenty percent of the energy required for depolymerization. This result suggests that heat transfer to the surface from the flame rather than surface oxidation controls the pyrolysis, and therefore, burning rate.

B. Soot Formation

At the last UJNR meeting, we mentioned work about to begin on soot formation in flames. The formation of soot in a combustion environment leads to dramatic and important consequences. In large fires, the thermal radiation from soot is the dominant energy transfer mode for pyrolysis and flame spread. Inhalation of soot poses serious health hazards due to absorption of toxic gases, and heavy smoke production in a fire hinders escape due to visual obscuration. It is clear that a fundamental understanding of soot formation processes would greatly aid in developing methods for reducing the amount of soot produced and in controlling its properties. One of our principal goals is to develop a detailed understanding of soot formation processes in flames. The early chemistry is not well understood, and several proposed models have yet to be validated or disproved.

We have recently discovered that in rich hydrocarbon flames, just on the lean side of the first observable soot luminosity, a laser induced ionization signal can be detected which is critically dependent upon the stoichiometry and position. Further studies have indicated that we are observing surface heating and ionization of small soot particles (diameters of 10-20Å), which are most difficult to detect by laser scattering methods. In our experiments an electrode is immersed in a premixed or diffusion flame and a pulsed laser induces an increase in ionization some distance away. Under the influence of an applied electric field, the resulting positive ions drift to the electrode; their average and differential velocities can be measured with high accuracy as a function of the laser beam-to-electrode distance. From these measurements the mobilities of the ionized soot particles can be determined, and one can estimate the corresponding molecular weight (~ 5000 amu) and size.

We are now able to readily track very small soot particles in a variety of flames. Future work will concentrate on the effects of fuel structure and the correlation of our observed ionization signals with scattering and fluorescence measurements.

2. The Application of Existing Instrumental Techniques to Fire-Related Problems

A. Solid Phase Nuclear Magnetic Resonance:

For many years, nuclear magnetic resonance (NMR) of liquids and solutions has been a powerful tool for chemical analysis. Until recently NMR of solids has been of little use to chemists because of poor signal to noise and broad resonance lines which obscure the chemical information desired. The technique of cross polarization improves the sensitivity of NMR of solids and the combination of high power decoupling and magic angle sample spinning improves the resolution such that the ^{13}C NMR linewidths of many organic materials are a few Hz.

This approaches the resolution obtainable in ^{13}C NMR of liquids. Unfortunately, the inherent inhomogeneity of solids precludes obtaining linewidths as narrow as are found in liquids where isotropic motion provides averaging and consequent narrowing of NMR resonances.

Presently several studies are underway in the Center for Fire Research aimed both at understanding the basic physics of NMR in solids and at applying the technique to characterization of solid materials. A series of experiments have been completed on the identification of the ^{13}C NMR peaks in cellulose. These studies illustrate the sensitivity of NMR to morphology and crystalline structure. More studies are planned to add to our understanding of the physical structure of cellulose. Model studies on various simple sugars have been started in an attempt to quantify the chemical shift of the resonance lines due to hydrogen bonding and conformational changes. The simple mono and disaccharides are excellent model compounds because their solution NMR is well understood and many of the crystal structures are known. Solid state NMR is currently being used to observe the chars from pyrolysis of cellulose in nitrogen and from smoldering of cellulosic loose fill insulation. These studies are just starting, with the expectation that we will be able to observe intermediate compounds in pyrolysis and that we will be able to distinguish the smoldering of the cellulose from that of the lignin in the smoldering of paper. It is already clear that the large number of free radicals in the chars make these experiments somewhat difficult but we are able to clearly see that a char generated by pyrolyzing cellulose at 625K is primarily aromatic in chemical structure.

B. The Mechanism of Cellulose Smoldering Retardance by Sulfur

Molecular sulfur is known to retard smoldering in cellulose and cellulosic materials. At present there is little commercial use of sulfur as a smoldering inhibitor because of the odor and problems of application. An understanding of the detailed chemical mechanism of this retardance would provide a starting point for looking for other compounds which could be used to retard smoldering in cellulose.

The approach to this problem involved multiple instrumental techniques including: x-ray fluorescence, electron paramagnetic resonance, mass spectrometry, thermal analyses and simple measurement of rates and temperatures of smoldering. Using thermal analysis it was shown that molecular sulfur is not simply acting as a heat sink through its various phase transitions. The direct sampling mass spectrometric experiments show that the sulfur is primarily oxidized in SO_2 and COS and that oxygen depletion by reaction with sulfur is not the mechanism of retardance. Electron paramagnetic resonance with careful spin counting, showed a large decrease in the number of free radicals in the char of material treated with sulfur. The x-ray fluorescence measurement of sulfur remaining in the char showed a significant amount of sulfur bound to the carbon skeleton of the char. The quantity of bound sulfur is comparable to the quantity of free radicals lost by sulfur treatment. The conclusions from this work are: sulfur acts as a radical scavenger, reacting with free radicals generated in the pyrolysis step of the cellulose smoldering. This radical scavenging stops the free radicals from further reaction thus reducing the amount of heat generated for further pyrolysis. One of the important properties of sulfur is that vaporization of the sulfur occurs between 490 and 650K so that it is mobilized and available for reaction at temperatures where the pyrolysis of cellulose is beginning to generate large numbers of free radicals.

C. Antimony-Halogen Interactions

Early organohalogen/antimony oxide research efforts were primarily concerned with determining optimum antimony to halogen and antimony oxide/organohalogen to polymer substrate ratios for specific flame retardant applications. From these studies the concept of an antimony/halogen synergistic effect was developed. While this concept has been accepted for many years, we have only recently begun to understand some of the mechanistic aspects of this interaction. More recently, mass spectrometric techniques have been used to monitor the formation of volatile antimony halide and oxyhalides as a function of temperature. Brauman, et. al., studied a wide variety of antimony oxide/organohalogen combinations using a wide variety of experimental techniques and concluded that the volatilized antimony was the dominant retardant species in the gas phase. Yeh and Drews used calorimetric techniques to measure the efficiencies of antimony oxide/organohalogen finishes and additives. Their data show that while the efficiencies of the antimony/halogen systems were greater than those measured for the halogen alone, the calorimetric responses were similar.

While these data have shown that the concept of a antimony/halogen synergism appears to be a valid one for many different organohalogen/antimony oxide combinations, the solid state chemistry involved in the generation of the volatile antimony species must be quite different. Accordingly, research to determine the importance of the solid phase interactions which occur among antimony oxide, organobromine additives and polymer substrates in the solid phase to the overall system chemistry in combustion is now in progress. The role of the polymer substrate in the generation of the volatile antimony species is of particular importance in this work.

For the future, research designed to increase our understanding of the solid phase chemistry of these retardant systems can be expected to continue. In addition, efforts to more completely elucidate the flame chemistry of antimony/halogen inhibited flames will be necessary to answer some of the questions posed by the calorimetric data of Drews.

Progress Report
on
Building Systems and Smoke Control

by

T.Wakamatsu and Y.Morishita

I. Building Systems

The interests on the subjects to develop the Total Evaluation and Design Systems of Fire Protections in Buildings are still more growing in Japan. At the consultative meeting on archtectual design and also at that on fire prevention which were held at the time of the Annual Meeting of Archtectual Institute of Japan, September 1980, the necessity to solve this subject was emphasized from the view point to make the fire safety regulations synthetic and clear, which are now only becoming complex and multiplex.

As reported at the U.J.N.R. 3rd Joint Meeting, the researches on this subject are conducted mainly at Fire Safety Systems Committee which was founded in April 1977 by Japanese Association of Fire Science and Engineering.[1]

The principal results of the researches which had been conducted in this committee until December 1979, were published as the Occasional Report No.3 of Japanese Association Fire Science and Engineering.

The contents of this repot is attached as Appendix I.

The 10 studies out of 13 ones which were printed in this report were already reported at the U.J.N.R. Joint Meeting, so the summaries of unreported 3 studies are introduced here. ((a) - (c))

Besides these studies which were printed in this occasional report, several studies have been done on this subject recently. They are also introduced in this paper. ((d) - (g))

(a) Concepts and Methods on Optimization of Fire Safety Planning (Y.Aoki) [2]

The Concepts and methods on optimization of fire safety plannings are examined in this paper. First, fire losses are classified into the reparable loss and the irreparable one by using the state transition model, and the method to indicate these losses by the two dimensional vector is proposed. Further, the concepts on optimization of fire safety planning is analyzed by dealing them as two dimensional optimization problem from the view point of the decision thory, and the optimization method of fire safety planning is proposed.

(b) Some Discussions on Interior Finishing Materials and/or their Components for Building Fire Safety (S.Sugawara) [2]

The significance of interior fire protective methods should be evaluated by the contributivity to the total systems for fire safety design. From such a point of view, it is necessary to accumulate the real fire data which will give useful informations about the contributivity of interior finishing. In this paper, the establishment of " International Fire Information Center " is proposed for the purpose to develop a new automatic data processing system, etc. Further, some stochastic approaches are tried in order to estimate the contributivity for fire development.

(c) Engineering Design for Structural Fire Safety (H.Saito) [2]

There are several proposals for the engineering design of structural fire safety which are different in the setting of fire characteristics or in the design method for fire resistive performance of structural elements. In this paper, after such recent status of design for fire resistance is introduced, the optimum value of fire resistance design is discussed. Further, the author refer to the necessity to examine the factors which have the effects on the reliability of fire resistance design, such as the maintenance conditions, the durability of fire resistance, etc.

(d) Development of Computer Programme for the Evaluation of Fire Protection Performance of Dwelling Houses (T.Tanaka) [3],[4]

In relation to the evaluation method for fire protection performance of dwelling houses which has already been reported at the U.J.N.R. 4th Joint Meeting, the computer programmes for the evaluations were developed on the prevention performance against inter-house fire spread and on the evacuation performance. The programmes were applied to some examples of dwelling houses, and some problems on such evaluation method were discussed.

(e) Reliability Analysis of Network Systems (M.Kobayashi) [5]

Network systems can be applied to the examination of the functions and the configurations of evacuation routs in buildings, etc. In this paper, the computer algorithm is developed in order to estimate the reliability of a network system which is expressed by nodes and links, if the abilities between adjacent two nodes are given in probability. Using the methods developed here, important links and optimum configurations of networks could be obtained as well as reliabilities even though their structures are considerably complex.

(f) Study on the Fire Protection Performance of a Fire Preventing Zone with Two Glass Doors (T.Tanaka) [6]

In place of fire proof doors ordinarily used for preventing fire spread in buildings, it is now planned to use "fire preventing zone" composed of two doors with large glass panes and fire resistance area between them, for the convenience of fire extinguishment activities, occupants' evacuation and prevention of smoke spread. In this paper, the performance of "fire preventing zone" is examined, by developing the calculation method of thermal radiation heat transfer through it. The results show that it is practically possisible for the zone to prevent the thermal radiation heat transfer caused by fire more effectively than fire proof steel doors of Class A, provided that the zone is appropriately designed.

(g) Evaluation of Fire Extinguishment Devices by Paired Comparison Method (Y.Morishita) [7]

The questionnaire on the effect of the combination of three kinds of fire extinguishment devices was made on the experts of fire research in BRI, in which the paired comparison method was used for the estimation. From this result, the main effect and the interactions of these devices were estimated. Further, the differences of judgements among evaluators were shown by analysing them with " Cluster Analysis " and " Principal Component Analysis ". Such results of the analyses are expected to be useful informations when the evaluation method of such devices is determined by the discussions of experts.

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II. Smoke Control

The studies on smoke control in Japan have been developed for the purpose of establishing the prediction method of smoke movement and the evaluation method of smoke control systems, by means of which more rational design of smoke control systems will be possible. In these studies, a few field experiments to validate the theory are included, but the theoretical approaches have been centered so far.

Recently, the priority of the studies in this field is moving to the experimental approaches by the fact that the theoretical approaches have achieved an expected goal and that the new Full Scale Fire Testing Laboratory for smoke movement and its control was built in BRI, Tsukuba. The main purpose of these experiments is to validate the theory, to supplement it, to comfirm the effectiveness of various smoke control systems, etc.

1. Field Study in Tsukuba

The laboratory for smoke test in Tsukuba has 7 stories and is equipped with facilities and equipments for smoke control such as fans for air supply and smoke exhaust. The experiments using this laboratory started from April last year. In last year, first, the flow resistances of the small openings of doors, windows, etc. and the vertical shafts such as staircases were measured. Then, the preliminary experiment was conducted, through which the experimental values were compared with the theoretically caluculated ones concerning the pressures and the current velocities at the points significant on smoke control. This year, the experiments on free spread of smoke are conducted on 80 cases combinating the conditions such as wind pressures (controlable), the position of smoke generation, flow path structures composed of opening and shutting doors, windows,vents, etc. In these experiments, smoke candles and methyl alcohol are principally used for the smoke generation. The combustion of wood fuel and SF_6 as a tracer gas are now planned to be used.

On and after next year, a series of experiments is planned in order to examine and confirm the effectiveness of various smoke control systems.

2. Field Tests in New Buildings

The design of smoke control systems of two high-rise buildings recently constructed at Shinjuku, Tokyo, namely, Shinjuku Nomura Building (completed June 1980, with 50 stories and 5 basements) and Shinjuku Center Building (completed Nov. 1979, with 55 stories and 5 basements), are made under the guidance of BRI, based on the results of many case studies by computer simulation on smoke movements or the smoke control effectiveness. The field experiments for the smoke control effectiveness were carried out on these two buildings just after their completions. The main purpose of these experiments was to ascertain if the function of control works as expected at the time of design, by operating smoke control systems under some possible fire situations. By the results of these experiments, the function of control was ascertained to work as expected as for Shinjuku Center Building, but for Shinjuku Nomura Building, it couldn't be enough ascertained since the measurement of the pressure and the current velocity was not conducted sufficiently.

Appendix I : " Evaluation of Fire Safety in Buildings ", Occasional Report of Japanese Association of Fire Science and Engineering No.3, Dec. 1979

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PROGRESS REPORT

Detection in U.S.A. 1979-1980

By Irwin A. Benjamin

Current surveys indicate that about 50% of the U.S. homes now have smoke detectors. However, the distribution of detectors varies according to socio-economic groupings. About two-thirds of the homes with incomes of over $20,000 have detectors compared with about one-third of the homes with incomes less than $20,000. However, in spite of this discrepancy there has been a real increase in the number of detectors in both these groups over the 1979 to 1980 period.

The detector industry has begun a trend toward consolidation, with several small manufacturers going out of the business. There have been no major technical innovations in the detection industry during the last year. New development activity has slowed down and the Underwriters Laboratories have indicated that their applications for approvals of new models and new designs have dropped off radically in the recent period. A couple of years ago a residential detector combining ion chamber and photoelectric sensing units in the same head was put on the market. This represents the only recent development in detector technology; and there does not appear to be a substantial growth in the sales of this combined unit, possibly because of the increase in price.

The Underwriters Laboratories Test Method 217 which was originally published in October 1978 is now in effect, after an initial 18 month waiting period. This test method, now includes a smoldering test based on heating small pine sticks on a hot plate to meet a predetermined optical density curve. The smoke level is measured both with a photoelectric beam and also with a MIC (measuring ionization chamber). For the smoldering test a criteria of 7% per ft. OD is the maximum for the response of the detector. This value is being disputed as being too high and has been subject to discussion.

Some technological development is being done for commercial installations. Some of the manufacturers have been working on developing a remote sensitivity monitoring system so that the detectors can be checked from a central panel. Also, methods for the continuous monitoring of detectors are being investigated. In general, fire detectors are being combined with the energy sensing devices into an integrated system which attempts to address the total energy problem. Likewise, for residential systems combined fire and burglary systems are being promoted. However, these more complex systems represent only a small share of the installations.

Much effort in the past period has gone into monitoring performance of fire detectors. One of the major studies is being conducted by the Ontario Housing Authority, Ontario, Canada. They installed 87,000 single station detectors in apartment units in 1976 and 77 and are checking them yearly. There are seven models of detectors, six ionization and one photoelectric. Six of the models are U.L. listed and one is a Canadian listed detector. From the Spring of 1977 to the Spring of 1979, 150,000 detectors have been tested and 3,244 have been found defective--a 2.2% overall failure rate. This failure rate seems to be consistent for all the six U.S. detectors in the study. Recent data from Ontario has indicated that about 5% of the detectors have been disconnected by the tenants because of their desire to eliminate false alarms. In general, the observations of the Ontario Housing Authority are that the ion chamber seems to be giving a slightly higher false alarm rate. This would not be unanticipated for these apartments which are in the range of 50 sq. meters in size. In such a small area the ionization detector would be subject to the effects of cooking vapors.

One other recent development in the U.S. has been the promotion of what is called ARRAS (Automatic Residential Remote Alarm Systems). One such system is installed in Woodland, Texas in a large number of residences. The system is being run in conjunction with a cable T.V. system. Preliminary data is starting to come in on the effectiveness of this system; but it is still too early to draw any conclusions. One observation however does seem to be that the ion chambers may be giving a slightly higher false alarm rate than the photoelectric types. It is interesting to note that the preliminary data indicates that about 30% of the apartments have had false alarms. This again is associated with a fairly small size apartment.

Detectors do appear to be effective. Recent statistics from NFIRS (National Fire Information Reporting System) indicate that the death rate in fires in homes without detectors appears to be double the rate for homes with detectors. Although there may be socio -economic factors involved in this statistic yet it is is a good indication that the detectors are effective. In a study recently conducted by IAFC (International Association of Fire Chiefs) fires were studied in ten cities around the country. Their data would indicate that the first warning of a fire in homes having detection was given by a detector in 40% of the cases. This indicates a very substantial achievement for detection, particularly if one takes into account the fact that many reported fires occur during the day time with the person directly involved with the fire.

The overall statistical data on the fire loss rate in the U.S. has not yet reflected the effect of detectors. It is believed however that such evidence may be premature and that it will be several years before the gross fire statistics will reflect the fact that 50% of the homes now have detectors.

In summary, the past period has been one of limited technological growth and little new research. Studies are being initiated or conducted to determine effectiveness of detectors and identify the magnitude of the false alarm problem.

PROGRESS REPORT ON HUMAN BEHAVIOR

by

S. Horiuchi and T. Jin

We would like to introduce to the reader briefly two lines of research we have been undertaking for the past year and a half here in Japan on the subject of human behavior at the time of a fire.

1. STUDY OF THE SAFETY SIGN FOR EMERGENCY EXIT[1)]

The markings on safety sign of emergency exit must be simple so as to be clearly visible even from a distance, and the indication of emergency exits must possess a concreteness that would be immediately understandable even by a foreigner. We have commenced research in this area in order to modify the characters presently used in Japan (非常口) to a pictograph that fulfills the above stated conditions. We solicited generally for such pictographs and made a selection from 3,334 entries based on the following evaluative processes.

First Process:

Employing video signal technics, we excluded those pictographs which were hard for people with deficient eyesight to distinguish.

Second Process:

We eliminated those which according to the designer were considered inappropriate.

Third Process:

We ranked the entries according to what the general public of about 150 persons would find both pleasing and appropriate in a pictograph indicating an emergency exit.

Fourth Process:

After transferring the top ten pictographs, as determined by the third process, to panels of actual luminaire devices and then installing these devices in corridors, we measured the visual distance of each pictograph under normal illumination conditions.

Fifth Process:

Using the same devices as in the above, we tested the visibility of each under smoky conditions.

Comprehensive Judgement:

After tabulating the results of the above processes, we determined which pictographs were most effective. These are to be found in Figure 1. This research was carried out under the leadership of the Fire Defense Agency of the Ministry of Home Affairs.

T. Jin[2)] then took the pictographs which emerged from the above tests and tested their visibility comparatively against those indicated in ISO/TC21/SC1/DP6309 NO.4 (Figure 2). These results showed the Japanese-devised pictographs to be more visible at a greater distance than the ISO-produced symbols by about 20 % under normal smokeless illumination conditions and by about 10 % under smoky conditions. Though both sets of pictographs resemble each other in design, the symbols within the Japanese set are superior in their simplicity, and this is thought to be the reason for the differences found in the above tests.

2. LIMITS TO HUMAN ENDURANCE OF THERMAL RADIATION DURING FIRES[3)]

Y. Hasemi and K. Shigekawa measured this endurance time. Using a Schwank burner as their heat source, they had their test subjects stand directly facing the burner (Figure 3). With thirty minutes as the upper limit for the exposure period, the subject's own judgement was used to determine whether he had reached that endurance limit at any time within the 30-minute period. The incident radiant flux densities thus found were of five kinds--1790, 1950, 2100, 2290, and 2510 $Kcal/m^2h$. In addition, the clothes of the test subjects were those typically worn indoors in winter. But with two or three of the subjects, tests were also run for the case of short-sleeve garments.

The relation between the incident radiant flux density and the endurance time is given in Figure 4. It was found that if the density were below 1800 Kcal/m^2h, the endurance time of most of the subjects exceeded 30 minutes.

3. THE ADDITIONAL RESEARCHES CONCERNING HUMAN BEHAVIOR AT THE TIME OF A FIRE.

Y. Watanabe has performed experiments using a continuous maze[4)]. For subjects given only one chance in the maze, it was found that, upon turning three corners, less than half of the subjects could return to the starting point. However, a large number of the subjects who had walked the same course a number of times were found to be able to return to the starting point even after turning seven or eight corners.

S. Okazaki made a simulation model concerning walking in the case where there are markers to lead the way[5)].

Using questionnaires, Y. Murozaki surveyed residents evacuated from a twelve-story apartment building which had caught on fire[6)]. In this apartment building, fire occurred two times for one year.

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The Progress Report
on
FIRE DETECTION and SMOKE PROPERTY

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The progress report on Fire Detection and Smoke Property summarizes researches, investigations, and developments in both fields since the Fourth United State - Japan Panel on Fire Research and Safety meeting in Tokyo during February, 1979.

The report consists of two parts; i. e., Part I is concerned with fire detection and was described by J. Miyama, and Part II is concerned with smoke property and was described by F. Saito, according to their respective specialty.

Part I

Part I consists of two reports on fire experiments in full-scale houses, comparative study on the absorption of visible and infrared ray in smoke, a report on the study of beam type smoke detectors, and several recent developments on smoke detectors and fire alarm systems.

1.1 A fire experiment in a full-scale house for the investigation of detector's response time concerning feasibility of extinction and refuge (1)

The experiment was performed in a room of an evacuated tenement house to investigate time allowable for the residents to extinguish a fire at its incipient stage and take refuge when it has occured in their room.

Three kind of detectors; i. e., an ionization chamber type, phtoelectric type, and rate-of-rise and spot type were installed on the ceilling.

Fire was set to a waistpaper basket in front of a closet, whose sliding door caught fire after about 1 minute. And fire alarm was released after 1 minute 6 seconds by the ionization chamber type, 2 minutes 46 seconds by the photoelectric type, and 4 minutes by the rate-of-rise and spot type.

Meanwhile, after 10 minutes from the beginning the room was filled with dark smoke, making both of extinction and refuge almost infeasible.

It was concluded that the time allowable for extinction and refuge should be about 6 - 9 minutes after the alarm had been given, corresponding to the type of the detectors. Naturally, the rate-of-rise and spot type gave the least time.

1.2 A full-scall fire experiment in a residence for the investigation on effectiveness of residential fire detectors (2)

The house prepared for the experiment was a twostoried residence whose total area was 104 m^2. There were three rooms on the first floor including two lounges and five rooms on the second including three bedrooms.

In the lounge where a fire was started a photoelectric type residential detector had been installed, together with ordinary ionization chamber type, photoelectric type, and rate-of-rise and spot type to make a comparison. Detectors were similarly installed on both ceilings above a bottom and head of the staircase.

The response time of the detectors and the sound level of the residential ones were measured. Mice were also placed to detect toxic gas. A crib in one of the lounges was ignited and the door was closed at the beginning of the experiment.

Main conclusion obtained is as follows:-

(1) There is the possibility that the alarm released on the first floor would not be heard distinctly in the bedrooms on the second floor.

(2) Among the detectors installed above the head of the staircase, photoelectric type is the most sensitive. Estimating from the death time of the mice, in this case, the sleeping persons will be given 4 minutes to take refuge.

(3) In such a case, rate-of-rise and spot type should not be used because alarm will be given too late for the residents to take refuge.

1.3 Comparative Study on the absorption of visible and infrared ray by smoke

It was made clear that the optical density of smoke due to ISO test fire takes different value according to the type of the optical smoke density meters used; i. e., the value of the optical density measured in infrared ray range differs from the value measured in visible ray range.

The experiment was performed in a test room whose dimension is 9 m in length, 7 m in width, and 4 m in hight. The fireplace was placed at the center of the floor and the measuring instruments were installed on the ceiling 3 m apart from its center.

The ratio k of the optical density measured with infrared ray to that measured with visible ray was shown in Table 1.3.1 as well as k's reciplocal 1/k.

Table 1.3.1

test fire	k	1/k
1. open cellulosic fire	0.552	1.81
2. smouldering pyrolysis fire (beech wood)	0.773	1.29
3. glowing smouldering fire (cotton)	0.591	1.69

4.	open plastic fire	0.689	1.45
5.	liquid fire (n-heptane)	0.683	1.46

This table shows that visible ray is more intensely absorbed by every kind of smoke from the test fire than infrared ray is. Although in the present photoelectric smoke detectors infrared ray is used as a light emitting source, from a point of view of taking refuge from a fire, it should be appropriate to measure optical density with visible ray regarding the fire sensitivity test under the test fire.

1.4 Study on the beam type smoke detectors (4)

Beam type smoke detectors are considered to have various kinds of distinctive characteristics in comparison with spot type smoke detectors due to differences in working principle and construction.

For example, in buildings with a high ceiling such as warehouse, aircraft hangers, theaters, museums, etc., smoke diffuses during its rise on to their ceiling, decreasing too intensly its density for spot type smoke detectors to operate.

On the other hand, beam type smoke detectors are considered to be able to detect such thin smoke because they do detect integral value of the diffused smoke over the span (length) of the beam.

Furthermore, reguler maintenance of spot type scattered throughout on the surface of high ceilings will be very difficult, while that of beam type will be easy because they can be installed on the walls.

Even in an ordinary large building, in the corridors leading to the kitchen area of a restaurant where it may likely present locally smoke in higher concentration, use of the beam type would be preferable to eliminate false alarm.

Under such conditions, recently in Japan, several companies have began to develop the beam type smoke detectors and a research and study group was organized in Sep., 1979, consisting of the representatives from manufacturers and government person concerned. The group has been studying and evaluating effectiveness, sensitivity and location of the developed detectors and conducted a fire test, making reference to the test fire proposed by ISO/TC21/SC3.

The results thus obtained are as follows:

(a) In flaming fire, large signal values was obtained due to rapid rise and diffusion of smoke.

(b) In smouldering fire, no special features of the beam type as seen in flaming fire were observed.

(c) As an intermediate report, it can be said from this fire test, that a suitable sensitivity level of beam type smoke detectors spanned 30 meters is between 30 - 60% and a beam pitch should be less than 14 meters.

1.5 Several recent development and improvement on fire detectors and fire alarm systems

1) An ionization chamber type smoke detector was recently developed which can operate with two classes of sensitivity; i.e., class II and class III which is less sensitive.(5) Thus, it has two output terminals; one is for releasing fire alarm and another for starting related fire protection facilities.

2) A photoelectric type smoke detector was recently developed which will not be affected by incoming insects.(6) It is making use of infrared ray radiated downwards into conical space. When it is scattered by smoke, the scattered ray is forcused on a solar cell by a lens.

3) A fire alarm system was developed, which can indicate the exact location of the detector making response.(7) It releases fire signal in audio frequency, which is proper to the respective detectors. So that it can be discriminated to indicate the location of the detector operated.

4) A control board for complex use was recently developed which will be utilized to give indication about fire alarm

system and fire protection facility on the same indicators. Accordingly, it diminishes space occupied.[8]

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Part II

The purpose of research into formation of smoke particles to apply the result to the study of fire detection and escape from fires.

For the former, characteristic relation between size distribution of particulates, including invisible particulates, and smoke detectors has been pursued.[1)]

For the latter, relation between decrease of visibility by smoke particulates and human activity in smoke has been pursued.

For a boundary study between physico-chemical and ecological surface area of various kind of smoke particulates and artifical particles are measured by means of Brunauer-Emmett-Teller (B.E.T.) method for getting a suggestion to toxicity.[2), 3)]

In the field of smoke control design, study on smoke load in fire rooms and on control of the flow of smoke in building have been pursued.

Although characteristics of smoke production from many materials have been pursued by many researchers, characteristics of smoke from composit materials are difficult to predict in fire. This seems to disturb the further development of smoke control system.

In the region of ventilation control fires, especially the stage of developing fires, the ratio of ventilation factor to combustible materials is more important factor than characteristics of smoke production from materials.

For the study on smoke production, development of measurement method for high temperature smoke in fire rooms, study on absorption of smoke particulates on walls and coagulation during travelling in the building are also expected.

Measurement of attenuation of light intensity for the smoke density is sueful at a low temperature atmosphere, but this method can't be useful at a high temperature atmosphere as in a fire room.

Therefore, weight concentration method is substitutional for the attenuation method in a fire room.

A linear relationship between optical density and weight concentration at flaming and smoldering combustion has been reported by T. King.[4)]

However, any linear relationship between the two could not be obtained when plastic and wooden materials were burnt under the temperatures between 600 and 800°C.[5)]

It's reasonable that ther's no relation between the optical density method and weight concentration method for smoke. Because the main factors for the former are size distribution and shape and surface condition of the particulates, but the mass of particulates for the latter.

Measurement of optical density of smoke and the flow rate of smoke in a tube or in a corridor whose thermal property is known, which is connected with a combustion chamber in which a fire condition can be simulated, and where the temperature is low enough to measure the light attenuation, may be useful.

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2) F. Saito : Research Work for the Period, Building Research Institute (1970)

3) H. Suzuki : Annual Conference on Fire Research, P64, May (1980)

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5) F. Saito : Unpublished

Saito Presentation on Fire Retardance

Benjamin: Could you briefly give us an idea of what method is now being used to evaluate plastic foam?

Saito: The size of the sample is a slick shape of 10 cm square with about 30 cm height (demonstrated on blackboard). The cross section of the same is drawn on the board. Alcohol cup with about 2 cm diameter is installed. Burning of the sample starts from the inside in this configuration.

Emmons: In Table 4, the first two columns are labeled CO, is this correct?

Saito: No, the second column should be labeled CO_2

Clarke: For clarification in the fire in the warehouse involving polyurethane foam, you state that the combustion took place inside the plastic foam. Was the plastic foam covered with a fire resistance or non-combustible material? Was the surface exposed to air?

Saito: The material was not protected. It was exposed to the air.

Clarke: We have had similar trouble in the United States and one of the results is that building codes have retroactively changed to require all exposed foams be covered.

Clarke Presentation

"Recent Advances in Flame Retardant Research"

Handa: What is the temperature used for BC measurement -- 200°C?

Clarke: At the moment, most of our temperature measurements have been well below the combustion temperatures because of the difficulty of finding probe materials to withstand prolonged high temperatures. At higher temperatures we need to conduct the experiment, stop it, and put the material into the NMR sample probe. We cannot do the experiment in the NMR sample chamber, which would be most desirable.

Handa: Did you include pump procedure?

Clarke: No. I don't believe that works effectively for solids.

Chaiken: Regarding the amount of surface oxidation in the combustion of solids, the measurement that Dr. Clarke refers to here is polyethylene. I would strongly suspect that in charring combustion such as wool, coal, the amount of surface oxidation is probably considerably greater than 20%.

Morishita Presentation

"Building Design and Smoke Control"

Emmons: In which publication does the measurements of the flow resistancy of small openings of doors, windows, etc., appear?

Wakamatsu: This report has not been officially published.

Chaiken: In reference to smoke in high rise buildings and in your laboratory, is this smoke generated by an actual fire, a large heat source, or is it strictly from a smoke generator?

Wakamatsu: Since the building was newly built and we could not make a fire, we generated smoke using a smoke generator and burned methanol.

Chaiken: We are concerned with smoke in mine networks in two- and three-dimensional configurations and how the affect of a large fire influences any ventilation system being used. There is a very strong coupling between the smoke and where the smoke goes, and the generation of smoke and the fire itself. So that one designs a smoke protection system and does not take into account the influence of fire on the air dynamic forces you have to work with. This could cause problems.

Jin Presentation

"Human Behavior in Fires"

Bryan: Relative to the 20% difference in visibility between the normal illuminating condition and 10% for smoking conditions, how smokey is smokey conditions?

Jin: The concentration of smoke set below extinction coefficient was 0.3 m^{-1}. The source of smoke was smoldering wood.

Emmons: Have you considered requiring the placement of such figures near the floor as well as near the ceiling?

Jin: The Japanese Fire Code requires that first emergency indicator lights should be posted right above the emergency exit. Then the blinking lights, or sirens, should be placed 20 meter intervals guiding towards the exit. They must be posted within 1 meter from the floor.

Miyama Presentation

"Detection and Smoke Properties"

Friedman: In referring to the infrared attenuation of smoke that you mentioned relative to the visible attenuation, do you know the wavelength of infrared that was used in that test?

Miyama: I do not have the data but it is the same that appeared in the International Standards Organization (ISO) material.

2. ARSON AND FIRE INVESTIGATION

Early Intervention in Arson Epidemics: Developing a Motive-Based Intervention Strategy

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Introduction

The reported incidence of arson in the United States has been increasing since 1975.[1] Several observers cite arson committed for economic gain as a major factor in the nationwide growth, while other sources attribute the rise to non-economic problems that are related to deeply rooted stresses in society.[2] According to the latter interpretation, interpersonal and societal strains give rise to a variety of non-economic arson motives, with revenge and mindless vandalism being cited most frequently.

The most logical explanation for the recent increase in arson centers on the growth and accumulation of various stresses in society. These can increase, for example, domestic disturbances and other interpersonal conflicts (affecting the revenge motive for arson) and juvenile delinquency (influencing the vandalism motive). Exacerbation of social, or personal problems which underly each of these motives seems to have an impact on other motives as well. This may be so because as the aggregate incidence of arson increases, more and more arsonsists remain uncaught. This development may establish arson as an emotional or financial outlet for a variety of stresses which ordinarily are discharged either in less harmful or by other violent means. During such a progression, contagion builds and arson epidemics may prevail for substantial periods of time. Three-to-five-year spans over the past decade have been noted in such cities as Buffalo, Detroit, Boston, New York and Seattle. However, the time series is too short to determine whether these undulations are cyclical or random in nature.

The mix of arson motives seems to differ from one jurisdiction to another because of variations in the types and relative frequencies of each of the various stresses, and to differences in the size of populations which experience them. Despite such variations, however, most of the commonly prescribed remedies treat arson as though it were a monolithic phenomenon, unaffected by differences in motives and the personal, social, and economic pressures which underly these influences. In general, the criminal justice response is the most frequent form of intervention. But, since it is primarily reactive (i.e., post fire) in nature, its deterrent value is dubious.

A brief review of investigative and prosecutive responses to arson demonstrates the difficulties inherent in designing more effective strategies to combat this crime problem. To begin with, it is difficult to gauge the true extent of arson because the fire's cause is often difficult to determine, and many incendiary incidents are mistakenly labeled as suspicious, unknown, or of accidental origin. Estimates of the actual incidence of arson fires range from twenty-five to fifty percent of all fires.[3] Where an incendiary cause is suspected, the shift in control of the fire scene from firefighters to fire or police investigators can result in the loss of valuable time and in compromising the integrity of the evidence at the scene.

Next, the transfer of the case from investigators to prosecutors often results in diminished continuity. Most arson evidence is overwhelmingly circumstantial and in most cases implicates the suspect only indirectly.[4] Because of prosecutors' desire to maximize conviction rates, they have an understandable aversion to new or troublesome kinds of cases. Consequently, prosecutors have been reported to avoid arson cases and to discourage investigators from pursuing them effectively.[5] This in turn generates an understandable reluctance on the part of investigators to try to interest a prosecutor the next time an arson case develops. Consequently, many investigations languish for lack of momentum. Overall,these impediments to enforcement have a debilitating affect on investigator morale, which serves to undercut the rate of progress essential in arson investigations.

Suspects who commit arson out of emotional impulses such as revenge and pyromania appear to be those most likely to be caught, for the irrationality of their actions diminishes caution and increases the likelihood that they will leave behind incriminating evidence. For this reason, those who commit arson out of strong emotional stimuli tend to be overly represented in arson arrest and conviction statistics, while those who commit arson in a calculated and planned manner stand to gain a de facto type of "informal immunity" as a result of their ability to destroy or conceal evidence. Thus, the low arrest and even lower conviction rates for arson substantially dilute the deterrent power of the criminal sanction.[6]

Despite lingering questions about the impact of punitive sanctions, local public officials have focused on prosecution and punishment as the most potent deterrents. Two implications follow from this view. First, a broad range of non-criminal justice prevention or early intervention strategies may either be ruled out prematurely or identified too late to arrest a developing arson epidemic. Second, strong reliance on criminal santions places considerable pressure on investigators and prosecutors to "solve" arson cases and "punish" arsonists. Both the pressure and the official response interact in a political environment which focuses on those offenses that are most readily subject to solution. As noted above, in cases of arson the most vulnerable population of offenders is likely to consist of persons are emotionally motivated.

Focusing on Arson Through a "Motive-based" Strategy

To summarize the foregoing discussion, a primary reason for the difficulty of enforcement agencies in combatting increases in arson is the highly reactive nature of the law enforcement response. Traditionally, the objective of investigators and prosecutors has been the arrest and conviction of persons who commit arson, rather than some form of intervention to prevent future criminal acts. Since relatively few arsonists are caught, and still fewer are convicted, the threat of punishment is arguably not a very effective deterrent in this case, nor in combatting most other forms of crime.

Early Warning Signs and Early Intervention Strategies

The most frequently cited motives for committing arson are revenge, pyromania, vandalism, concealment of another crime, intimidation, and arson-for-profit. In many cases, decisions to commit an incendiary act will be so impulsive--and therefore unplanned--that the potential firesetters generate few noticeable warning signs of criminal intent. For example, a family dispute may escalate so rapidly to an act of arson that no one could have foreseen or forestalled the oncoming tragedy. Unanticipated firesetting may also stem from erratic or irrational behavior of disturbed or psychotic persons. Conversely, arson for other motives such as profit is usually planned in a rational manner over a relatively longer period of time, and although executed in stealth often follows a known pattern that permits trained investigators to detect the crime.

If arson motives are arranged along a continuum which ranges from "rational" to "irrational," then arson for profit should be posted near the former, with revenge near the latter, and other motives falling between. If a second vertical dimension is added (see Figure II) which arranges the motives according to numbers of prior warning signs, then motives can be further distinguished according to their susceptibility to early intervention. For example, several prior warning signs of revenge arson may exist, manifested in earlier disputes ranging from moderately noisy to extremely violent.[7] The problem posed by revenge arson however, is the absence of an effective monitoring apparatus to detect and notify authorities when early warning signs are observed. Usually, neither the disputants nor witnesses, nor even experts, can as yet distinguish between conflicts that will escalate into violent acts and those which will dissipate with the passage of time. Although obviously desirable, intervention to stem the rise in arson is still in its earliest stages and a long way from realization.

FIGURE I

Arson Motives: Rational To Irrational

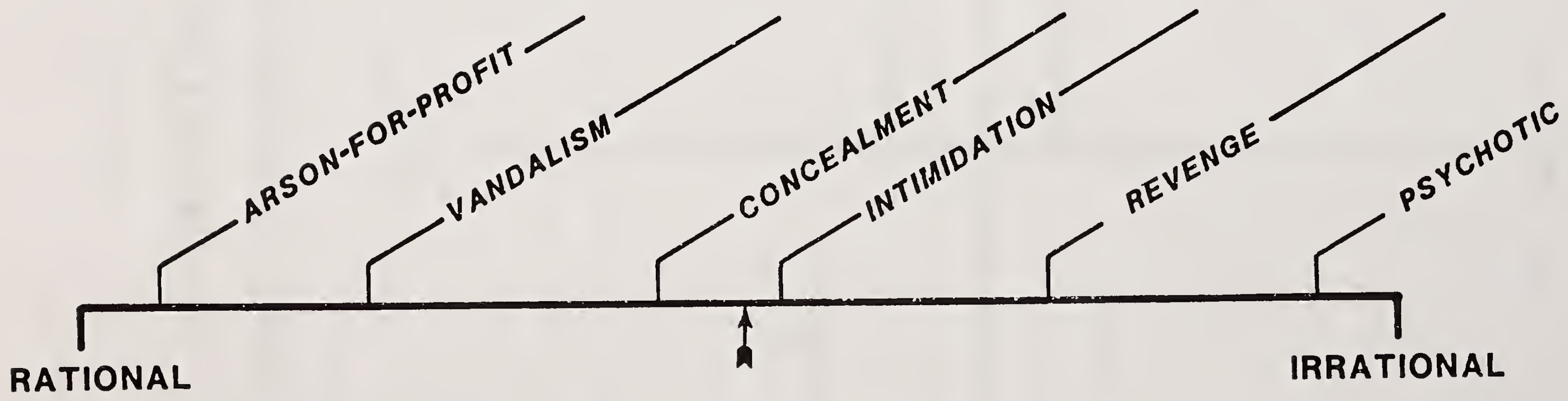
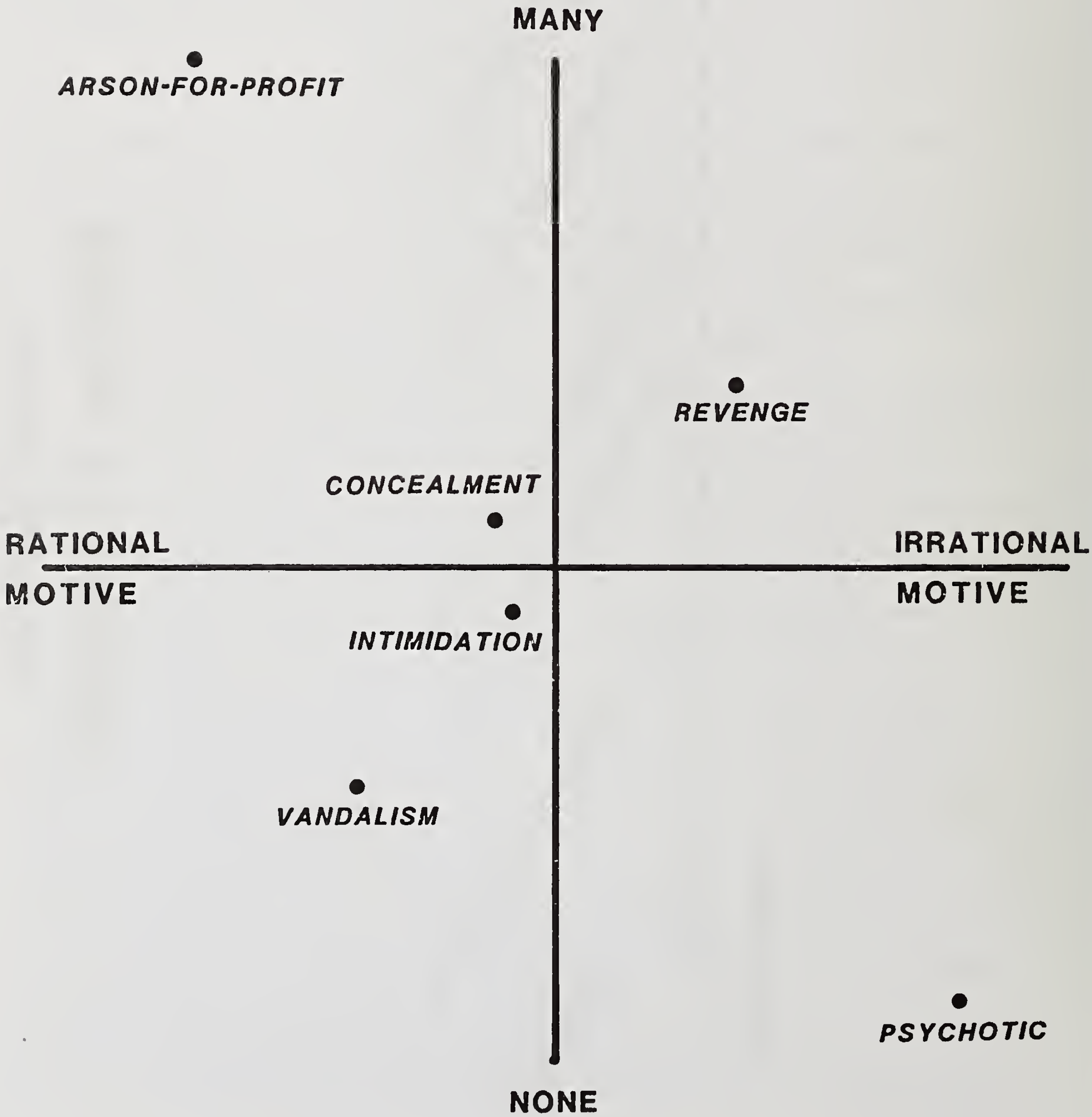


FIGURE II

Arson Prevention: Early Warning Signs



In order to examine the range of arson motives from rational, to mixed, to irrational, it is instructive to use the notion of "moral hazard" as it may be applied to arson. A term drawn principally from the insurance lexicon, moral hazard refers to specific factors in the decision processes of an individual that identifies him/her as arson-prone, and therefore an imprudent risk to an insurer. When applied to arson motives there are psychological, social, and economic pressures which weigh, for example, on pyromaniacs, revenge arsonists, and those who commit arson for monetary gain. The interplay of psychological and perhaps social stresses are far more significant, if less subject to detection, in the case of the revenge arsonist. In contrast, economic stress factors are salient with respect to the profit-motivated arsonist. The distinction between these two types of moral hazard, however, lies in the presence of identifiable and easily traceable indicators of the antecedent stress situations influencing the potential arsonist. The indicators of prior stress factors left by the revenge arsonist are, in most instances, clear and identifiable after the fact. But only a small proportion of cases that possess these characteristics actually result in the commission of a crime, and the detection of relevent factors prior to a crime would require the establishment of a surveillance system so pervasive that it would present a civil liberties problem of enormous magnitude. Even then it would still be necessary to identify which of the arson prone people would actually commit the crime.

In the case of arson-for-profit, the issues are markedly different. The pressures which weigh on the arsonist, and his/her preparation for the arson, leave two converging trails; (1) financial stress indicators, and (2) pre-arson planning steps. Although these factors affect the condition of the arsonist's moral hazard, the emphasis here is largely on economic components because the general indicators of financial stress (such as business recession or impending bankruptcy), and their affect on local economies, can be identified and measured with a moderate degree of accuracy.

In sum, economic stress situations profoundly affect the condition of moral hazard. For arson prevention purposes therefore, it would be ideal to be able to identify three categories of information, each with its own predictive capabilities:

- Situation-based information, to focus on variable impacts of economic conditions on different business sectors (e.g., restaurants, home building, furniture, etc.)

- Location-based information, to focus on various types of buildings (e.g., schools, single-family and multi-family housing, etc.) which are probable arson targets.

- People-based information, to focus on individuals whose index of moral hazard indicated that they would be likely to commit (or cause to be committed) an act of arson.

Each of the seven Arson Information Management Systems (AIMS), supported by the U.S. Fire Administration addresses one or more of the above categories of information. In most cases, the projects deal with arson for profit, because of the presence of prior warning signs and the frequent rationality of the perpetrators. Certain AIM systems are purely preventive in nature. They seek to identify financial stress and other causal factors early enough to enable official intervention to prevent arson. Other AIM systems analyze information on multiple prior fires and involved individuals, in the hope of determining whether groups of people have conspired to set or to arrange to set fires. The following discussion covers three representatives of the seven AIM systems that have established methods of information gathering, analysis, and dissemination. The three cities in which these systems are located are New Haven, Boston, and Phoenix.

There are several general similarities among the systems. They all use electronic data processing equipment, to some extent, in order to expedite the collection and analysis of fire and arson-related information. All three employ some form of statistical or other type of information analysis to determine the correlation between arson fires and other variables. Arson prevention measures are outlined in each of the three jurisdictions based on the use of the arson information once it is obtained.

Despite these similarities, the three AIM systems represent a range of available options that can be used to determine the most appropriate system for a specific jurisdiction. For example, the Phoenix system is based on a reactive strategy: the arson prevention measures designed for that jurisdiction come from post-fire incidence reports. The other jurisdictions, on the other hand, have developed preventive early warning systems used primarily to target pre-arson building risks.

The early warning systems in New Haven and Boston rely on a mixture of manual and electronic data processing systems. They have attempted to implement, gradually, the electronic data processing aspects of their AIM systems in order to facilitate the changeover from manual systems. The greater complexity of the system in each of these three cities compared to the one in Phoenix offers them a highly versatile and potentially more effective arson prevention system.

I. New Haven Arson Warning and Prevention System (AWPS)

A. Purpose of the System

The primary purpose of the New Haven model is to prevent arson from ocurring by identifying those buildings most arson-prone in the near future. The intention of the program is to spur preventive measures by members of the public and private sectors. These include: (1) city officials (e.g., to increase housing and building code enforcement); (2) law enforcement agencies (e.g., to increase arson patrols in "at-risk" areas); (3) insurance companies (e.g., to monitor increases in insurance coverage); and (4) financial institutions (e.g., to consider risk information when making loan decisions). In addition, the information provided by the early warning system is also useful in post-fire investigations. Such latter uses include: disting-
is also useful in post-fire investigations. Such latter uses include: disting-
uishing common characteristics in arson fires, identifying the public adjusters and insurers frequently involved with policyholders who suffer arson losses, and obtaining information on property history.

B. How the New Haven AWPS Works

The arson warning system is based on the premise that a certain set of "events" (independent variables) is closely associated with an arson fire, (dependent variable). To determine which independent variables would be the best predictors of future arson fires, the New Haven analysts examined historical data for a five-year period. The first step in this process involved obtaining information on arson fires that took place between January 1973 and September 1978 using these criteria:

- All structural fires occurring between January 1973 and September 1978 in occupied buildings where there was a monetary loss and the cause of the fire was listed as suspicious, incendiary, vandalism, or reckless burning;
- All structural fires in vacant buildings regardless of loss or cause; and
- All structural fires in occupied buildings where there was a monetary loss and the cause was listed as "undetermined." These incidents were reexamined to decide whether the cause of the fire was, in fact, suspicious. A limited number of these were included in the list.

The product of this information gathering process was a list of 1,432 structural fires, identified by street address. In order to compile a list of dependent variables, a random sample of 110 was chosen for the actual analysis. In addition, there was the corresponding selection of a control group from fire records of buildings which had not sustained a suspicious fire during the 1973-1978 time period. Buildings in this control group were selected by matching their characteristics with the experimental group on such features as use, size, construction material, and number of dwelling units. This selection process involved on-site visits as well as the study of local files.

The next step involved the selection of the various independent variables to be analyzed statistically vis-a-vis the dependent variable. The original list of variables included over 200 possible specific items in a wide range of categories. Information was collected from the city building department, clerk's office, tax collector's office, fire department, housing conservation and code enforcement agency, and police department.

For each structural fire in the sample and for each control group item, the information regarding the various independent variables was gathered, coded on worksheets, and then keypunched and verified. A statistical package called SAS (Statistical Analysis Systems) was used to determine the correlation between the various independent variables and the arson fires. Through the use of frequency procedures and a statistical regression model, the variable list was ultimately reduced to four key indicators or "trigger" variables:

- Total amount and number of years of tax arrearage,
- Previous structural fires,
- Housing code violations cited by the New Haven Housing Conservation and Code Enforcement Agency, and
- Liens and other claims on the property.

Statistical analysis revealed that 78 percent of the variance in arson incidence between the structural fire group and the control group could be explained by these four variables.

Having determined the "trigger" varibles for an arson prediction system, the New Haven staff has mounted a program to test the findings. A decision was made to collect a two-year back history on each of the four trigger variables. Information on structural fires, tax arrearages, housing code violations, and liens which occurred or were issued in New Haven between January 1, 1977, and December 30, 1979, was collected. This work was executed manually utilizing off-duty firefighters, student interns, and the AWPS staff.

Once collected, the information was recorded and stored by address, on color coded index cards. The cards were arranged alphabetically, and a master list of each address and the trigger variables which are now available. These lists form the basis of the at-risk group.

Buildings which indicate the presence of all four trigger variables are "red flagged" for immediate arson prevention intervention by the AWPS staff. In addition buildings with three trigger variables are flagged for less urgent intervention. Additional information on "red-flagged", or at-risk buildings was obtained on assessed value, insurance coverage, physical description of the property, and mortgage data. Thus, a great deal of information was consulted and analyzed by the AWPS staff prior to the actual contact with the owner of the building.

C. Testing, Implementation, and Evaluation

The New Haven early warning system has completed testing of the "trigger" variables. Implementation of the model and its preventive measures began in March, 1980. An important part of the evaluation of the system has involved the determination of the degree to which the various organizations receiving the "at-risk" information act on it to reduce the incidence of arson.

D. Resources Required

1. Staffing. Responsibility for design of the early warning system was given to the Director of Planning and Information Services in the New Haven Fire Department and to a civilian coordinator specifically hired for this purpose. To collect the extensive amount of information regarding building history and financial characteristics, four firefighters from the New Haven Fire Department were hired for ten hours per week during their off-duty hours to collect the information from various city agencies. In addition, several student interns from nearby colleges helped with the data collection as part of the city's intern program. The information on the "trigger" variables was collected by seven firefighters hired on part-time basis during off-duty hours. The number of data researchers required will be reduced as the manual collection of data diminishes. AWPS staff presently includes a program coordinator, a housing rehabilitation specialist, an adminstrative assistant, and a secretary. Future staff plans include a full-time AWPS insurance adjuster and a part-time computer programmer/statistician.

2. Equipment. The statistical analyses performed by the AWPS staff required the use of a computer. Keypunching and data processing facilities at the Yale University Computer Center were utilized. The availability of the SAS packaged computer program was also necessary for the statistical analyses.

3. Funding. The development of the original design and data collection of the system was completed under a $10,000 award from the Factory Mutual System. The testing phase of the program was funded by the U.S. Fire Administration and the implementation phase by the Aetna Life and Casualty Company.

4. Access to Essential Records. Other types of resources required to design, test, and implement the early warning system include the various records held by public agencies or private organizations.

In the New Haven model, the following categories of information were collected for the initial analysis:

Source	Type of Record
Building Department	--Building code violations and abatements --Record of building inspections --Demolition information --Record of building permits issued
City and Town Clerk	--Transfers of property --Type of conveyances --Liens on property
Collector of Taxes	--Total amount of tax arrearage --Number of years in arrears --Address where tax bills are sent
Fire Deparement	--All structural fire responses --Use and occupancy of structures at time of fire --Situation found at fire --Ignition factor at fire --Property damage loss from fire --Fire code violations and abatements
Housing Conservation and Code Enforcement Agency	--Housing code violations and
Police Department	--All police responses

II. Boston: Arson Early Warning System (AEWS)

A. Background

The Boston AEW System was developed following an investigation into an organized arson ring which operated in the Symphony Road area of that city. The ring was involved in setting dozens of fires during the period 1974 to 1977. Following the deaths of several tenants in arson fires within a short time, the residents formed a group (Symphony Tenants Organizing Project) to combat the problem. The symphony Road group felt that a prediction system could be created to prevent arson because buildings that were ignited had similar characteristics. A decision was made to undertake a pilot study, conducted by Urban Educational Systems, Inc. (UES), of Boston, a firm created for the purpose of conducting arson research. UES received a grant from the U.S. Fire Administration to develop an arson early warning system. Three manuals have been produced by UES growing out of their work on this project. These manuals published by UES in 1979 and available from them, are: (1) Arson Action Guide, (2) Research: A Manual for Arson Analysis and Property Research, and (3) Tools: Anti-Arson Programs and Legislation.

B. Purpose of the System

The arson prediction system is utilized to identify buildings that are most prone to arson fires. This information is used to initiate a variety of arson preventive measures such as enforcement of building codes, reduction in over-insurance of property, promotion of neighborhood awareness, and proactive investigation by law enforcement agencies.

As in the New Haven AIM system, the Boston AEWS serves as both a data collection system and an arson prediction system. Information from city agencies on building or owner characteristics can be collected and made accessible in an efficient manner. This will aid in the investigation and prosecution efforts in post-fire search for evidence, in the event that arson is not prevented.

C. How the System Works

The AEWS study selected 78 residential, absentee-owned, multi-unit rental buildings in the Boston area in which a fire had occured between June 1, 1978 and May 31, 1979 as their sample population. To meet the criteria, the fire had to have caused a loss of more than $500 and had to be classified as incendiary, suspicious, or one that caused abandonment. The 78 sample buildings were matched with a control sample of 78 buildings in which there had been no fire in the same time period.

Historical differences between these two groups over a 10-year period were determined on the basis of information on over 300 variables collected for each building.

Results from the analysis suggest that combinations of as many as a dozen variables will constitute the best indicators of high arson risk. Variables can be assigned relative weights depending on their correlation with past arson fires.

The variables examined are divided into two categories: (1) economic stress factors of the building, include such items as: vacancy rates, debt-to equity ratio, sale and resale transactions, previous fire record, building code violations, santiary code violations, tax arrearage, liens, attachments, rent control data, and time lag between building citations and repairs; and (2) the owner's characteristics include such factors as: previous fire record, owner's other property, and the owner's financial status. In many cases a distinct separation between economic stress factors and owner-characteristic factors is not possible. For example, code violations and tax arrearage bear on both.

D. Implementation, Testing, and Evaluation

The process of collecting the building and ownership information has been completed.

E. Resources Required

1. Staff and Equipment. The staffing required for this study is provided

by Urban Educational Systems, Inc. Three full time equivalent staff members have been assigned to the AEWS study, including two computer specialists (one full-time, one half-time), one researcher, and an administrative assistant (half-time).

2. Funding. Funding for the AEWS study was provided by a grant of $200,000 made to UES by the U.S. Fire Administration. Approximately one-half of this grant is devoted to research purposes, and the other half to providing technical assistance to other communities throughout the nation.

III. Phoenix: Arson Prevention and Analysis Unit (APAU)

A. Background

The Phoenix program is managed by the Arson Prevention and Analysis Unit (APAU) in the Phoenix Fire Department. Data located and analyzed in separate local agencies will be collected and studied by the Arson Prevention and Analysis Project.

The APAU project serves three general purposes:

(1) Output from the analysis of data is distributed to local agencies, thus providing each with information generated by the others.

(2) The data analysis indicates patterns of arson incidence in the Phoenix area which can facilitate deployment of arson investigative personnel.

(3) Information provided through the data analysis assists in joint planning of strategies among the various Phoenix agencies, including the police and fire departments, insurance companies, county prosecutor's office, the arson task force, city manager's office, city council, the chamber of commerce, and other civic groups.

B. How the System Works

The Phoenix AIMS staff has developed special record-keeping forms for arson investigations undertaken in the city. Arson investigations in Phoenix are conducted by the Fire Department (Fire Investigation Squad) and the Police Department (Bomb and Arson Squad). Both units are provided with the improved data collection forms. These forms can be used to establish several files including an "Arson Location" file, an "Arson Suspect/Victim Investigation Lead" file, a "Property Management" file, and a "Fire Dollar Loss Reported" file. Additional information is collected from various insurance companies, from the Property Insurance Loss Register (PILR), and from other city departments including Zoning, Parks and Recreation, and Public Housing.

The information received from these sources can be programmed, coded, and entered into a work processor to allow rapid retrieval of requested information. Multiple listed information (e.g., an owner's name under "previous fires," "housing code violations" and "insurance claim files"). Unlike the New Haven and Boston AIM systems, the Phoenix model does not attempt to predict the risk level of specific owners or buildings, but instead focuses on geographic areas.

C. Implementation and Evaluation

The output of the Phoenix AIM system is distributed to a wide range of potential users. Police and fire units utilize if for arson investigations (e.g. intelligence operations, surveillance decisions, property loss information retrieval, etc.). The local Arson Task Force uses the information as a basis for community outreach programs, legislative lobbying efforts, and as a means of informing the media. Other recipients of the output include, when appropriate, insurance companies, civic groups, the city council and mayor's office, and other law enforcement agencies.

D. Resources Required

1. Staffing. Staff are drawn from existing personnel in the Fire Department Arson Investigation Unit and Police Department Bomb and Arson Squad. Operation of the AIM system is handled by a Loss Prevention Analyst in the Arson Prevention and Analysis Unit.

2. Funding. The project has been funded by a U.S. Fire Administration grant of $20,000, which is used to support the Lost Prevention Analyst.

3. Equipment. The word processor and other equipment necessary for the information analysis are supplied by the Arson Investigation Unit of the Fire Department.

Conclusion

The above discussion focused on those aspects of arson motives that render certain motive patterns (and principally arson-for-profit) more susceptible to prediction and early intervention than others. A most important finding that emerges from a review of current arson control programs is that the number of indicators of prior intent to commit arson, rather than the rationality or irrationality of each motive, provides officials with arson reduction opportunities that are just becoming appreciated. Arson-for-profit is believed to constitute the most costly motive, in that perpetrators routinely cause the widespread destruction which they have planned. The discernible motive pattern for this profit-motivated crime provides officials who are willing to probe for background information on the financial distress that often can be traced to distinct pre-arson planning steps, and frequently culminates in arson. Consequently, it is likely that future arson control demonstration programs will focus on profit-motivated arson. The considerable potential to prevent acts of arson committed for other more irrational motives such as revenge, remains to be tested.

ENDNOTES

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3/ Boudreau, supra, note 1, p. 1.

4/ Note. "Arson Fraud: Criminal Prosecution and Insurance Law. Fordham Urban Law Journal, 3 (1979).

5/ See Dale Tooley and Christopher Munch, "The Need for Prosecutor Involvement in Arson Cases," Firehouse Magazine, August, 1979. Mr. Tooley is the District Attorney in Denver, Colorado.

6/ See Boudreau, supra, note 1, pp. 29-31; and Robert McGann, "DA's are Urged to Become Involved in Early Stage of Fire Investigations," in Fire Engineering, August, 1978.

7/ See Marie Wilt and James Bannon, Domestic Violence and the Police (Washington Police Foundation, 1977); and Morton Bard, Family Crisis Intervention: From Concept to Implementation (Washington: Government Printing Office, 1973).

INCENDIARY FIRES IN JAPAN

by Tetsuhiko Kawamura
Japanese Association of
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1. Incendiary Fires in Japan Today

Arson has been thought a rural type of offense until rather recently. There are as many arson fires in rural areas as urban areas when compared with the number of occurrences per population of the areas. It has also been said that since the beginning of this century, arson has been on the decrease except in the periods of depression.

However, this tendency has recently been changed a little and in cities, especially in Tokyo, Osaka and in other big cities arson has exceeded the fires with other causes. But when looking at the whole country, from the classification as shown in the Fire Journal, March 1976, arson occupies not the top place but the fourth, both in number of and loss by fires, as shown in Figs. 1 and 2.

Incidentally, little change has been found in the number of fires and amount of loss in Japan for the last few years. In 1978 Japan experienced 70,423 fires and loss of ¥130,539 million (approximately $593 million).

2. Types of Incendiaries

Most malicious fires are started by individuals in secret. Many fires are started for reason of revenge or spite, which are brought about by the feud between relatives, neighbors, or other acquaintances. Some fires are caused by persons who have a sort of enmity against society, or by pyromaniacs whose motive is to obtain a sort of satisfaction from the fire and the accompanying events. Other types of firesetters include thieves who want to destroy evidence or who start fires because of dissatisfaction over their spoils. And it is remarkable that many fires are caused by incendiaries committing suicide nowadays by setting fire to the fuel gas leaked intentionally or such flammable liquids as gasoline or kerosene. But incendiary fires motivated by "defrauding insurance companies" are very few as shown in the reports by Yamaoka and Murakami.

What Insurance Companies Do to Prevent Fraud by Arson

As mentioned above, there are very few cases of arson for the purpose of insurance fraud in Japan. Insurance companies have established organizations some years ago to investigate suspicious cases related to insurance fraud, but almost all the cases are related to automobile insurance, whereas very few cases are involved in fire insurance -- one or two cases in a year.

Early in the sixties, we had several remarkable arson fraud cases -- rubber-shoe manufacturers in Osaka, textile wholesaler in Kyushu. Since then insurance companies have exchanged information with each other, making their underwriting more cautious.

Summary

Except in Tokyo and other big cities, incendiarism is not taken as a very grave problem today in Japan. And even insurance companies do not pay much attention to it. There may be many reasons for this situation. The fact that economic conditions as a whole are not so bad may be cited as one of them, traditionally strong guilt feelings against playing with fire can be a second force to prevent the increase of incendiaries, the high percentage of arsonist apprehension, which exceeds 30%, may be another factor. And the fact that Japan is ethnically an almost uniform nation and consists of a very stable society is one of the effective factors, I should say.

Although these are the incendiary situations as of today in Japan, the following two facts are to be noted:

(1) Repetitive or serial incendiary fires by arsonists, who are often mental defectives or people with low intelligence, are caused from time to time in big cities, more often in larger cities.

(2) Incendiary fires or sometimes explosions which are caused by firesetters who want to commit suicide setting fire to fuel gas intentionally leaked by them, or flammable liquids such as gasoline and kerosene. There were 531 such people who committed suicide in 1978, and in the case of leaked gas, these incidents tend to cause damage to other people and property, in such a densely built-up area as Tokyo.

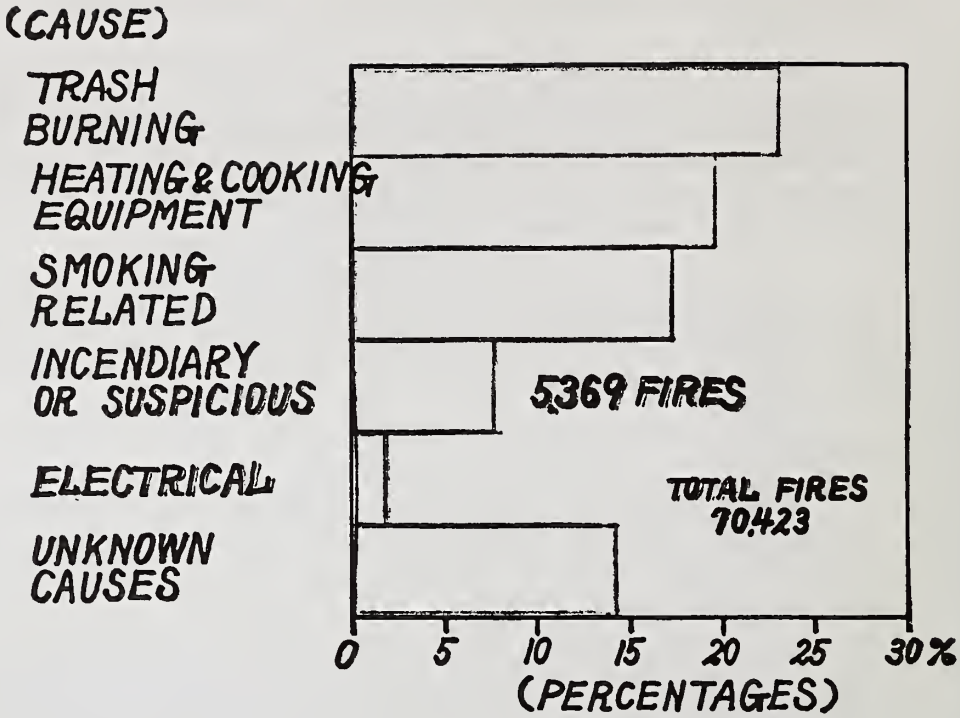

Fig 1 Percent of fires by cause, 1978

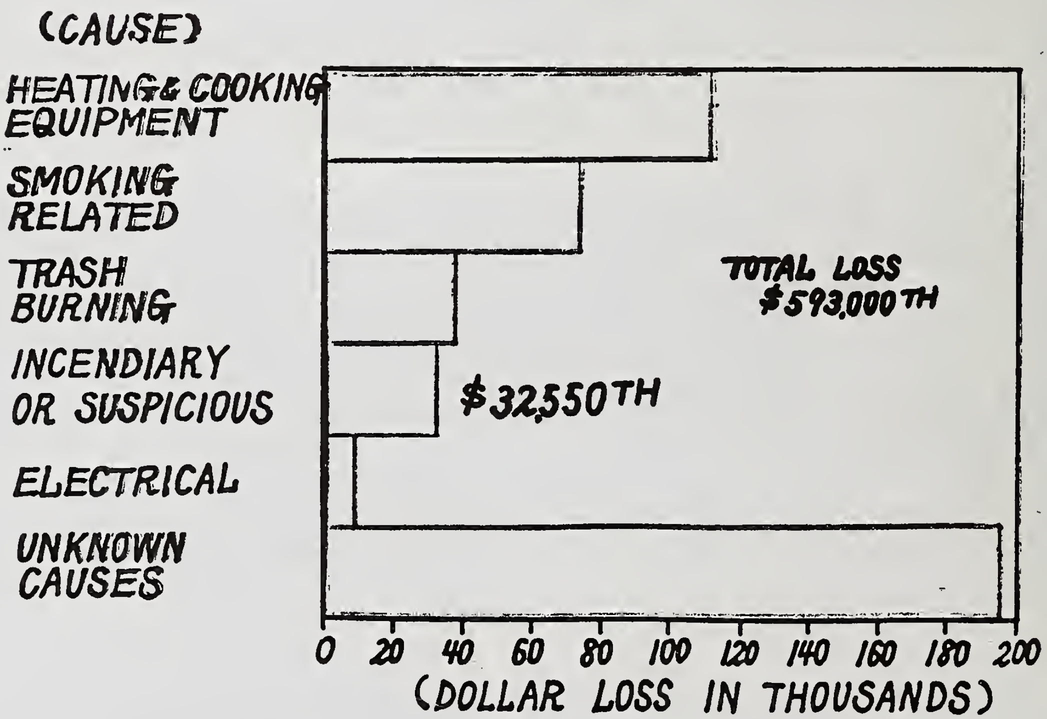

Fig 2 Dollar loss from fires, 1978

Discussion of Presentations on Arson

Karchmer Presentation

Handa: You mentioned several cities. I wonder whether the pattern of each jurisdiction varies according to the city.

Karchmer: Each of the four cities I reported on had different types of arson problems. New York and Boston were primarily multi-family residential housing. New Haven was primarily single-family housing. Arson for profit is a problem in both these cities. Phoenix was single-family housing with commercial arson as a problem. So, you have at least three different kinds of arson problems to which these AIMS systems were a response.

Furthermore, the New York and New Haven multi-family housing was "absentee" owned by absentee landlords. That gives us a further difference among the different programs.

All four AIMS projects are currently working on refining their output and figuring ways to utilize that information. The issue of the impact of its evaluated information is forthcoming, but is several months away.

Handa: When business is bad and/or there is a death, is this one indication of motivation for arson?

Karchmer: Yes, let me explain. A study was done several years ago that is reported in the Journal of Insurance. Between 50 and 75 variables were analyzed to determine what would predict deaths of increases in arson in the U.S. Data from the U.S. Department of Commerce and its various reports were utilized. The one variable that correlated most closely with the increase in arson, was non-personal bankruptcy which included several different kinds of bankruptcy under our laws: partnership, corporateship, as well as corporateship reorganization. But the real value of the information is that bankruptcy and arson statistics so closely followed each other. The problem with predicting commercial arson which includes industrial arson, in contrast to residential arson, is that the indicators of residential arson all come from public sources of information: liens, code violations, firefighters. The comparable stress indicators for commerical or industrial arson are found in the business's financial books, its tax receipts and other private nonpublic sources of information. This means that it is next to impossible for a researcher to use related financial stress information to attack commercial arson.

The indicators of commerical arson, therefore, are most useful as indication of criminal intent. For example, insurance may be increased drastically on the premises just prior to the fire. In many states it is possible to obtain that information. Secondly, there may be changes in inventory levels in that company; such that cheap inventory is substituted for expensive inventory prior to the fire. In some cases, it is easy for an investigator to get that kind of circumstantial evidence of a likely involvement of an owner in the arson. But it is difficult to prove the involvement.

Apart from that, the intervention strategies to combat commercial arson deal with the development of criminal intelligence programs to gather criminal information about the kinds of people the business owner may be dealing with, and they are very different from the statistical and other kinds of records upon which the AIMS projects are based.

I have just completed an enforcement manual on arson for profit for the Justice Department which details that type of a program. I would be happy to provide those who are interested in receiving a copy. It is much better to do that than raise the discussion here.

Handa: Can you include the information of explosives used in arson cases for revenge?

Karchmer: Presently apart from location and time of day, I do not believe any other kind of information is gathered by any of the seven AIMS systems which would help in predicting revenge arson.

Kawamura: I am interested in any figures and/or statistics. What is the rate of arresting arsonists? How many of them are convicted from trials?

Karchmer: I do not have that information. The personnel who work in these AIMS systems developed better case tracking mechanisms. I can provide you with the names and addresses of those people and they can provide you that information.

Levine: Did you say that all fires in Tokyo are investigated?

Kawamura: We do investigate as many as possible, but the data in which we understand the motive of arson clearly are used in my Figure 1.

Levine: Can you investigate all fires, not just arson?

Kawamura: Not all of them.

Levine: That is a very important factor in this country. Those cities which do little investigating of fires, do not report much arson. The fires you describe as unknown causes, are about 15% of the fires. Is there a reason that the fires of unknown causes have a much larger than 15% portion of the loss in yen?

Kawamura: We regret that we have no answer to this question. The data in this figure are based on the entire country, not just Tokyo.

Clarke: I'm amazed at the remarkably small number of cases to defraud insurance companies in Japan, as compared to the very large number in the United States. My question is whether a large fraction of commercial property in Japan is covered by casualty insurance? In the United States virtually all commercial property is covered by insurance.

Kawamura: It is true that people in Japan are less insurance minded than in U.S., but almost all commercial properties in Japan are covered by insurance. The percentage of dwellings covered by insurance is not as large as U.S.

Miyama: With respect to Figure 2, please explain why money for unknown causes is high. In Japan, persons who cause accidental fire can be criminally penalized.

Kawamura: I think that is not true. Person who pays damage does not get penalized. However, business people who are in charge, (i.e., maintenance or building guards) if proven negligence on their part, would be criminally charged.

The legal point of view is described above, but traditionally there might be penalty from society.

Karchmer: In some cities one of the arson for profit problems involves a building that is profitable that is destroyed for the purpose of creating an even more profitable business on that location (some types of urban renewal or urban development). Do you have anything comparable to that?

Kawamura: More specifically, do you mean to cause arson to make profit in specified development area after demolition of the old site?

Karchmer: Yes, exactly.

Kawamura: There is no criminal penalty on hospitals. However if patients are hurt or die during the fire, the hospital can be penalized for their negligence in not taking care of their patients.

Handa: I should like to speak concerning the number of cases of unknown causes. Sometimes the agencies are unable to handle responsibility for all cases. For convenience, they are classified as unknown causes without detailed investigation. I've found this to be true when I was asked to be a legal adviser.

Levine: A note of interest, for four years we've had a program at Johns Hopkins University to investigate the causes of all deaths in fires in the state of Maryland. During that time about 3% of the people killed in fires were killed by self immolation, by pouring gasoline over themselves. If we use that same percentage for the 8,000 people in this country who are killed every year in fires, that would be about 240 people which is not all that different from your statistics on suicide. Perhaps it is a little lower.

Kawamura: I think that the percentage of suicide arson in Japan is high, because total number of people who died in fire is a little less than 2000 and the number of people who died in suicide arson is about 530.

3. TOXICITY OF COMBUSTION PRODUCTS

Theme
TOXICITY

BASIC CONCEPT OF TOXIC HAZARDS IN BUILDING FIRES

by

Koichi Kishitani, Dr.Eng., Prof.

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Shyuitsu Yusa, Dr.Eng.

1. Introduction

Losses due to fire may be divided into material damage and human losses. It may be said that material damage is caused by heat and human losses by smoke and gas.

Consequently, with respect to fire protection measures, the procedures of research will be dissimilar since there are great differences between measures against heat which cause structural damage to buildings and safety measures for occupants of buildings in connection with the principal factors causing damage and the concepts in making evaluations. The first matter to be taken up usually when discussing measures to secure safety of human lives during fire is the problem of smoke and gas, and there is not much said concerning heat. This is because loss of human life attributed to heat is due to burns as seen from fire statistics, and countermeasures are heavily dependent on compartmentation of fire and fire fighting activities.

In contrast, measures against smoke and gas in building fires must be discussed based on the relations of the flow characteristics of heat, smoke and gas from the room on fire to the various parts of the building, the varieties and quantities of the components emitting the above, and the corresponding activities of humans. Obstructions to human behavior must be considered first of all from the standpoint of physiological obstructions. Accordingly, as impeding factors, the types and quantities of combustion gases, the thickness and humidity of smoke, and further, although perhaps not of a degree to cause burns, the rise in atmospheric temperature must be taken into consideration.

In other words, whereas many research works have been only on compositions of gases in studies of gas toxicity, for the problem of toxic hazards in fire, examinations must be made not only of gas, but all combustion products including the entire lot of factors mentioned above.

The varieties and quantities of combustion products will differ according to the correlations between the varieties and quantities of materials burned and the conditions of the building, namely, the thermal properties and geometrical sizes of constituent materials, ventilation, etc. of the space on fire or in combustion.

Further, the method of evaluation and the level of safety indicated will differ greatly depending on whether toxicities of combustion products are to be evaluated as acute or chronic, and still further, whether the toxicities are to be evaluated on the basis of absolute or relative degree.

These interrelations and the governing factors are shown in summarized form in Fig. 1.

That is, for acute toxicity, it is possible for the limit to evacuation activity according to one's own will or physiological death to be made the basis for evaluation, but for chronic toxicity, it is necessary to consider a range from a degree that light activity is possible to that where the person will become a human vegetable due to complete functional impediment.

With regard to the former in this case, it is possible to proceed with research by animal experiments, but for the latter, it will be unavoidable to rely on chemical analysis employing instruments.

For evaluation of toxicity by chemical analysis, there will be the extremely complex problem of making detailed studies of progress made in analytical techniques and of the type of gas and the degree of trouble, and further, establishment of a plural number of mixed gas toxicity evaluation formulae.

Meanwhile, there are large amounts of high-polymer materials being used in the forms of building materials, furniture and daily necessities, and it is surmised that the toxicity of gases is greatly increased by combustion of these materials.

It must be considered that it will be too late to establish a measure against gas waiting for research on toxicity which includes chronic toxicity to be completed.

In view of the above, it is necessary in coping with actual situations for combustion conditions to be those under which prediction of combustion properties of materials in a real fire will be possible, and for an evaluation method considering acute toxicity to be established.

2. Analyses of Full-Size Fire Experiments

For evaluation of gas toxicity of a material, it is necessary to be able to predict the combustion products to be emitted by that material in a real fire, and for that purpose it is necessary to set the conditions of heating to which the material will be subjected in a real fire.

However, since buildings are of various configurations depending on their uses while at the same time manifold objects are placed indoors, although fires may be caused by combustion of identical materials, the combustion products coming from the fires must be considered to be of differing compositions.

Consequently, it may be expected that there will be many combinations of temperatures and supply of air in combustion in real fires. It is difficult, and unrealistic, to attempt to evaluate toxicity by heating a material subjected to these many different combinations. Therefore, it will be necessary to find basic combustion conditions under which gross errors will not result in evaluation of the gas toxicity of a material by analyzing in detail the properties during fire.

As a method of solving such a problem, it will be useful to make detailed investigations of buildings after fires, but it is difficult to estimate dynamic behaviors of fires. Accordingly, it becomes necessary for fire experiments to be carried out with buildings of actual size to accumulate and analyze data.

Many fire experiments have been conducted in Japan with the purposes being various studies regarding fire. The objectives of these fire experiments have differed according to the needs of the time, but may be broadly divided into the five categories below.

1. Hazard of spread of fire to neighboring building
2. Compartmentation of fire
3. Room temperature and duration of fire
4. Properties of room on fire
5. Generation and control of smoke and gas

These experiments were carried out to verify the many laboratory and theoretical studies and to gain rough concepts of fires, and there were not a few which led to development of new research fields through analyses of experimental results. Consequently, the purposes of fire experiments have close relations with the trend of research on fire. That is, in fire experiments at the initial stage, there were many which had the objective of safety of structures of buildings, but as buildings became taller, large underground shopping areas were developed, and fire statistics were analyzed, more and more experiments in which studies of smoke generation and gas toxicity were added came to be conducted.

There were experiments in which buildings were newly constructed for the purpose of fire tests, but since these required considerable testing expenses and labor, many of the experiments were carried out on modifying parts of buildings planned to be demolished. Consequently, the testing conditions did not coincide in many cases. The fire experiments carried out in Japan up to this time which were concerned with emission characteristics and toxicities of smoke and gases are summarized in Table 1.

In these experiments, adequate measurements were made on temperatures necessary for combustion conditions of materials, but there were few in which measurements were made of air supply which is an important factor in establishing combustion conditions.

3. Hazards to Humans

3.1 Analysis of Victims of Fire

The classification of the present causes of fire fatalities in Japan today consists of carbon monoxide poisoning, burns, contusions and bone fractures, unknown, other and suicide[1)]. It is surmised that among those classified as deaths due to burns, there was a good proportion consisting of those who initially (principally) were victims of toxic gases. Reports of the results of investigations on degrees of carbon monoxide-hemoglobin saturation in persons killed in fire substantiate this[2].

Many high polymer materials are located inside buildings as interior finishing materials and articles accomodated, and there is a possibility for gases of high toxicities other than carbon monoxide which are peculiar to these materials to be emitted during fires.

As a result of investigating the degrees of CO-Hb saturation and cyanide levels in serum of 30 cases of fatalities in fire, it was reported that most of those killed had cyanide in their blood, with some having reached minimum lethal doses[3].

In the U.S.A. and elsewhere, the connections with alcohol and illnesses have been pointed out[4] and clinical studies of casualties due to fire have become of increasing importance. This is necessary also from the standpoint of studying unconfirmed toxic substances produced in decomposition and combustion of high polymer materials. It is regrettable that cases of study regarding this are few in number in Japan because of various restrictions.

3.2 Criteria for Evaluation

At the present stage, checks by animal experiments are indispensable when examining combustion toxicity. The correlation between humans and test-animals, and selection of the kind of test animal are the problems in such case. In studies made in the past, with regard at least to lethal limits among physiological effects of toxic gases on various test animals, classifications could be made according to those for which the limit of lethal concentration rose with increase in body-weight and those for which body-weight was of no concern and a more or less constant level was indicated. It may be said that the latter is more desirable from the standpoint of handling in experiments.

With respect to selection of the kind of test animal, it may be said that bigger animals would be suitable in case of carrying out biological analyses in detail, but otherwise, it may be said that small animals are desirable from the standpoints of availability, rearing and management, securing of quantity, ease of handling, and number required for a single test. At present, using mice and rats are mainstreams in Japan and the U.S.A., respectively, and it is necessary at least for the correlation between these two to be investigated.

Regarding evaluation of gas toxicity, there are the problems of acute toxicity and chronic toxicity. In relation to acute toxicity, it would suffice to consider impediment of activity or fatality. In contrast, with regard to chronic toxicity, further studies must be made on setting of period of observation after exposure, items of observation after exposure, and methods of observation.

In consideration of the above, it is thought suitable for acute toxicity which considers observation for a short period after exposure to be taken as the tentative criterion for evaluation.

4. Method of Evaluating Gas Toxicity During Building Fire

4.1 Evaluations of Relative Degrees of Toxicity of Various Materials

In Japan at present, the combustion toxicities of materials generally are being evaluated through relative comparisons. The methods of evaluating toxicities of combustion products may be broadly divided into evaluations by chemical analyses of products and evaluations by biological analyses using test animals. The former have the advantage that combustion conditions can be readily set in large number, but problems remain concerning appropriateness of overall evaluation and oversights in detection of toxic components. With the latter, there is the advantage that the physiological effects on humans can be estimated to an extent by the effects seen in the test animals, but there is a slight drawback with respect to reproducibility. From the standpoint of overall evaluation it may be said animal tests are advantageous at present.

Evaluations using test animals may be broadly divided into methods evaluating with sample weights and heated surface areas constant and methods (LC_{50}) applying techniques to determine median lethal doses (LD_{50}). It will be necessary to select the toxicity evaluation method considering 2 and 3 previously described.

With the technological level presently available, including combustion conditions and measures for evaluating toxicity, the problem presently faced may be said to be how an evaluation method on which a consensus can be reached is to be decided.

4.2 Overall Toxicity Evaluation Based on Standard Materials

As stated up to this point, there remains a mountain of problems which must be solved in order to establish an overall toxicity evaluation method which includes sure "safety."

In such circumstances, a method such as that indicated below will be effective in getting close to "safety" by the slightest degree.

There is a method where natural materials which have been used by humans inside buildings for ages are considered as standard materials (for example, of interior finishing materials and materials accomodated indoors, wood among board-like materials, and cotton among fibers), and it is demanded that the combustion toxicities of the materials at the least must not be more hazardous than the standard materials. If still more "safety" is to be pursued, there will be a method, for example, in which one half the toxicity of a standard material is sought of other materials.

In order to secure "safety." it is necessary for the gas concentration in the building during fire to be grasped, the interior finishing materials restricted, and combustible furniture and the like to be reduced for the allowable gas concentration, but it will still be premature for a conclusion to be drawn at the present stage.

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Table 1 Experiments on Gas Toxicities and Main Objectives Thereof

Date	Experiment	Structure	Main Objective	Gas Analysis	Animal Test
May 2, '51	Half-scale Fire Experiment	RC	Room fire properties	o	-
Jan. 31, '56	Old Yamaichi Securities Bldg.	RC	Room fire properties	o	o
June 20, '61	Mitsubishi Naka #15 Bldg.	RC	Fire propagation	o	-
Mar. 5, '62	JHC* Akabane-dai Development	RC	Room fire properties	o	o
Sept. 14-16, '64	Daiun Bldg. Experiment	RC	Flashover of interior finishing materials	o	-
May 17, '65	BRI** Experiment 1	Wooden	Flashover	o	-
May '65	BRI Experiment 1	RC 2 flr	Flashover	o	-
Dec. '66	Tokyo Kaijo Bldg.	RC	Flashover, smoke propagation	-	o
May '67	BRI Experiment 2	Wooden, 1 flr	Flashover, smoke generation	o	-
Apr. 5-7 '68	JNR*** Central Hospital, Shinjuku, Tokyo	RC	Flashover, smoke flow	o	o
June 16, '69	BRI Experiment 3	Wooden, 1 flr	Flashover, smoke generation	o	-
Dec. 3, '69	National Housing Experiment	RC	Flashover	o	o
Mar. 22, '72	JHC Hoshijima	RC	Smoke propagation	o	-
Mar. 24, '73	JHC Hachioji	RC	Flashover, smoke & gas emission	o	o

Table 1 (Cont'd)

Date	Experiment	Structure	Main Objective	Gas Analysis	Animal Test
May 9, '73	Ministry of Health and Welfare Bldg. Fire Experiment	RC	Roof fire properties, smoke flow, gas	o	o
July '73	Yokohama Fire Dept. Fire Experiment	RC	Flashover, smoke, gas	o	o
Feb. 20, '75	CAPS Fire Experiment	RC 2 flr	Fire properties	o	-
Oct. 18, '75	Fukoku Life Insurance Experiment	RC	Smoke flow	-	-
July 27-29, '76	Frame Construction Method Fire Experiment	Wooden, 2 flr	Compartmentation of fire	o	-
Sept. 18, '77	Lightweight Prestressed Concrete Housing	RC 2 flr	Fire properties	o	o
Dec. 12-16, '78	Frame Construction Method Town House	Wooden, 3 flr	Fire properties, smoke, gas	o	o
Jan. 12, '79	Conventional Construction Method Housing Fire	Wooden, 2 flr	Fire properties, smoke, gas	o	o
Mar. 27, '79	House 55 Fire Experiment	Steel, 2 flr	Fire properties, smoke, gas	o	o

* Japan Housing Corporation

** Building Research Institute, Ministry of Construction

*** Japanese National Railways

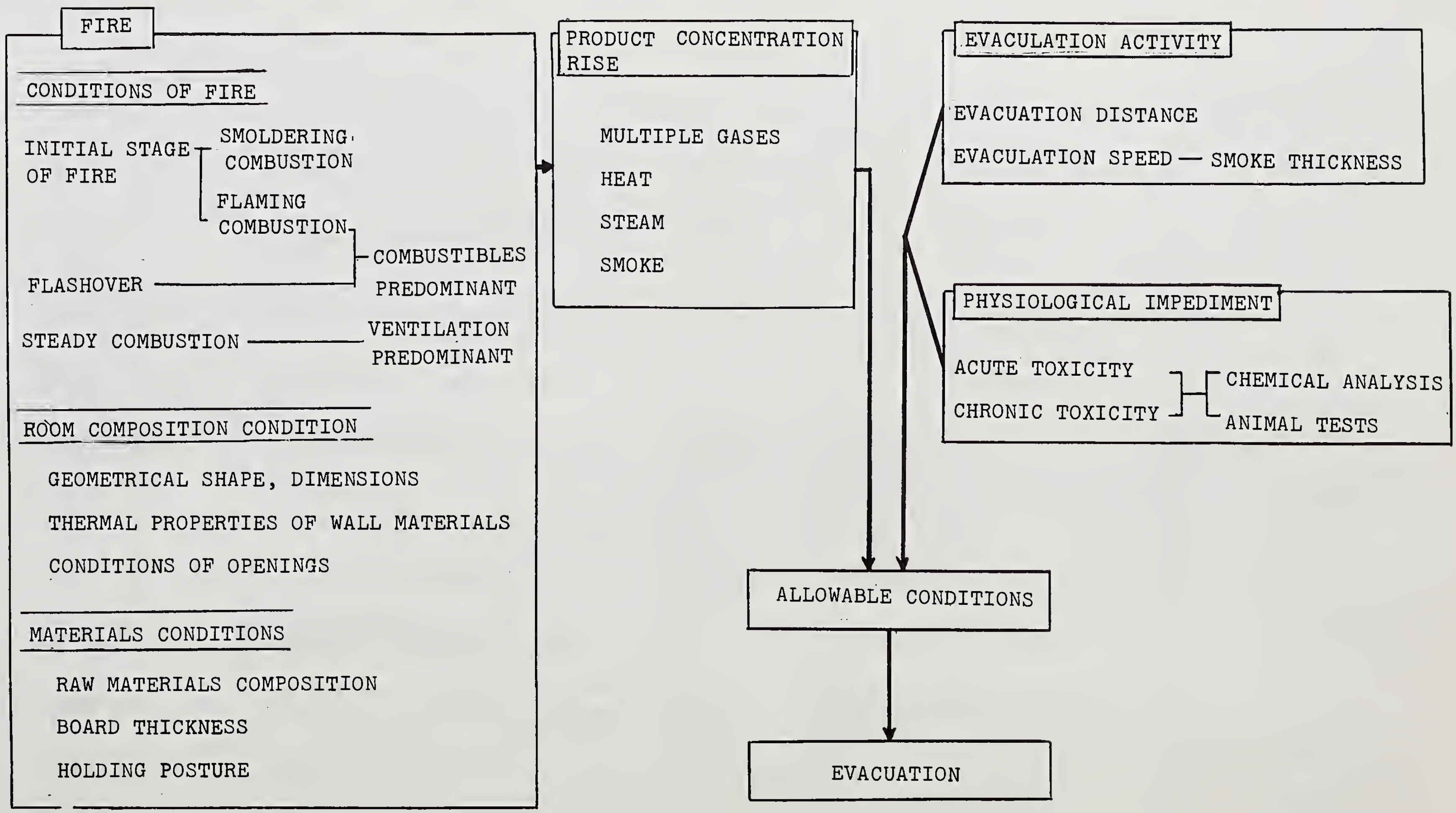

Fig. 1 Flow Chart of Research on Combustion Gas Toxicity in Fire Research

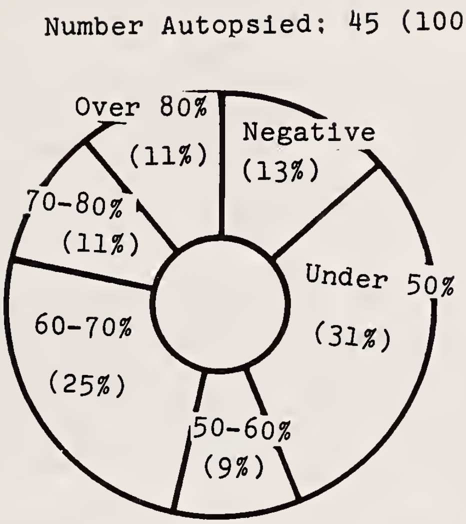

Fig. 2 Carbon Monoxide-Hemoglobin Saturation Degree in Serum of Fire Dead

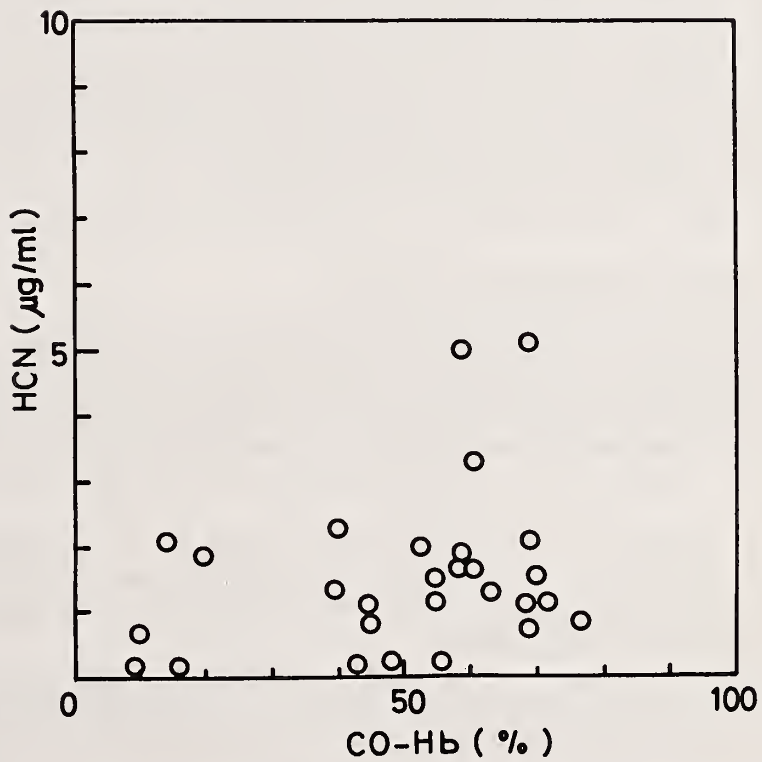

Fig. 3 Relation Between Cyanide and Carbon Monoxide-Hemoglobin in Serum of Fire Dead

PRELIMINARY COMPARISON OF COMBUSTION MODEL IN TOXICITY TEST METHOD WITH A LARGE SCALE FIRE SCENARIO

by

M. Birky

1.0 Introduction

The objective of the large scale fire studies was to determine if a correlation exists between the toxicity test method fire "model" and "real" fires. The fire "model" used in the proposed combustion toxicity test method consists of a cup furnace reported by Potts [1]. Toxicity determinations on materials are made in a flaming and non-flaming mode of operation to approximate a flaming fire and a smoldering fire.

Since each "real" or accidental fire is different, the scenario that leads to the single largest number of fire fatalities was chosen for the comparison studies. The scenario of choice is the cigarette ignition of upholstered furniture and bedding [2]. This type of accidental ignition results in smoldering (non-flaming) combustion of cotton and flexible polyurethane foam as the primary materials used in these types of furnishings.

The proposed comparison or correlation parameters between the two experimental procedures were chemical analysis and toxicological analysis of the combustion products of a non-fire retarded, flexible polyurethane (GM-21) and cotton batting. The analytical comparison was based on the analysis of carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbon (THC), hydrogen cyanide (HCN), and "fingerprint" analysis of hydrocarbons. Toxicological comparison was based on the exposure of rats to the products from the two different scaled experiments.

2.0 Facilities and Sampling System

The facility for carrying out the smoldering combustion of these 2 materials is shown in Figure 1. Gas sampling ports for the chemical analysis are designated as ports 'A'. The letter 'B' indicates the port used for filling the animal exposure chamber used in the proposed standard test method. Port 'C' is the return port from the animal chamber.

As noted in Figure 1, the sample was placed on a load cell for weight loss determinations. Weight loss information was used to determine mass loading of smoke for toxicity determinations and for comparison between the 2 experimental procedures.

Figure 2 illustrates diagrammatically the gas sampling system and animal exposure system as interfaced to the large scale fire room.

3.0 Polyurethane Results

3.1 Analytical

A summary of the preliminary analysis of the various gas species for the large scale experiments and the test protocol on flexible polyurethane at various concentrations is shown in Table 1. As noted in the table the HCN concentrations are higher in the large scale experiments by a factor of 2 or 3 depending on size of sample decomposed. However, from a toxicological perspective this difference is not very significant since the lethal level for HCN is about 200 ppm for a 30 minute exposure.

The THC (total hydrocarbon) concentrations are higher in the test protocol system than in the self smoldering large scale tests (Table 1). However, the "fingerprints" of the hydrocarbons as determined by gas chromatography using a flame detector (FID) are nearly identical.

As noted in Table 1, the CO and CO_2 concentrations are very similar in the 2 sets of experiments.

3.2 Toxicological Comparison

The LC_{50} for this polyurethane foam in the non-flaming model as determined by the test protocol is about 16 mg/l. The deaths are not due to HCN or CO. This fact was substantiated by environmental measurements of HCN, CO, and blood chemistry. This conclusion is further verified by deaths that occur 3 to 15 days post-exposure. The cause of the deaths in terms of chemical species has not been identified. However, death is attributed to lung damage due to a chemical irritant. TDI is a possible candidate. Analytical measurements for TDI are in progress to confirm this hypothesis.

Exposure of animals to the products generated in the room by self-smoldering combustion results in an LC_{50} of 35-40 mg/l. Death in this case is due to CO.

As noted, the LC_{50} and the toxicological syndromes are different in the 2 experimental set-ups. A factor of 2 difference in the LC_{50} values is not too significant. However, the difference in toxicological syndrome suggests that the mode of combustion is not entirely the same even though the chemical analysis shows very little difference.

4.0 Cotton Results

4.1 Analytical

A summary of the analytical results on cotton is shown in Table II. This work is still in progress.

Carbon monoxide and carbon dioxide are somewhat higher in the protocol system. At 40 mg/l the ratio of CO/CO_2 for protocol system is 0.17 and for the large scale is 0.20. Total hydrocarbon concentrations in the test system are approximately 2 times the concentrations produced in the large scale self-smoldering case.

4.2 Toxicological Comparison

The LC_{50} for the cotton materials as determined by the test method in the non-flaming mode is about 54 mg/l. Death was attributed to carbon monoxide. Similar data from the large scale, although incomplete, gave an approximate LC_{50} of 60 mg/l. Again the cause of death was attributed to carbon monoxide.

From the analytical and toxicological data on cotton, the test protocol approximates a large scale self-smoldering fire very well.

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[2] Clarke, III, F. B. and Ottoson, J., Fire Death Scenario and Fire Safety Planning, Fire Journal, Volume 70, No. 3 (May 1976).

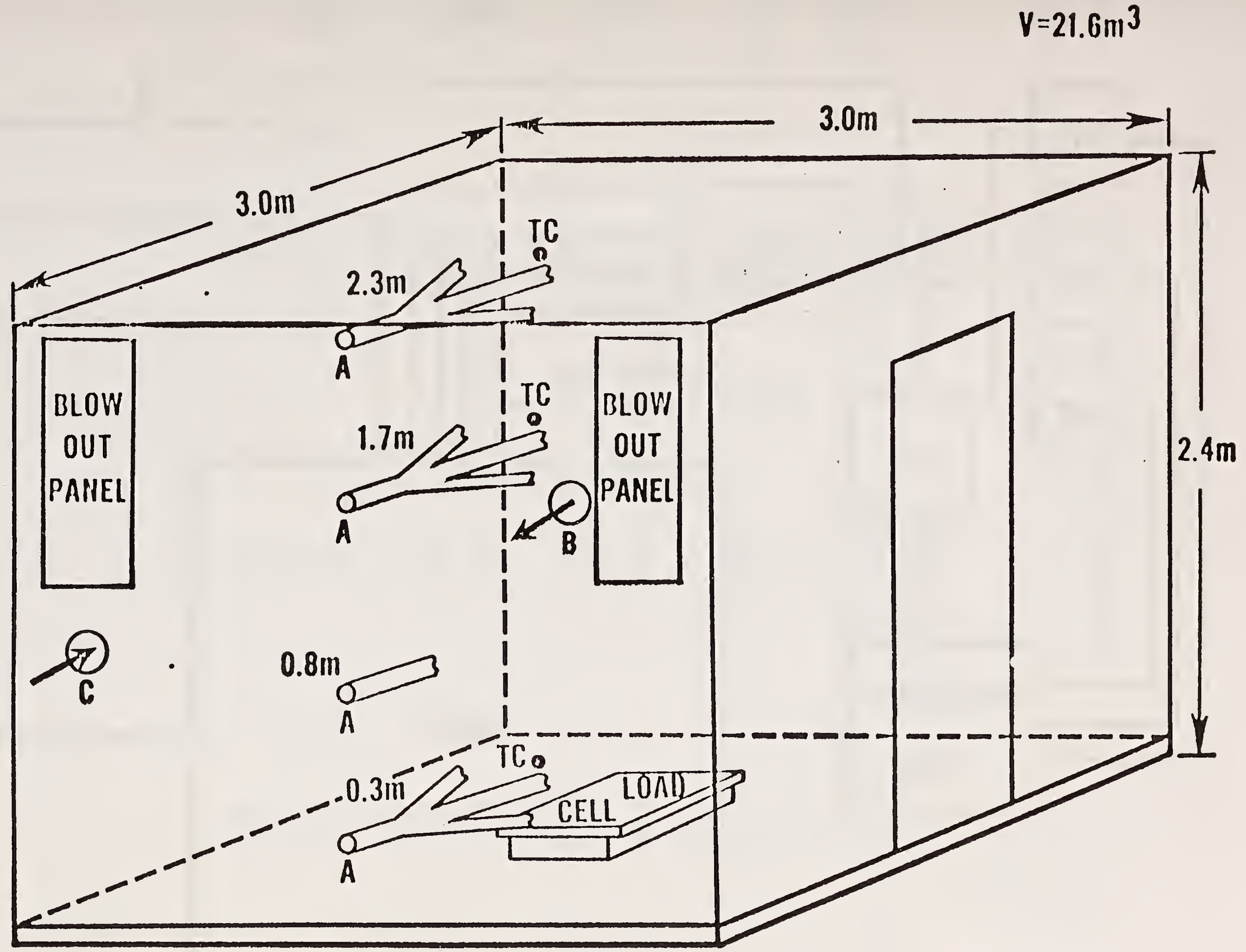

V=21.6m3
3.0m
3.0m
2.4m
TC
2.3m
A
TC
1.7m
A
BLOW OUT PANEL
BLOW OUT PANEL
B
C
0.8m
A
TC
0.3m
A
LOAD CELL

Figure 1

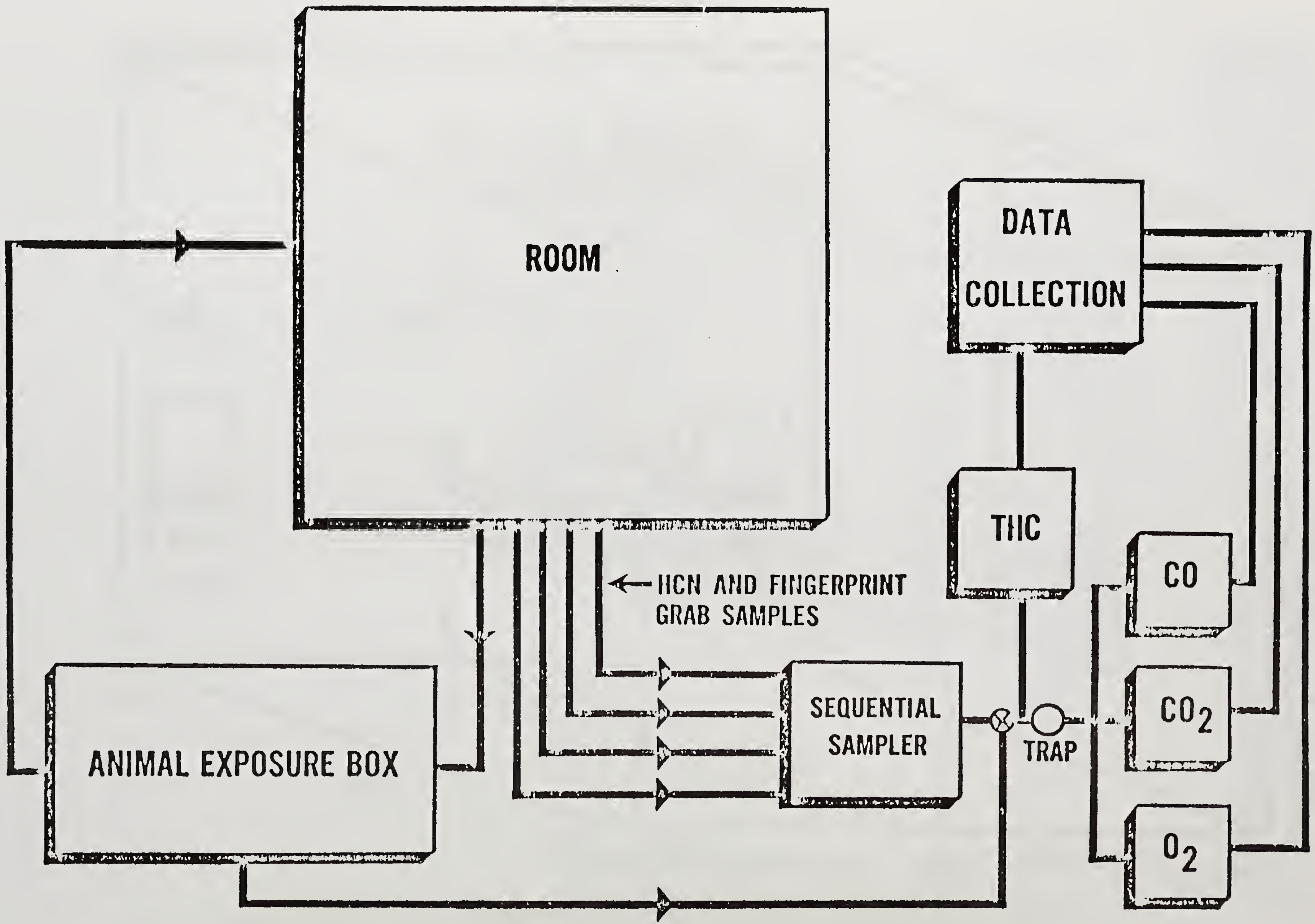

ROOM
DATA COLLECTION
THC
CO
CO_2
O_2
HCN AND FINGERPRINT GRAB SAMPLES
SEQUENTIAL SAMPLER
TRAP
ANIMAL EXPOSURE BOX

Figure 2

Table 1

Preliminary Results from the Large and Small Scale Tests

Polyurethane Foam GM-21 Non-Flaming Mode

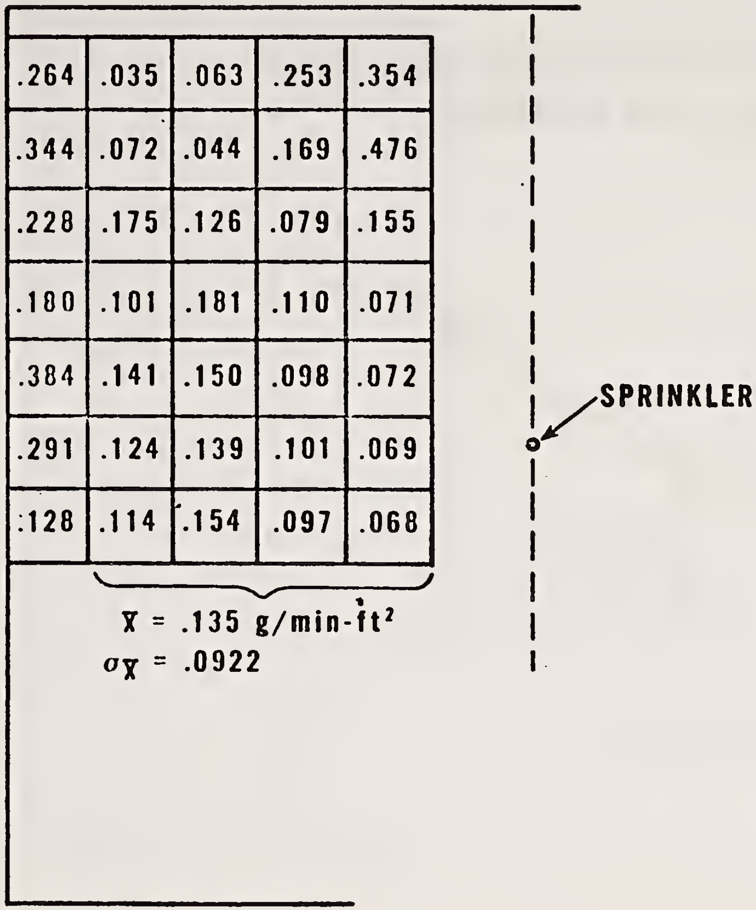
Combustion Products	Combustion Products Concentration mg/l	Maximum Concentration, ppm Estimated from several runs	
		Exposure Box Potts Furnace	Large Scale
Total Hydrocarbon	15.6	3650	2500
	20.0	--	--
	23.4	5500	3400
	30.0	--	5000
	40.0	--	6400
Carbon Monoxide	15.6	1400	1450
	20.0	--	--
	23.4	2100	2100
	30.0	--	3000
	40.0	--	4000
Carbon Dioxide	15.6	2060	2150
	20.0	--	--
	23.4	2750	2900
	30.0	--	4300
	40.0	--	5900
Hydrogen Cyanide	15.6	6	9
	20.0	8	15
	23.4	11	19
	30.0	10	30
	40.0	--	50

Table II

Preliminary Results from the Large and Small Scale Tests Cotton

Non-Flaming Mode

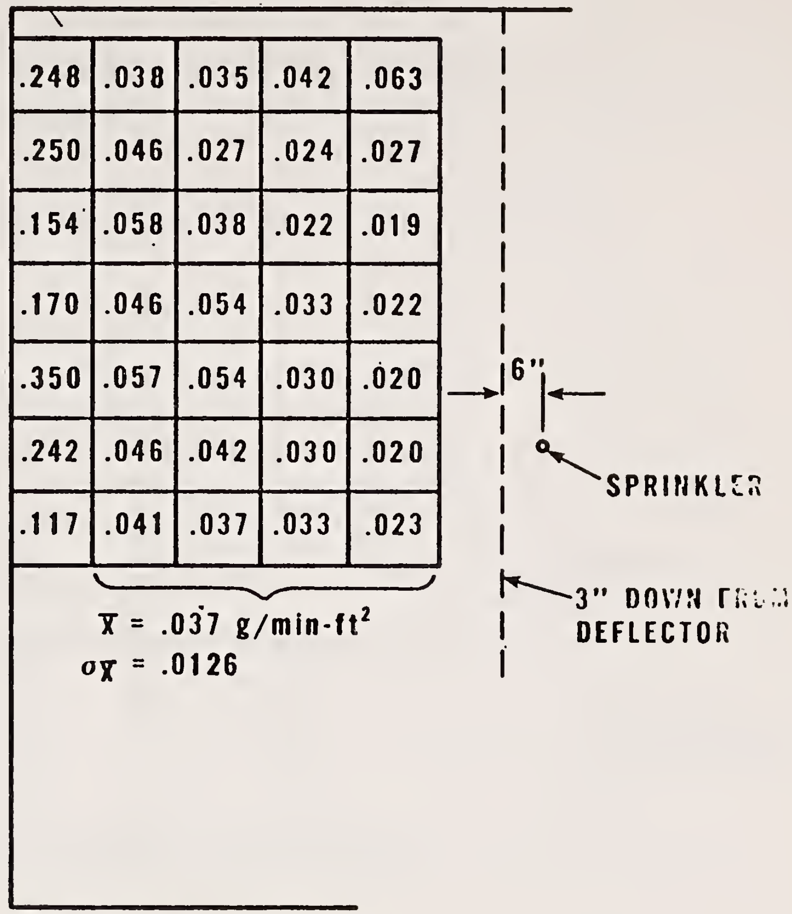
Combustion Products	Smoke Concentration mg/1	Maximum Concentration, ppm	
		Small Scale	Large Scale
Total Hydrocarbon	10	1100	600
	20	2100	1100
	30	3100	1600
	40	4100	2000
	50	4600	2500
	55	4800	2800
Carbon Monoxide	10	--	1000
	20	--	1800
	30	--	2500
	40	4000	3200
	50	4900	3900
	55	5400	4200
Carbon Dioxide	10	--	3600
	20	--	7100
	30	--	10300
	40	23300	13200
	50	27600	16100
	55	29000	17500



.264	.035	.063	.253	.354
.344	.072	.044	.169	.476
.228	.175	.126	.079	.155
.180	.101	.181	.110	.071
.384	.141	.150	.098	.072
.291	.124	.139	.101	.069
.128	.114	.154	.097	.068

SPRINKLER A ($\dot{G}$=27 g/min)

Figure 17. Spray Distribution Test



.248	.038	.035	.042	.063
.250	.046	.027	.024	.027
.154	.058	.038	.022	.019
.170	.046	.054	.033	.022
.350	.057	.054	.030	.020
.242	.046	.042	.030	.020
.117	.041	.037	.033	.023

SPRINKLER A ($\dot{G}$=27 g/min)

Figure 18. Spray Distribution Test

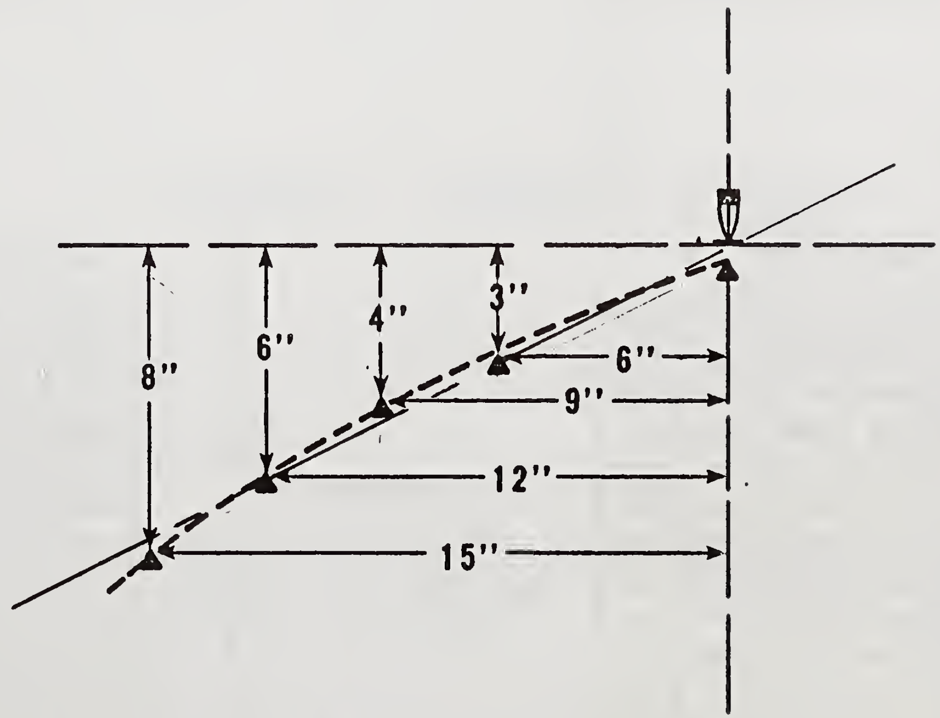
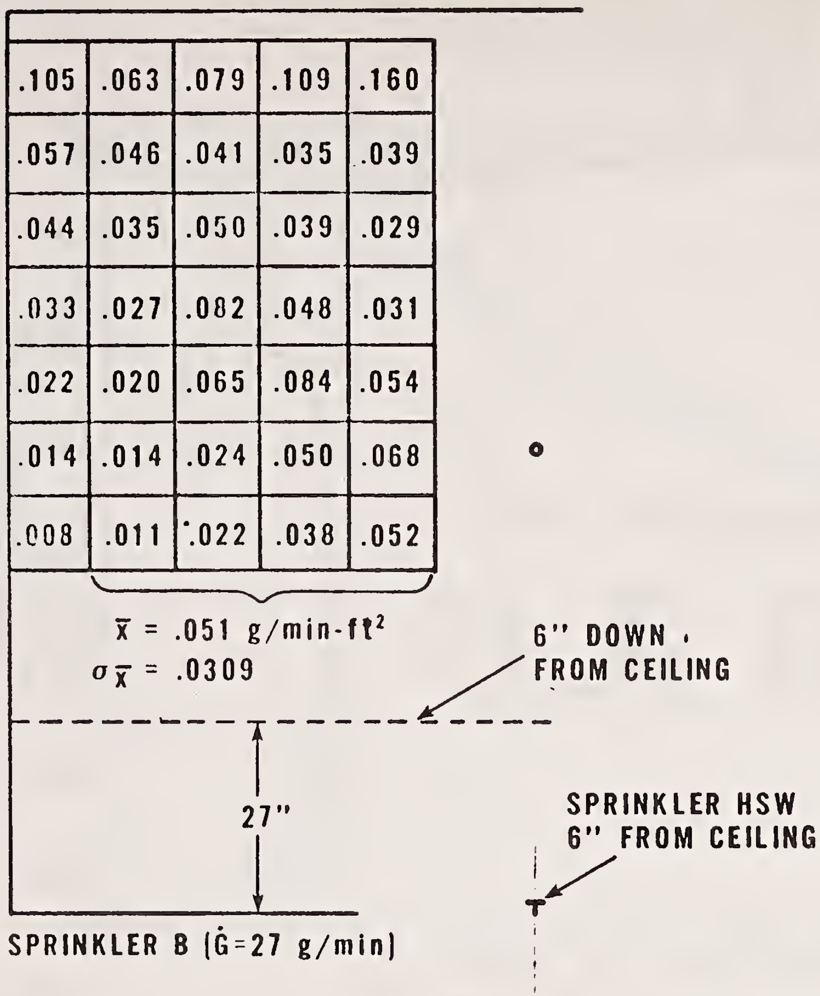
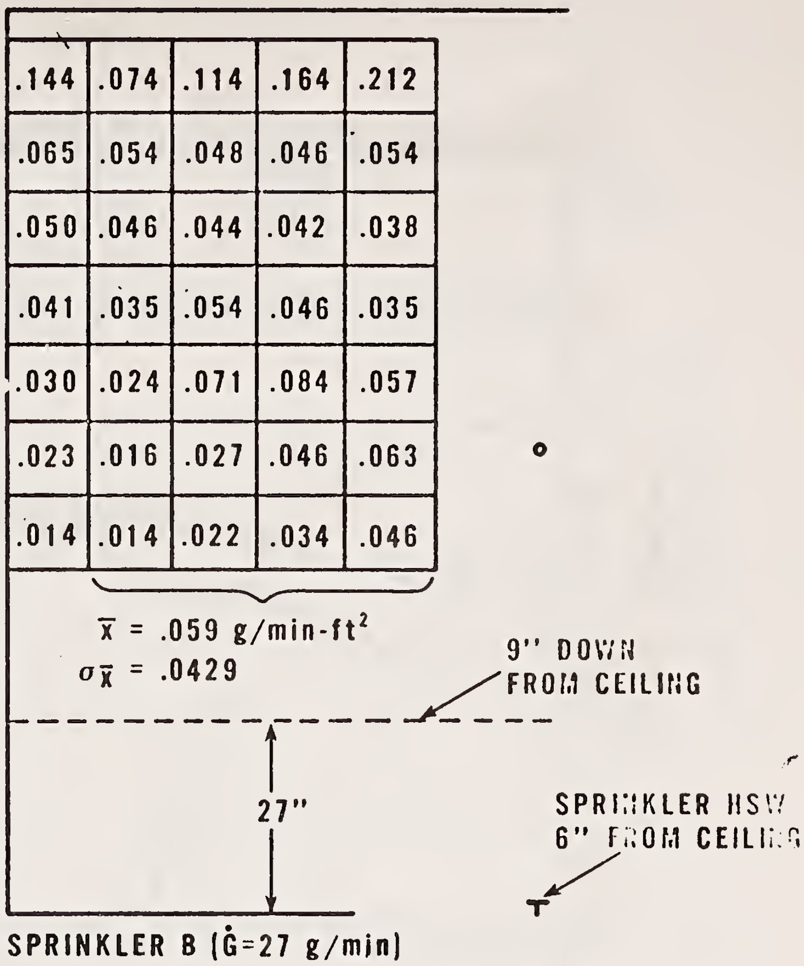


Figure 19. **MINIMUM VERTICAL CLEARANCES SPRINKLER DEFLECTOR TO TOP OF PRIVACY CURTAIN**



.105	.063	.079	.109	.160
.057	.046	.041	.035	.039
.044	.035	.050	.039	.029
.033	.027	.082	.048	.031
.022	.020	.065	.084	.054
.014	.014	.024	.050	.068
.008	.011	.022	.038	.052

Figure 20. Spray Distribution Test



.144	.074	.114	.164	.212
.065	.054	.048	.046	.054
.050	.046	.044	.042	.038
.041	.035	.054	.046	.035
.030	.024	.071	.084	.057
.023	.016	.027	.046	.063
.014	.014	.022	.034	.046

Figure 21. Spray Distribution Test

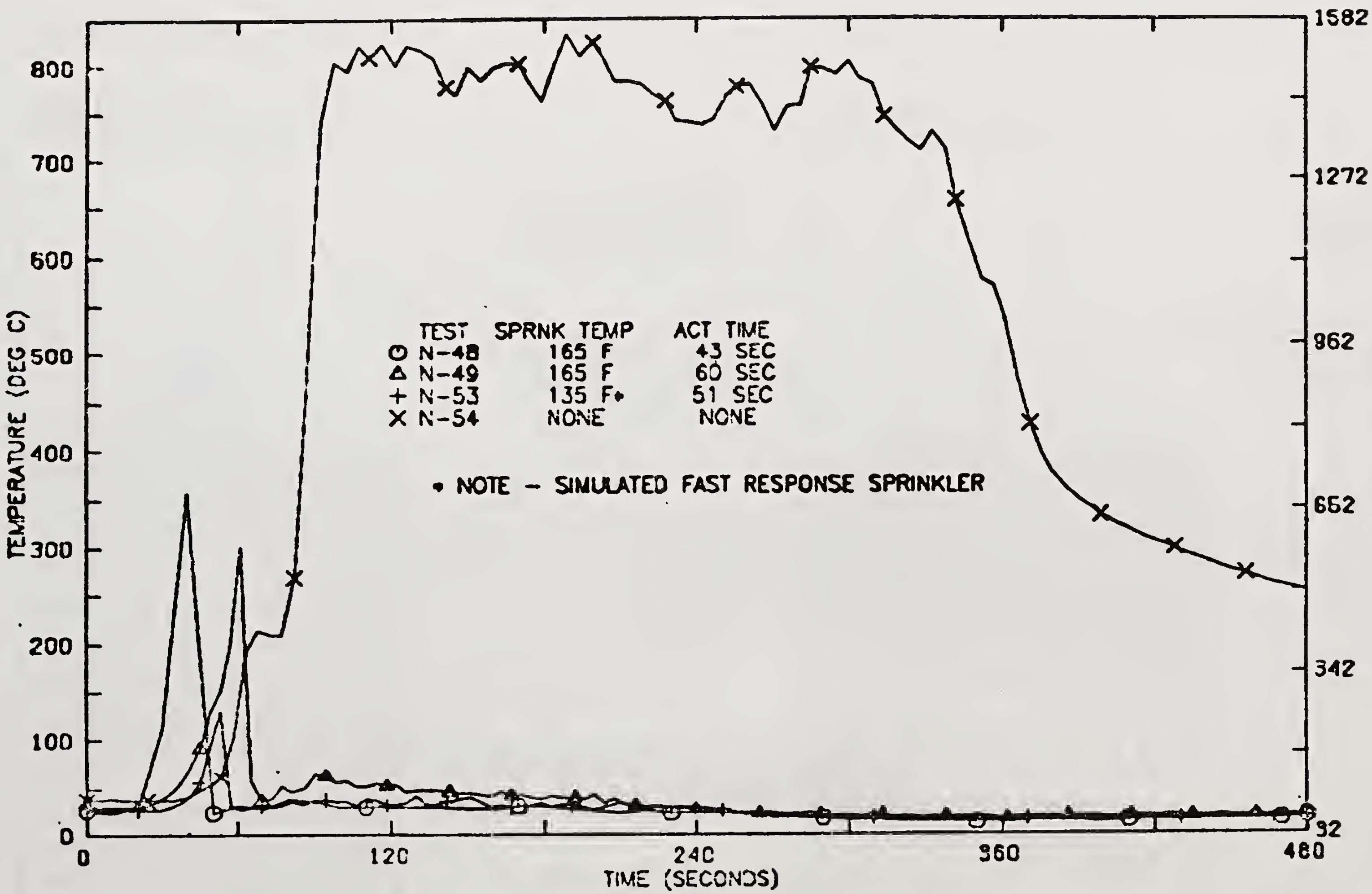


Figure 22. CENTER OF CEILING AIR TEMPERATURE
WARDROBE FIRE TESTS – CENTER CEILING PENDENT

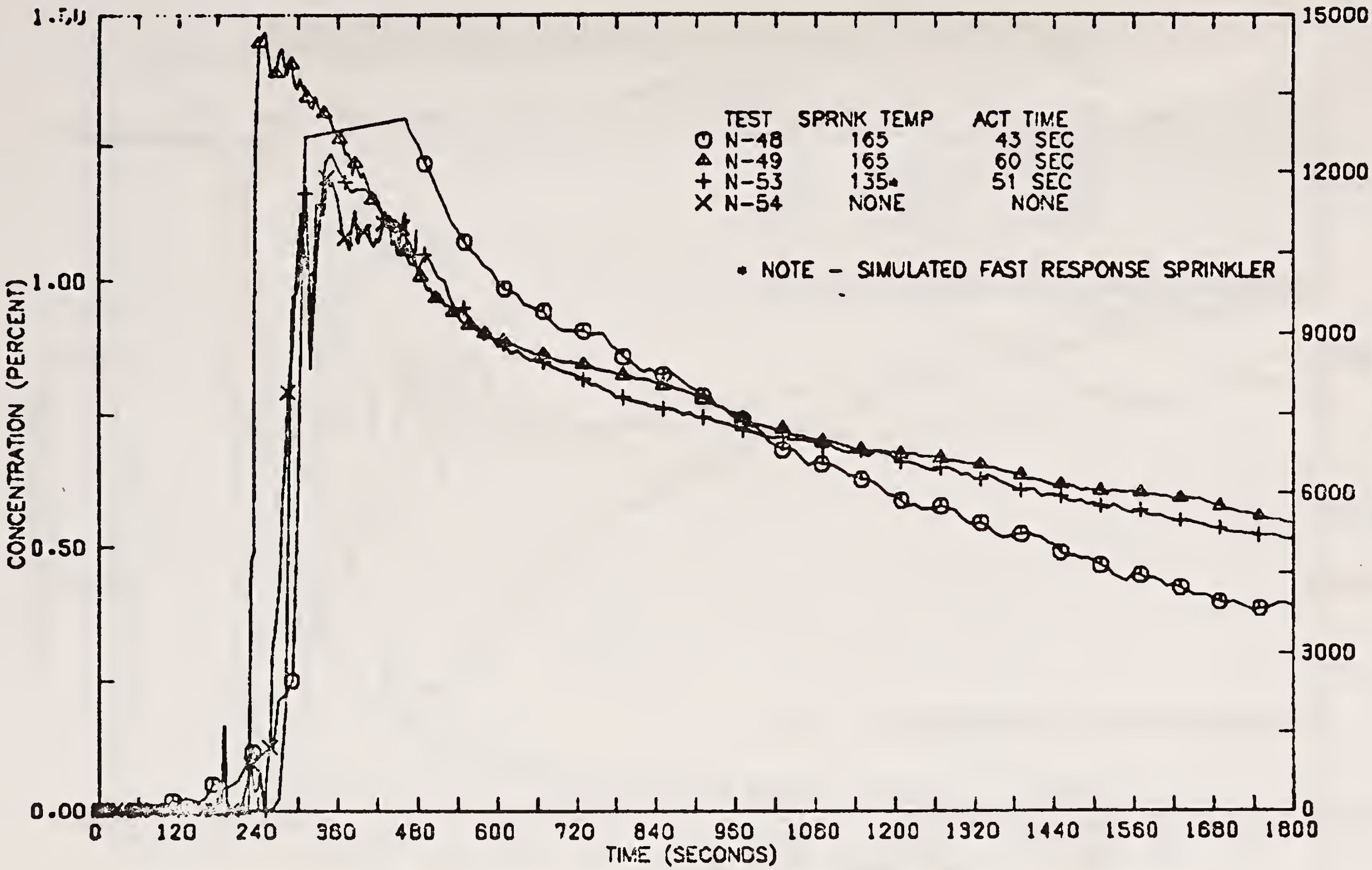


Figure 23. CARBON MONOXIDE CONCENTRATIONS - ADJACENT PATIENT LEVEL WARDROBE FIRE TESTS - CENTER CEILING PENDENT

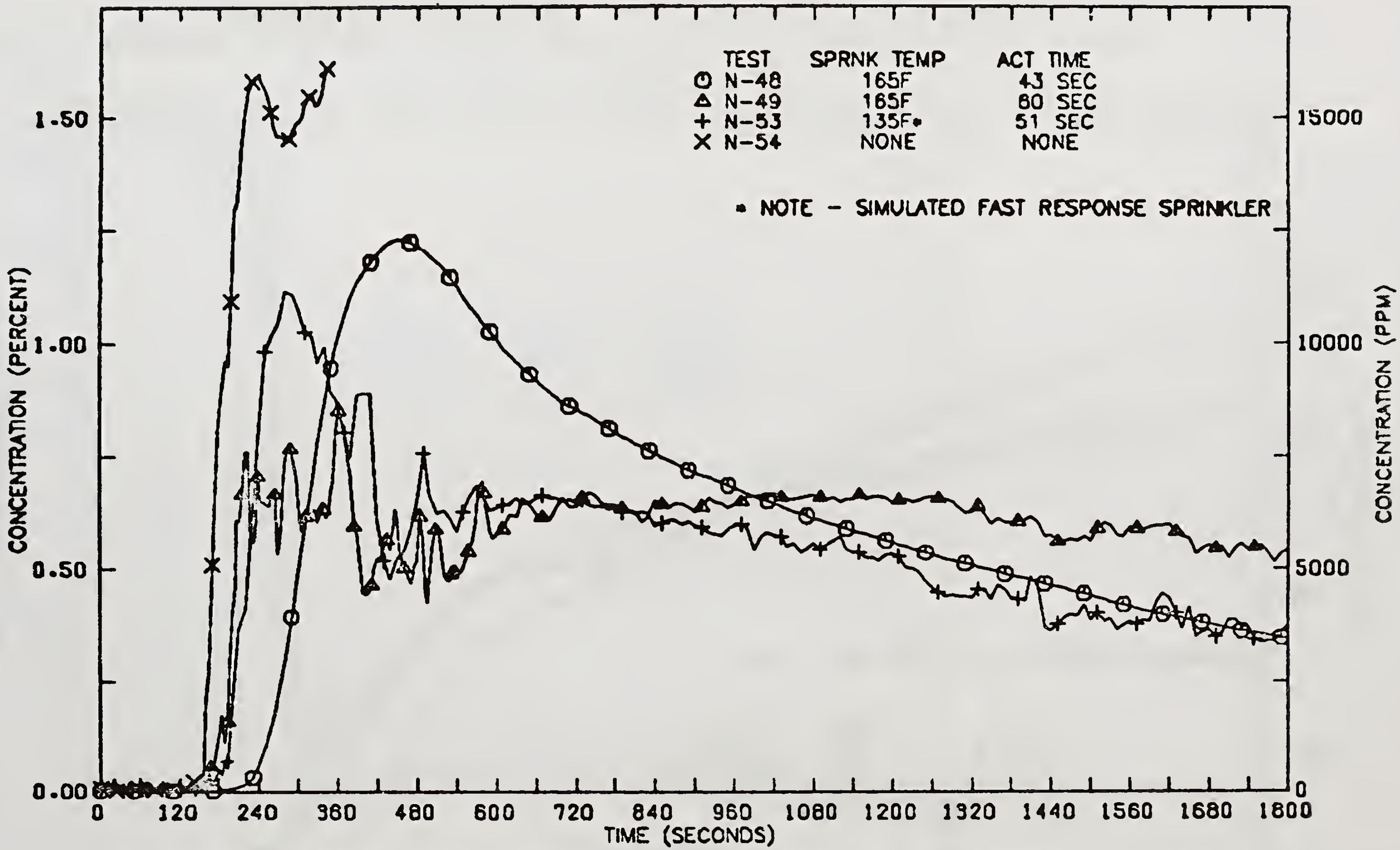


Figure 24. CARBON MONOXIDE CONCENTRATION IN THE LOBBY WARDROBE FIRE TESTS — CENTER CEILING PENDENT

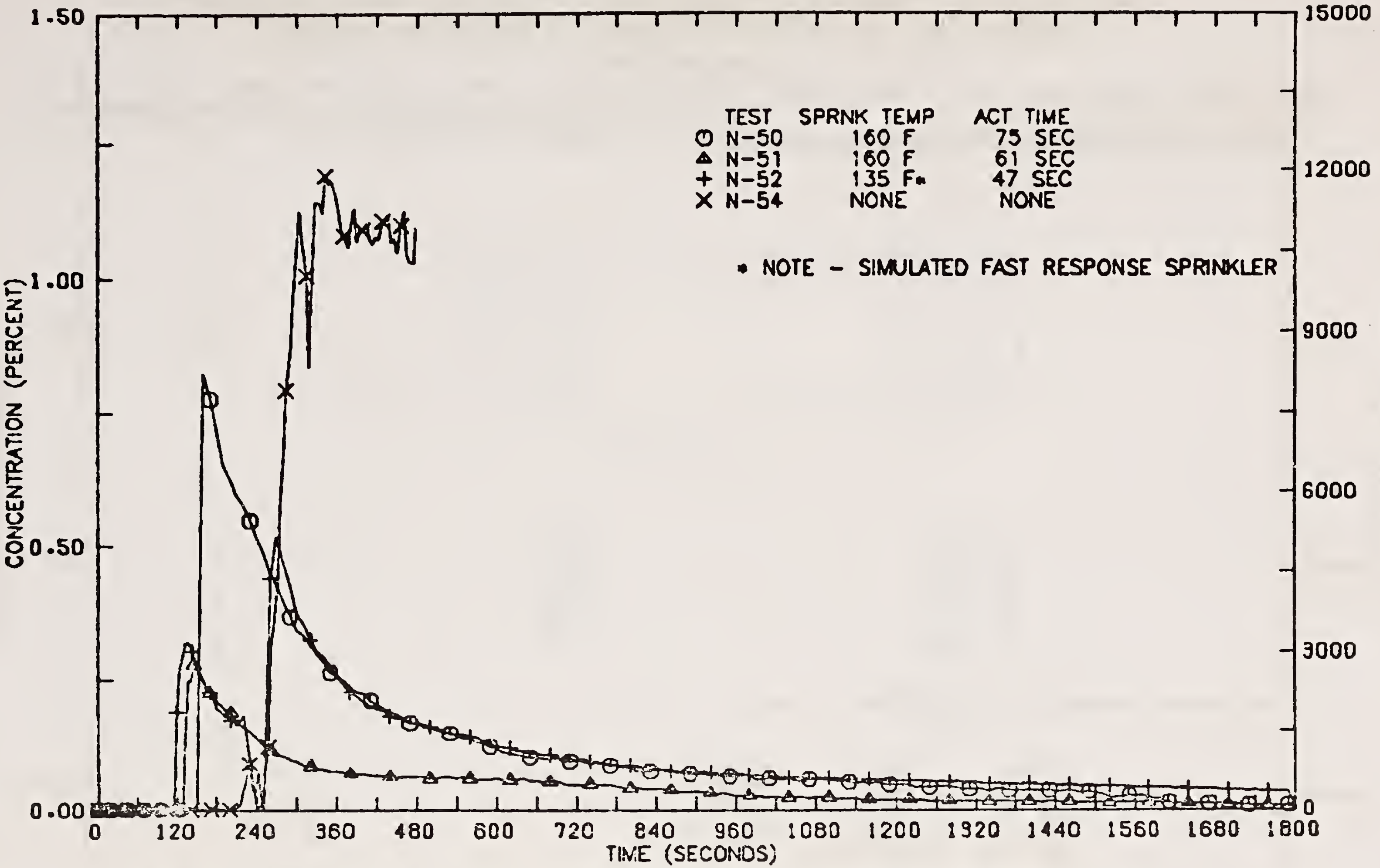


Figure 25. CARBON MONOXIDE CONCENTRATIONS – ADJACENT PATIENT LEVEL WARDROBE FIRE TESTS – HORIZONTAL SIDEWALL OVER DOOR

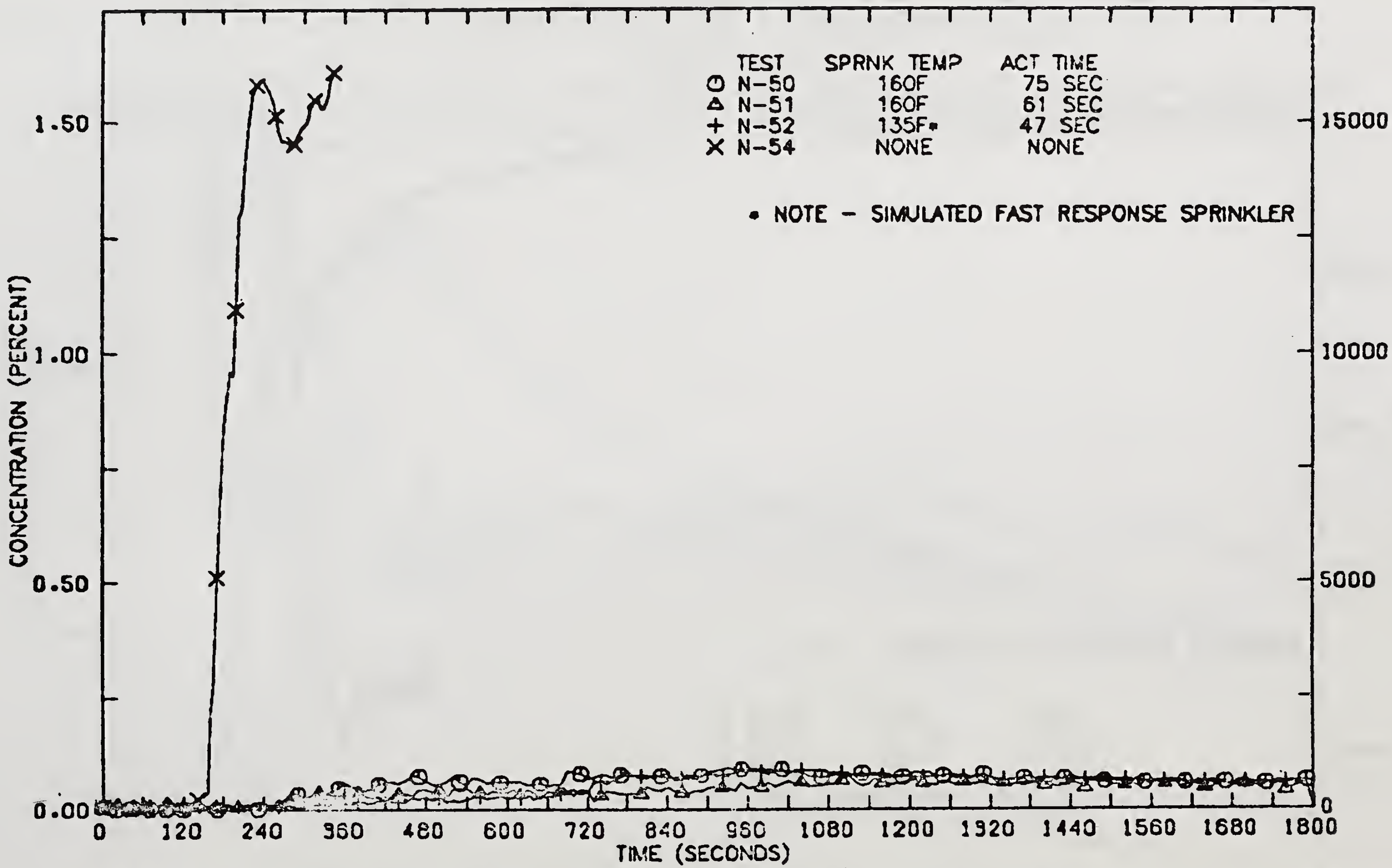


Figure 26. CARBON MONOXIDE CONCENTRATION IN THE LOBBY WARDROBE FIRE TESTS - HORIZONTAL SIDEWALL OVER DOOR

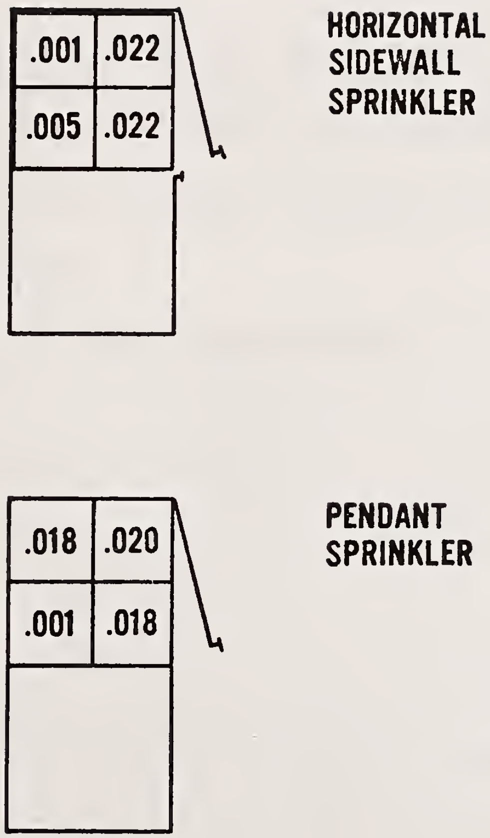


Figure 27. Spray Distribution Tests Clothing Wardrobe

Study of Toxic Gas Generated During Combustion

-- In Case of Natural & Artificial Lawn --

by

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Department of Legal Medicine

Yokohama City University, School of Medicine

October 16, 1980

For presentation at 5th UJNR Conference on Fire Research

(Japan - United States Panel on Natural Resources)

1. Introduction

In present Japan, the great interest and fear of people's are strong earthquake attack. We, Japanese people dwelling in those overpopulated cities and living considers that if we encounter a strong earthquake, damages and casualities must be beyond our expectations.

In such case, sufferers are supposed to seek refuge at the public extensive refuge designated by each local self-governing body. However, as refuges which require certain extent are exceedingly limited in big cities, Golfcourses, Baseball game studiams and so on are designated actually.

Though Yokohama City which is the second biggest city in Japan in its population, has a small mumber of extensive refuges in a center of the city. Its typical refuges are natural lawny golf courses or artficial lawny baseball game studiam.

In case of a fire spread to those places, assuming what sort of damages and casualities are occured, we burnt artificial lawn and natural lawn in the experimental facilities for combution based on the standard of the Ministry of Construction and then test on living animals in it for studing what type of toxic gases generated during combustion and how to influent on them.

2. Experiment & Result

2-1. Control Experiment-1.

One experimental group is eight ddy-male mice (over 4 weeks after being born and their weight are 25-30g.). These normal mice before the absorption of gases that produced by combustion, are killed and there are taken value of pH and the dencity of CO, in total blood (their arterial and venous blood).

All parenchyma organs in their thorax and abdomen are homogenized, are taken the density of CN in blood by Pyridin-Pyrazolon method.

The result are shown at Fig. 1.

2-2. Control Experiment-2.

** Experimental Apparatus   Shown at Fig. 10.

2-2-1. Experimental Method & Result

The mice are placed in test chamber, and it burn without test materials in furnace. Observed the condition of mice and gases. The behavior of mice being in the test chamber are recorded by the mice-monitor, and the concentration of gases (HCL, CO, CO_2, O_2) produced during burn, are recorded by each analitical apparatus. And the concentration of HCL are mesured by HCL test tube, after 6 minites beginning the combustion.

The result are shown at Fig. 2 and Fig. 3.

** Combustion Method : When the appratus is switched on, air (3 ℓ/min.) and propane-gas (350 mℓ/min.) are automatically taken into the furnace. After this, the propane-gas is burned. After 3 minutes, electric heater (1.5 kw) is switched on and after 6 minutes, switched off, in automatically. Burn by propane-gas is put out after 10 minutes.

2-3. Experiment-3. (Material : Natural lawn)

2-3-1. Experimental Method & Result.

The method and object are same the Control Experiment -2. In this time, the test material in furnace is natural dry lawn (90g.).

The result are shown at Fig. 4 and Fig. 5.

2-4. Experiment-4. (Material : Artificial lawn)

2-4-1. Experimental Method & Result.

In this experiment, we use the artificial lawn as test material in furnace. This material is 90g. in weight, 20x20cm. in width at one time.

The result are shown at Fig. 6 and Fig. 7.

3. Summary

If a strong earthquake attacks a great town and a fire accident occures, the people in the town will take refuge in the public extensive refuge laid natural lawn or artificial lawn on the ground.

Therefore, in this experiment, we conducted the combustion test on natural lawn and artificial lawn brewed polypropylene. Fig. 8 and Fig. 9 show the results of each experiments (Fig. 2-7).

** In the case of natural lawn :

1) The concentration of CO in the chamber was 0.35%, while that of CO_2 was 4.6% and that ofHCN was 8.2 ppm. The lowering of the quantity of O_2 was 14%. Production of HCl has not been noted by test-tubes.

2) The concentration of CO in the blood of mice was 39.09%.

3) Only four mice among forty mice were dead.

** In the case of artificial lawn :

1) The concentration of CO in the test chamber was 0.83%, while that of CO_2 was over 5%, and that of HCN was 6.3 ppm.. The lowering of the quantity of O_2 was 13.1%. Production of HCl has been noted about 4600 ppm. by test-tubes.

2) The concentration of CO in the blood of the mice was 39.54%.

3) The all mice were dead.

The results of this experiment have shown, that a place laid artificial lawn on the ground was unfit for a public extensive refuge.

表 1　Concentration of carbon monoxide and hydrocyanide in blood

concentration / group	pH	CO (%)	HCN (μg/ml)
The 1st group	7.025	3.60	0
The 2nd group	7.178	3.27	0
The 3rd group	7.114	1.94	0
The 4th group	7.336	0.99	0
The 5th group	7.589	7.20	0
Average	7.248	3.40	0

表 2　Combustion on no test material in the furnace (Concentration of gases)

group	Maximum temperature in the furnace	concentration of poisonous gases in the test chamber				O_2 minimum concentration in the test chamber	Number of dead mice
		CO	CO_2	HCN	HCL		
The 1st group	500 ℃	150ppm	2.30 %	0ppm	0ppm	17.2 %	0
The 2nd group	520 ℃	100ppm	2.25 %	0ppm	0ppm	17.8 %	0
The 3rd group	495 ℃	150ppm	2.15 %	0ppm	0ppm	17.8 %	0
The 4th group	490 ℃	150ppm	18.0 %	0ppm	0ppm	18.0 %	0
The 5th group	580 ℃	150ppm	2.10 %	0ppm	0ppm	17.4 %	0
Average	517 ℃	140ppm	2.18 %	0ppm	0ppm	17.6 %	0

表 3　Combustion on no test material in the furnace　(Concentration of carbon monoxide and hydrocyanide in blood)

concentration / group	pH	CO(%)	HCN(μg/ml)
The 1st group	7.098	0.00	0
The 2nd group	7.277	7.78	0
The 3rd group	7.196	3.99	0
The 4th group	7.154	3.59	0
The 5th group	7.073	13.91	0
Average	7.160	5.85	0

表 4　Combustion on natural lawn (Concentration of gases)

group	Maximum temperature in the furnace	Concentration of poisonous gases in the test chamber				O_2 minimum concentration in the test chamber	Numbers of dead mice and weight loss of material
		CO	CO_2	HCN	HCl		
The 1st group	625℃	0.45%	4.0 %	14ppm	0ppm	14.4%	4 (65g)
The 2nd group	695℃	0.33%	4.65%	6ppm	0ppm	14.0%	0 (65g)
The 3rd group	695℃	0.30%	4.4 %	6ppm	0ppm	14.7%	0 (65g)
The 4th group	660℃	0.33%	4.95%	8ppm	0ppm	14.2%	0 (65g)
The 5th group	655℃	0.33%	5.0 %	7ppm	0ppm	14.4%	0 (65g)
Average	663℃	0.35%	4.6 %	8.2ppm	0ppm	14.3%	0.8 (65g)

表 5　Combustion on natural lawn (Concentration of carbon monoxide and hydrocyanide in blood)

concentration / group	pH	CO(%)	HCN(μg/ml)
The 1st group	7.228	29.07	0
The 2nd group	7.106	39.33	0
The 3rd group	7.296	46.85	0
The 4th group	7.332	39.02	0
The 5th group	7.401	41.19	0
Average	7.268	39.09	0

表 6　Combustion on artificial lawn (Concentration of gases)

group	Maximum temperature in the furnace	Concentration of poisonous gases in the test chamber				O_2 minimum concentration in the test chamber	Number of dead mice and weight loss of material
		CO	CO_2	HCN	HCl		
The 1st group	580℃	0.72%	4.95%	3.5ppm	2375ppm	13.8%	8 (54g)
The 2nd group	660℃	0.87%	over 5%	5.4ppm	3000ppm	13.2%	8 (60g)
The 3rd group	655℃	0.90%	over 5%	6.0ppm	6050ppm	13.8%	8 (75g)
The 4th group	590℃	0.66%	3.8%	3.0ppm	2100ppm	14.4%	8 (50g)
The 5th group	630℃	1.02%	over 5%	4.6ppm	13200ppm	12.5%	(65g)
The 6th group	675℃	0.78%	over 5%	10.5ppm	800ppm	12.2%	8 (59g)
The 7th group	670℃	0.84%	over 5%	11.0ppm	4840ppm	11.8%	8 (37g)
Average	637℃	0.83%	over 5%	6.3ppm	4623ppm	13.1%	8 (56.7g)

表 7　Combustion on artificial lawn (Concentration of carbon monoxide and hydrocyanide in blood)

concentration / group	pH	CO(%)	HCN (ug/ml)
The 1st group	6.470	34.67	0
The 2nd group	6.506	49.90	0
The 3rd group	6.579	43.58	0
The 4th group	6.361	37.92	0
The 5th group	6.443	24.57	0
The 6th group	6.757	37.60	0
The 7th group	6.863	48.53	0
Average	6.568	39.54	0

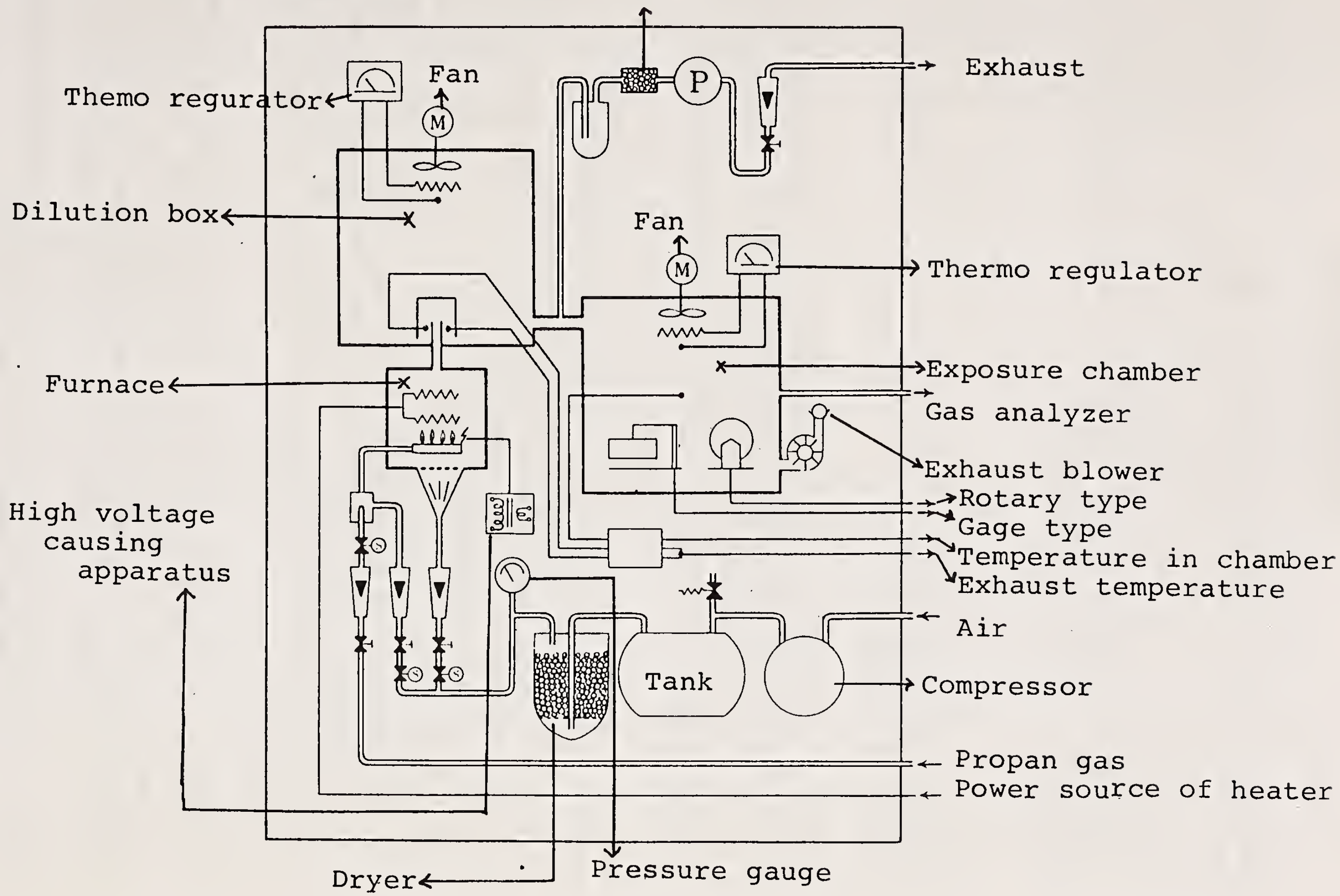
表 8

	Combustion on no test material	Combustion on natural lawn	Combustion on artificial lawn
CO	140 ppm.	0.35 %	0.83 %
O_2	17.6 %	14.3 %	13.1 %
CO_2	2.18 %	4.60 %	over 5.0 %
HCN	0 ppm.	8.2 ppm.	6.3 ppm.
HCl	0 ppm.	0 ppm.	4.623 ppm.
Number of dead mice	0/40	4/40	56/56
Temperature in the furnace	517℃	663℃	637℃

表 9

	Control	Combustion on no test material	Combustion on natural lawn	Combustion on artificial lawn
pH	7.248	7.160	7.268	6.568
CO (%)	3.40	5.85	39.09	39.54
CN (μg/ml)	0	0	0	0

Fig. 10. Test Apparatus



Saito Presentation

Benjamin: I have a question regarding Figure 2. We reported to the Panel a couple of years ago on the work done by Johns Hopkins University on a similar study of autoposies. The findings at that time indicated that over 80% of the deaths could be attributed to carboxyhemoglobin. Figure 2 would indicate that the conclusions that we had drawn--that carbon monoxide was the prime factor in deaths--may not be a correct conclusion. I would like to ask Dr. Saito if he has any ideas as to why we seem to be different.

Saito: In my opinion there is a difference in the availability of autoposies for fire death between our two countries. In Japan, an autoposy only was done for the case if it was connected to a crime. However, in United States autoposies are done relatively easy. I would like to confirm this with Prof. Nishimaru.

Nishimaru: In Figure 2, we believe that at least 50% of deaths were caused by CO. I notice that recent Johns Hopkins data indicate that this rate changed from 80% to 60%. In my opinion, it is not clear whether the availability of autopsy in Japan, as mentioned by Dr. Saito, or different materials used in Japan are the cause of different types of toxicants.

Myers: Again in reference to Figure 2, we are looking at a small number. I don't think there is that much variance from our own clinical experiments. In our clinical experiments involving some work on a current report, we have been taking blood samples from people involved with fires--survivors in the field--and we have found that the blood caroxyhemoglobin HBCO level at the field is dramatically higher than the indications in the hospital twenty minutes later; field level is 60 and hospital level is 40. In looking at your figure, it would appear that your people were dying with higher levels of carbon monoxide. There are a great number above 50%, but Halpin and Fisher's data are lower than that. It may be the materials of the fire in the building that makes the difference, if there is a difference.

Nishimaru: Your report on the different discrepancies between figures of blood samples in the field and in the hospitals has been very informative. The Dr. Halpin that you mention, is he the Medical Examiner in New York? We noticed some difference in data between Halpin's and ours. It might be due to the difference in materials.

Myers: Dr. Halpin was one of the people on the Hopkins grant. Dr. Fisher is the Medical Examiner in Baltimore, Md.

Birky Presentation

Saito: I would like to ask two questions. Is there a significant difference in gas concentration (mg/l) between the large scale experiment and the small scale one. I think there may be a significant loss of combustion products through the sampling line between the chamber to the detector instrument.

Birky: Yes, that is correct and may be part of the problem. The other part of the problem is that in the large scale experiment, we take about an hour and a half to generate the concentration required to expose the animals. So we have time for loss of reactive components.

Saito: The table showed mg/l as units. Is a time factor included in this figure.

Birky: The exposure of the animals takes place over thirty minutes in both cases. However, to generate the products takes longer in the large scale.

Saito: You described that the smoldering mode was used for the large scale experiment and the small scale one. Could we assume that the smoldering condition is identical for both the scales?

Birky: No, in the small scale we have the sample decomposed in a furnace that is preset at some temperature.

Nishimaru Presentation

Birky: Was exposure time three minutes?

Nishimaru: With which samples?

Birky: Didn't you test all the materials the same way?

Nishimaru: I will try to explain the burning condition used in this study. 3 l/min of air and 350 ml/min propane, 1.5kw electric heater were turned on. Six minutes later, the electric heater was automatically turned off and the propane gas was turned off ten minutes later. Therefore, animals in the chamber were exposed to products for fifteen minutes.

Birky: Does the concentration of the gases in the table represent the average over that 15 minute period?

Nishimaru: Yes.

Birky: In Table 1 does it concern you that the variation is fairly large from a biological point of view?

Nishimaru: Do you mean from 7.25 to 7.58?

Birky: Yes, are those control values?

Nishimaru: Yes, principally it is. The pH value shown in Figures 1 and 3, should be about the same because there are no effects of products. However, there are some scatter and we interpret this as a biological difference among individual animals.

Birky: In terms of interpretation of Tables 6 and 7, how do you establish a correlation between any of the factors in those two tables? For example, what is the cause of death and correlation to reduce pH to the highest P_{CO} level?

Nishimaru: Since the amount of each toxicant is way beyond the critical amount for the correlation, it is rather difficult to evaluate. I misunderstood the previous question. O_2 and CO_2 concentrations are automatically recorded. Values shown in figures are maximum CO_2 and minimum O_2.

Huggett: We find that the toxic dangers being associated with materials depend on the toxicity as measured in laboratory tests, but also on the quantity of material and the probability that it is likely to be involved in a fire. We find that carpets, floor coverings, ground covers are difficult to involve in a fire. They usually will burn only if they are preheated by radiation from a ceiling, from a hot gas in a large fire. I find it difficult that you could get a substantial fire on a carpet (ground cover) in the open, such as a golf course. I wonder if any tests have been run in determining the likelihood of a fire developing under the conditions that this material is being used?

Nishimaru: I do not have any experience with that. I agree that we do not worry about fire hazards for golf courses. It might be an extreme case, but I keep remembering what happened fifty years ago. Japan had a very serious earthquake which caused extremely large fires and many deaths and included large buildings. We do not know what caused the deaths of the people in this extreme case. The Japanese government suggests that we don't use any kind of potentially toxic materials. We should use safe materials. With this in mind, we tested these materials. In crowded places such as a baseball stadium, it might happen as an extreme case. So, our point of view is just in case.

Saito: In Japanese building code, the floor materials are considered to be less fire hazardous at early stage of fire and were not included in the fire code. Prof. Nishimaru considered these materials as a chemical compound instead of floor covering for artificial turf. The floor covering might get involved after flashover. Then, this study might be useful.

Clarke: The issue raised here, expressing the evolution of hydrogen chloride, prompts me to ask a related question of a somewhat different subject of this paper. In the United States we have very little work going on in the treatment of fire victims who have inhaled hydrogen chloride and yet this is going to be a problem because of the increasing prevalence of chloride-containing polymers in the environment. Has there been any research in Japan that Prof. Nishimaru and colleagues know of on the treatment of HCl (hydrogen chloride) inhalation?

Nishimaru: My personal opinion is that there is not much affect of these gases on plants, animals or humans. However, it is almost impossible to remove all these gases or all materials which produce these gases from our present society. After this meeting, I will discuss with Dr. Saito how we will explore a new type of study to determine if animals will survive without permanent damages after we stop the test in the middle of experiment; rather than the present type test in which we continue the test until the death of the animals.

Clarke: We have a few cases in the U.S. of people being injured where the symptons look very much like hydrogen chloride inhalation, although I know of no cases where it was definitely established that that was the cause of the problem. But I share the view that chloride containing materials are increasingly finding their way into the environment and we may find this to be more of a problem in the future. The most likely victims of exposure to this kind of situation would probably be the firefighters. How common is the use of breathing apparatus--independent air tank--by Japanese firefighters?

Jin: When firefighters go into a smoke filled area, they usually breathe from air tanks.

Benjamin: Dr. Jin mentioned that the firemen will wear their mask when there is visible smoke. Our experience has been, particularly with PVC type fires, that the smoke was not visible and many of the injuries have been the result of firemen who went into an atmosphere where there was no visible smoke and they did not put their masks on.

Jin: When the smoke is visible, obviously, then it is mandatory that they wear gas mask. Where you don't see any smoke, they have to decide whether or not to wear the mask. If toxicants are expected, then they wear the mask; otherwise they just go in without masks.

I personally do not know any casualties caused by invisible toxic atmosphere. Medical doctors of the laboratory of Tokyo Fire Defense Agency are studying the toxic hazards of combustion products and they recommend more awareness of the danger of these gases for firefighters than used to be.

4. ADVANCES IN SPRINKLER TECHNOLOGY

LIFE SAFETY FACTORS INVOLVED IN THE USE OF SPRINKLERS

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LIFE SAFETY FACTORS INVOLVED IN THE USE OF SPRINKLERS

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1. INTRODUCTION

The Center for Fire Research (CFR) at the National Bureau of Standards (NBS) has conducted an extensive research program into the use of automatic sprinklers in health care facilities. The purpose of this paper is to present some of the results of this project which may impact future installation criteria and product design criteria for automatic sprinklers in health care facilities. These results may also apply to other occupancies where life safety is also the primary purpose for installing automatic sprinklers.

The CFR project, which was originated in 1977 and then resumed in 1979, consisted of a series of full-scale tests to develop engineering design information concerning the use of automatic sprinklers to minimize life loss and injury in the event of fire in health care facilities.

An interim report by O'Neill and Hayes has been published and it covers the first eight tests in this project [1][1]. A final report on phase II of the project was published in July, 1980 [2].

2. OVERALL PROJECT OBJECTIVE

The overall project objective was to measure the performance of the sprinklers in terms of:

a. Overall fire control.

b. Time available for evacuation of patients in the fire area.

c. Maintaining tolerable environmental conditions for patients who cannot be evacuated.

3. EXPERIMENTAL FACILITIES

3.1 Test Area and Instrumentation

The experimental approach used in this project was to conduct full-scale fire tests in a two patient sized room with an adjoining corridor and a remote room located at one end of the corridor, as shown in figure 1. The performance

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

of the sprinklers in these tests was determined through the analysis of data recorded with instrumentation installed in key locations throughout the test area. The instruments measured temperatures, total heat flux, weight loss of burning items, gas velocities, carbon monoxide (CO), oxygen and smoke obscuration. Measurements of gas temperature and velocities, CO and smoke obscuration were made at different elevations in the doorway to the patient room and in the corridor in order to obtain a profile of smoke movement and CO concentrations during the tests.

3.2 Automatic Sprinkler System

The automatic sprinkler system for this project provided use of either a center ceiling pendant sprinkler in the patient room or a horizontal sidewall sprinkler located over the door opening in the patient room. Flow rates to the sprinklers were established prior to and maintained throughout each test by means of a control valve and flow meter located outside the test area. Generally, the water flow for the sprinkler in the patient room was set at 102 ℓ/min (27 g/min) to provide the equivalent specified minimum flow resulting from one sprinkler head operating if the system was hydraulically designed in accordance with the National Fire Protection Association (NFPA) Standard No. 13 [3]. The standard requires a minimum average density of 4.1 mm/min (0.10 g/min/ft^2) for this type of occupancy. The standard, however, states that for this type of installation sprinklers outside the room must be considered in the calculation. This requirement resulted in an actual 6.9 mm/min (0.17 g/min/ft^2) density with one sprinkler operating in the room.

Sprinklers used in the project included 13 mm (1/2 in) and 10 mm (3/8 in) pendant sprinklers and 13 mm (1/2 in) horizontal sidewall sprinklers which meet the requirements of UL 199 [4].

In addition to the "wet" sprinkler head, three dry sprinkler heads were placed at the center of the burn room ceiling. The purpose was to obtain data on response times of other types of sprinkler heads in the full-scale fire tests. The dry sprinkler heads were pressurized by nitrogen which was pumped through copper tubing placed above the fire resistive ceiling. A pressure switch was connected into the tubing which led to each sprinkler head and, when the sprinkler operated, the pressure switch activated a relay which stopped a clock. Thus, response times relative to time of ignition were automatically recorded. Dry sprinkler heads included the following fusible elements:

Rapid-response 57°C (135°F) (commercially available)

Fusible pellet 74°C (165°F)

Link-lever 75°C (165°F) duplicate of wet sprinkler head

3.3 Ventilation of Test Area

A simulated heating, venting and air conditioning (HVAC) system was installed in the burn room for the tests reported in this paper. The HVAC system consisted of a supply duct mounted high in the wall, and an exhaust duct in the lower opposite wall as shown in figure 2. The air flow rate for the burn room was based on criteria contained in the Minimum Requirements of Construction and Equipment for Hospitals and Medical Facilities [5]. This standard requires a minimum ventilation rate of 2 air changes per hour for patient rooms with zero pressure difference between the patient room and corridor. For this sized room the flow rates for both supply and exhaust were established at 1.2 m^3/min (42 ft^3/min) to give the minimum air change rate without creating an air flow between the patient room and corridor. A fan coil unit was installed to provide recirculated air in the room. A separate system provided conditioning for the burn room to maintain a limited range of temperature and relative humidity conditions in the burn room throughout the series of tests. The fan coil unit was set at a low speed which recirculated air in the burn room at an approximate rate of 3.4 m^3/min (120 ft^3/min).

4. ELEMENTS OF HAZARD ANALYSIS

Consistent with the overall project objectives the results of the fire tests were measured in terms of the following:

Fire Spread

Heat Flux

Toxic Gases

Smoke Obscuration

Specific quantitative values for fire spread were not developed to measure the performance of sprinklers. However, weight loss data as well as the record of visual observations were analyzed to determine the relative performance of sprinklers in limiting fire growth.

Quantitative values were selected as estimated limiting conditions for the other elements. These values based on previous studies, were as follows:

a. For the heat flux measured at the adjacent patient level a threshold for burn injury of 2.5 KW/m^2 was selected as an upper limit prior to one feeling pain [6].

b. A threshold of 25% carboxyhemoglobin was established as a limiting condition for continuous exposure to CO [7]. A concentration of 1% (10,000 ppm) CO was selected as a hazardous threshold for instantaneous exposure to CO [8].

c. A minimum of oxygen concentration of 14% was selected as a lower limit for determining the impact of O_2 depletion on occupants [9].

d. For smoke obscuration two limiting conditions were selected. The first concerned the rescue of a patient inside the room of fire origin. A smoke obscuration threshold of 0.5 OD/m was estimated as the level where rescue of a patient would be impaired. The second concerned egress in the adjoining corridor. A threshold of 0.25 OD/m was estimated as the level where movement in the corridor would be impaired [10, 11].

5. TEST PROCEDURES

The series of full-scale fire tests and sprinkler spray distribution tests was based on fire scenarios involving either bedding and mattresses or clothing wardrobes in a two patient room environment. These furnishings represented typical contents in patient rooms of health care facilities and in the test procedures they served as the principal burning items. The experimental procedure for the sprinkler evaluation was limited to the flaming ignitions of these items.

5.1 Mattress and Bedding Fires

In all fire tests where a mattress and bedding served as the burning items, a hospital specified polyurethane innerspring mattress was used. The bedding which consisted of various cotton and cotton polyester materials, was also specified for hospital use. In several tests a privacy curtain was installed around the bed and located between the bed and the pendant ceiling sprinkler to determine the effect on sprinkler performance.

The test was initiated when the contents of a small waste container next to the bed were ignited with a match and the fire then spread to the bedding and then to the mattress. As discussed in the interim technical report, this procedure was very repeatable [1].

5.2 Clothing Wardrobe Fires

The clothing wardrobe fire scenario was also included in the project in order to assess the impact of sprinklers on what was estimated to be a very severe (but also realistic) fire in a patient room.

In an effort to develop a reproducible test fire, the same loading was initially used in each test. The loading consisted of various fabrics which represent materials found in present day clothing. The materials were placed on wire coat hangers and arranged loosely in the wardrobe to provide a clear space between each hung fabric. This arrangement was chosen since it was desirable to have a fire which would develop rapidly inside the wardrobe. A cardboard box containing crumpled newspaper was placed on the floor of the wardrobe and the newspaper served as the pilot flame inside the wardrobe. Each wardrobe test started when the crumpled newspaper was ignited with a match. Following ignition the left hand door was closed tightly while the right hand door was left partially opened resulting in a 7.6 cm (3 in) opening along the vertical edge of the door. The position of the wardrobe in the patient room is shown in figure 3.

6. RESULTS

6.1 Mattress and Bedding Test Results

In tests where the mattress and bedding served as the burning items, the estimated limiting condition for smoke obscuration was exceeded with both the standard pendant and horizontal sidewall sprinklers. The range of response times for the 165°F (74°C) pendant sprinkler was from 330 to 388 sec. In one test in which a standard 160°F (71°C) horizontal sidewall sprinkler was installed, the response time was 388 sec.

The estimated limiting conditions for smoke obscuration as measured at the patient room doorway and in the corridor were exceeded before the sprinklers operated. The smoke layer lowered to within .9 to 1.2 m (3 to 4 ft) from the floor before sprinkler operation. Following sprinkler operation, there was essentially total obscuration from floor to ceiling throughout the test area. It should be noted that in previous tests involving the same type of mattress and in which sprinklers were not installed, the smoke filled the corridor and also created essentially total obscuration from floor to ceiling.

None of the other estimated limiting conditions outlined in paragraph 4 were exceeded except for carboxyhemoglobin levels in the fires where the privacy curtain was installed. These results are discussed in 6.2.1.

6.1.1 Movement of Smoke and CO - Analysis of Data

The impact on smoke movement by the sprinklers was significant, especially in the doorway where velocity measurements, smoke meters, and gas measurements indicated a reversal of flow of smoke through the doorway and the shifting of peak CO concentrations from ceiling to floor level. Figure 4 provides the record of CO measurements in the burn room and doorway for Test N-37. Concentrations of CO shifted after sprinkler actuation at 330 sec. The CO data from the corridor instrumentation tree indicated that the sprinkler acted to redistribute the smoke layer (represented by the CO measurements) away from the immediate area of sprinkler actuation. Figure 5 gives the CO measurements at the corridor tree. Following the initial sprinkler flow, higher concentrations were recorded at 0.9 m (3 ft) and 1.5 m (5 ft) from the floor. The concentrations measured near the ceiling were lower than those measured at the other elevations following sprinkler actuation.

The concentrations of CO measured at all locations were low and estimated COHb levels did not exceed a limiting condition of 25% in tests where the privacy curtain was not installed. The increase in CO in the corridor and the redistribution of the CO throughout the test area, however, verified that, in these types of fires, the sprinkler acted to lower the smoke layer throughout the test area and to project the combustion products from the patient room into the adjoining corridor at a more rapid rate than before the sprinkler operated. This resulted in the severe smoke obscuration recorded throughout the test area which in an actual health care facility could seriously hamper the movement of staff and patients in the adjoining corridor.

An analysis of the data revealed that the smoke filling rate in the test area was roughly proportional to the fire growth rate as reflected in the record of gas temperatures measured at the ceiling in the center of the burn room. Figures 6 and 7 demonstrate this correlation where the depth of the smoke layer is defined as the time a smoke meter located in the doorway or in the corridor measured an obscuration of 0.25 OD/m. This boundary value for the smoke layer was arbitrarily established in this analysis in order to assess the impact of sprinkler response time as a function of the estimated depth of the smoke layer in the test area. (As mentioned in section 4, 0.25 OD/m was selected as a hazardous threshold for visibility and personnel movement in the corridor.)

Figure 6 provides the results of Test N-37 in which a pendant automatic sprinkler was installed in the center of the room. Although the sprinkler had a temperature rating of 165°F (74°C), the thermal lag of the fusible element was such that the sprinkler finally operated at 330 sec. At this point the ceiling gas temperature had reached 200°C near the sprinkler and the smoke layer had lowered to approximately 0.9 m (3 ft) from the floor.

This lag was even more significant in a test in which a horizontal sidewall automatic sprinkler was located over the door. The sprinkler had a temperature rating of 160°F (71°C) and at time of actuation, 388 sec., the smoke layer was less than .9 m (3 ft) from the floor. See figure 7.

By plotting the smoke filling rate on the same time axis as the ceiling gas temperatures, one can see that a fusible element operating at approximately 135°F (57°C) would actuate the sprinkler when the volume of smoke in the patient room and corridor was significantly less than when the standard 74°C sprinkler actually operated. Since the instrumentation as well as visual observation revealed that the flowing sprinkler lowered and redistributed the smoke layer, it follows that if a sprinkler operated sufficiently early enough in the fire, there would be significantly less smoke and toxic gases such as CO present to be redistributed by the sprinkler. Based on this, the project focused on the investigation of sprinklers operating at an earlier stage of the fire development and their impact on smoke movement.

6.1.2 Simulated Rapid Response Sprinkler Tests

6.1.2.1 Preliminary Test

In Test N-37, a commercially available dry sprinkler which was rated for 135°F (57°C) operating temperature and designed for rapid response, responded at 285 sec. At this time, as shown in figure 6, the center ceiling gas temperature was approximately 120°C and the smoke layer in the corridor had lowered to within 4 ft from the floor.

This suggested that a fusible element with a thermal inertia lower than that which exists for current technology sprinklers was necessary if the sprinkler was expected to operate shortly after the gas temperature near the sprinkler reached its nominal temperature rating.

Initially, a test (No. N-38) was conducted to determine the feasibility of preventing the smoke obscuration from reaching hazardous thresholds by actuating the sprinkler sufficiently early in the fire. This test included the same mattress, bedding, and waste container ignition sequence described earlier. The sprinkler system consisted of an open 10 mm (3/8 in) pendant sprinkler arranged to flow 64.3 ℓ/min (17 g/min) which provided an average density of 4.1 mm/min (.10 g/min/ft^2) in the burn room. The open sprinkler was fitted with a resilient plug, and the system piping was primed with water downstream of a closed control valve.

During the fire test the gas temperature measured near the sprinkler was continuously monitored. To simulate the rapid response, the sprinkler valve was opened at 10 seconds after the time the center ceiling gas temperature at the sprinkler reached 135°F (57°C). The sprinkler was opened at 105 seconds into the test and the subsequent smoke obscuration was very low throughout the test area. The maximum obscuration measured at 1.7 m (5 ft 8 in) in the burn room doorway and at 1.5 m (5 ft) in the corridor were 0.10 and 0.086 OD/m respectively. These levels were considerably below the estimated limiting conditions.

The results of this test indicated that for this type of fire, the smoke obscuration problem both before and after sprinkler operation could be greatly reduced by means of a sprinkler with a low thermal inertia fusible link which would operate soon after the ceiling gas temperature reached 57°C.

6.1.3 Verification Tests

Following this preliminary test the investigation sought to quantify the dynamic heating measurement of a successful fast response sprinkler in terms of a dynamic heating test which was proposed by Factory Mutual Research (FM) and is discussed in the appendix [12]. The dynamic heating measurement of the fusible element is expressed as a time constant "τ". In order to model sprinklers with a τ less than standard sprinklers (i.e. fusible elements with a thermal inertia lower than standard sprinklers), FM manufactured and furnished brass discs designed and verified for τ factors of 9.0, 14.4 and 21.5 sec. The temperatures of these discs were measured and the data were used during the tests to activate simulated fast response sprinklers.

The results of these tests verified that smoke obscuration was significantly decreased with the use of fast response sprinklers with a time constant of approximately 21.5 sec. Figures 8 thru 10 demonstrate that the use of a fast response pendant or horizontal sidewall sprinklers (Tests N-40 and N-45) resulted in significantly lower smoke obscuration than in the tests with standard pendant and horizontal sidewall sprinklers (Tests N-37 and N-39).

6.1.4 Discussion

The tests discussed in this section were conducted in a limited volume test area which represented a typical patient room and corridor arrangement but it did not represent as great a volume as would likely be in a smoke zone in a health care facility. Thus, limited extrapolation could be made for other geometries and larger volumes. Despite the limitations which prevent extensive extrapolation to other building sizes, the experimental work reported here clearly demonstrates that a lower thermal inertia or fast response sprinkler can reduce significantly the impact of smoke obscuration for a patient room mattress and bedding fire. Since the lowering of the heated gas layer and severe obscuration was immediate in and near the patient room, where the conventional sprinkler operated, this phenomenon suggests that the obscuration problem is severe near the room of fire origin regardless of the volume of the building or smoke zone. The impact of the fast response sprinkler, in reducing the smoke obscuration problem in and near the room of fire origin, could increase the time available to rescue the patients closest to the fire.

6.1.5 Impact on Sprinkler System and Hardware Design

In addition to these findings, the results of an ongoing residential sprinkler test program have indicated that the dynamic heating characteristic of a sprinkler is an important variable in the performance of a residential sprinkler system. (This test program is being conducted by NFPA, Factory Mutual Research and the Los Angeles City Fire Department and sponsored prinicpally by the U.S. Fire Administration.) In earlier tests FM determined that a sprinkler fusible element of a $\tau = 21$ sec was needed to insure that the sprinkler would operate early enough in the fire to prevent flashover in a ventilated living room test fire [13].

The results of both of these programs, the residential sprinkler program and the CFR patient room sprinkler program strongly suggest that product testing criteria should include a dynamic heating measurement. For life safety, the results also suggest the need for a more rapidly responding sprinkler than conventional sprinklers. It should, however, not be inferred that sprinklers, in general, should respond faster than a standard conventional sprinkler. In industrial and storage occupancies where it is desirable to limit the number of operating sprinklers to prevent the overtaxing of the water supply, a high τ factor, (i.e. slow response) sprinkler may be more effective. In any case it appears that a dynamic heating measurement of the sprinkler, in addition to the temperature rating of the sprinkler, should be a primary design variable in future sprinkler criteria.

6.2 Privacy Curtain Tests

6.2.1 Fire Tests

In several mattress and bedding tests a privacy curtain was placed around the bed as shown in figure 2. The purpose of these tests was to determine the effect of the privacy curtain on the sprinkler spray distribution and subsequent fire control by the sprinkler. The results of the tests indicated that the sprinkler cooled and controlled ceiling temperatures in the burn room. The results, however, also indicated that CO concentrations were higher throughout the test area when the privacy curtain was present. The differences in CO concentrations are shown in figures 11 and 12 for Test N-25, without the privacy curtain and Test N-33 with the privacy curtain. In Test N-33, calculated carboxyhemoglobin levels at the adjacent patient level exceeded the estimated limiting condition of 25% approximately 20 minutes after ignition. After Test N-33 was completed, it was noted that the mattress and bedding were totally consumed. (In tests without the privacy curtain, approximately 20% of the bedding and mattress was consumed prior to final extinguishment by the sprinkler.)

It was clear that the position of the privacy curtain with respect to the sprinkler as shown in figure 13 presented a serious obstacle to the sprinkler spray distribution. The higher concentrations of CO were apparently due to the position of the privacy curtain which shielded the burning bed from the water spray and adversely affected the extinguishing performance of the sprinkler.

6.2.2 Spray Distribution Tests

6.2.2.1 Test Plan and Procedure

Based on these findings an investigation was conducted to quantify the interference of the privacy curtain in terms of spray distribution; and to develop recommendations concerning the location and arrangement of the privacy curtain with respect to the sprinkler. A simple collection container array was installed in the burn room at the location of the bed to obtain spray density measurements over the horizontal plane of the bed, as shown in figure 14.

The results of these non-fire tests clearly indicated that the privacy curtain as installed in the previous fire tests severely blocked the water spray from the sprinkler. Figures 15 and 16 provide a comparison of results of one of the pendant sprinkler tests with and without the privacy curtain. Repeated tests with other models of pendant sprinklers and a horizontal side-wall sprinkler provided similar results.

The investigation then proceeded to determine design information on the placement of the privacy curtains with respect to the sprinkler to minimize the impact of the curtain on the spray distribution of the sprinkler.

Initially criteria were established for the minimum spray density which was necessary to extinguish a fire involving a mattress and bedding. Kung et al. suggested a critical application density of 1.4 mm/min (0.033 g/min/ft^2) for halting fire spread underneath a urethane foam mattress [14].

To facilitate the experimental work, a plywood screen was fabricated and it served in the place of the privacy curtain. As various tests were conducted with sprinklers flowing at 102 ℓ/min (27 g/min) the screen was raised and lowered and moved to various positions horizontally in an effort to determine the position boundaries for the cases where the critical density could not be obtained. During the experimental work it was noted that variations existed among standard pendant sprinklers of different manufacturers, such that, the spray from one tended to project more water directly parallel to the plane of the deflector than others. Therefore, measurements were made for these different sprinklers in order to insure that recommendations developed from the experimental work were not biased toward the most favorable spray pattern.

Spray distribution measurements were also conducted with the horizontal sidewall sprinkler to determine the impact on the sprinkler spray pattern. The simulated curtain was placed 40.6 cm (16 in) from the foot of the bed and 68.6 cm (27 in) from the corridor wall, with the height of the curtain being varied for each measurement. The flow from the sprinkler was also set for 102 ℓ/min (27 g/min) to provide an average density of 6.9 mm/min (.17 g/min/ft^2).

6.2.2.2 Results

In all of the spray distribution tests it was observed that the collectors which were placed along the wall collected most of the water which hit the wall. While the wetting of the wall may be an important benefit, the quantities of water collected in these containers do not reflect the actual density for that "slice" of the horizontal plane of the protected surface. Therefore, data obtained from these containers were not included in the calculation of the average density over the plane of the bed.

The results of the tests with pendant sprinklers verified that the effective spray density reaching the bed was dependent on both the vertical distance of the top of the privacy curtain from sprinkler deflector and, the horizontal distance of the curtain from the sprinkler. With the screen placed directly beneath the deflector of the sprinkler, there was no adverse effect on the effective density reaching the bed. As it was moved from the sprinkler toward the bed the screen was progressively lowered to achieve the minimum density criterion of .033 g/min/ft^2. Data shown in figures 17 and 18 indicate some of the results which served as the basis for the recommended installation criteria shown in figure 19. These criteria include a vertical distance from the sprinkler deflector to the top of the curtain as a function of the distance of the curtain up to 15 inches away from the sprinkler. A linear approximation has been developed as a guideline for the installation of privacy curtains installed further than 15 inches from the sprinkler. The formula is as follows:

$$Y = 0.5x + 0.5$$

where x = horizontal distance of curtain from sprinkler
Y = vertical distance from top of curtain to sprinkler deflector

The horizontal sidewall sprinkler was found to project a high percentage of the discharged water toward the ceiling and in a radial direction horizontal to the center line of the orifice. This spray pattern reduced the effect of the privacy curtain on the horizontal sidewall sprinkler as compared to the pendant sprinkler. The results as shown in figures 20 and 21 indicated that a minimum average effective density could be achieved over the plane of the bed if the height of the privacy curtain was equal to or lower than the height of the horizontal sidewall sprinkler.

6.3.1 Nonsprinklered Wardrobe Fire

In order to obtain a baseline for evaluating the performance of sprinklers when exposed to combustible wardrobe fires, a fire test (No. N-54) without sprinklers was conducted.

The initial rate of fire growth was essentially the same as in the tests with sprinklers. With no other furnishings in the room, flashover occurred at approximately 120 sec. into the test (see figure 22). At this time all limiting conditions were exceeded throughout the test area. Several smoke meters in the corridor and in the doorway were damaged by heat and much of that data was lost. Measurements made at the key elevations in the doorway and in the corridor, however, indicated that limiting conditions had already been exceeded prior to the instrument failures. The test was terminated at 480 sec. when an open sprinkler was activated.

6.3.2 Pendant Sprinkler Test

In the initial wardrobe test, No. N-48, a standard 160°F (71°C) pendant sprinkler was installed and arranged to provide the 6.9 mm/min (.17 g/min/ft^2) density. As expected the fire quickly enveloped the interior of the wardrobe and gas temperatures in the burn room rose rapidly. Following actuation of the sprinkler, the ceiling gas temperatures were lowered as shown in figure 22; however, the fire could still be seen burning inside the wardrobe for approximately 60 sec. following the initial flow of the sprinkler. Eventually, the smoke obscuration prevented any observations of the burn room from a window in the corridor across from the burn room doorway.

Analysis of the data from this test indicated that concentrations of CO were very high throughout the test area. The instantaneous limiting condition of 1% was exceeded not only in the patient room but also in the remote lobby area (figures 23 and 24). Estimated COHb percentages also well exceeded the limiting condition of 25%.

This test was repeated and the overall results were comparable. The fire developed rapidly inside the wardrobe and, although CO concentrations were slightly less than in No. N-48, limiting conditions were exceeded or approached in the burn room at the adjacent patient level, at the 1.5 m (5 ft) elevation in the corridor as well as in the remote lobby area.

6.3.3 Horizontal Sidewall Sprinkler Tests

Using the same wardrobe fire scenario, a test was conducted using a standard 160°F (71°C) horizontal sidewall sprinkler set to provide a 6.9 mm/min (.17 g/min/ft^2) density. The sprinkler was installed over the door as in the previous mattress test (N-39).

The initial fire development was as rapid as in the previous tests and following sprinkler actuation, the fire was visible for a brief time inside the wardrobe. As in the previous tests the visibility was limited soon after sprinkler operation. A major difference, however, was noted in the CO concentrations, compared to the previous tests with the pendant sprinkler. CO concentrations were significantly lower; the instantaneous threshold level of 1% was not reached, and the 25% COHb was exceeded only in the burn room at the adjacent patient level at approximately 17 minutes after ignition. The test was repeated, (No. N-51) and approximately the same results were obtained. Figures 25 and 26 provide the record of CO.

The record of total weight losses of the combustible wardrobes for the four tests tracked closely with CO data. In the pendant sprinkler tests the weight losses and CO concentrations throughout the test area were much higher than in the tests with the horizontal sidewall sprinklers. See table 1 and figures 23 thru 26. These measurements indicated that the horizontal sidewall sprinkler achieved better fire control than the pendant sprinkler.

In the initial analysis of the results, it was believed that the orientation of the partially open wardrobe door with respect to the direction of the spray from the horizontal sidewall sprinkler allowed more water to penetrate the interior of the wardrobe. Spray distribution measurements were made in nonfire tests for both the pendant and horizontal sidewall sprinklers operating at the same flow rates as in the actual fire tests. The results of the tests are shown in figure 27. The spray measurement tests indicated that no more water penetrated the wardrobe with the horizontal sidewall sprinkler than with the pendant sprinkler.

6.3.4 Simulated Rapid Response

Analysis of the disc temperature data from the sprinklered wardrobe tests indicated that fast response sprinklers would have operated only 10 to 15 sec. prior to the actual standard sprinklers. A review of the photographic record of the test showed that at the time the discs reached 57°C the fire was just beginning to issue from the wardrobe. Two tests were conducted each simulating a fast response, τ = 21 sec., 57°C fusible element; one test (N-53) with the pendant sprinkler and the other (N-52) with a horizontal sidewall sprinkler. The purpose of the tests was to determine if the extinguishing performance of the sprinklers could be improved through the use of fast response sprinkler. As shown in figures 23 thru 26, and in table 1, no significant improvements were noted for either sprinkler over the standard fusible element sprinklers. It appeared as though the fire growth rate inside the wardrobe had reached the point where the spray from the fast response pendant sprinkler could not extinguish the fire any better than the standard fusible element sprinkler.

6.3.5 Discussion

The greater extinguishing performance of the horizontal sidewall sprinkler over the pendant sprinkler was apparently not due to a greater flow density inside the wardrobe. At least two possibilities can be postulated for the distinct differences:

a. The droplet size of the spray from the horizontal sidewall sprinkler was such that they penetrated the intense fire plume from the wardrobe and acheived more rapid extinguishment. (To date the droplet sizes have not been measured for these sprinklers.)

b. The spray from the horizontal sidewall sprinkler located over the door was somewhat parallel to the flow of combustion air into the wardrobe. The spray may have been entrained in the combustion air stream.

6.3.6 Impact on Sprinkler System Design

The reasons for the differences between the two types of sprinklers are not immediately clear and need further investigation. These differences are significant in terms of the impact of sprinklers on life safety and could have an effect on design recommendations. As the CO data, in particular demonstrate, the prevention of flashover by the sprinkler will not in itself assure life safety outside the room of fire origin. Limiting the generation of toxic gases, which in these fires was dependent upon the extinguishing performance of the sprinkler must also be considered.

In terms of possible impact on future sprinkler system and hardward design, several points are offered based on these wardrobe tests:

a. The benefit of a fast response sprinkler for very rapid developing (and partially concealed) room fires may not be as significant as it was for the mattress and bedding fires.

b. The droplet size and distribution may be an important performance variable where sprinklers are used to reduce the life safety hazards resulting from rapidly developing room fires.

c. The control of materials in the room such as the combustibility of the interior of the wardrobe (or a closet) may be the only practical solution for insuring life safety regardless of whether sprinklers are installed in the room.

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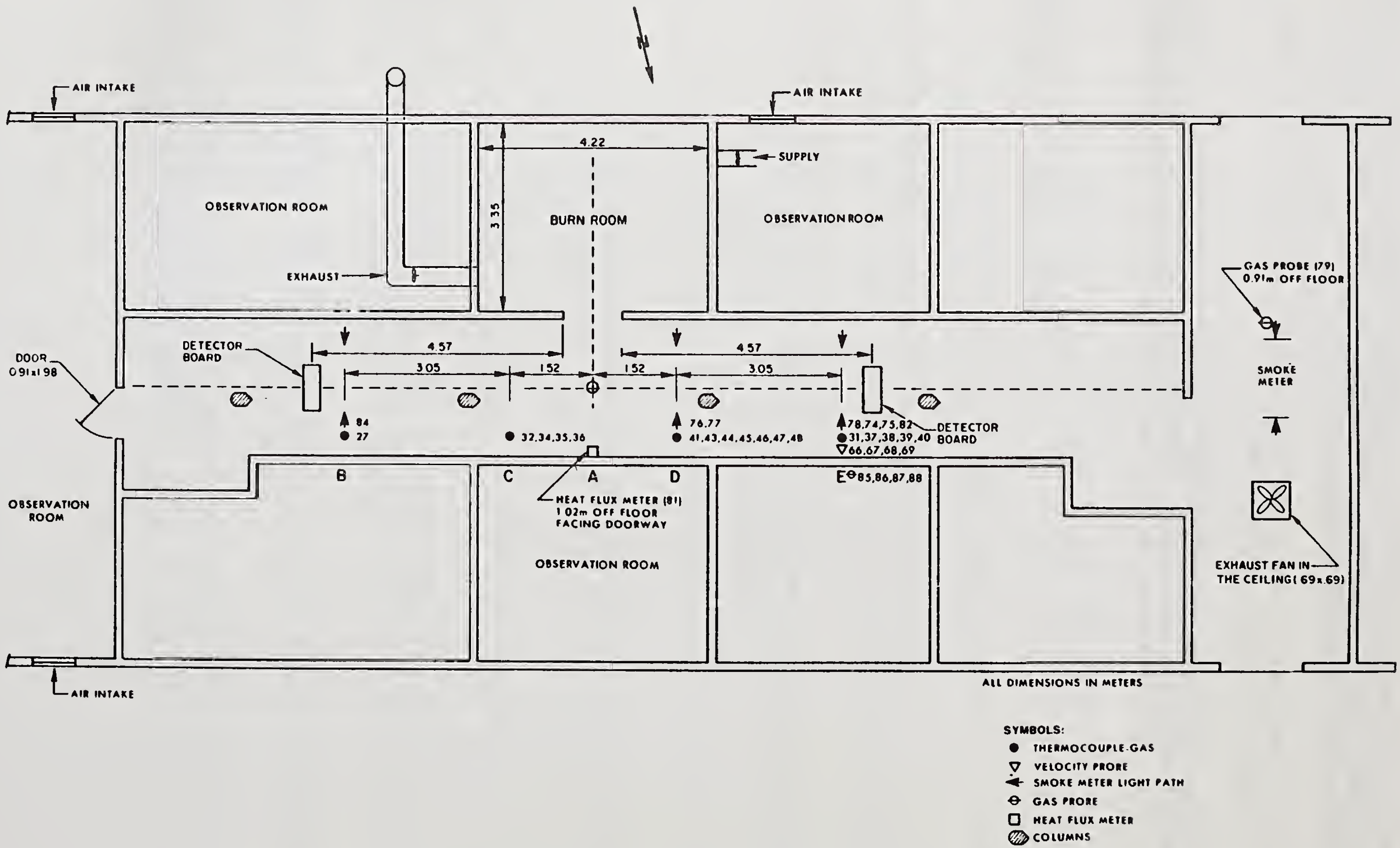


Figure 1. Test Area - Floor Plan

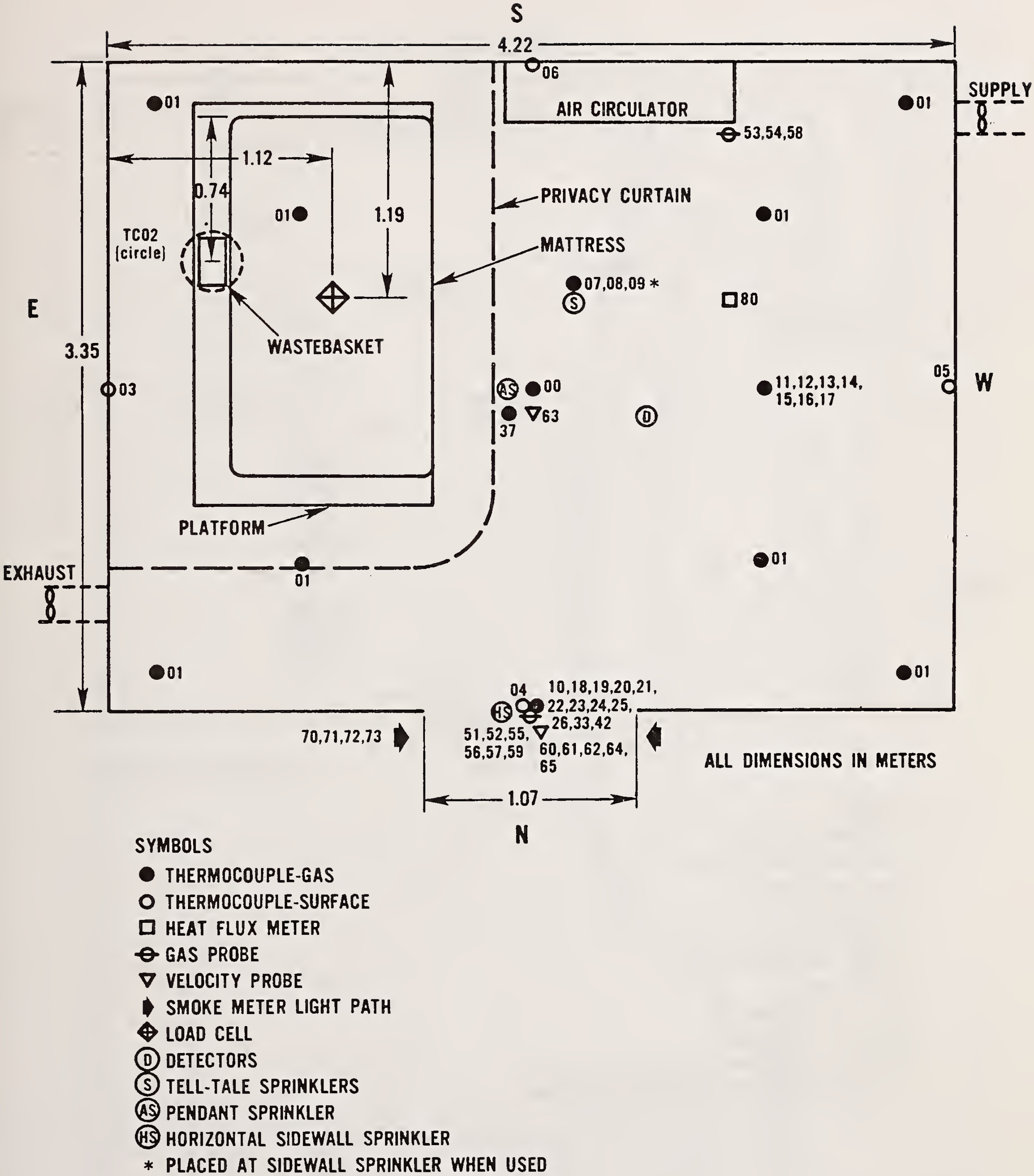


Figure 2. Patient Room Floor Plan Mattress and Bedding Tests

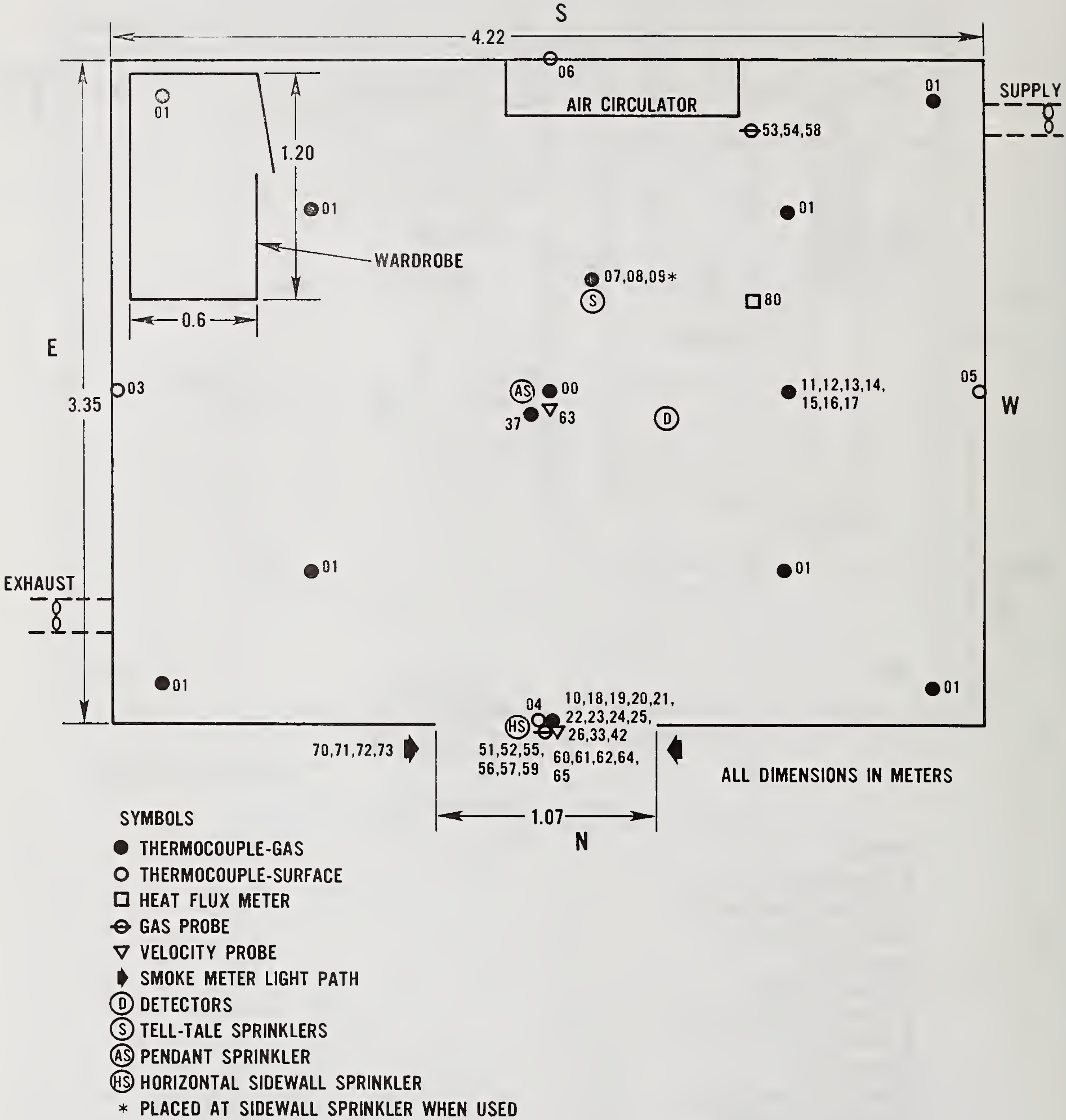


Figure 3. Patient Room Floor Plan Clothing Wardrobe Tests

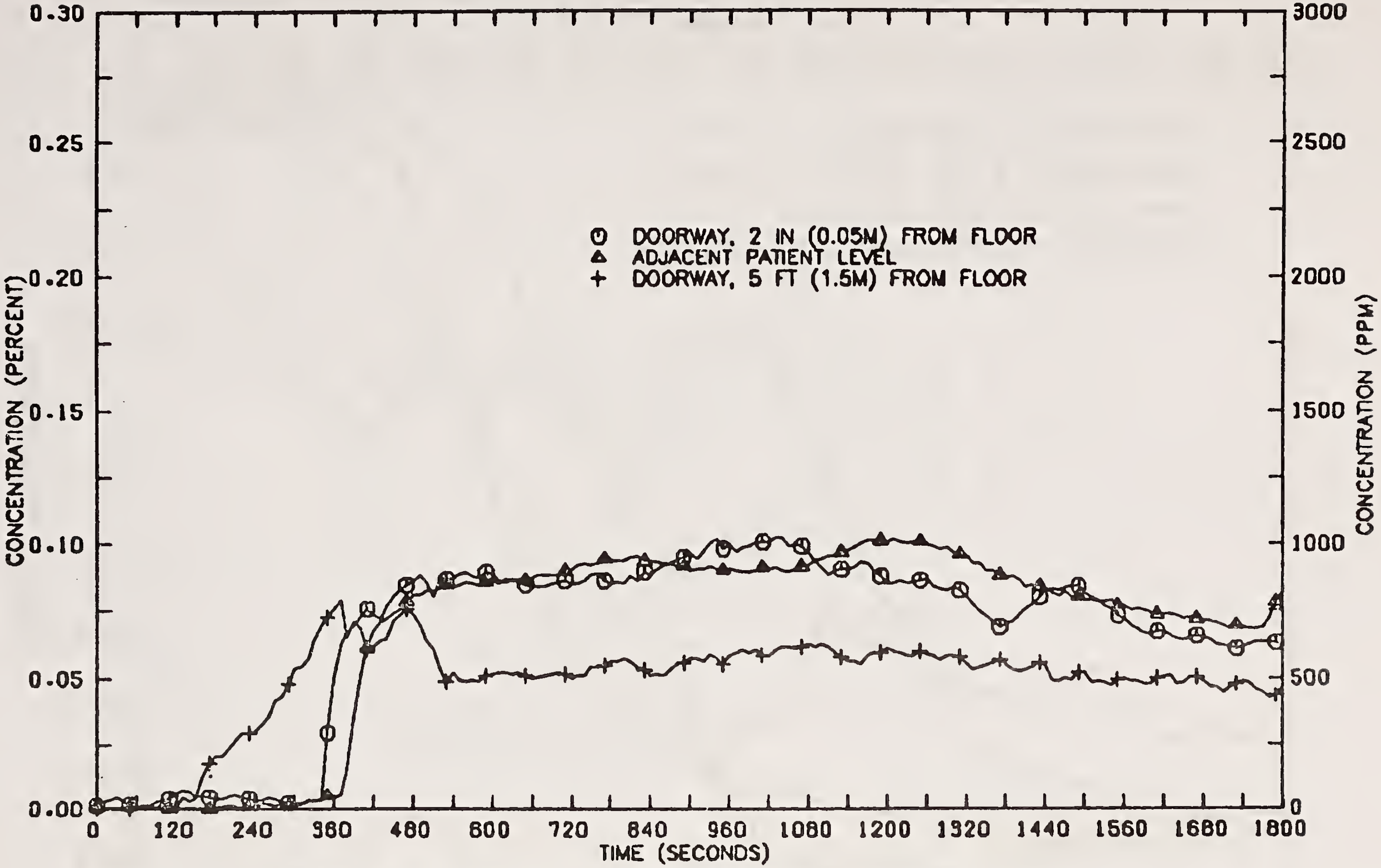


Figure 4. CARBON MONOXIDE CONCENTRATIONS (TEST N-37)

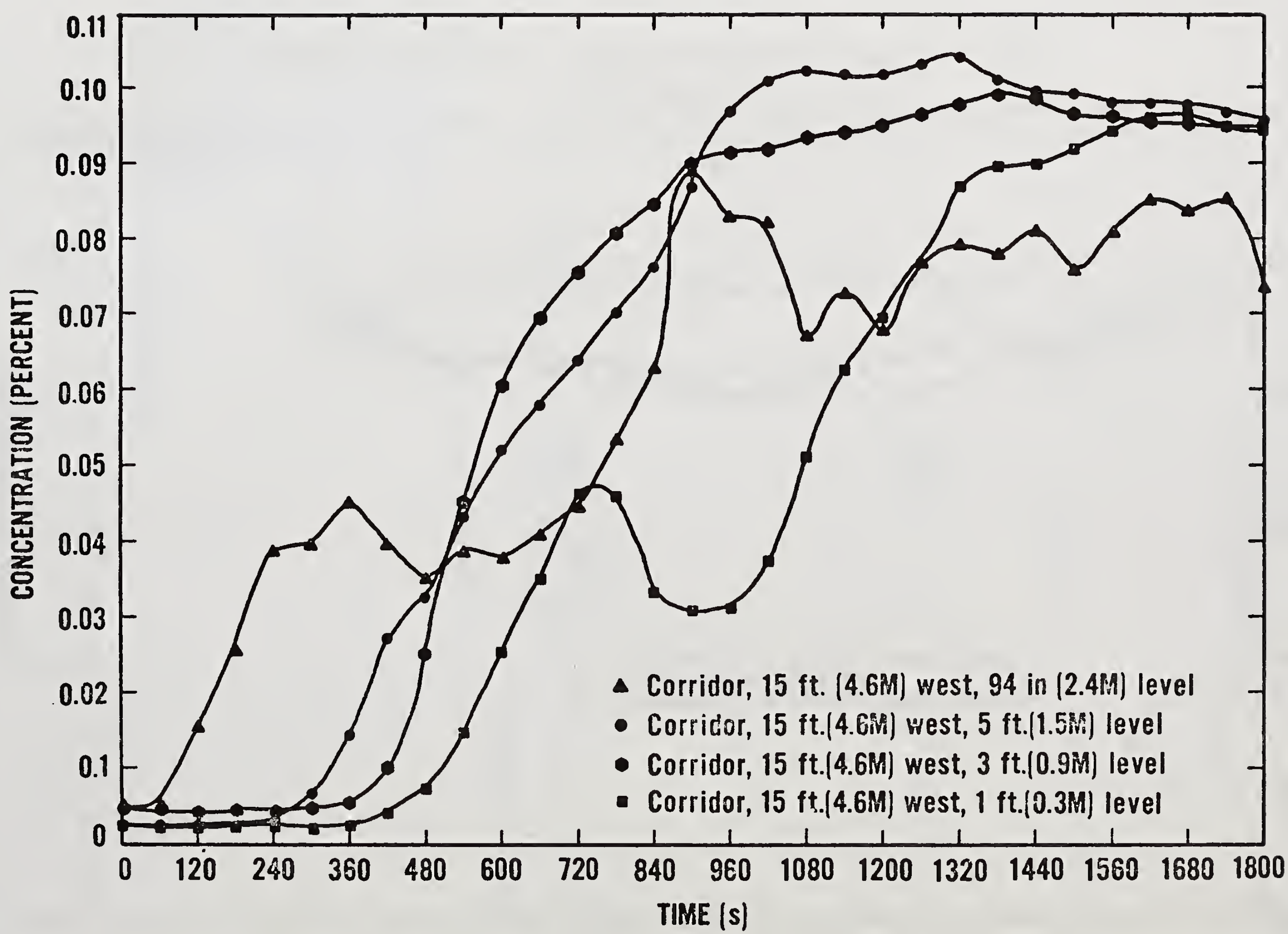


Figure 5. Corridor Carbon Monoxide Concentrations (Test N-37)

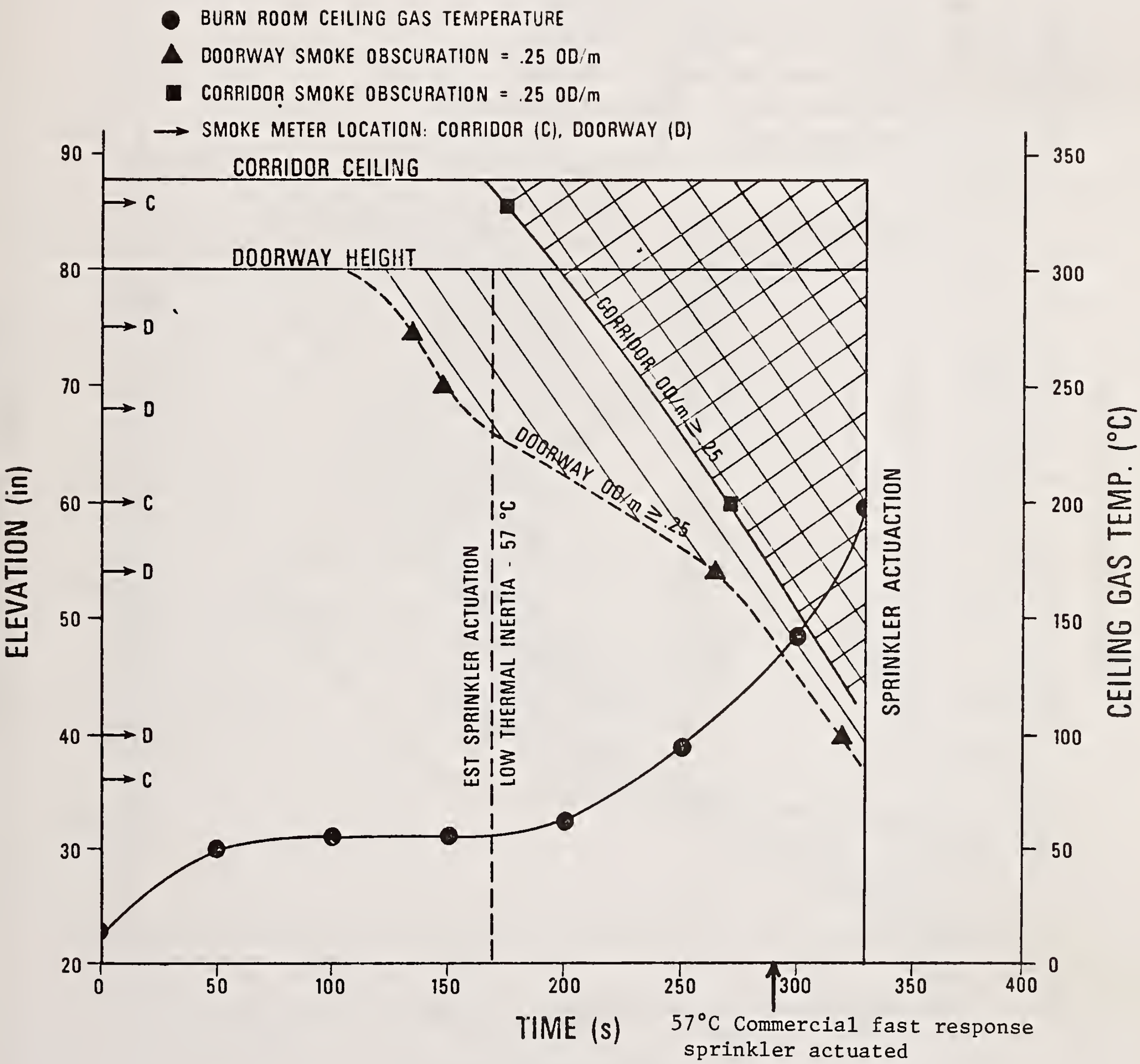


Figure 6. Test N-37 Standard Pendant Sprinkler

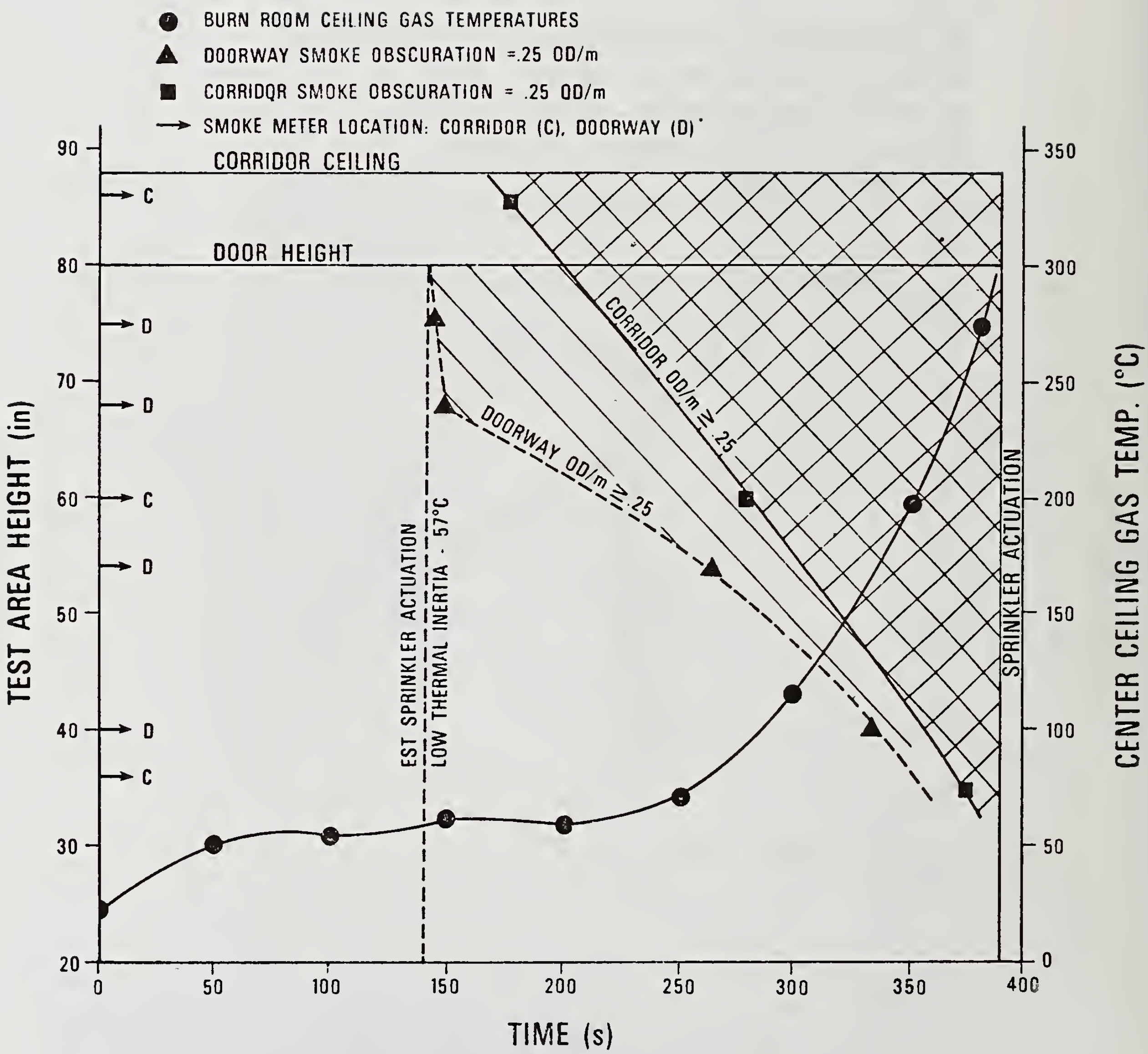


Figure 7. Test N-39 Standard Horizontal Sidewall Sprinkler

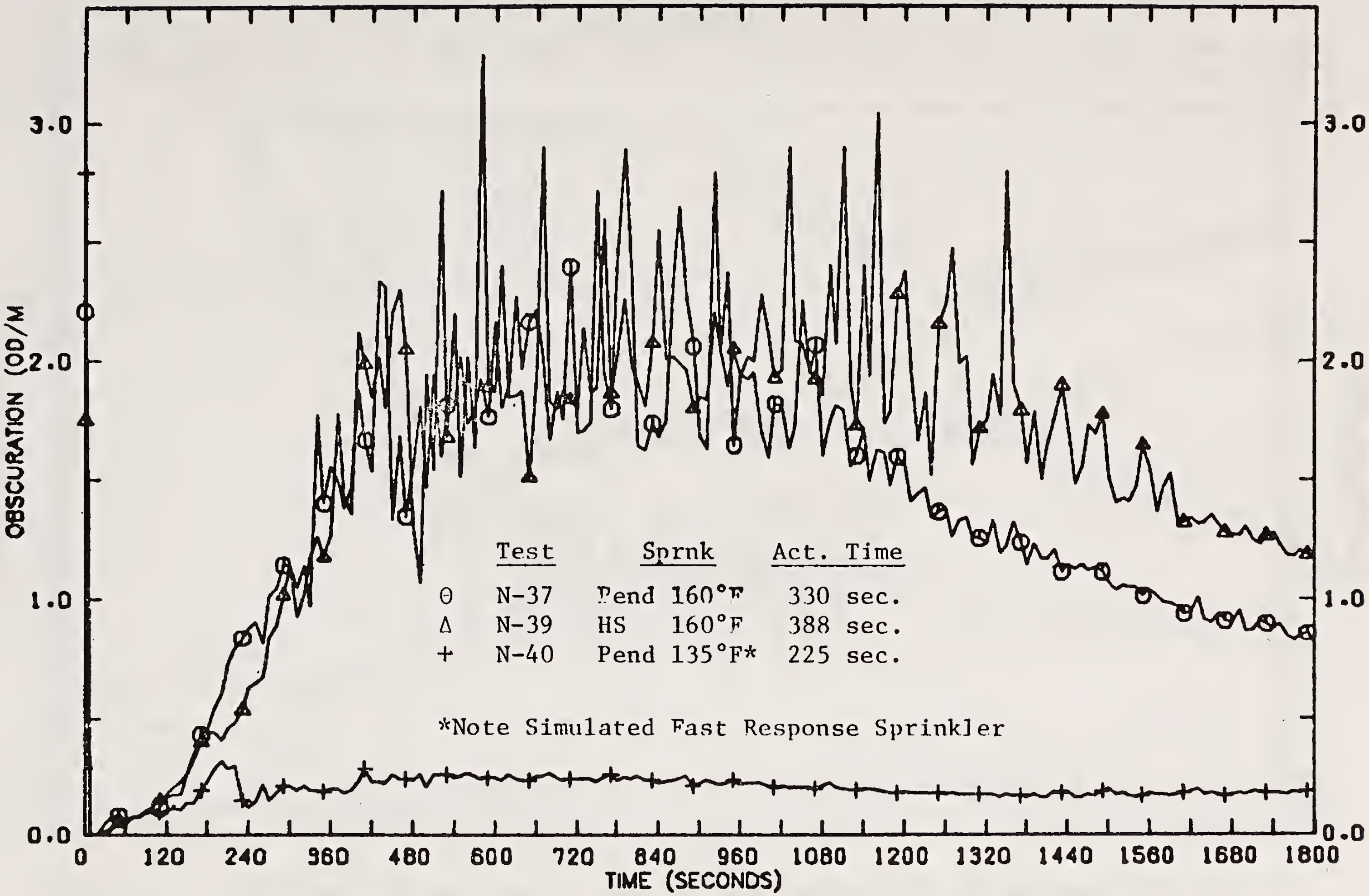


Figure 8. SMOKE OBSCURATION AT 68 IN LEVEL IN DOORWAY

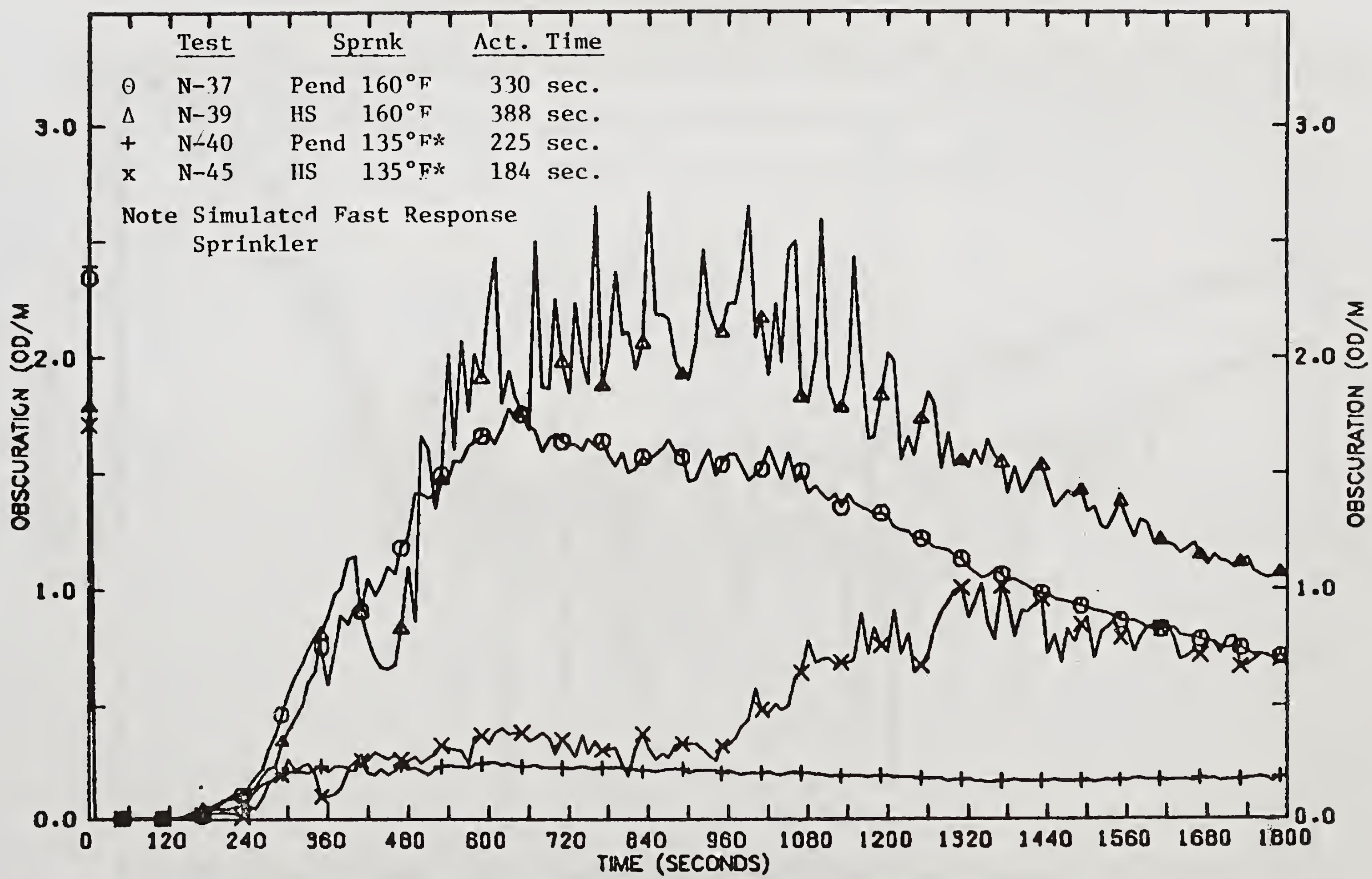


Figure 9. SMOKE OBSCURATION AT 5 FT LEVEL IN CORRIDOR

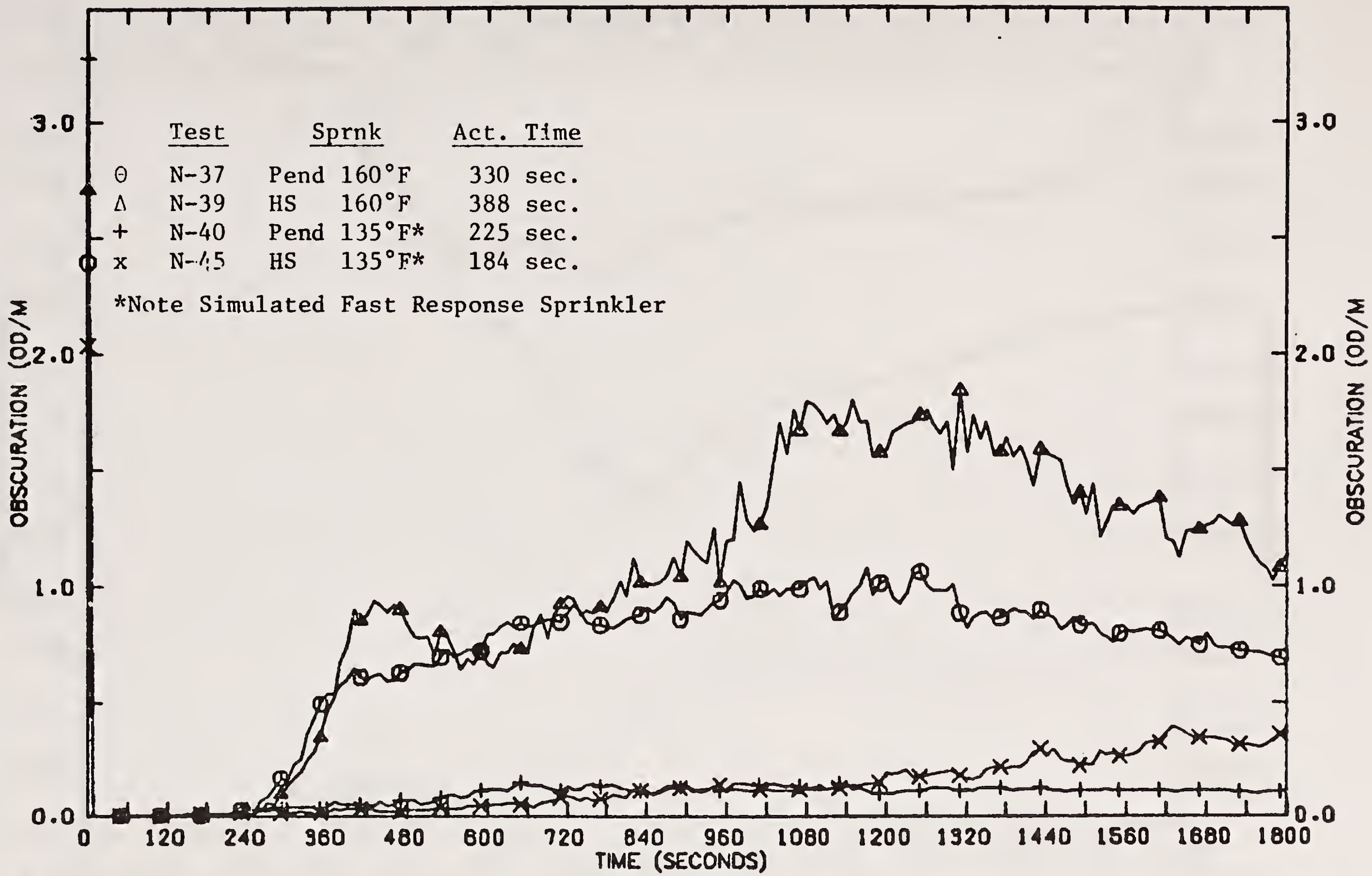


Figure 10. SMOKE OBSCURATION AT 5 FT LEVEL IN LOBBY

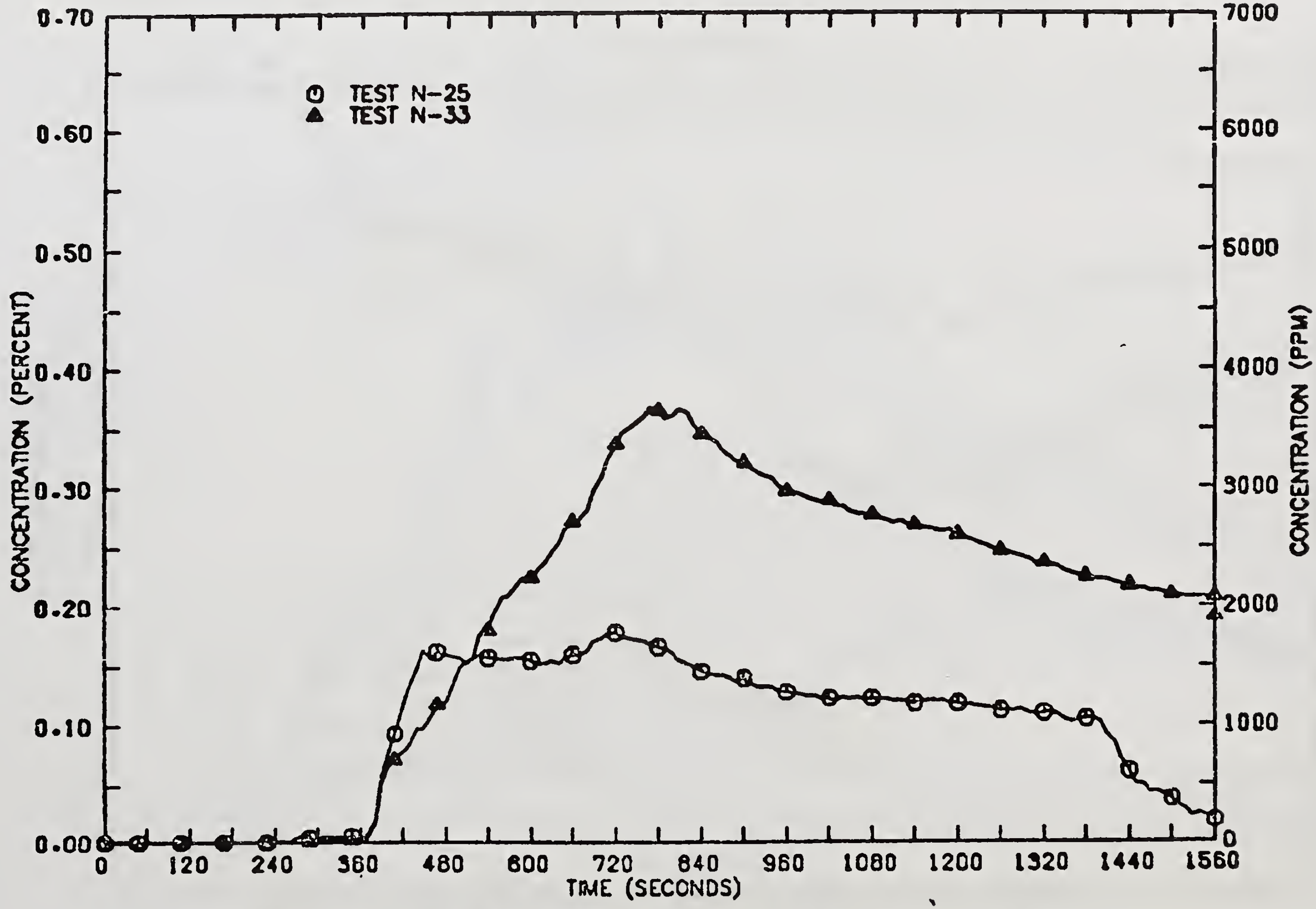


FIGURE 11. CARBON MONOXIDE CONCENTRATIONS ADJACENT PATIENT LEVEL

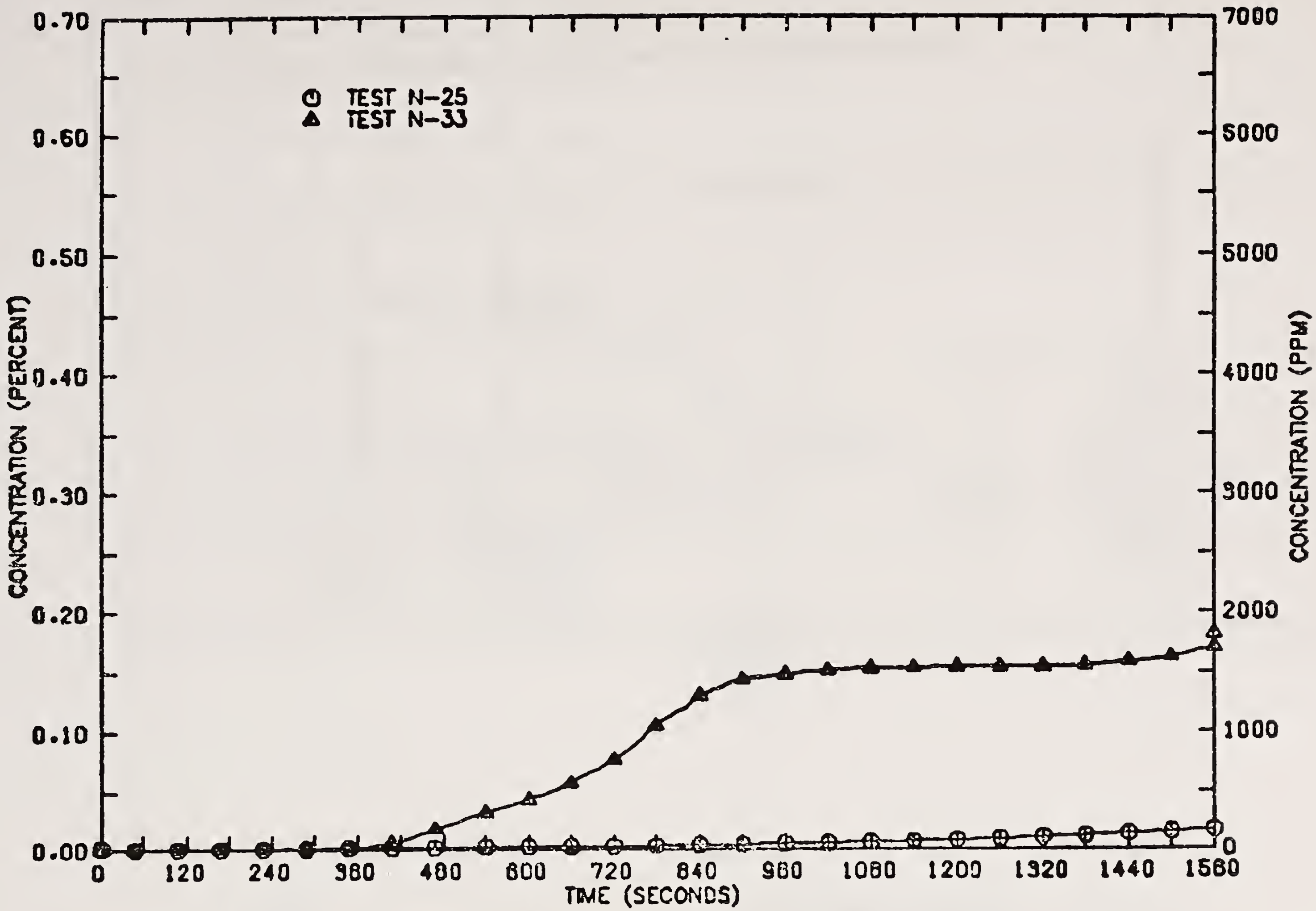


FIGURE 12. CARBON MONOXIDE CONCENTRATIONS
LOBBY, 5 FT (1.5M) FROM FLOOR

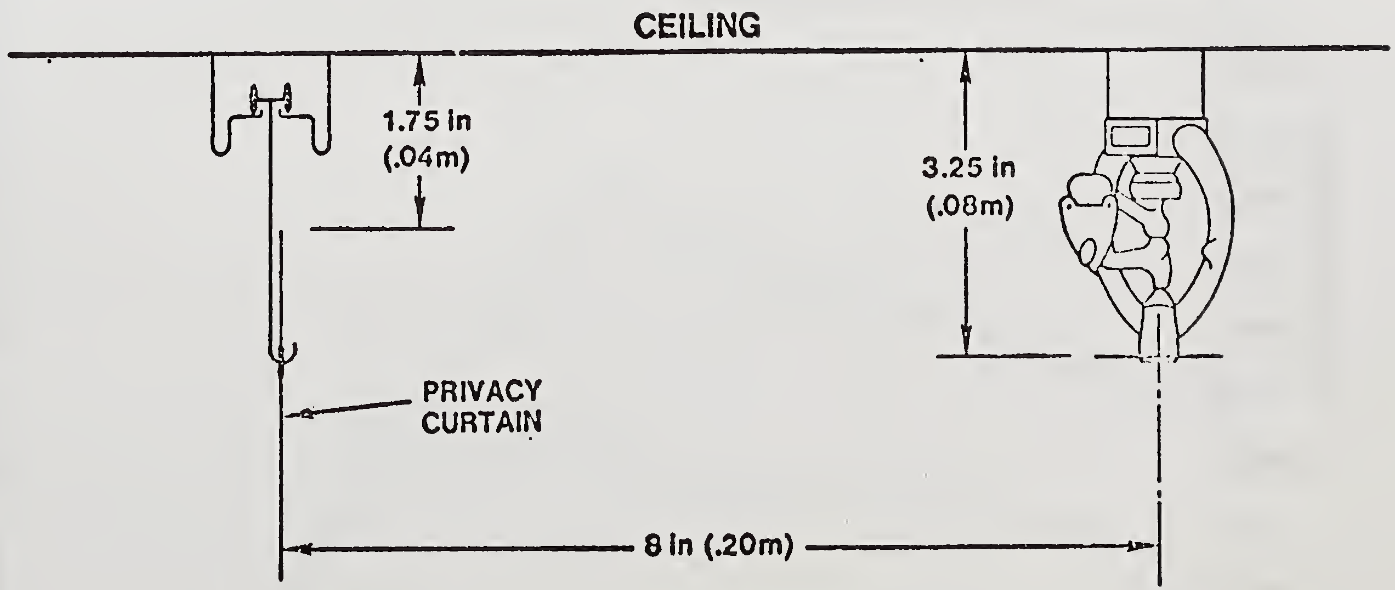


Figure 13. Privacy curtain details

SPRINKLER DISTRIBUTION TEST

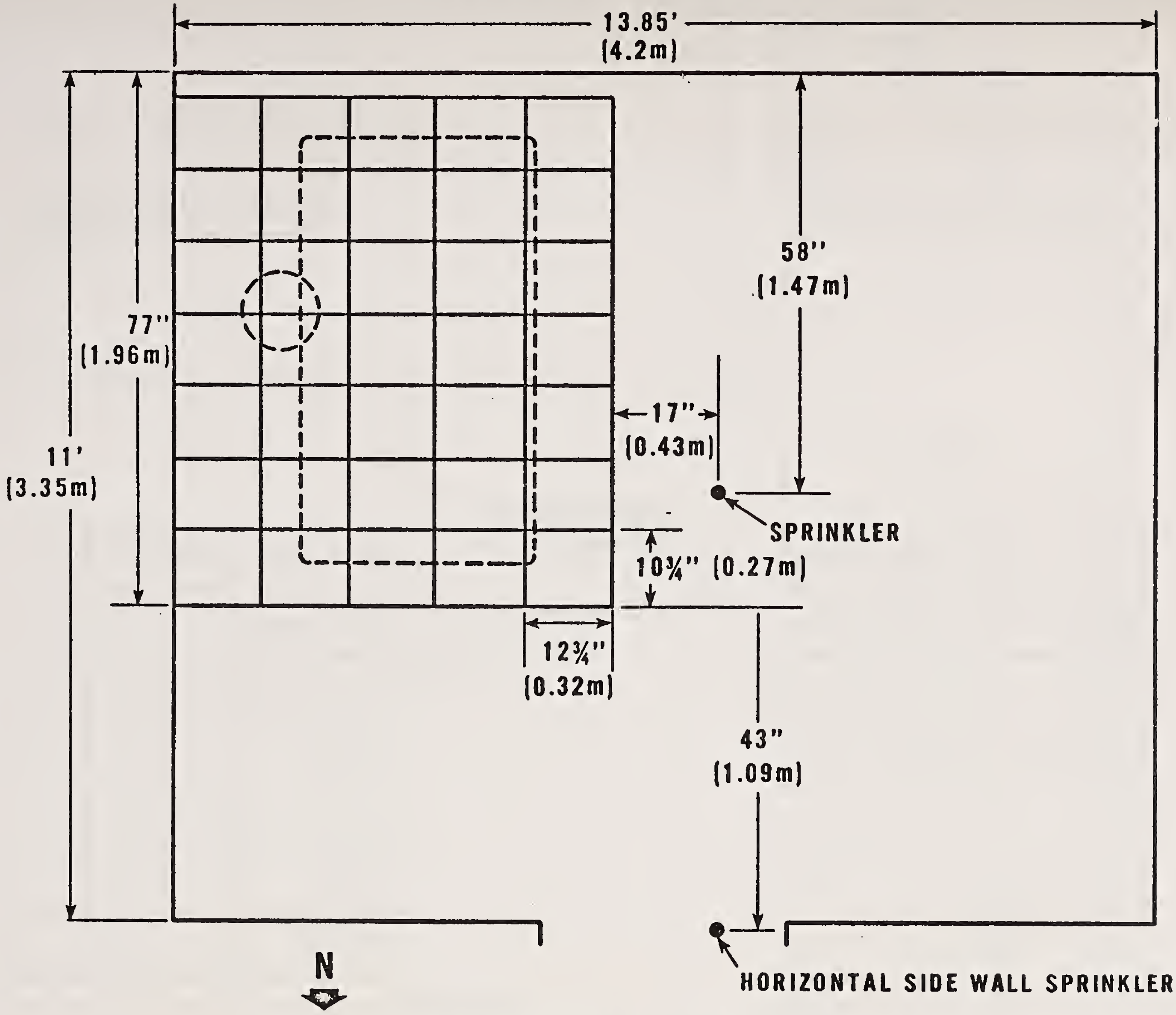
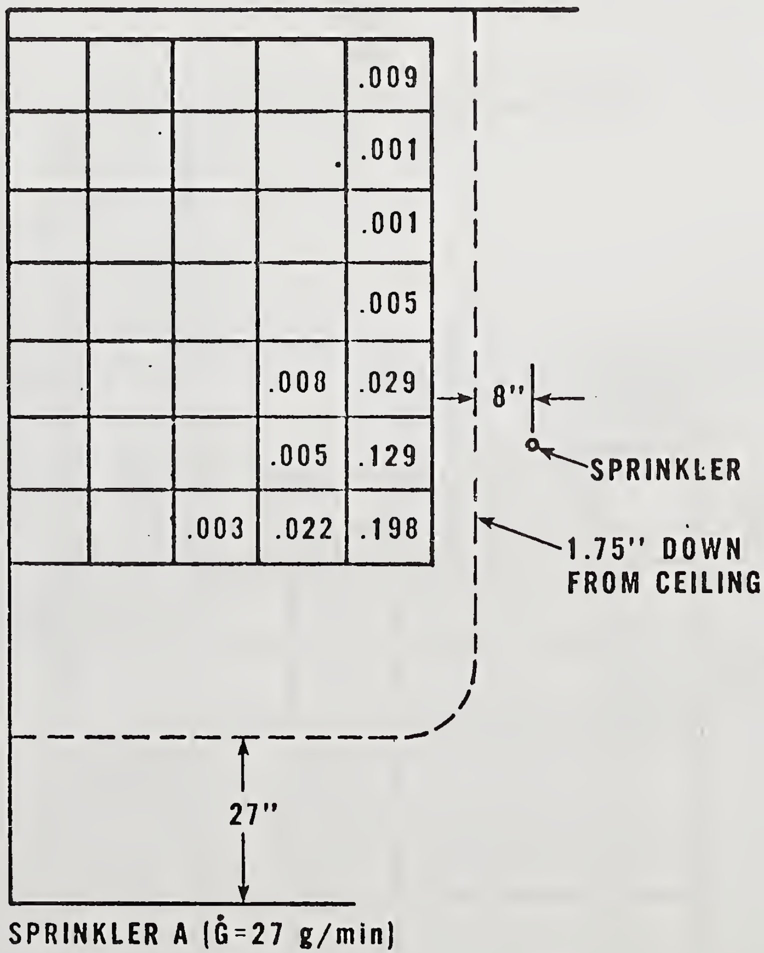
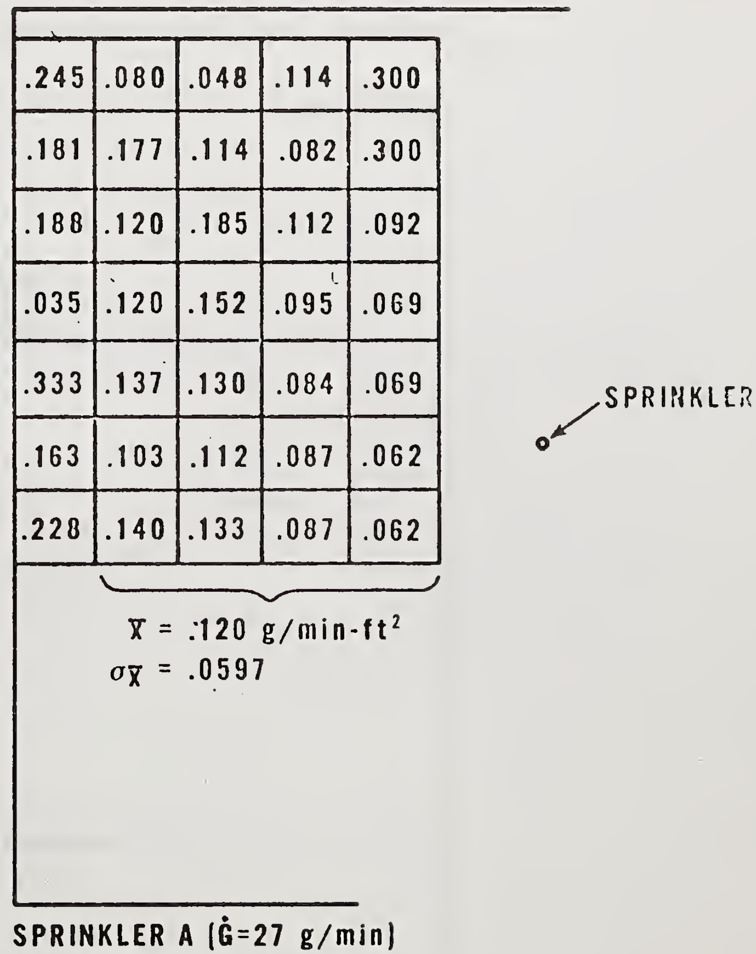


Figure 14. **BURN ROOM PLAN VIEW**



				.009
				.001
				.001
				.005
			.008	.029
			.005	.129
		.003	.022	.198

Figure 15. Spray Distribution Test with privacy curtain



.245	.080	.048	.114	.300
.181	.177	.114	.082	.300
.188	.120	.185	.112	.092
.035	.120	.152	.095	.069
.333	.137	.130	.084	.069
.163	.103	.112	.087	.062
.228	.140	.133	.087	.062

Figure 16. Spray Distribution Test without privacy curtain

Table 1. Total Weight Losses Combustible Wardrobe Tests

Sprinkler Type	Test No.	Weight Loss (lbs)
Pendant	N-48	38.2
Pendant	N-49	17.4
Pendant*	N-53	40.7
Horiz Sidewall	N-50	14.2
Horiz Sidewall	N-51	9.4
Horiz Sidewall*	N-52	9.2

*Simulated fast response sprinkler τ = 21 sec.

APPENDIX

The dynamic heating measurements used in this presentation to characterize fast response sprinklers were based on a proposed test called the "plunge test" developed by Heskestad and Smith at FM. The test, which has been proposed to determine the response time of sprinklers, is based on the assumption that in actual fire situations, the sprinkler fusible element is primarily heated by convection and the effect of radiation on the element is relatively small. The dynamic heating measurement of the fusible element is expressed as the time constant τ; where

$$\tau = \frac{(\Delta T_g - T_L)}{d(\Delta T_L)/dt}$$

where ΔT_L is the increase in temperature of the fusible element (relative to ambient or initial temperature) and ΔT_g is the excess temperature of the gas. τ, therefore, has units of time. Heskestad and Smith found that selected standard sprinklers when tested in a "plunge test apparatus" varied in terms of τ_o from 100 to 280 seconds at a reference velocity, μ_o = 5 ft/sec.

SPRINKLER TECHNOLOGY AND DESIGN IN JAPAN

by Juzo Unoki*

August 1980

ABSTRACT

In Japan installation of sprinklers is mandatory by law for buildings where many and unspecified persons are accommodated, high-rise buildings, dangerous material storages, etc. The records of fire suppression by sprinklers indicate very efficient performance of these sprinkler systems.

The heads used in these systems are designed to meet the standards which are characterized by the following : the water distribution test is to be conducted using a single head, and the relationship between permanent and elastic elongation is defined. The proposal on time constant as the requirement of heat response of heads is also being discussed.

In these sprinkler systems it is not permitted to directly connect underground supply pipe of the systems to a public water main due to the regulations, and it is necessary to install a water reservior with fire pumps. The water supply arrangements for the sprinkler systems in newly-constructed high-rise buildings are shown.

Use of larger orifice sprinkler heads in dangerous material storages, etc., the behavior of smoke and water vapor during fire suppression by sprinklers, prevention of water damage by interlocking with automatic fire alarm systems, etc. are being studied in response to future needs.

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* Director, Japanese Association of Fire Science and Engineering

1. MANDATORY INSTALLATION OF SPRINKLERS

In buildings where many and unspecified persons are accommodated, e.g., department stores, theaters, hotels, hospitals, there is a great probability that a lot of lives would be lost if a fire happens in the premises. Especially, in high-rise buildings it is difficult to extinguish the fire and rescue the occupants externally by use of Fire Department equipment operating from ground level, and in underground shopping malls and windowless floors hot gases and smoke from the fire could readily permeate the whole premises. Besides these buildings rack storages and dangerous material storages would have the greatest fire hazard. For these reasons installation of sprinklers in these buildings over a certain floor area is mandatory by the Fire Service Law and ordinances in Japan as summarized in Table 1.

In those buildings where many and unspecified persons are accommodated the following premises are subjected to the codes requiring mandatory installation of sprinklers: all floors above 11th floor; floors of 1,000m^2 or 1,500m^2 or more as classified by occupancies from 4th to 11th floors; basements.and windowless floors of over 1,000m^2; buildings over 6,000m^2 in total floor area except those including different occupancies; underground shopping malls over 1,000m^2. In addition all floors above the 11th floor of all buildings, rack storages over 10m in ceiling height and over 700m^2 in total floor area concurrently, buildings where dangerous materials or hazardous materials, etc. are stored or handled in excess of the predetermined amount are subjected to mandatory installation of sprinklers.

In Japan the mandatory installation of sprinklers is applied to those buildings constructed before the regulations took effect, not to mention newly-constructed buildings. The number of buildings where installation is mandatory is returned as 7,651, of which 6,551 buildings have finished installation, and the completion rate is 86% in the whole country as of March 31st 1979.[1) 2)] Because there are many cases in which persons concerned with the buildings must bear much expenses when they install sprinklers in existing buildings, they are given facilities for the reduction of taxes and the loan by financial institutions associated with the government.

Sprinkler heads, alarm valves, etc. used in these buildings must be approved by Japan Fire Equipment Inspection Corporation which has given official approvals to 1,272 thousand sprinkler heads and 7 thousand alarm valves during one year from April 1979 to March 1980.

It is important for the effective operation of sprinklers in case of fire to maintain equipments in satisfactory condition. Accordingly qualified persons should inspect and repair the equipments twice per year and report the results to Fire Department once per year in buildings where installation of sprinklers is mandatory based on the Fire Service Law and ordinances in Japan.

2. SPRINKLER PERFORMANCE IN FIRE SUPPRESSION

According to Watanabe's research[3] the number of sprinkler heads operating in fires in Japan is as shown in Fig.1. The data have been obtained from records of sprinkler operating in about 100 fires, and the following is found from this figure. The curve I which shows the sprinkler performance in Japanese buildings is below the curve IV which shows the performance in USA. That is, the number of sprinkler heads extinguishing or controling fires in Japanese buildings is less than those of USA.

This is probably due to the following factors. The first factor may be the lower average fire hazard of occupancies compared with USA where there are many installations of sprinklers in factories, warehouses, etc., because occupancies where installation of sprinklers is mandatory in Japan are determined based on life safety above all things. The second may be the smaller area and lower ceiling height of rooms. Besides the discharge density of sprinklers mentioned below and the water distribution of sprinklers mentioned in the next chapter may be related, too.

In Japan the provision of design discharge density in Japanese regulations is as follows except special buildings, e.g. rack storages. The discharge rate of a 15mm nominal orifice diameter sprinkler head should be more than 80 ℓ/min. per head (at minimum head pressure 1 kgf/cm^2, when 10 to 30 heads discharge simultaneously classified by occupancies and structures of buildings). The sprinkler spacing should be determined in such a way that all floors will be covered by circles whose centers are just under heads and radii are 2.3m. It is estimated from these provisions that the maximum coverage per head is 10m^2 and so the minimum design discharge density is 8 mm/min. This density is higher than 4 mm/min. required in USA Light Hazard Occupancies, and similar to 10 mm/min. specified in New York high-rise buildings[4),5)]. The duration of discharge is 20 minutes.

On the relationship between discharge density and extinction time, Takahashi[6) gives eq. (1) by dripping water slowly on the upper surface of wood crib. An example of its results is shown in Fig.2.

$$te = \left(\frac{No}{\alpha} \right) P^{-\frac{m}{n}} \qquad (1)$$

where te = extinction time, min.
No: number of layers of crib
P : water application rate, ℓ/min.
α : function of the weight loss of cribs before water application
m, n: constant ($m \gtrsim n \approx 0.5$)

That is, the extinction time is short when the water application rate is large.

On the relationship between water discharge rate and the amount of water required for extinction, Kida[7) gives eq. (2) by discharging water from spray nozzles on wood crib fires whose weights are 0.5 to 30 kg. An example of its results is shown in Fig.3.

$$Q = 0.9\ (GV)^{0.6} \qquad (2)$$

where Q: amount of water required for extinction, ℓ
G: weight loss of cribs before water application, kg
V: burning rate of cribs before water application, kg/min.

In this case the amount of water required for extinction is not affected by the water discharge rate.

Nakakuki [8) investigated the effects of water sprays, especially air entrainment by the spray discharge on the extinction of various solid and liquid fuel fires, and also the effect of type and pile arrangement of solid combustibles in an enclosure on the growth of fires and so the response time of sprinkler heads.

3. TESTS ON SPRINKLER HEADS

The test method of sprinkler heads are prescribed in the regulations and standards based on the Fire Service Law in Japan. A few of them which have been amended recently or will be amended in near future are presented as follows.

3-1 WATER DISTRIBUTION

In Japanese hotels and hospitals there are many small rooms and closets, many of which are protected by one or two sprinkler heads. The water distribution test was formerly conducted using four heads in Japan as in USA. However, there were some cases in which the water distribution was good when discharged from four heads simultaneously but not good when discharged from a single head. In the latter cases there was only a little water distribution onto the area directly under the head or in the direction of arms of a pendant type head. If such one or two heads would be installed in a room, there would be an area not to be covered by sprinklers and the effective protection could not be expected. Therefore, the standards were amended in 1976, and since then the water distribution test has been conducted by using a single head.

It was formerly prescribed in standards that the head pressure for the test should be 1 kgf/cm^2. Many high-rise buildings were lately constructed and their sprinkler systems were divided into several zones, each having pump or tank. Therefore, there was a considerable head pressure difference between top and lowest floors of the zone. If such heads showing a small coverage under high head pressure were installed in the lowest floor of the zone, discharge densities near wall or in the middle of four heads became smaller. Therefore, the standards were amended in 1976 to require that the water distribution test be conducted under head pressure 1 to 10 kgf/cm^2.

The apparatus of the water distribution test for standard sprinklers is shown in Fig.4 and the following are required under head pressure 1 to 10 kgf/cm^2.

(1) The average discharge density at every distance from a sprinkler head should be more than the value shown in Fig.5, where the average discharge density is estimated by averaging the amount of water distributed to measuring pans on each of 10 concentric circles whose centers are located just below the sprinkler head.

(2) At least 60% of total discharge should be distributed within a circle with a radius of 3m and its center located just below the sprinkler head.

(3) The difference between the amount of water distributed to measuring pans on each concentric circle should be small.

Examples of water distribution of two different types of sprinkler heads used today in Japan are shown in Fig.6. Examples of heads whose water distribution is not good are shown in Fig.7, in which it can be seen that the amount of water distributed just under the head is small or the coverage of a head is small under high head pressure. In both figures those of an ordinary pendant type heads are shown on the left and those of a multi-nozzle type heads on the right. The latter is a specific type head which is manufactured only in Japan and discharges water through several nozzles provided in its side wall. These data have been obtained by Japan Fire Equipment Inspection Corporation.

3-2 STRENGTH OF FRAMES

In Japanese standards the strength of frames is required as follows to maintain the operating force of sprinkler heads for a long time. The permanent elongation of a frame shown when the frame is subjected to twice the service load in the axial direction of the head should be less than 50% of the elastic elongation shown when the frame is subjected to the service load. This relationship is shown in Fig.8 and the difference between elastic and permanent elongations keeps the operating force of the head and stops water leakage from a orifice during the service life of the head.

In Japan it was formerly determined that the permanent elongation of a frame should be less than 0.1% of the distance between the load-bearing points of heat sensing element when the frame is subjected to twice the service load, but the relationship between the permanent and elastic elongations was not clear in this case. Therefore, the above-mentioned provision has been noted on the standards amended in 1976.

3-3 HEAT RESPONSE

Under the existing Japanese standards, a sprinkler head is required to operate within the response time classified by the nominal temperature when placed in a test oven where the temperature rise follows a time-temperature relationship as shown in Fig.9.

But the actual response time of the sprinkler heads installed in buildings is determined mainly by the cumulative convection heat transfer. It may therefore be worth while considering to adopt a hot air wind tunnel test for the sensitivity test of a head as in the case of a heat detector.

Oshikawa[9)] conducted wind tunnel tests using some existing sprinkler heads of fusible link and glass bulb type. One of these results is shown in Fig.10. In this case test sprinkler heads were set in hot air flow facing their bottoms to the flow direction. The velocity of the flow was constant (2.5m/s) and the temperature of the air was raised linearly at a constant rate (50°C/min) from the same temperature as the head temperature prior to the test. The head temperature prior to the test were kept at the maximum permissible ambient temperature (the maximum permissible room temperature not to cause gradual weakening of heat sensing elements). K in the figure is the time constant of the heat sensing element and estimated from eq. (3).

$$Tm - Ta = N \left[to - K \left(1 - e^{-\frac{to}{k}}\right) \right] \qquad (3)$$

where Tm: nominal temperature of heads, °C
Ta: initial temperature of heads and air flow, °C
N : rate of rise of air flow temperature, °C/min.
to: response time of the head, min.
K : time constant of the heat sensing element, min.

From Fig.10 the following findings can be noted. So far as the above-mentioned hot air wind tunnel tests are concerned, the time constant of heat sensing elements are mostly situated between 2 and 4 min. in fusible link type, 4 and 7 min. in glass bulb type. As a rule the smaller the time constant is, the more sensitive the sprinkler is, and the quicker it responds to a fire. Therefore, heads with small time constant and rather higher nominal temperature may be better for the reliable detection and early suppression of a fire. From this point of view, amendment of the standards on the time constant of sprinkler heads is desired.

4. WATER SUPPLIES FOR SPRINKLER SYSTEMS

As water sources of sprinkler systems fire pumps are generally used besides gravity tanks. In Japan it is not permitted to directly connect underground supply pipe of sprinkler systems to a public water main due to the provision of Public Water Law, and therefore a water reservoir should be installed with fire pumps. This reservior capacity is required to ensure a minimum discharge duration of 20 minutes to 10 - 30 heads determined by occupancies and structures of buildings. If it is desired to commonly use the water source for service and sprinkler systems, a minimum available water capacity for sprinkler systems must be secured by means of determining a lowest water level for service water systems by a water level gage, e.g. electrodes, as shown in Fig.11. It is also necessary to install a testing equipment of discharge capacity as shown in Fig.12 to test the fire pump performance.

Sprinkler heads are required to have the prescribed water distribution at 1 - 10 kgf/cm^2 head pressure in Japanese standards as mentioned above. Accordingly the water supply arrangement in high-rise buildings must be designed in such a way that the head pressure will be less than 10 kgf/cm^2 on the operating of one head and more than 1 kgf/cm^2 on the simultaneous operating of 10 - 30 heads.

An example of the water supply arrangement for sprinkler system in a high-rise building equipped with booster pumps in intermediate floors is shown in Fig.13. This building in Tokyo is 60 stories in height with a 4-storied basement and a 3-storied tower, and the area of its standard floor is 3,105m2. The floors equipped with pumps and fed by pumps are as follows.

Pump	Floor equipped	Floor fed
Main pump	3rd basement	4th basement - 14th
1st booster pump	21st	15th - 35th
2nd " "	42nd	36th - 56th
3rd " "	1st of tower	57th - 3rd of tower
Pressure maintenance pump	"	"

In floors from 4th basement to 56th floor, when a sprinkler head operates by a fire, the alarm valve in the floor of the fire origin opens by pressure difference from the intermediate tank, the pressure switch for pump start on the alarm valve is actuated, and so all pumps up to the floor of the fire origin begin to operate at the same time.

In floors from 57th floor to 3rd of tower, when a sprinkler head operates by a fire, pressure of the pressure tank connected to the 3rd booster pump and kept usually constant by the pressure maintenance pump drops, the pressure switch for pump start on the pressure tank is actuated, and so all pumps begin to operate at the same time.

An example of the water supply arrangement for sprinkler systems in a high-rise building equipped with gravity tanks is shown in Fig.14. This building in Tokyo is 54 stories in height with a 4-storied basement and a 3-storied tower, and the area of its standard floor is 2,629m2. This system is divided into 4 zones fed by gravity tanks and a zone fed by a pump. A gravity tank on the 54th floor has a capacity of 72m3 and additional gravity tanks on the 40th, 27th and 14th floors have respectively a capacity of 15m3.

5. FUTURE PROBLEMS

5-1 LARGER ORIFICE SPRINKLER HEADS

Because installation of sprinklers is mandatory mainly in the aspect of life safety in Japan as mentioned above, sprinkler heads of 15mm nominal orifice diameter are standardized to be suitable for buildings where many and unspecified persons are accommodated. These standard sprinkler heads are used for protection of dangerous or hazardous material storages, etc., as well, in which case satisfactory protection can only be achieved by reducing the area allocated to one head or increasing the duration of discharge with these heads. In view of the increase of storage size and commodity variety, however, studies are being made with respect to use of larger orifice sprinkler heads, e.g., 20mm nominal size head, which is capable of discharging large drops penetrating through severe fire plume.

5-2 BEHAVIOR OF SMOKE AND WATER VAPOR SUPPRESSION WITH SPRINKLERS

When the fire has been suppressed by sprinklers, the burning rate decreases and so the smoke generating rate surely decreases, too. But simultaneously a large amount of water vapor generates, the ceiling smoke layer falls near floor, the visibility in the room reduces, and so those may have a bad effect on the escape of occupants. Regarding vapor generation resulting from water application, Takahashi[10] reported that when wood crib fire were suppressed by water spray, the density of generating vapor increased to a maximum value and afterward decreased again, with the increase of the water application rate. On the other hand the density of smoke and vapor in actual-scale fire tests was measured by light path maters, but any conclusion has not yet been reached.

5-3 PREVENTION OF WATER DAMAGE

Sprinklers are very effective on the suppression of a fire in its early stage, but it is strongly required especially by department stores, etc. that water damages be limited to a minimum extent. However this requirement is not always satisfied as they must manually close the stop valve near the alarm valve to stop the water discharge after the extinction. In Japan automatic fire alarm systems are mostly installed in buildings where installation of sprinklers is mandatory. And so it may be rather easy to install preaction systems or cycling systems in these buildings by the interconnection of above-mentioned two systems. The future study including the amendment of regulations is desired.

ACKNOWLEDGMENT

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Table 1. Buildings where installation of sprinkler systems is mandatory

<table>
<tr><th rowspan="2">Occupancies</th><th colspan="4">Area where installation is mandatory</th><th colspan="2">Situations on Installation 2) as of March 31st, 1979</th></tr>
<tr><th>General standards</th><th>Basement, windowless floors</th><th>Floors from the 4th to the 11th floor</th><th>Floor above the 11th floor</th><th>Number of buildings where installation is mandatory</th><th>Number of buildings where installation has been finished</th></tr>
<tr><td>Department stores Retail stores, etc.</td><td rowspan="7">Building over 6000m2 in total floor area except single-story building</td><td rowspan="8">Floor over 1000m2</td><td rowspan="2">Floor over 1000m2</td><td rowspan="8">All</td><td>1804</td><td>1703</td></tr>
<tr><td>Cabarets, Amusement halls, etc.</td><td>379</td><td>338</td></tr>
<tr><td>Theaters, Public halls, etc.</td><td rowspan="5">Floor over 1500m2</td><td>377</td><td>301</td></tr>
<tr><td>Restaurants, etc.</td><td>33</td><td>26</td></tr>
<tr><td>Hotels, etc.</td><td>644</td><td>404</td></tr>
<tr><td>Hospitals, Welfare Premises, Kindergartens, etc.</td><td>1040</td><td>692</td></tr>
<tr><td>Special bathhouse, etc.</td><td>2</td><td>0</td></tr>
<tr><td>Buildings including above-mentioned occupancies</td><td>Floor, including above-mentioned occupancies over 3000m2</td><td>Floor over 1000m2 or 1500m2 on occupancies</td><td>2151</td><td>1910</td></tr>
<tr><td>Underground shopping malls</td><td>Building over 1000m2 in total floor area</td><td></td><td></td><td></td><td>55</td><td>52</td></tr>
<tr><td colspan="5">Total</td><td>6485</td><td>5426</td></tr>
</table>

In addition to above-mentioned occupancies, they should install sprinkler systems in the following areas.

1) All floors above the 11th floor

2) Rack storages, over 10m in ceiling height and over $700m^2$ in total floor area.

3) Stages, having area over $300m^2$ in basement, floor without windows or floor above the 4th, and over $500m^2$ in other floors.

4) Buildings where larger amount of dangerous materials, hazardous materials, etc. are stored or handled in excess of the predetermined amount.

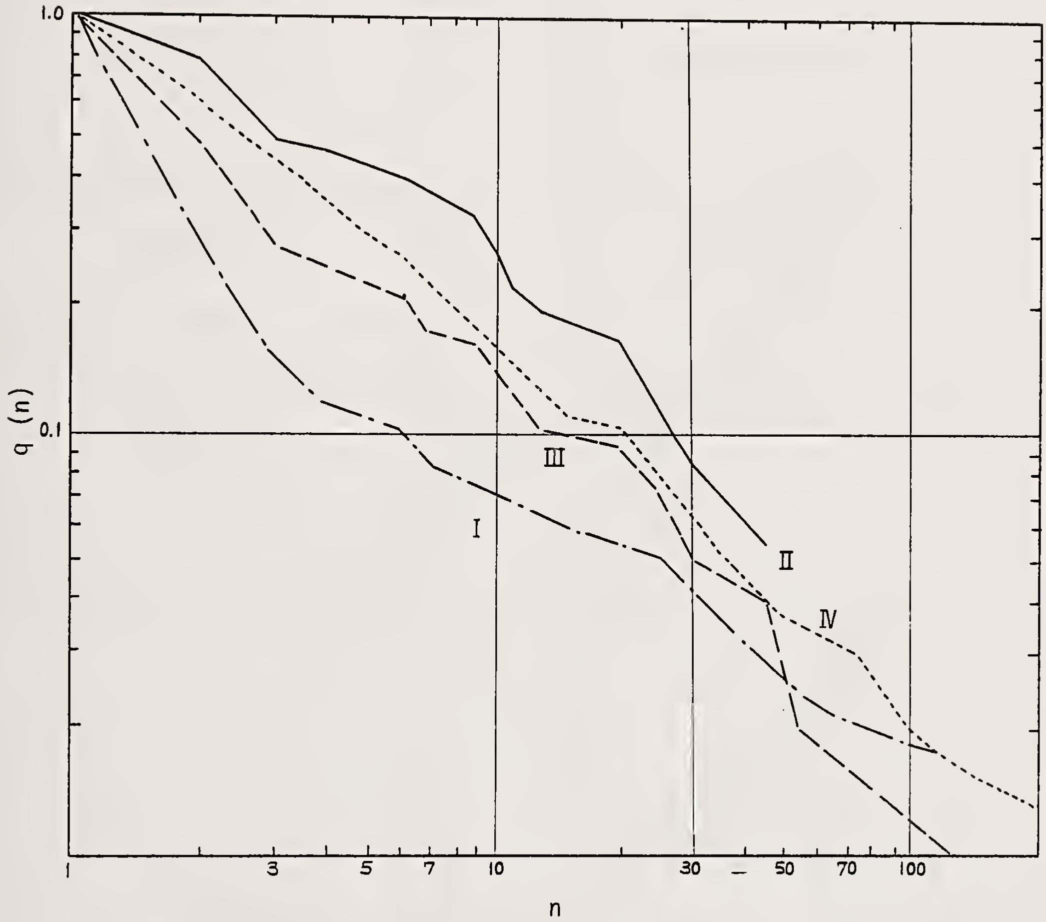


Fig.1 : q(n), Rate of fires suppressed or extinguished, in which N or more sprinkler heads operated.

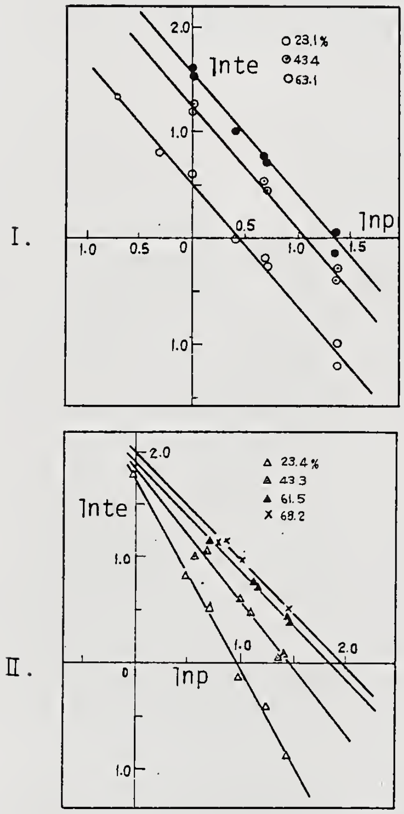
I : Buildings in which the installation of sprinkler is mandatory based on regulations in Japan (N=60).

II : Spinning mills in Japan (N=36).

III : I + II (N=96)

IV : USA

where N is the number of premises



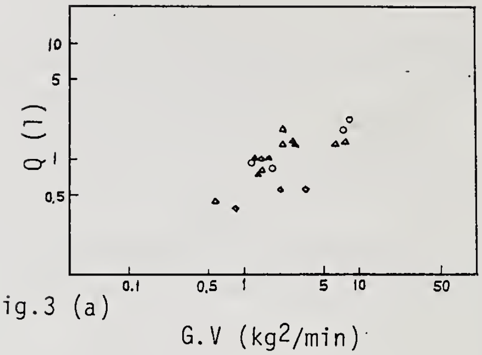


Fig.3 (a)

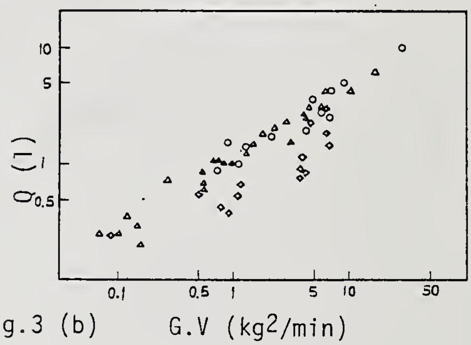


Fig.3 (b)

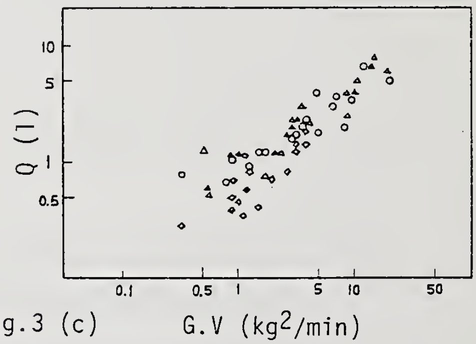


Fig.3 (c)

Fig.2: Extinction time vs the water application rate.
I. 3^2x33-6x8 II. 3^2x33-6x12

where the dimensions of the sticks and cribs are presented as (stick thickness)^2 x (stick length)-(number of sticks per layer) x (number of layers).
Symbols (○, △ etc.) show results correspond to the weight loss ratio of cribs before water application.

Fig.3: Variation of quantity of solution required to extinguish model fire with the value G.V.
Fig.(a), (b), and (c) show results correspond to cribs composed of sticks of thickness 1.7, 2.5, 3.5 cm, respectively.
△ Water discharge rate 0.8 ℓ/min.
○ Water discharge rate 1.3 ℓ/min.
◇ Diammonium Phosphate 20wt% discharge rate 0.8 ℓ/min.

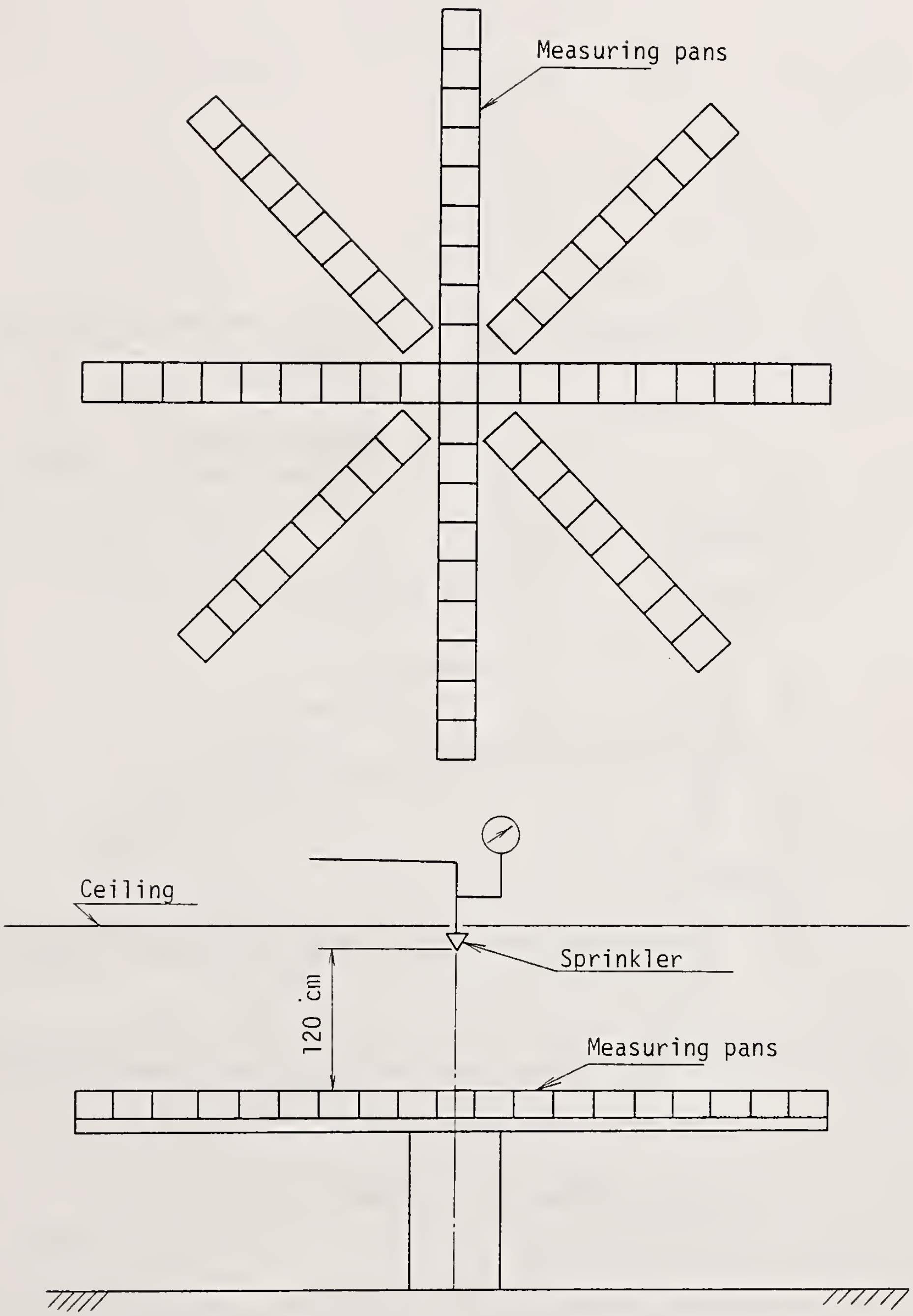


Fig.4: The apparatus of water distribution test for standard sprinkler

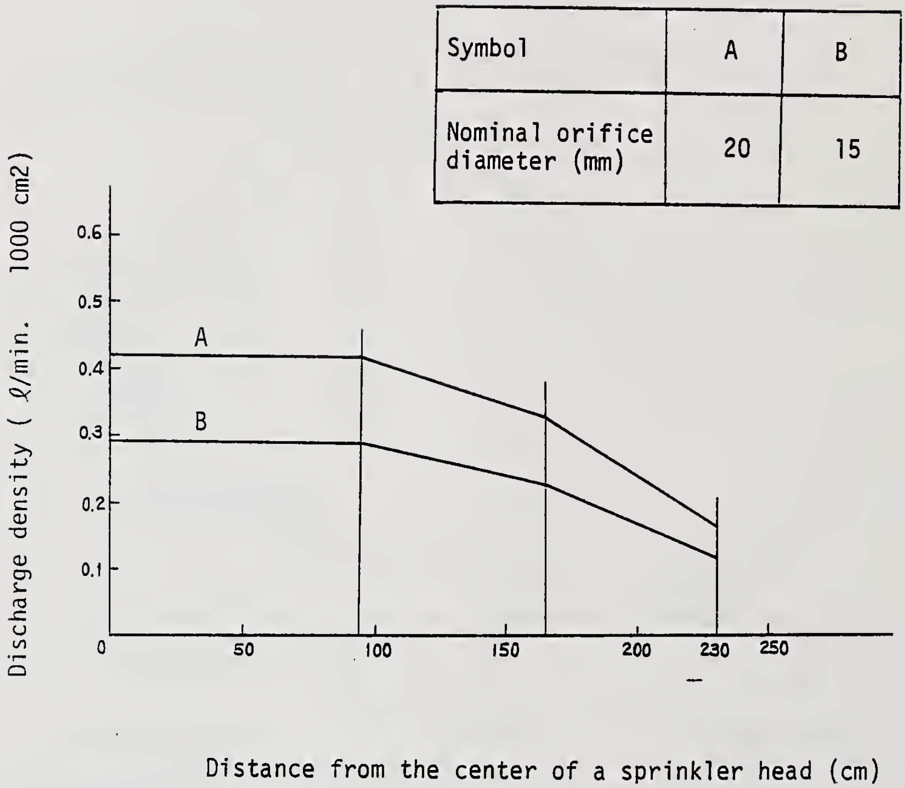
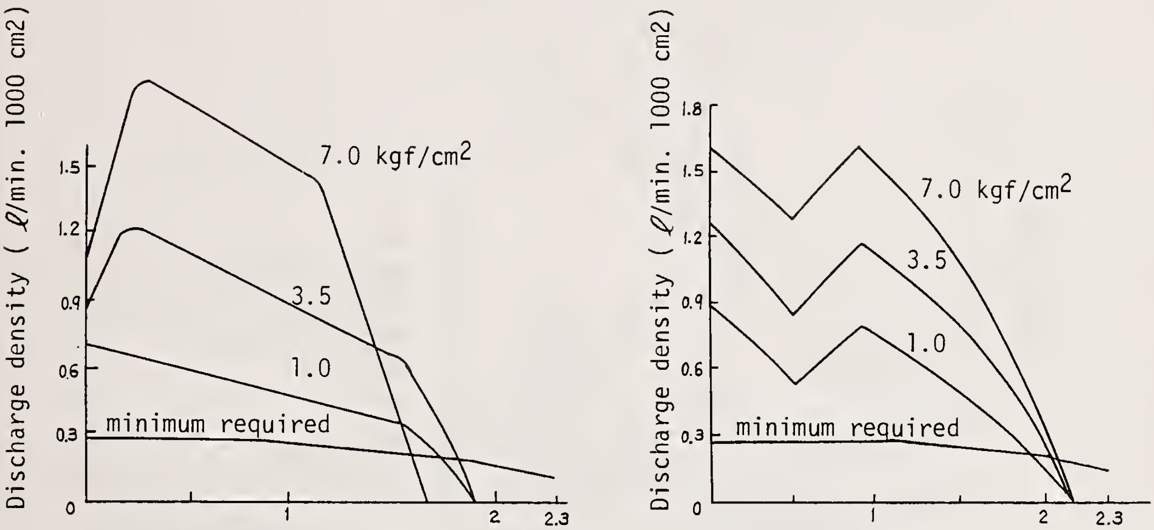


Fig.5: Minimum discharge density curve



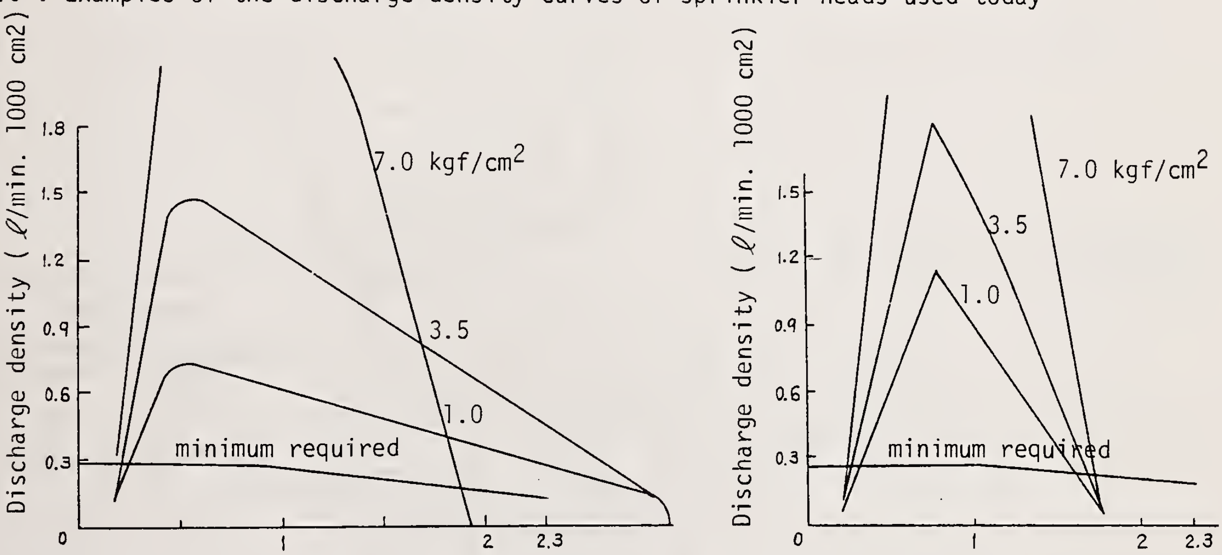
Distance from the center of a sprinkler head (m)

An example of pendant type

Distance from the center of a sprinkler head (m)

An example of multi-nozzle type

Fig.6 : Examples of the discharge density curves of sprinkler heads used today



Distance from the center of a sprinkler head (m)

An exmaple of pendant type

Distance from the center of a sprinkler head (m)

An example of multi-nozzle type

Fig.7 : Examples of the discharge density curves of sprinkler heads which don't comply with the standard

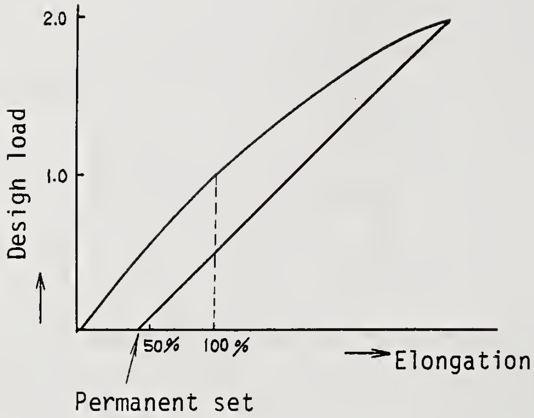


Fig.8: Requirement for the strength of sprinkler frames

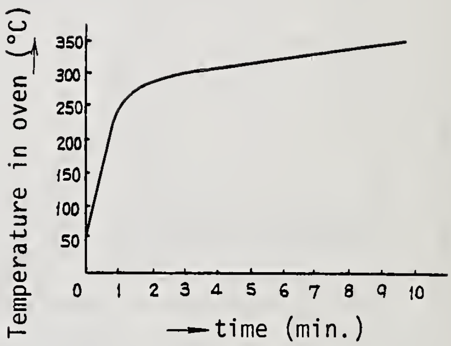


Fig.9: Temperature-time curve in testing oven of sprinkler heads

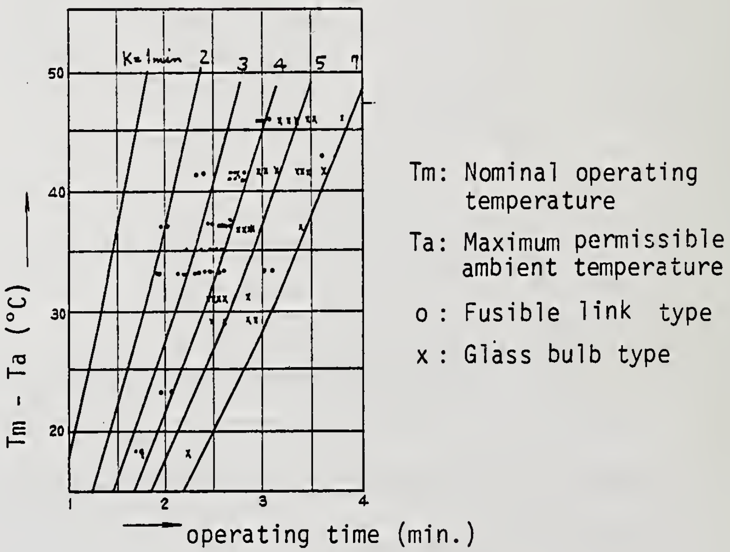


Fig.10: Operating performance of sprinkler heads in wind tunnel test with hot-air wind tunnel

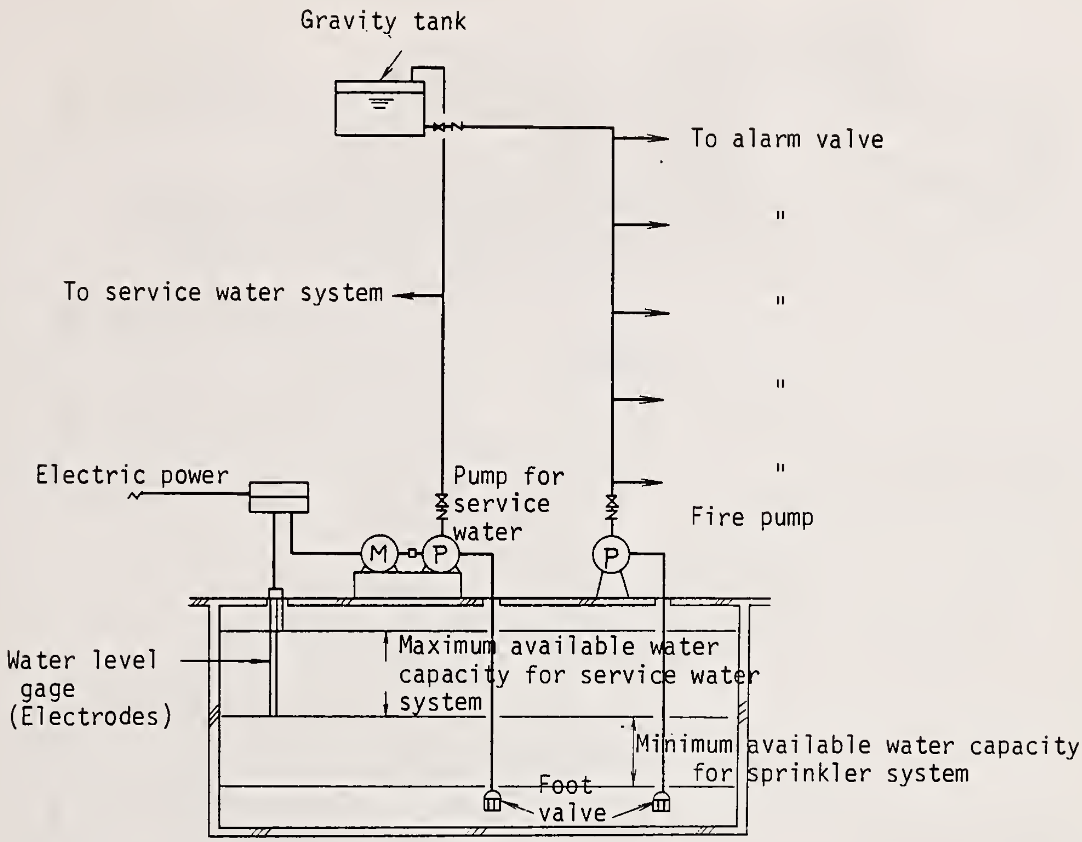


Fig.11: Example of the dual use of water sources for service and sprinkler system

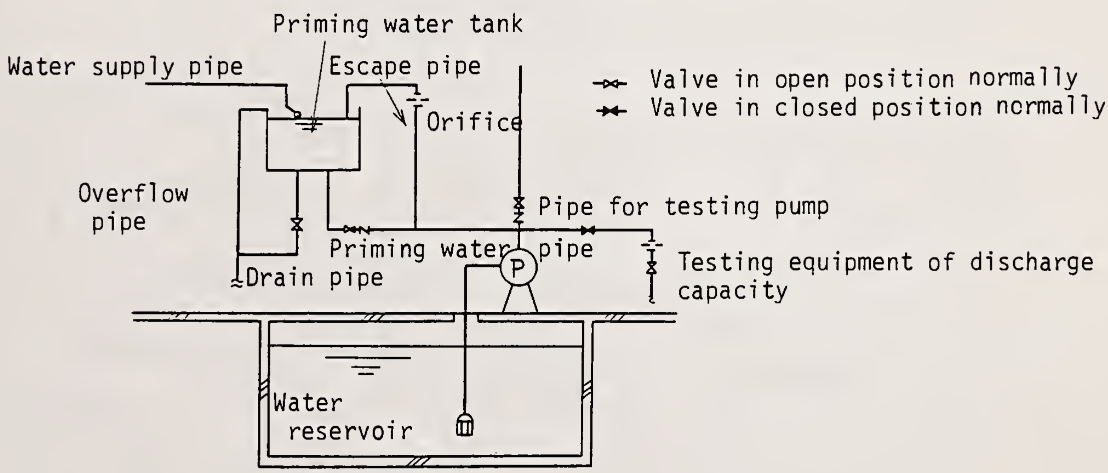


Fig.12: Testing equipment of the discharge capacity of fire pump

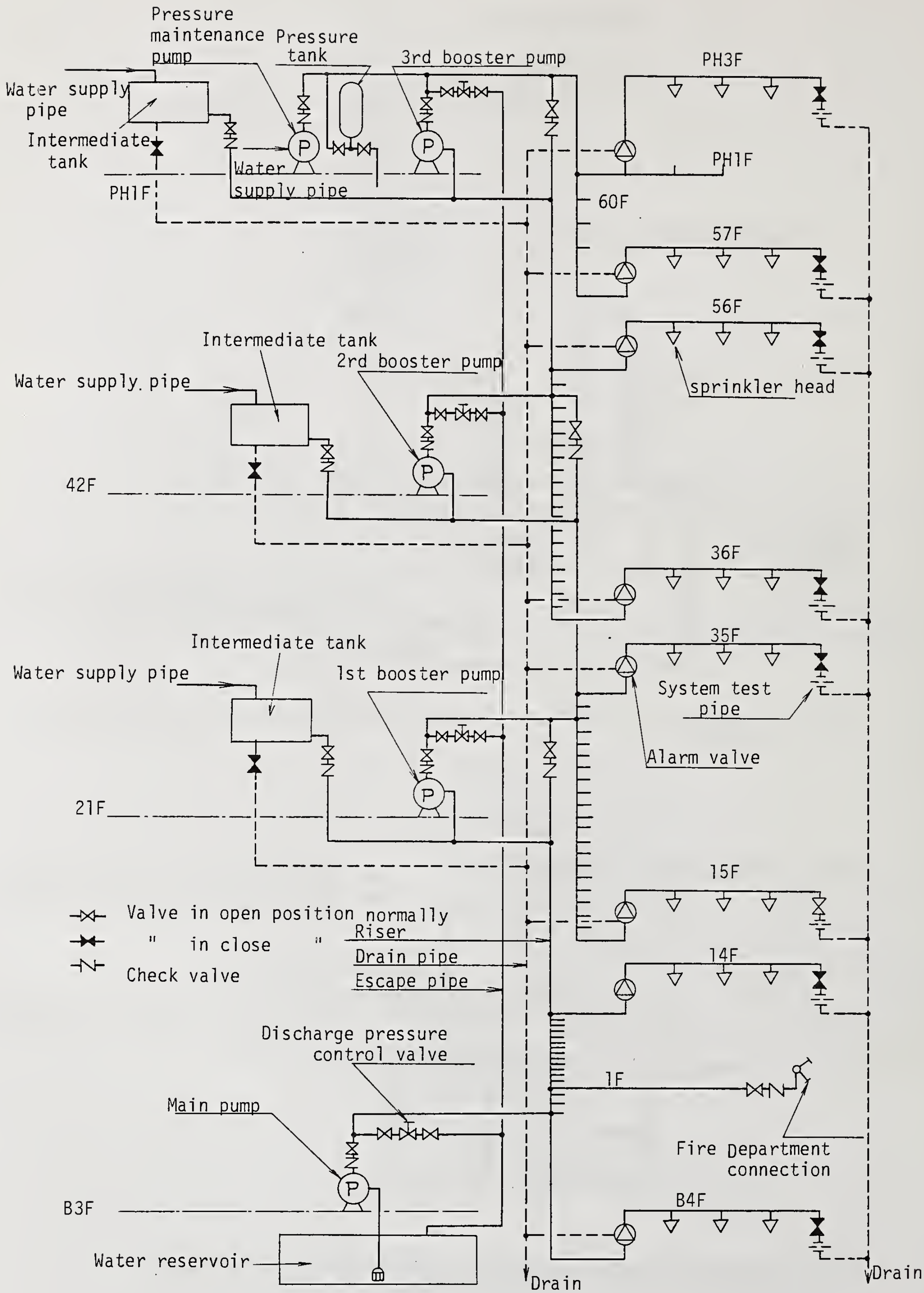


Fig.13: Water supply arrangement for sprinkler system in high-rise building (Booster pump system)

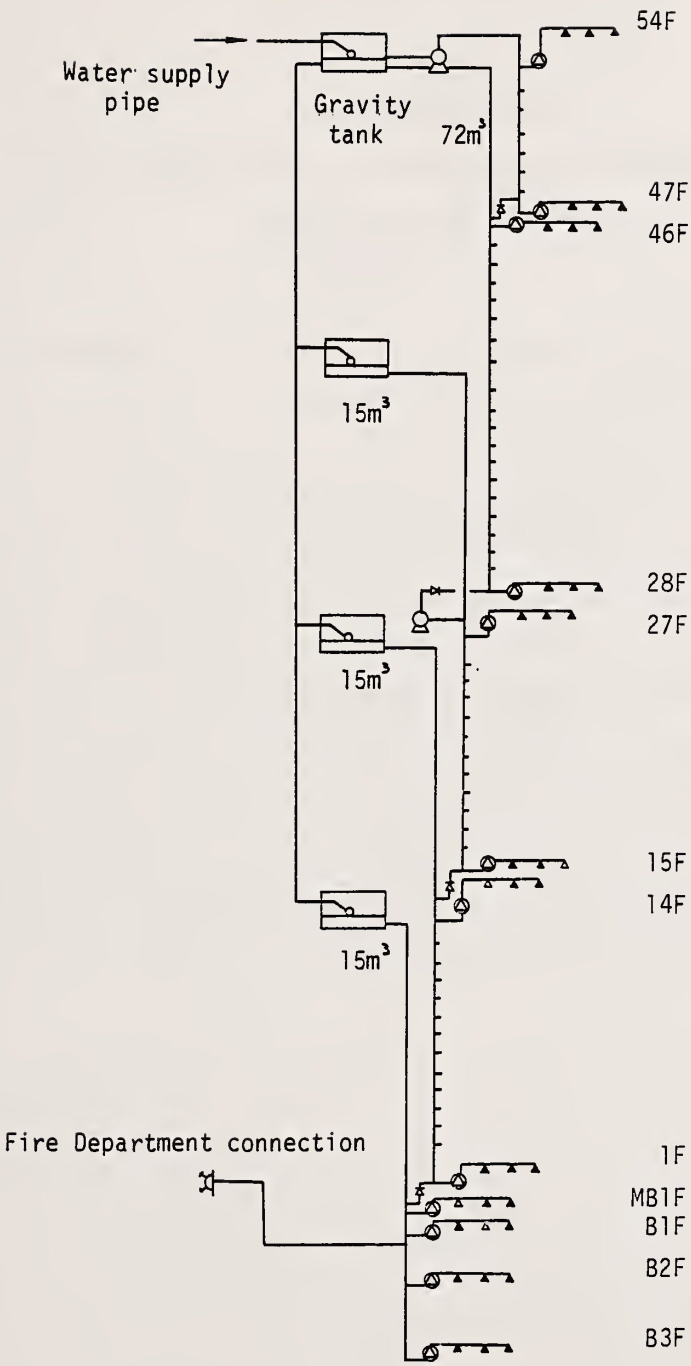


Fig.14: Water supply arrangement for sprinkler system in high-rise building (Gravity tank system)

ADVANCES IN RESIDENTIAL SPRINKLERS

by

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Factory Mutual Research Corporation
Norwood, Massachusetts

October 15-17, 1980

ABSTRACT

Sprinkler performance as affected by sprinkler link sensitivity, link temperature rating, and water distribution has been investigated in several typical flame-initiated residential fire scenarios.

Commercially available sprinkler links representative of the most sensitive on the market were employed for sprinkler activation. It was demonstrated that links considerably more sensitive than the commercial link are essential in providing adequate protection in residential fires.

In the ventilated living room fire tests with combustible walls and ceiling, the fire was fast developing and highly challenging. Adequate water application to the corner of the room, where the fire source was located, and to the walls was found to be critical in controlling such a fire. The required sprinkler operation conditions have been determined in terms of sprinkler water distribution associated with a link five times more sensitive than the commercial link.

ACKNOWLEDGEMENTS

The work was supported by the United States Fire Administration (USFA) under Grants No. NFPCA 76054 and USFA 79019 and monitored by Mr. Harry Shaw of USFA.

I INTRODUCTION

The statistics on 1978 fires published by the U.S. Fire Administration show that residential fires account for 77 percent of civilian fire fatalities, 46 percent of dollar loss, and over 50 percent of fire-fighter injuries[1]. It is evident that residential fires are our nation's number one fire problem.

For over 100 years, attempts have been made to reduce fire losses. Loss experience has provided evidence that sprinkler systems have significantly contributed to reduction of fire losses. In the 1860's, before automatic sprinkler systems appeared, annual fire losses at Factory Mutual insured properties averaged over 30 cents per $100 of insured value. Later, as sprinklers became installed in industrial and commercial properties, the figure dropped steadily to a level of 2 to 3 cents per $100 in recent years[2].

Since the introduction of sprinklers, fire tests have been conducted extensively to determine required sprinkler operation conditions for industrial fire protection in terms of water discharge density (water discharge rate in gpm in ratio to the designed coverage area in ft^2), sprinkler spacing, and sprinkler link temperature rating (link fusing temperature). The emphasis has always remained on industrial applications.

A National Fire Protection Association (NFPA) Standard on residential sprinkler systems (NFPA 13-D-1975) has been available since 1975[3]. However, NFPA 13-D, resulting from relaxation of the industry-oriented sprinkler standard, produces a system too costly to be widely installed. Furthermore, the adequacy of protection provided by commercial sprinklers in accordance with the NFPA 13-D Standard has not been evaluated sufficiently in realistic residential fire tests. Thus, sprinklers, the most effective means yet devised for fire suppression, are still limited almost exclusively to the protection of industrial and commercial properties.

Due to the low ceiling height and compartmentation in residental buildings, the hot ceiling gases generated by a fire tend to descend quickly below eye level. It is vital that the sprinkler link be sufficiently sensitive to respond to the fire at a sufficiently early stage to maintain a survivable environment in the room of fire origin throughout the fire.

Standard commercial sprinklers are designed for achieving fire control with several sprinklers operating at approximately 10-ft by 10-ft spacing. The voids in the water distribution pattern of a spray usually presented behind the arms of the sprinkler frame may be filled up by adjacent sprinkler sprays. However, in residential fires, the effective control of fire by sprinklers often depends on a single sprinkler operation in the room of fire origin. It is essential that sprinkler water distribution tend toward uniformity in angular distribution, so that, even if a fire starts behind the arms of the sprinkler frame, adequate amounts of water can still be delivered to the fire source. In addition, combustible items such as sofa, chair, bureau, and drapes are often placed close to or against the walls. A residential sprinkler is required to protect the furniture at the periphery of the room and even the combustible walls. The NFPA 13-D Standard permits the use of standard sprinklers in residences to cover a 16-ft x 16-ft floor area at approximately 25 gpm water discharge rate. Most standard sprinklers throw little water to the upper portion of a wall which is more than 6 ft from the sprinkler. New sprinklers with water distribution sufficient to protect the walls must be developed.

In 1976, the U.S. Fire Administration began to sponsor several programs in the area of residential fire suppression systems. In one of these programs, Factory Mutual Research Corporation (FMRC) has been engaged in evaluating sprinkler performance in residential fire tests. In the first phase of this program(4), a common residential fire scenario was simulated, a cigarette dropped into the crevice of a couch in the living room, with subsequent initiation of smoldering and eventual transition to flaming fire. There were no combustibles in the test room other than the couch; windows and doors were closed. Up to the time of flaming, the major burning areas were on the cushion and the bolster of the couch and the fires had developed rather slowly. The fire was exposed and could be reached by the sprinkler spray. The required discharge rate to control such a fire is quite small.

The second phase of FMRC's program is concerned with flaming-started fires(5). In these tests, several typical fire scenarios were selected. The second phase of the program was designed to investigate sprinkler performance as affected by sprinkler link sensitivity, link temperature rating, and water distribution. In this paper, only some of the important results from the second phase are presented.

The information gained in this program has served as a guide for the sprinkler industry in developing residential sprinklers. The research results of this program will provide a basis for new installation standards for residential sprinkler systems and will also lead to new evaluation standards for residential sprinklers for approval and listing by recognized laboratories.

II TEST VARIABLES

The fire tests were designed to investigate sprinkler performance as affected by sprinkler response time, water discharge rate, and water distribution in various typical flame-started residential fires.

The response time of a sprinkler in a fire depends on 1) the gas velocity and gas temperature histories (fire development) adjacent to the sprinkler, and 2) the sprinkler link sensitivity and its temperature rating. The link sensitivity is expressed by its time constant, defined as the time required for the link to reach an excess temperature (temperature above initial temperature of the link) which is a fraction, 0.632, of the excess gas temperature in a constant-velocity, constant-temperature gas stream. The time constant depends predictably upon gas velocity and is independent of gas temperature[6]. The time constants of the sprinkler links and the simulated sprinkler links used in this program were measured in a hot air wind tunnel[6] at 7.4 ft/s air velocity and 367°F temperature. All the time constants cited hereafter are referenced to a velocity of 7.4 ft/s.

Results of six fire tests are presented to illustrate the effects of sprinkler link sensitivity, link temperature rating, and water distribution on sprinkler performance. The six tests consist of a nonventilated small bedroom fire, two ventilated living room fires with noncombustible walls and ceiling, and three ventilated living room fires with combustible walls and ceiling.

In the small bedroom fire test, a commercial 5/16-in. orifice diameter sprinkler was used, discharging 4.3 gpm covering 12.3 ft x 8.8 ft floor area. The sprinkler was activated by a commercially avaiable sprinkler link representative of the most sensitive on the market. The time constant of the commercial link used was 73.9 sec.

In the two ventilated living room fire tests with noncombustible walls and ceiling, the same commercial 5/16-in. orifice sprinklers were used. In one of the two tests, commercial links were used for sprinkler activation; in the other test, simulated sprinkler links with much higher sensitivity (time constant = 16.9 sec) were employed for sprinkler activation.

TABLE I

TEST VARIABLES

Test No.	Ventilation	Wall and Ceiling Material	Sprinkler	Sprinkler Orifice *K factor (gpm/psi$^{1/2}$)	Link Sensitivity at 7.4 ft/s gas velocity (sec)	Link Temp. Rating (°F)	Initial Link Temp. (°F)	Water Discharge Rate (one sprinkler operation) (gpm)	Water Discharge Rate (two sprinkler operations) (gpm)
1 Small Bedroom	Windows and Door Closed	Combustible	Commercial 5/16-in. Orifice Sprinkler	2.01	73.9	165	77	43	Not Applicable
2 Living Room	Windows and Door Open	Noncombustible	Commercial 5/16-in. Orifice Sprinkler	2.01	73.9	165	69	6	6 + 6
3 Living Room	Windows and Door Open	Noncombustible	Commercial 5/16-in. Orifice Sprinkler	2.01	16.9	140	69	6	6 + 6
4 Living Room	Windows and Door Open	Combustible	Manufacturer's Prototype 1	2.69	15.1	136	66	12	9 + 9
5 Living Room	Windows and Door Open	Combustible	Manufacturer's Prototype 2	3.00	15.1	136	71	15	
6 Living Room	Windows and Door Open	Combustible	Manufacturer's Prototype	3.00	15.1	136	76	15	

In the three ventilated living room fire tests with combustible walls and ceiling, two different types of manufacturer's prototype sprinklers were used. Both manufacturer's prototypes were activated by links with a 15.1-s time constant. The sprinkler variables of these six tests are summarized in Table I. Figure 1 is a photograph of the three sprinklers used.

III TEST SETUP

3.1 TEST FACILITY

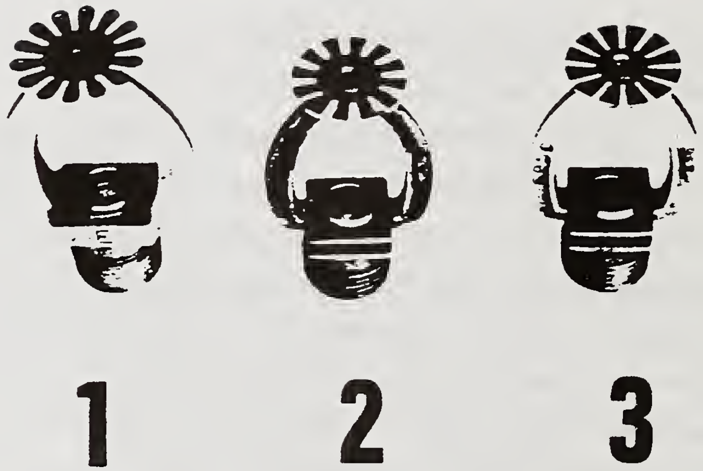
The fire tests were conducted in one of FMRC's test buildings in Norwood, Massachusetts. The building contains a 741 ft^2 apartment area and a 139 ft^2 instrument room.

The ceiling height in the apartment area and instrument room is uniformly 8 ft. With the exception of the north half of the living room, the ceiling was constructed with 2-ft x 4-ft Armstrong "Fire Guard" ceiling panels suspended from the beams of the building structure. Figure 2 shows the layout of the test apartment. Wall partitions are 5/8-in. gypsym boards framed in "Unistrut" channels (Unistrut Corporation). All the living room fire tests were conducted in the living room area of the test apartment. During all tests, the doors to the instrumentation room (close fitting), the observation room (11/16-in. undercut), and the bathroom were closed. During the ventilated living room fire tests, two windows in the north wall and the entry door were fully open. For the small bedroom fire test, a wall partition was erected 8.8 ft from the north wall in the living room to convert the northern area of the living room into a simulated small bedroom. During the bedroom fire test, the windows at the north wall and the door in the partition wall were closed.

3.2 FURNISHINGS

Scale layouts of the furnishings with location coordinates for the small-bedroom fire, and living room fire tests are shown in Figures 3 and 4 respectively. Full descriptions of the small bedroom and living room furnishings are included in Tables II and III. In the living room fire tests, the window curtains were pulled aside as shown in Figure 4. The dimensions and positions of the window openings are also shown in Figure 4.

For the small-bedroom fire test, a suspended ceiling was made of 2-ft x 4-ft combustible ceiling panels (297C Grenoble Temlock, Armstrong Cork Corporation), 1/2-in. thick, consisting of loblolly pine, oak and cornstarch. Plywood



(1) commercial 5/16-in.-orifice sprinkler

(2) manufacturer's prototype #1

(3) manufacturer's prototype #2

FIGURE 1 PHOTOGRAPHIC VIEW OF TEST SPRINKLERS

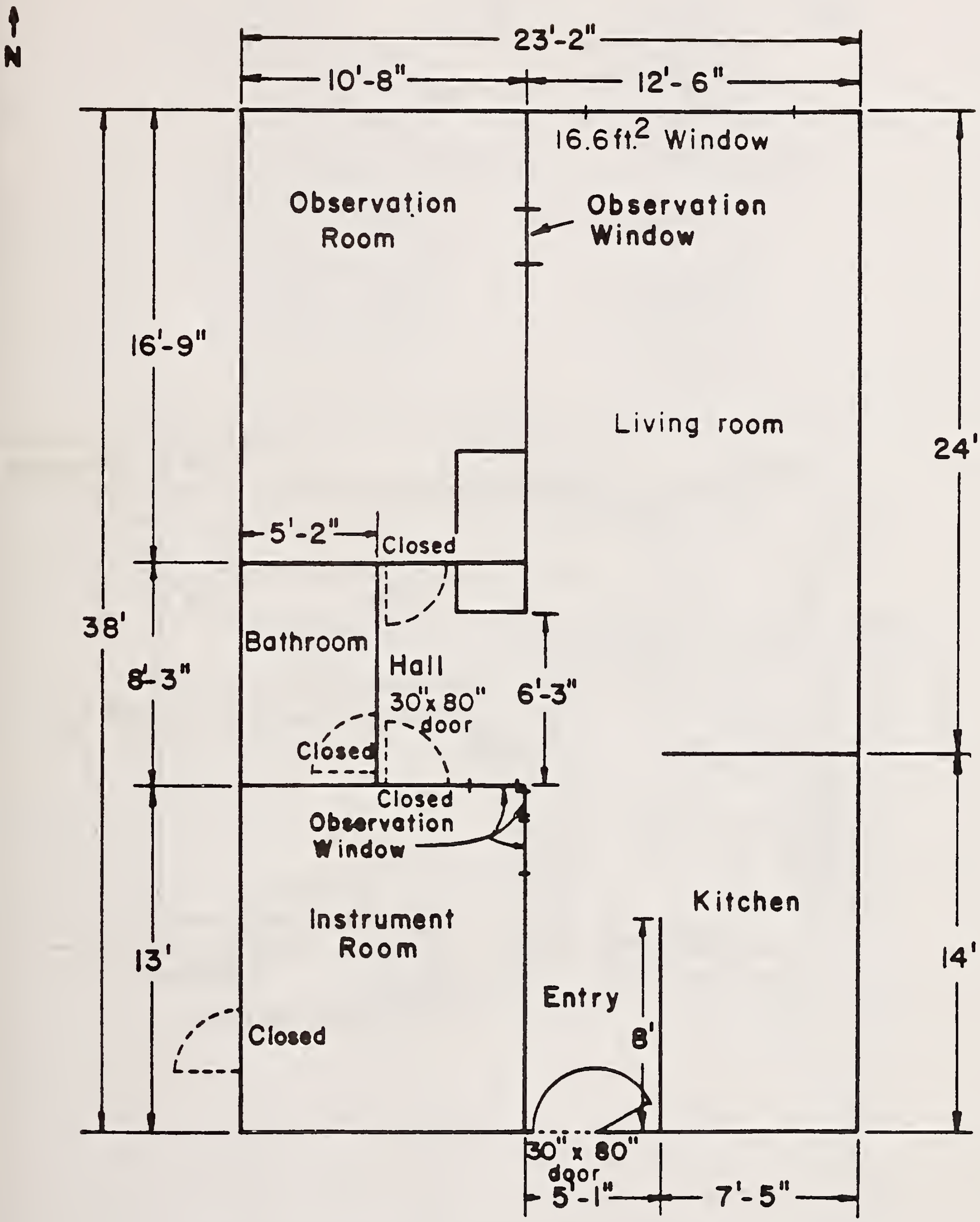


FIGURE 2 TEST APARTMENT FLOOR PLAN

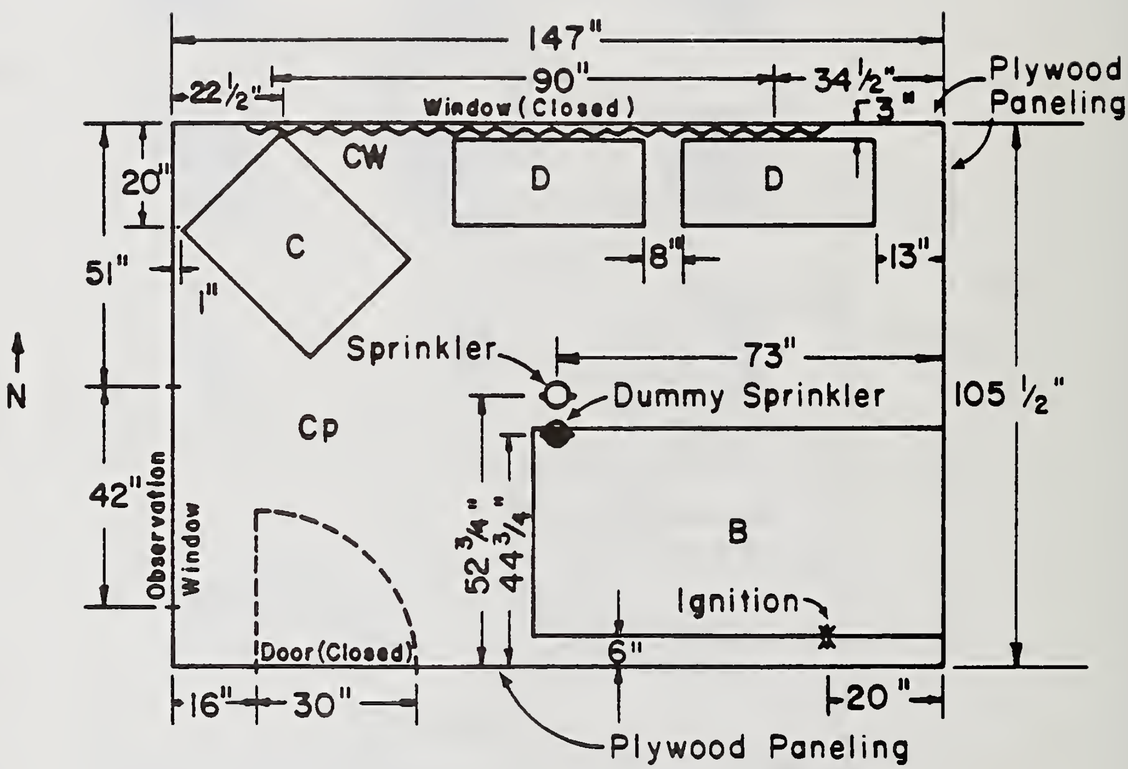
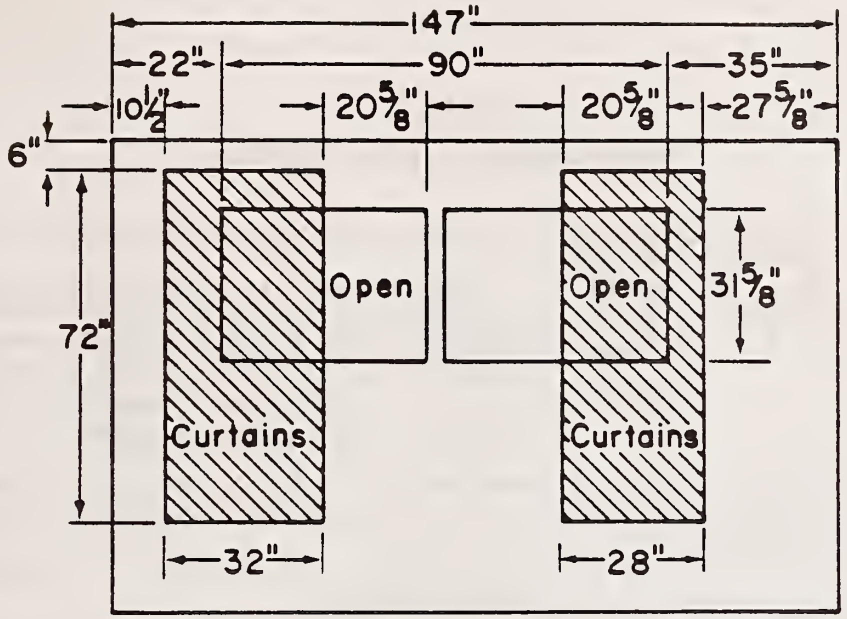
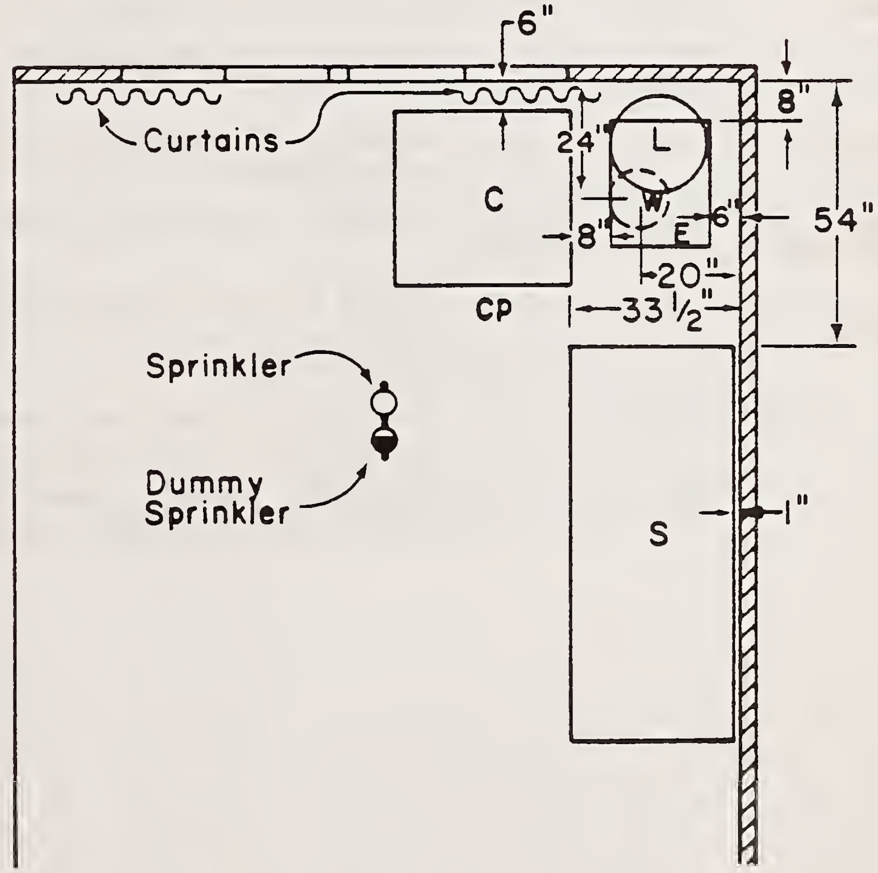


FIGURE 3 FURNISHINGS IN SMALL BEDROOM



NORTH WALL



FLOOR PLAN

FIGURE 4 FURNISHINGS IN THE VENTILATED LIVING ROOM

TABLE II

FURNISHINGS IN SMALL BEDROOM

Item	Code (Fig. 4)	No. of Units	Dimensions (in.) and Description
Bed	B	1	39Wx79L, mate's bed, solid hardwood, 2 guided drawers, maple finish, with mattressboard: 1 3/4-in. thick wood, covered in polypropylene nonwoven fabric, Sears 1K6761N2
Mattress	B	1	39Wx79Lx4H, polyurethane foam covered with non-woven polyester fabric, Sears 1K70112N
Bottom Sheet	B	1	Twin fitted, 50% cotton, 50% polyester Sears 96K6940
Top Sheet	B	1	Twin flat, 50% cotton, 50% polyester Sears 96K6944
Blanket	B	1	Twin size, 100% acrylic, Sears 96K8750H-543
Bedspread	B	1	Twin size, 100% cotton, Sears 24K14012H-561
Pillow	B	1	20Wx26L polyester fill cotton cover Sears 96K5305
Pillow Case	B	1	20Wx30L, 50% polyester, 50% cotton, Sears 96K6945
Curtains (2 panels/set)	CW	2 (sets)	72Wx63L, 100% cotton, Sears 24K14029H
Dresser (6 drawer)	D	2	36Wx13 1/2Lx29H, Solid knotty pine, with hard-board back, one coat of polyurethane finish, Sears 1K10866N
Chair	C	1	28Wx35Lx33H Pine frame, steel springs, 2-piece polyurethane vinyl coated cushions
Carpet	CP	1	147Wx105L, Indoor/outdoor olefin pile, latex backed, Sears 37K5031-NPH-6

TABLE III

FURNISHINGS IN LIVING ROOM

Item	Code (Fig. 5)	No. of Units	Dimensions (in.) and Description
Sofa	B	1	83Wx36Lx25H, Body-80% cotton felt, 20% urethane foam, cushions-80% urethane foam, 20% polyester fiber cover-herculon, J. Homestock #201310048
Chair	C	1	36Wx36Lx39H, Blended cotton felt, 40% (cotton liners 70%, cotton pickers 30%), polyurethane foam 50%, cellulose fiber pad 10%, cover-vinyl, J. Homestock #243-1-432-0
End table	E	1	Constructed with compressed wood slab (26 in. x 19.5 in. x 1/2 in. thick) and wood studs (1.5 in. x 1.5 in. x 19 in. high)
Curtains	CW	12	6 panels (40Wx72L) 56% cotton 27% rayon, 9% acetate, 8% polyester, 6 sheer panels (40Wx72L, 1.5 oz/yd) Batiste fabric woven/100% polyester Sears 24K4507H
Carpet	CP	1	96Wx96L, Indoor/outdoor olefin pile, latex backed, Sears 37K5031-NPH-6
Lamp	L	1	15 dia x 15 H, lamp shade made by Patterson Shade Co, Style No. 2540
Wastebasket	W	1	Model 2132, Cities Service Co., Box 826 Pittsburgh, Pa. 15230

panels (3/16-in.) thick were nailed to spruce studs (1 1/2 in. x 3 5/16 in.) mounted directly to the existing north and east walls. The partition was constructed with plywood panels nailed directly over spruce studs (1 1/2 in. x 3 5/16 in.). Photographic view of the pretest appearance of the small bedroom is shown in Figure 5.

For the living room fire tests with noncombustible walls and ceiling, Armstrong "Fire Guard" ceiling panels (2 ft x 4 ft x 1/3 in. thick, Model 915, Armstrong Cork Corporation) were fastened to the 5/8-in. gypsum board ceiling in the northern half of the living room. Instead of plywood panels, 5/8-in. thick gypsum boards were nailed to the wood studs on the north and east walls.

For the living room fire tests with combustible walls and ceiling, combustible ceiling panels (2 ft x 4 ft x 1/2 in. thick, 297C Grenoble Temlock, Armstrong Cork Corporation) were fastened to 5/8-in. gypsum board ceiling in the northern half of the living room. Plywood panels (3/16-in. thick) were nailed to the studs on the north and east walls. A photographic view of the ventilated living room with furnishings is shown in Figure 6.

3.3 INSTRUMENTATION

The room of fire origin was instrumented to measure: 1) gas concentrations of carbon monoxide, carbon dioxide, and oxygen at "eye level" (63 in. above the floor); 2) gas temperatures at five elevations (93, 84, 63, 36, and 6 in. above the floor) in one location; 3) ceiling surface temperature immediately above the ignition point; 4) optical density (a measure of smoke obscuration) at "eye level" (63 in. above the floor); and 5) gas velocities and gas temperatures near the sprinklers (3 in. below ceiling level). Figures 7 and 11 show the instrumentation plans for the small bedroom and living room fire tests. All data signals, except optical density, were monitored by a data acquisition system with a Hewlett-Packard 2100 S computer. Every second, the system scanned the data channels and logged the data on a computer disk.

Carbon monoxide, carbon dioxide and oxygen were measured at a single location near the center of the room using Beckman CO, CO_2, and O_2 analyzers. The gas sample was drawn to the analyzers through 3/8-in. ID (1/2-in. OD) aluminum tubes and Tygon tubing and then cleaned through a glass wool filter, a condenser, and a desiccant.

FIGURE 5 PRE-TEST APPEARANCE OF SMALL BEDROOM

FIGURE 6 PRE-TEST APPEARANCE OF VENTILATED LIVINGROOM
WITH COMBUSTIBLE WALLS AND CEILING

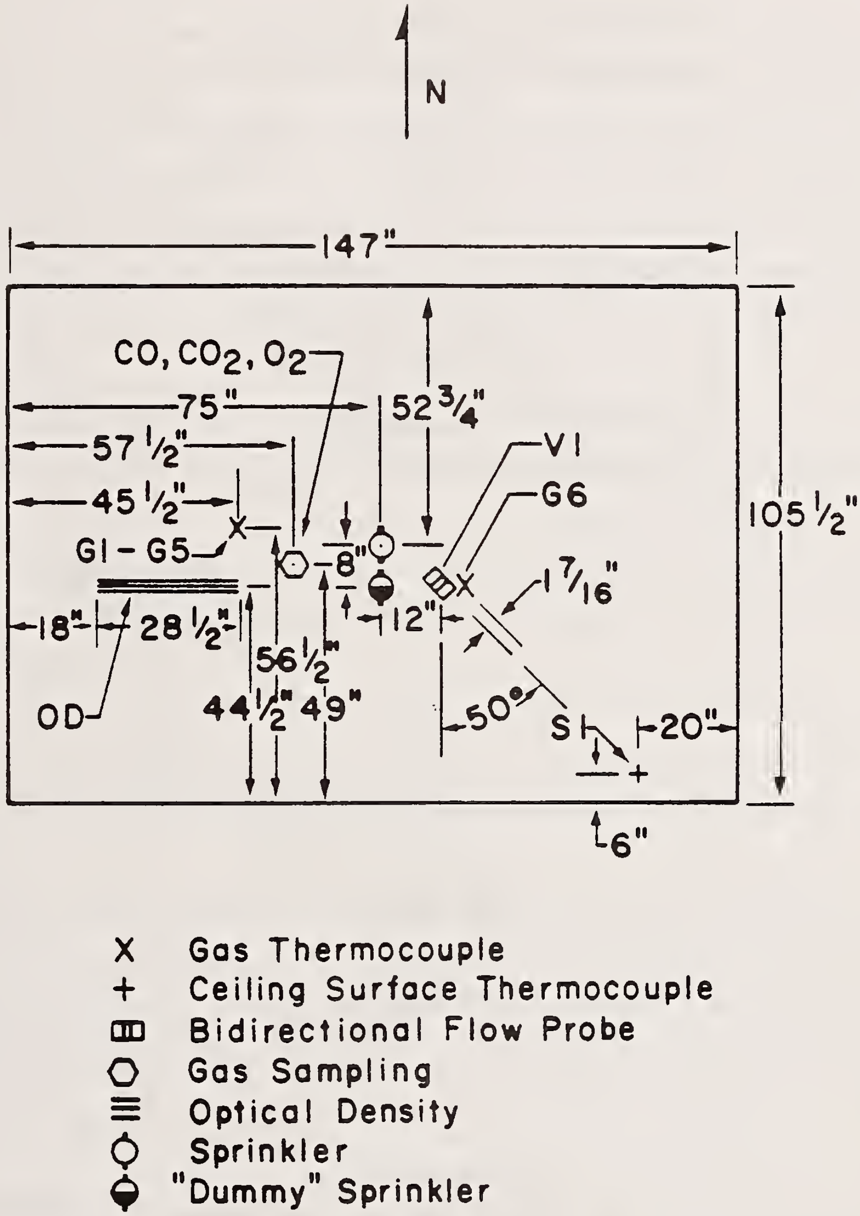


FIGURE 7 SMALL BEDROOM INSTRUMENTATION LOCATIONS

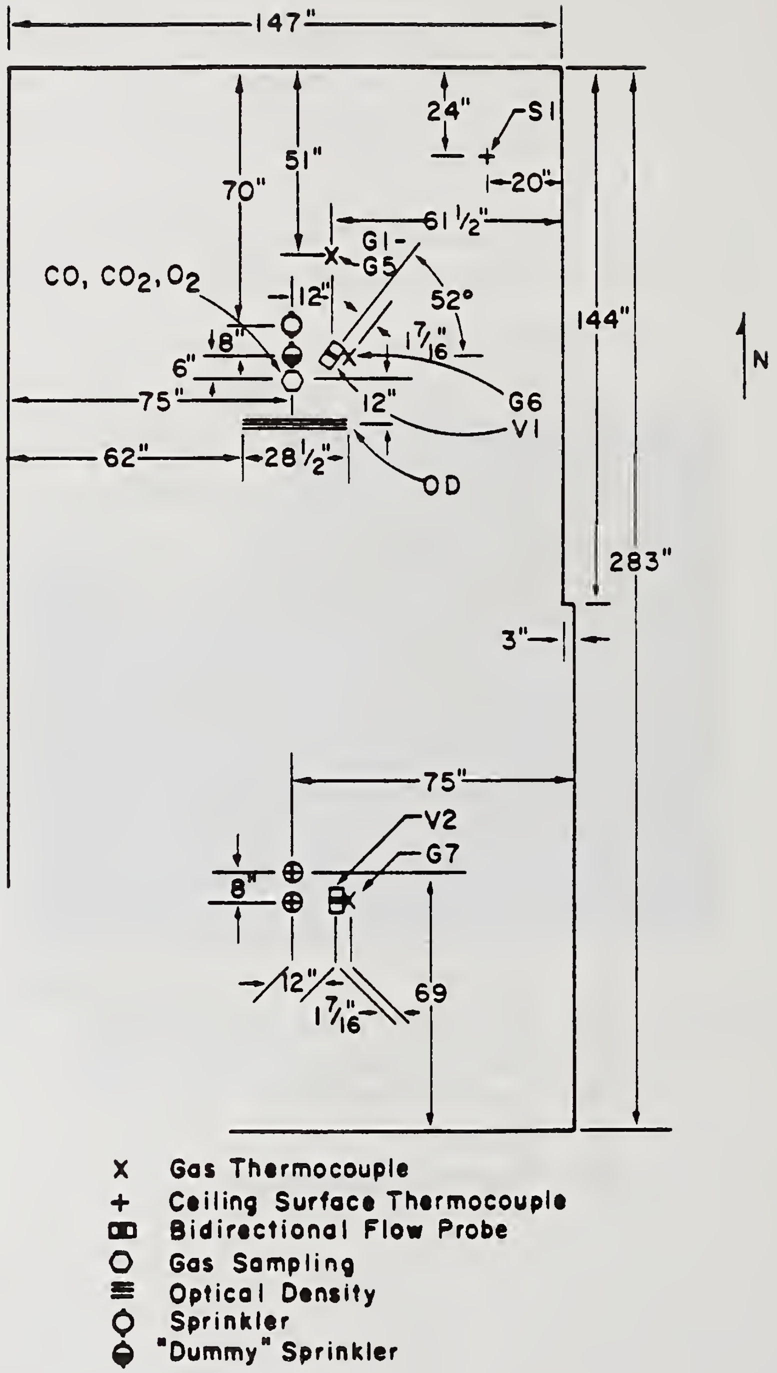


FIGURE 8 LIVING ROOM INSTRUMENTATION LOCATIONS

The delay times for the CO, CO_2, and O_2 measurements were 16.6, 15.4, and 24.5 sec respectively. All data presented in the report have been adjusted for delays of the sampling system.

Gas velocities in the vicinity of the sprinklers were measured 3 in. below the ceiling using bidirectional flow probes[(7)], which sense and indicate flows in opposite directions with equal sensitivity and are relatively insensitive to flow deviation from probe axial direction. The probes were connected to individual electronic manometers (Datametric Barocel). With this system, it was possible to measure reliably velocities down to 1 ft/sec. The locations and orientations of the flow probe in the small bedroom and living room are shown in Figures 7 and 8 respectively.

Thermocouples, fabricated from 30-gage, chromel-alumel thermocouple wire (inconel sheath), were used to measure gas temperatures. A vertical traverse of five thermocouples (93, 84, 64, 36, and 6 in. from the floor) was installed in the room of fire origin (G1 to G5 in Figures 7 and 8). A 1/2-in. wide "Unistrut" channel was used to support the five thermocouples and shield them from direct water impingement.

Adjacent to the velocity probe, a gas thermocouple (G6 in Figure 7; G6 and G7 in Figure 8) was placed 1 7/16 in. from the probe axis and shielded from the sprinkler by the probe to measure gas temperature in the vicinity of the sprinkler.

The ceiling surface temperature immediately above the ignition source (Figures 8 and 8) was measured by a thermocouple fabricated from 28-gage chromel-alumel thermocouple wire. The thermocouple was imbedded in a shallow groove filled with Kaowool paste such that the thermocouple bead was flush with the ceiling surface.

IV TEST PROCEDURE

A residential sprinkler system is intended to maintain a survivable environment within the fire room for a limited period of time, sufficient for occupants to be rescued (or possibly to escape). A period of 15 min after sprinkler operation appears reasonable. Therefore, all tests were conducted for a period from time of ignition to at least 15 min after first sprinkler operation.

Prior to each test, all thermocouples were checked; micromanometers were calibrated and set; the optical density meter was checked; and the CO, CO_2, and O_2 analyzers were calibrated and set. Weather conditions were noted: the wind condition, inside and outside air temperatures, and inside and outside relative humidity (see Table IV).

Before each test, the flow rate for the first sprinkler operation was set. In the living room fire test, at the time of second sprinkler activation the total flow rate was increased to a predetermined rate.

The ignition source for the small-bedroom fire (Test S1.2) was a full sheet of newspaper rolled up into a ball and placed on the floor under the side of the bed (see Figure 3 for ignition location). The newspaper was then ignited by a match. For all living room fire tests, ignition was accomplished by an electric match placed through a hole on the side of a plastic wastebasket 1 in. up from the bottom. The electric match was placed near three full sheets of newspaper, each rolled into a ball, that were placed in the basket. Above the rolled newspapers were four bundles, each consisting of seven full sheets of newspaper folded in half three times. The electric match was powered by 120 V/ac through a manually operated switch.

V SPRINKLER WATER DISTRIBUTION

In order to investigate the effects of sprinkler water distribution on sprinkler performance in the fire tests, water distributions on floor and walls were measured for the sprinkler discharge conditions employed in the test program (with the exception of the discharge condition in the small bedroom fire). Since each of the sprinklers was symmetrical with respect to the plane of the supporting arms of the deflector and also with respect to the orthogonal plane, only the water distribution of a quarter of the sprinkler spray bounded by these two planes was measured.

Water distribution measurements were conducted in the FMRC Hydraulic Laboratory. For the measurement of water distribution on the floor, 64 square water-collection pans, each having a collection area of 1 ft x 1 ft, were arranged in a square matrix of 8 x 8 pans on the floor with pans touching. The outline of the matrix of the collection pans relative to the sprinkler position

TABLE IV

PRETEST WEATHER CONDITIONS

Test No.	Wind (mph; dir)	Bar (in. Hg.)	Temp °F Outside	Temp °F Inside	Rel. Humidity % Outside	Rel. Humidity % Inside	Ventilation
1	N/A	N/A	N/A	71	N/A	81	No
2	N/A	N/A	N/A	63	N/A	39	Yes
3	14 WSW	29.80	46	55	73	N/A	Yes
4	10 NW	29.70	48	55	63	N/A	Yes
5	21 E	29.74	39	54	85	85	Yes

N/A - Not Available

is shown in Figure 9a. A 4-ft x 4-ft ceiling was installed 8 ft above the level of the top edges of the pans, below an existing 10-ft x 12-ft ceiling. (Note that the ceiling height in the fire test building is also 8 ft.) The sprinkler was installed at the center of the 4-ft x 4-ft ceiling with the deflector 3 in. below the ceiling and with the plane of the supporting arms parallel to one side of the matrix of the collection pans. A front view of this setup is shown in Figure 9b. Water collected in each pan over a period of time (3 min to 15 min) was measured in a graduated cylinder.

After completion of the floor water distribution measurements, all 64 pans were removed and the vertical water distributions were measured at three positions on each of the two vertical planes 6 ft from the sprinkler (see Figure 10). Three racks of collection pans were fabricated, each rack consisting of eight pans. Rack B in Figure 10 corresponds to the wall region behind the right arm of the chair where initial intense burning occurred in the living room fire tests. Each pan has a 1-ft wide x 1/2-ft high vertical collection area; Figure 11 provides the pan dimensions. The arrangement of the eight pans on a rack with the bottom pan positioned on the floor is shown in Figure 12. The distance between any two adjacent collection surfaces was 6 in. The elevation of the ceiling above the bottom edge of the bottom collection area was 7 ft 11 in. Measurements were first made with three racks placed on one plane, the bottom pans resting on the floor as in Figure 12. Then all the pans were moved up 6 in. to measure the water densities of the 1-ft x 1/2-ft gap areas initially not included. The procedure was then repeated on the othogonal plane.

Figures 13-16 present the floor and vertical water distribution data of the commercial 5/16-in. sprinkler operating at 6 gpm, the manufacturer's prototype 1 at 12 and 9 gpm, and the manufacturer's prototype 2 at 15 gpm.

The average water application density, w_c, over the 25 pans represented by the shaded area in the floor water distribution plan (Figures 13 to 16) is used as an <u>indicator</u> of the amount of sprinkler water reaching the fire source in the corner of the living room. The outer edges of the shaded area were 7.5 ft from the centerline of the sprinkler. In the actual living room fire tests, the east and north walls of the living room were 6 ft from the sprinkler, as indicated by the dashed corner in Figures 13 to 16. The water collection reported outside the dashed corner in Figures 13 to 16 is an indicator of the amount of water

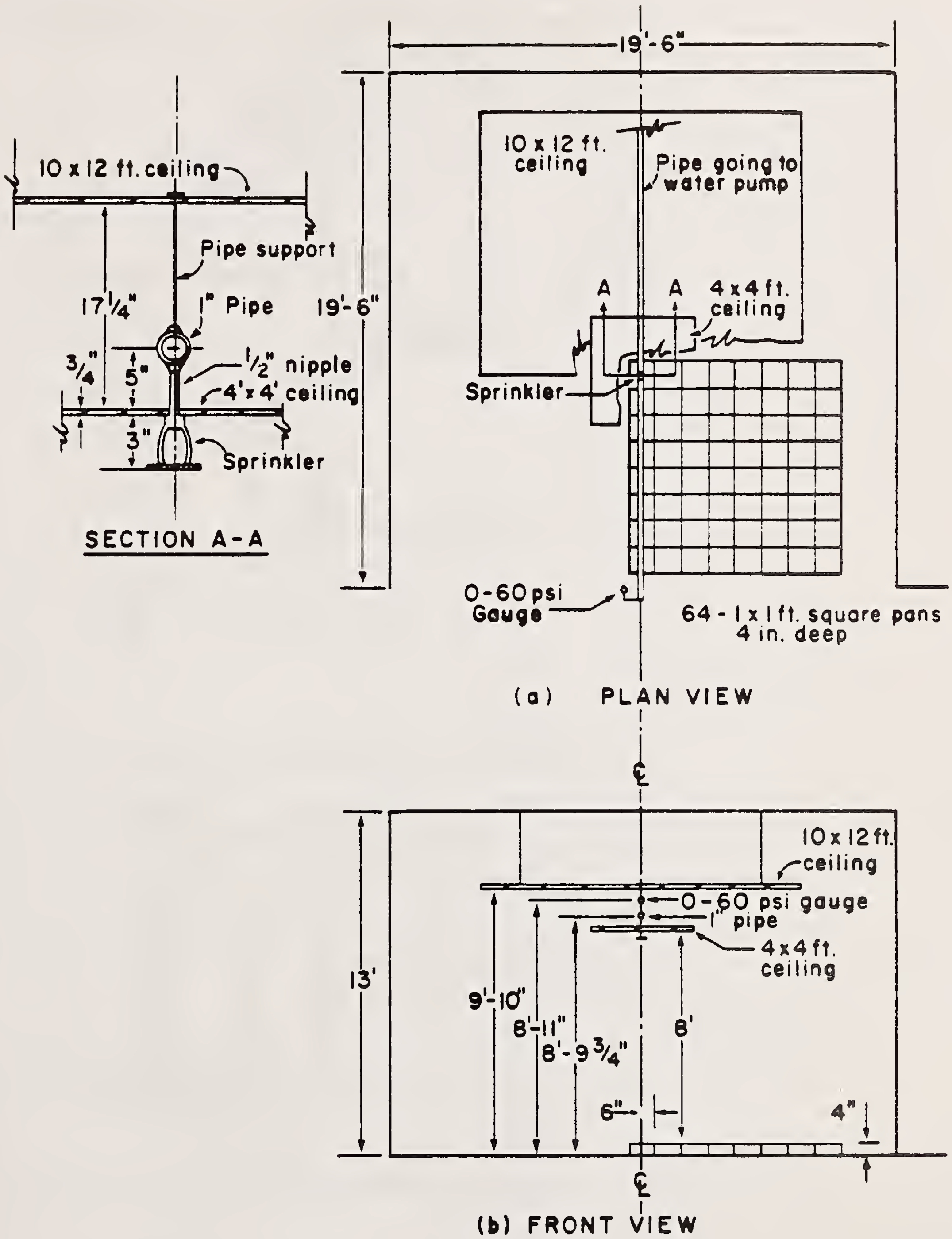
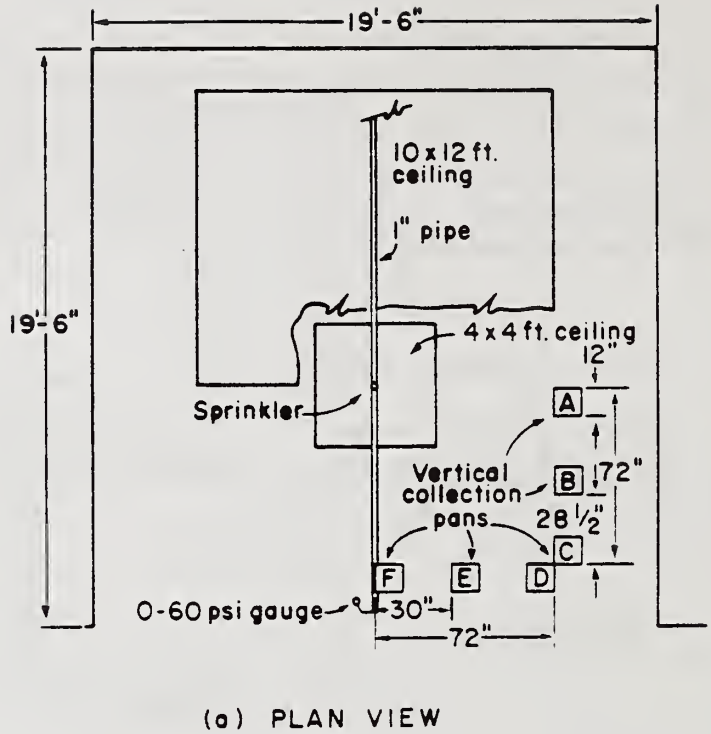


FIGURE 9 PLAN VIEW AND FRONT VIEW OF SETUP FOR FLOOR WATER DISTRIBUTION MEASUREMENT



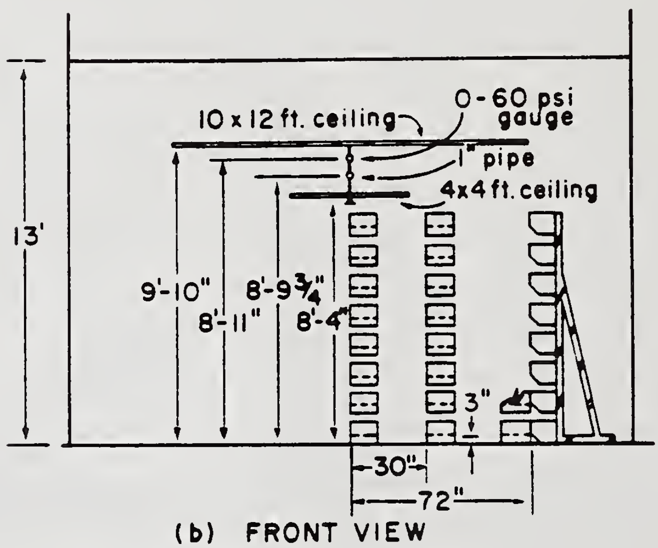


FIGURE 10 PLAN VIEW AND FRONT VIEW OF SETUP FOR VERTICAL WATER DISTRIBUTION MEASUREMENT

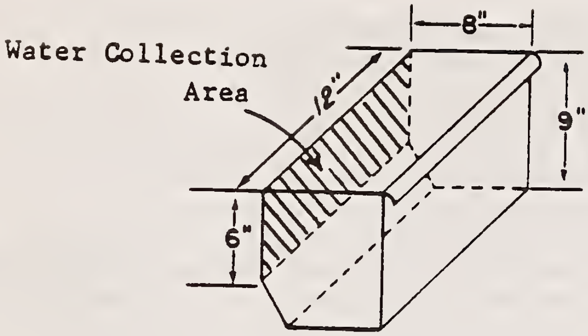


FIGURE 11 WATER COLLECTION PAN

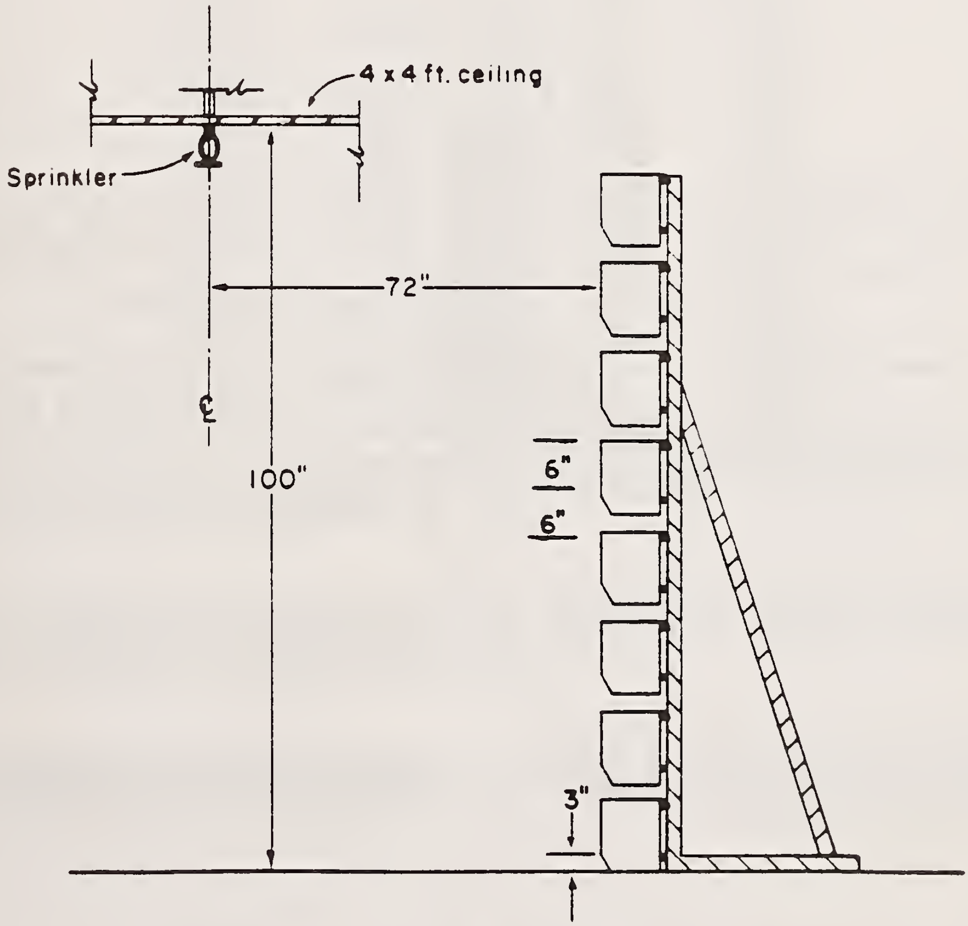


FIGURE 12 VERTICAL DISTRIBUTION RACK

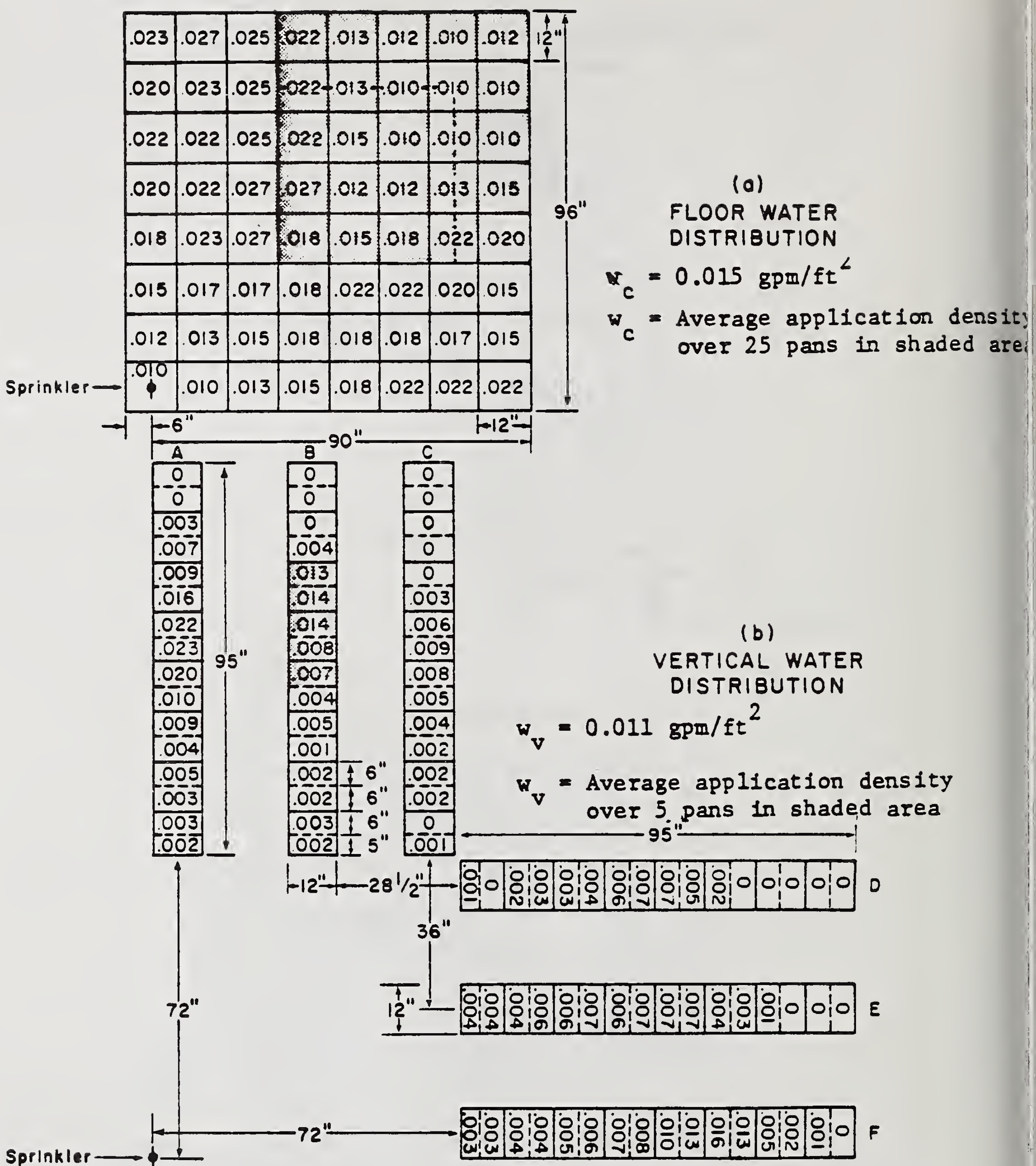


FIGURE 13 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Commercial 5/16-in. Orifice Sprinkler, K=2.01, 6gpm, 9psig, For Tests 2 and 3

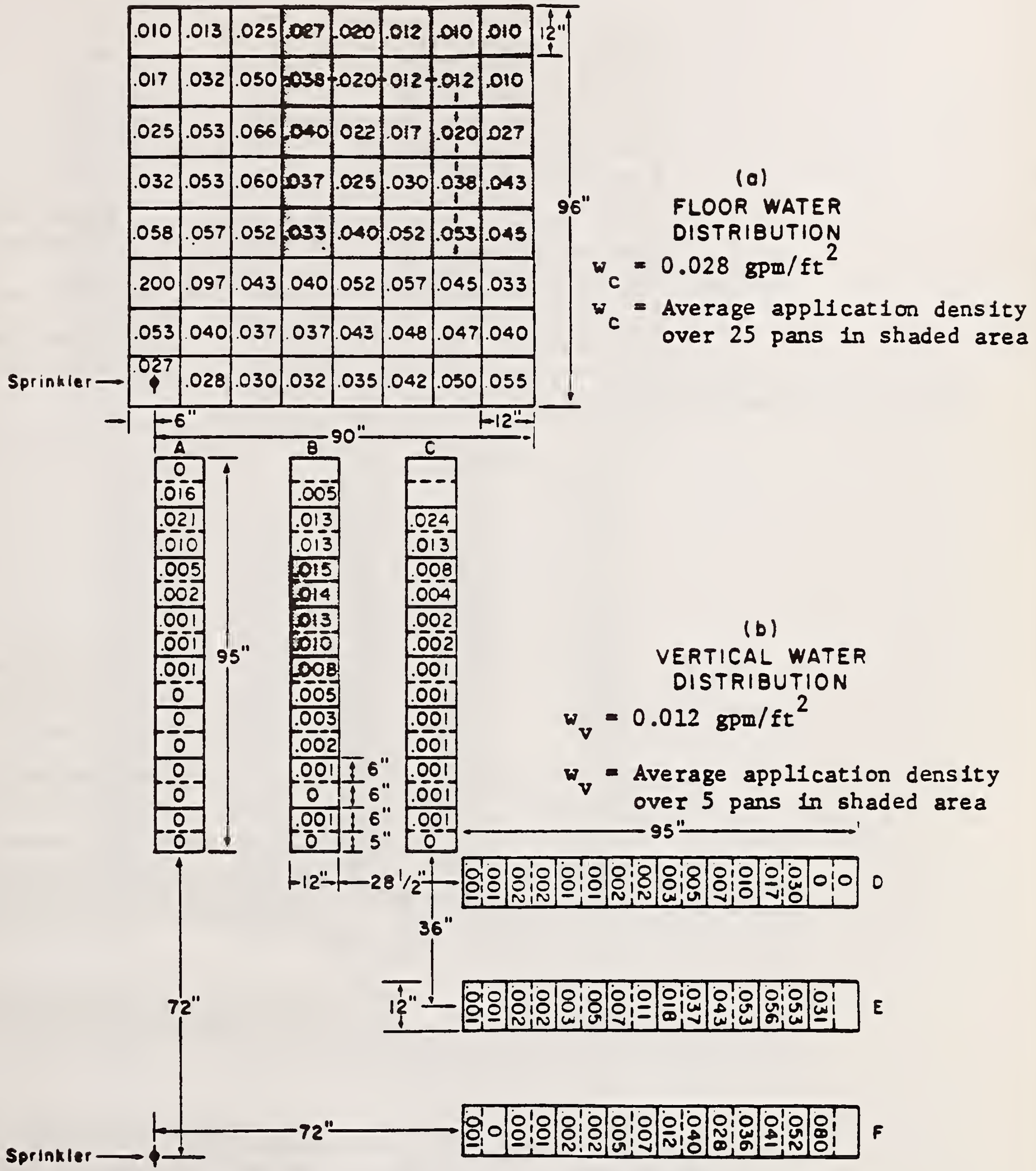


FIGURE 14 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Manufacturer's Prototype No. 1, K=2.69, 12gpm, 19.9psig, For Test 4

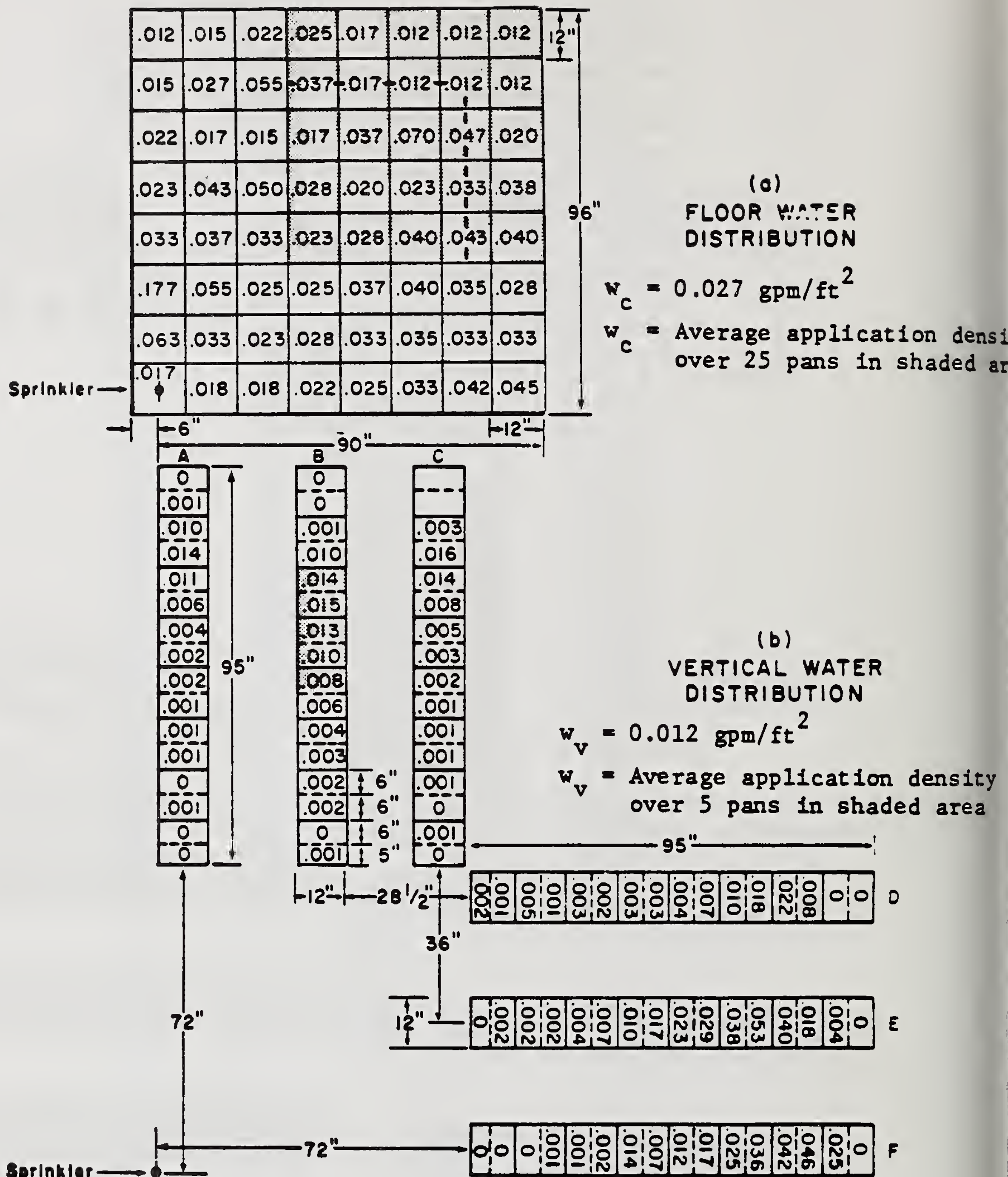


FIGURE 15 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Manufacturer's Prototype No. 1, K=2.69, 9gpm, 11psig, For Test 4

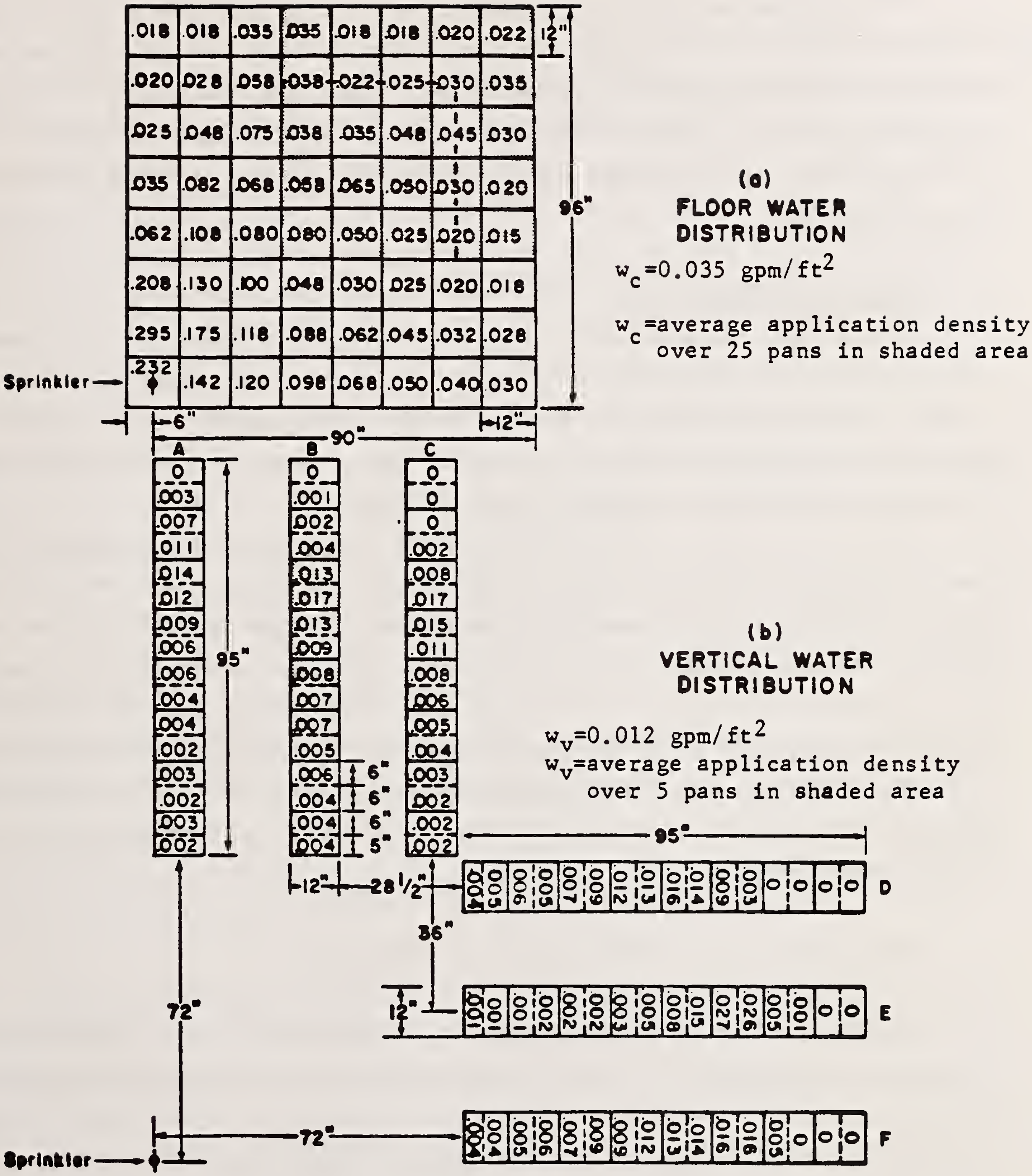


FIGURE 16 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Manufacturer's Prototype No.2, K=3.00, 15gpm, 25psig, For Test 5

which would have hit the lower portion of the walls if walls had been present during these water distribution measurements.

If walls had been present, water collected over the 1-ft x 2.5-ft shaded area of Rack B in the vertical water distribution plan of Figures 13 to 16 would have dripped along the plywood panel behind the chair, affecting ignition of the walls in the living room fires. The vertical application density, w_v, over the 1-ft x 2.5-ft shaded area indicates the amount of water delivered to protect the wall.

VI RESULTS AND DISCUSSION

To evaluate the adequacy of life-safety protection provided by sprinklers, measurements were made of CO, CO_2 and O_2 gas concentrations and gas temperature at eye level in the room of fire origin. The ability of residential sprinklers to provide property protection was assessed by measurement of the ceiling surface temperature over the fire source.

Sprinkler response time with known link sensitivity and temperature rating can be predicted theoretically by means of gas temperature and velocity histories at the sprinkler. Measurements of gas temperature and velocity in the vicinity of the sprinkler closest to the fire source were used to aid in the selection of a sprinkler link with a sensitivity such that, at the time of sprinkler activation, the fire would stil be in the early stage of its rapid development.

The sprinkler water distribution required to control residential fires has been determined from the fire test results, together with sprinkler water distribution measurements.

6.1 LIFE SAFETY AND PROPERTY PROTECTION CRITERIA

6.1.1 Life Safety Criteria

Measurements of CO and gas temperature at eye level in the room of fire origin were employed to evaluate the adequacy of life safety protection provided by sprinklers.

Carbon monoxide has been identified as the major toxic gas in the fire environment causing fatality[8]. The primary toxic effect exerted by CO is to reduce the oxygen-carrying capacity of the blood. Once CO enters the body, it combines reversibly with the chief oxygen-carrying protein of the red blood cells, hemoglobin. This complex of CO and hemoglobin is termed "carboxyhemoglobin" (CO Hb); a 16-20 percent CO Hb saturation in venous blood will cause headache and an "abnormal visual evoked response."[9] The amount of CO Hb formation in the blood depends on the concentration and exposure duration. It is estimated[9] that a 43-min exposure at 1000 ppm, a 100-min exposure at 500 ppm, or a 400-min exposure at 200 ppm will result in a 20-percent CO Hb saturation in blood. Estimates of "hazardous levels" reported by Yùill[10] are 1,600 ppm for 1/2 hr, 800 ppm for 12 hr and 120 ppm for 8 hr. Kimmerle[11] reported that CO concentration at 1500 ppm will cause death after one hour of inhalation. A conservative criterion was selected for evaluating the CO hazard in the test program; the maximum CO concentration at eye level in the room of fire origin was required to be less than 1500 ppm throughout the entire test period, i.e., from the time of ignition to 15 min after sprinkler activation.

Inhalation of carbon dioxide rapidly leads to abnormal breathing. As little as 2 percent of CO_2 by volume in the inspired air effectively stimulates respiration and 3 percent doubles the lung ventilation. Inhalation of 7 to 10 percent CO_2 may be fatal within a short period.[12]

The normal oxygen content of air is 21 percent. Diminishing the supply of oxygen to 12 to 15 percent will result in shortness of breath, headache, dizziness and rapid fatigue. An oxygen supply of 6 to 8 percent will cause collapse, with the possibility of death.[11,12]

On the subject of human tolerance to heat, Kimmerle[11] reported that gas temperatures of more than 212°F in a fire environment were capable of causing loss of consciousness and death within several minutes. The criterion adopted for evaluating the heat hazard in the program was that the gas temperature at eye level should be less than 200°F throughout the test period.

6.1.2 <u>Property Protection Criteria</u>

Measurements of ceiling surface temperature over the fire source were used to assess the ability of residential sprinklers to provide property protection. Cellulosic and plastic material usually begin to pyrolyze vigorously at a temperature of about 500°F.[13,14] The limit for the ceiling surface temperature directly above the ignition point is selected to be 500°F in order for sprinkler protection of property to be considered adequate.

6.2 TEST RESULTS

6.2.1 Small Bedroom Fire Test

Gas concentrations of CO, CO_2 and O_2 at the 63-in. level near the center of the room are shown in Figure 17. The maximum CO and CO_2 concentrations are 1107 ppm and 1.8 percent respectively, and the minimum O_2 concentration is 16.5 percent. The CO and CO_2 concentrations and O_2 deficiency were smaller than the critical values.

Gas temperatures at three elevations, 93 in., 60 in., and 36 in. from the floor, are shown in Figure 18. The gas temperatures measured at the three elevations reached maximum values at about the time of sprinkler activation (2 min, 5 sec). After sprinkler operation, the voltage readings from the thermocouples measuring these temperatures seemed to indicate that the thermocouple beads were wetted by the sprinkler spray. The eye-level gas temperature reached 241°F at the time of sprinkler activation. In such a small room, a more sensitive sprinkler link would have been required in order to activate the sprinkler before the eye-level gas temperature reached 200°F.

The maximum ceiling surface temperature over the ignition point was maintained below 165°F. In this test, combustible walls and ceiling were used but were not involved in the fires.

6.2.2 Ventilated Living-Room Fire Tests with Noncombustible Walls and Ceiling

In Test 2, commercially available sprinkler links with a time constant of 73.9 sec and a temperature rating of 165°F were employed. At the time of the first sprinkler operation, the fire was already in the very rapidly accelerating stage, and the gas temperature adjacent to sprinkler No. 1 already reached 465°F. The fire had spread to the full length of the curtains. The side of the chair was burning intensely and flames were sweeping across the ceiling. Fire jumped to the side of the sofa 1 sec before sprinkler activation.

In Test 3, simulated links with much higher sensitivity (time constant = 16.9 s) were used for sprinkler activations. Links were selected to have a sensitivity such that, as the link reached the rated temperature, 140°F, the curtains behind the chair would have just ignited and the major burning item would be still limited to the chair. The determination of the time constant of such a link was based on the histories of gas temperature and velocity adjacent to sprinkler No. 1, Test 2.

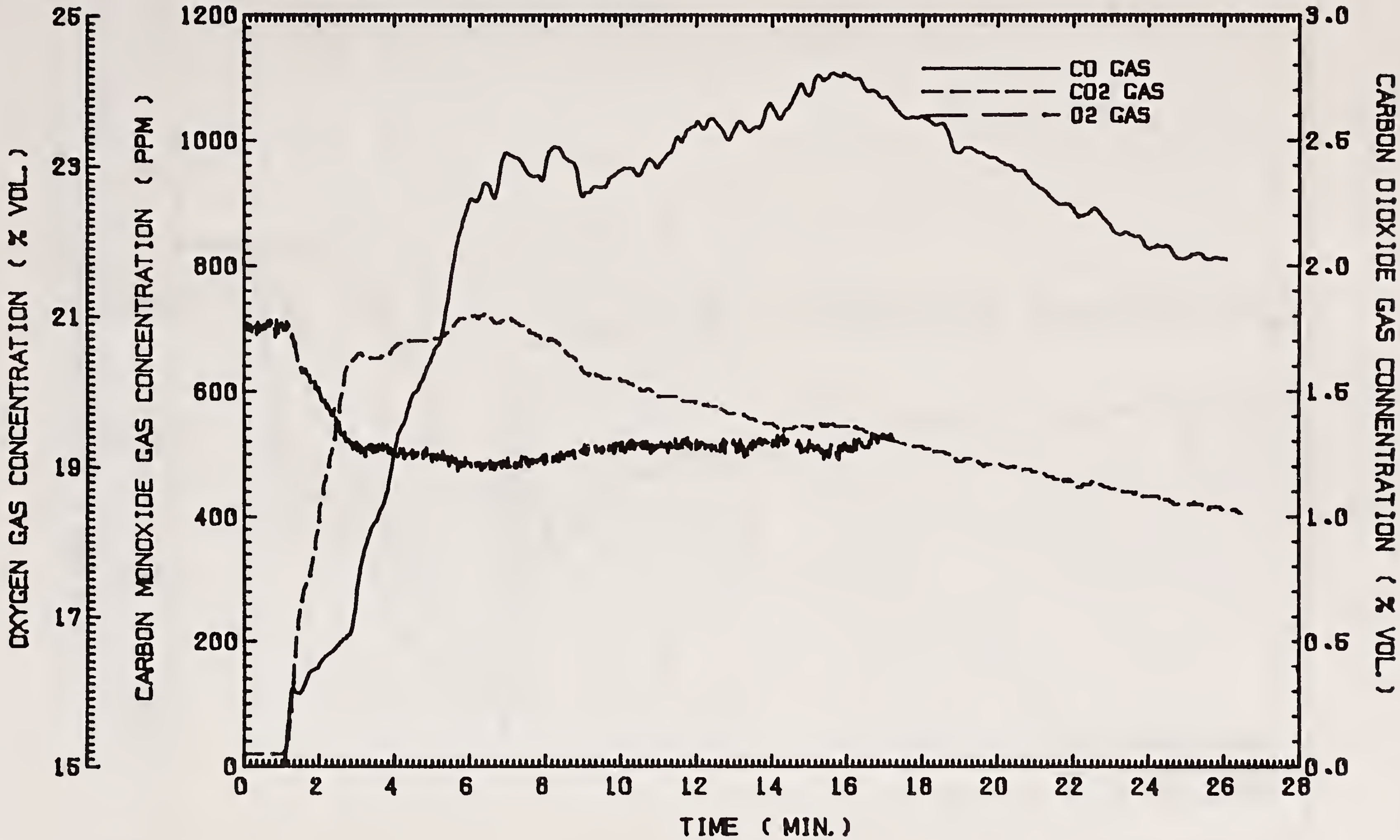


FIGURE 17 CO, CO_2 AND O_2 CONCENTRATIONS AT EYE LEVEL FOR TEST 1

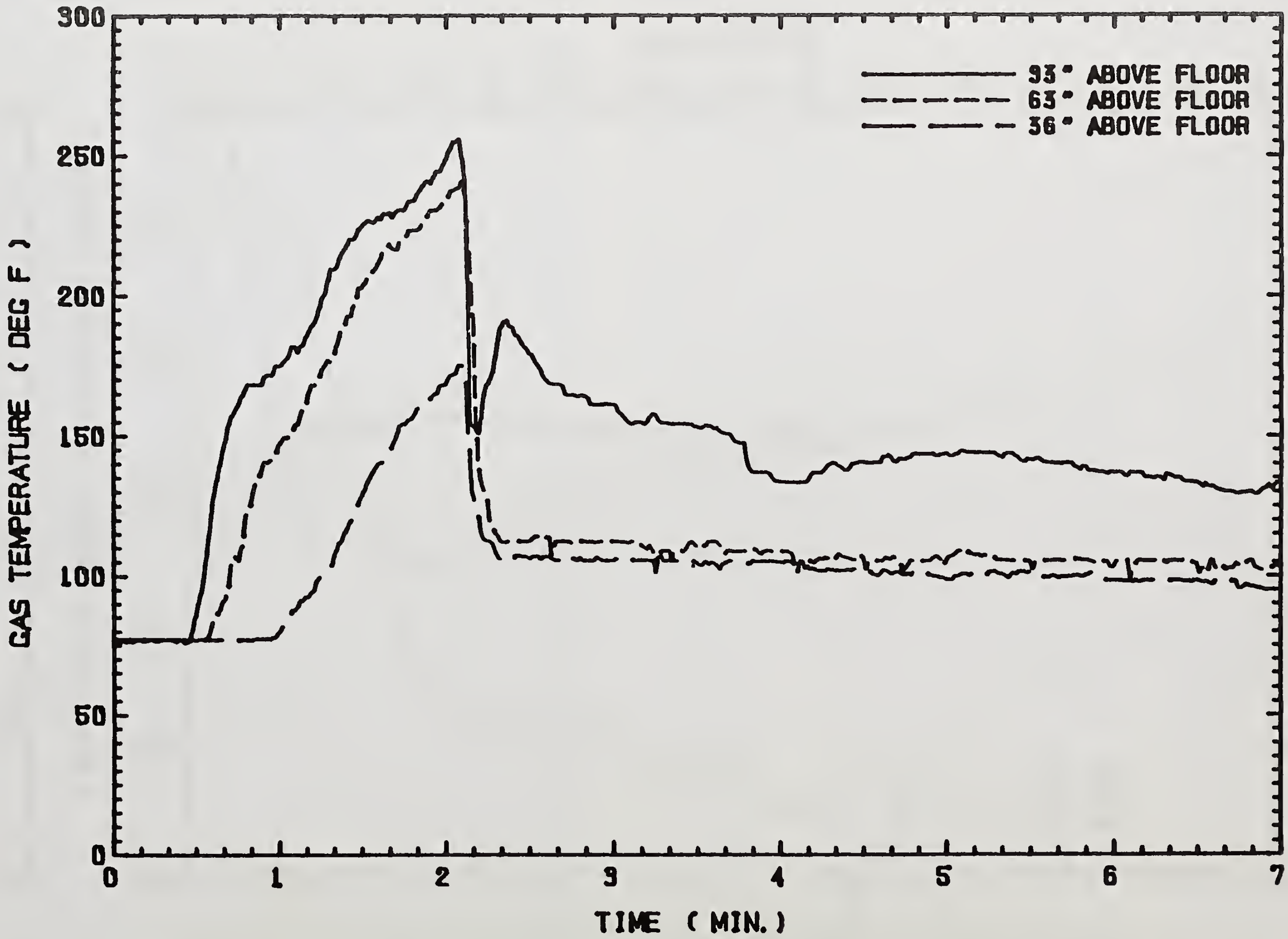


FIGURE 18 GAS TEMPERATURES AT THREE ELEVATIONS, 93, 63 AND 36 in. ABOVE THE FLOOR FOR TEST 1

The effect of sprinkler response time is investigated by comparing the results of Tests S2.1 and S2.3 which had the same water discharge rate but different link sensitivities. CO gas concentrations, gas temperatures at eye level, and ceiling surface temperatures are plotted in Figures 19, 20 and 21 respectively. For Test 3 the reference point of the time abscissa is the activation time of sprinkler No. 1 (at which time the simulated link temperature increased 71°F from its initial temperature), whereas for Test 2, the reference point of the time abscissa is the time, t_d, at which the temperature of a 16.9 sec time-constant simulated link would increase by 71°F. In Test 2, the maximum CO concentration was over 10,000 ppm, beyond the range of the CO analyzer. The maxmimum values of CO concentration, gas temperature at eye level, and ceiling surface temperature for Test 2 exceeded the critical values adopted for evaluation of sprinkler performance. The results of Test 3 demonstrate that the commercial 5/16-in. orifice sprinkler activated by a simulated link with a 16.9-sec time constant, rated at 140°F, discharging 6 gpm is capable of providing adequate life-safety and property protection in such a fast-growing fire.

In Test 3, at the time of sprinkler activation, the gas temperature adjacent to sprinkler No. 1 was only 202°F. Fire then gradually spread to the backside of the chair and was completely shielded from the sprinkler spray. The sprinkler spray tested was not capable of suppressing the fire and cooling the gases sufficiently, and the gas temperature reached a maximum value of 637°F, 129 sec after sprinkler activation. It is expected that sprinklers with the same links (rated at 140°F) in the hallway and the kitchen would also have operated.

The average water application, w_c, over the 25 pans represented by the shaded area in the floor water distribution plan in Figure 13 to 16 is used as an indicator for the amount of sprinkler water reaching over the fire source in the corner of the living room. For Tests 2 and 3, the value, w_c, was only 0.015 gpm/ft^2 (Figure 13). The fire test results indicate that, in order to suppress the fire and cool the gases sufficiently, more water is required to be delivered to the corner of the room.

6.2.3 Ventilated Living Room Fire Tests with Combustible Walls and Ceiling

The presence of the combustible walls and ceiling added a greater fire challenge to the sprinklers. With a low-sensitivity link, at the time of

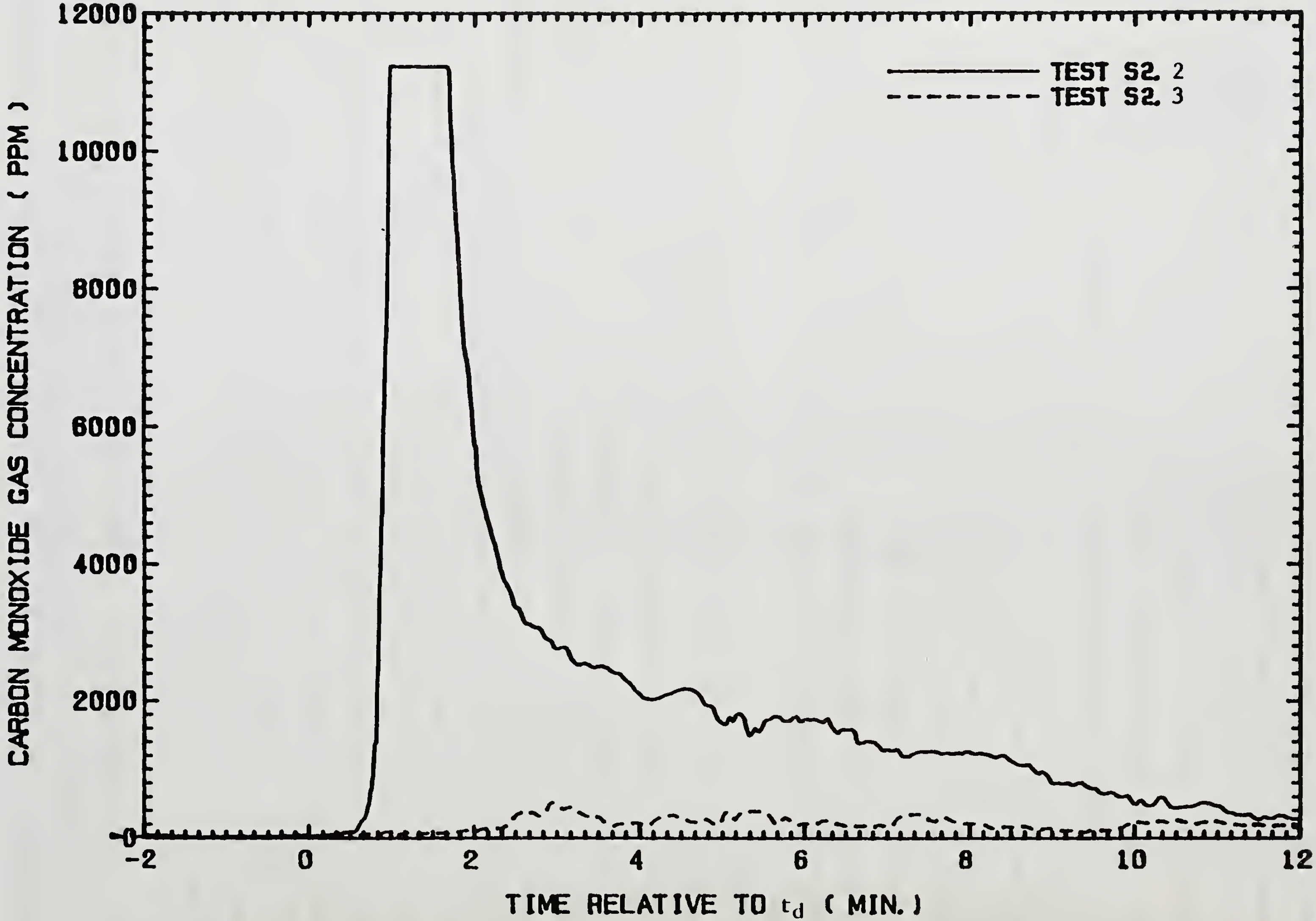


FIGURE 19 CARBON MONOXIDE GAS CONCENTRATION AT EYE LEVEL-TESTS 2 and 3
(Note: t_d= time at which the temperature of a 16.9 second time constant link would increase,or increased,by 71°F)

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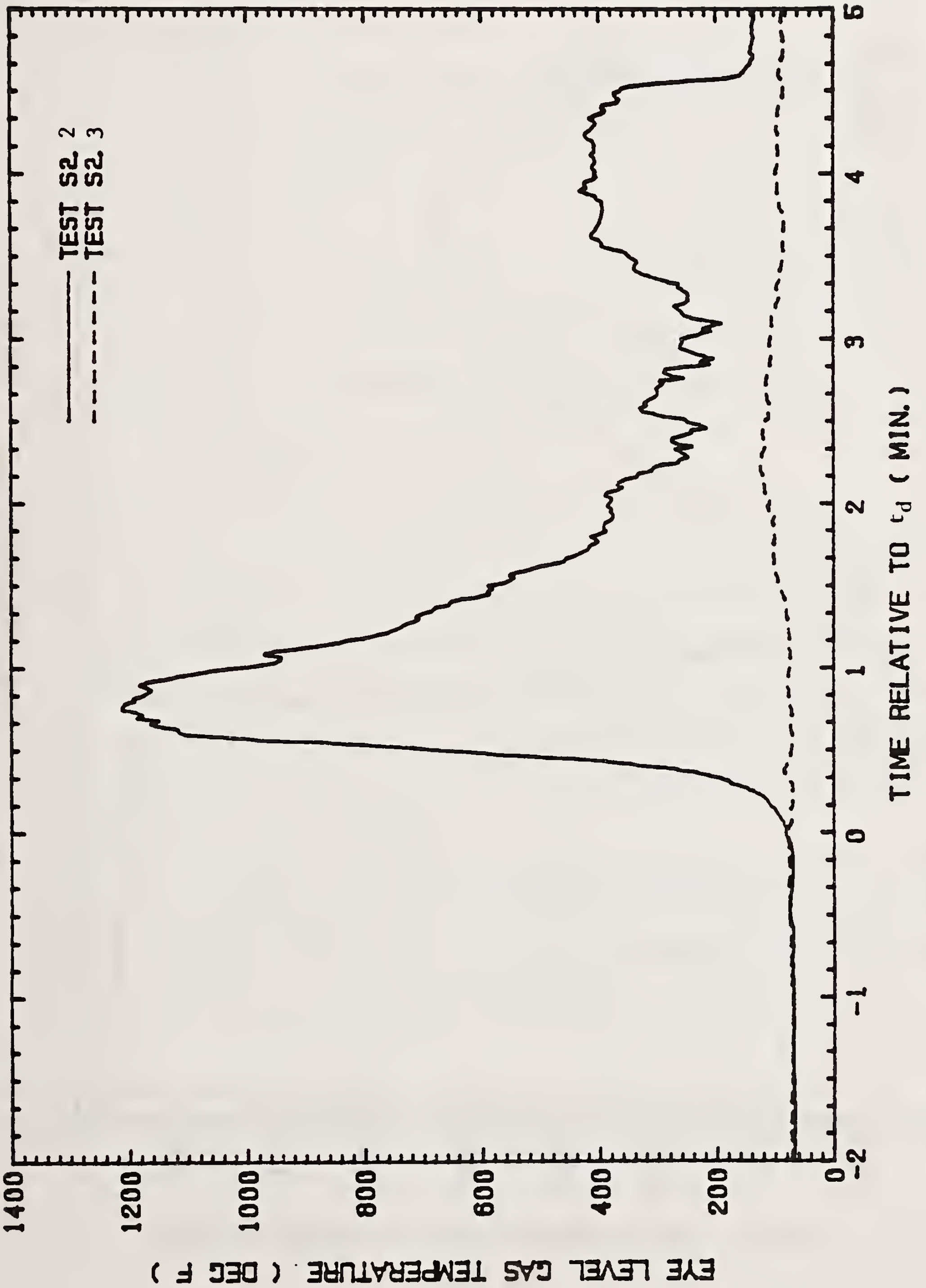

FIGURE 20 GAS TEMPERATURE AT EYE LEVEL - TESTS 2 and 3
(Note: t_d=time at which the temperature of a 16.9 second time constant link would increase,or increased,by 71°F)

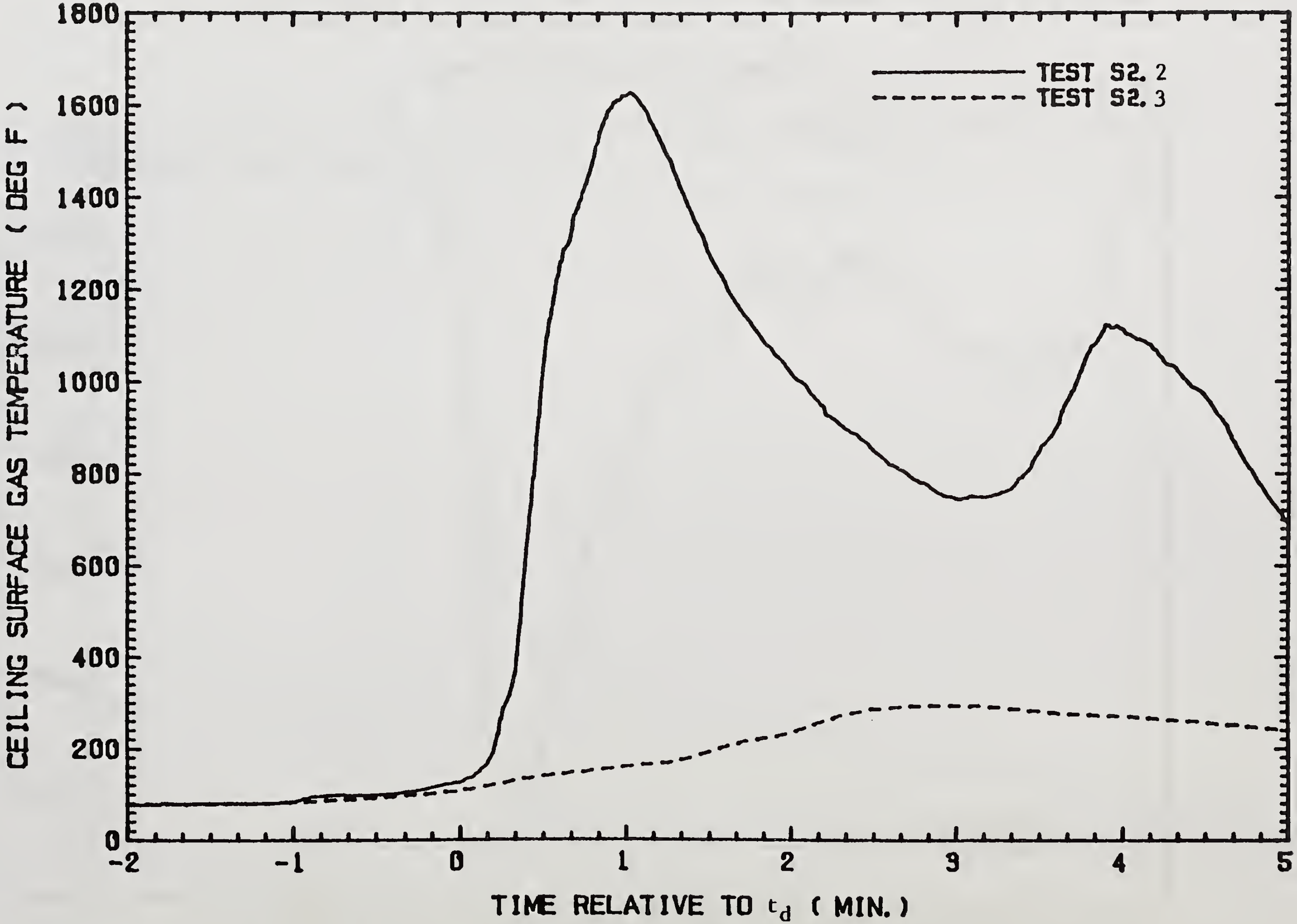

FIGURE 21 CEILING SURFACE TEMPERATURE - TESTS 2 and 3
(Note: t_d= time at which the temperature of a 16.9 second time constant link would increase,or increased,by 71^{o}F)

sprinkler activation the fire would have spread to the plywood panels and flames would be sweeping across the ceiling. Therefore, it is even more critical in such fires to have a sensitive link to activate the sprinkler when the major burning activity is still limited to the chair than in fires with noncombustible walls and ceiling. Furthermore, a sufficient amount of sprinkler water over the fire source is required to suppress the fire to prevent the ceiling panels from ignition, and adequate wetting of the combustible walls is essential to stop fire spread from the chair to the walls.

Two different kinds of manufacturer's prototype sprinklers were used. The spray patterns of these sprinklers had no apparent voids behind the arms of the sprinkler frame. Manufacturer's prototype 1, operating at 12 or 9 gpm delivers water to the walls at a height within 1 ft from the ceiling (Figures 14 and 15). Operating at 12 gpm, this sprinkler had an application density, w_c, of 0.028 gpm/ft^2 and a vertical application density, w_v, of 0.012 gpm/ft^2 (Figure 14); at 9 gpm, the values of w_c and w_v are 0.027 gpm/ft^2 and 0.012 gpm/ft^2 respectively (Figure 15). For manufacturer's prototype 2, at 15 gpm, the average application density, w_c, is 0.035 gpm/ft^2 and the vertical application density, w_v, is 0.012 gpm/ft^2 (Figure 16).

Manufacturer's prototype 1 was investigated in Test 4. With one sprinkler in operation, the sprinkler discharge rate was 12 gpm; when the second sprinkler was activated, the discharge rate through each sprinkler was 9 gpm. Although the water application density on the wall above the chair was adequate to stop the fire from jumping from the backside of the chair to the wall, the application density over the fire source, w_c, was not sufficient to prevent the fire source from igniting the ceiling above the fire and the plywood panels above the windows. Damage was quite extensive.

Manufacturer's prototype 2 was investigated in Tests 5 and 6. The discharge rate of the first sprinkler was set at 15 gpm. In both tests, only one sprinkler was activated. An adequate amount of water was delivered over the fire source and to the walls. The fire was controlled and the major burning was limited to the chair.

Gas concentrations of CO, CO_2, and O_2 at eye level for Test 4 are shown in Figure 22. The maximum values of CO and CO_2 concentrations and O_2 deficiency

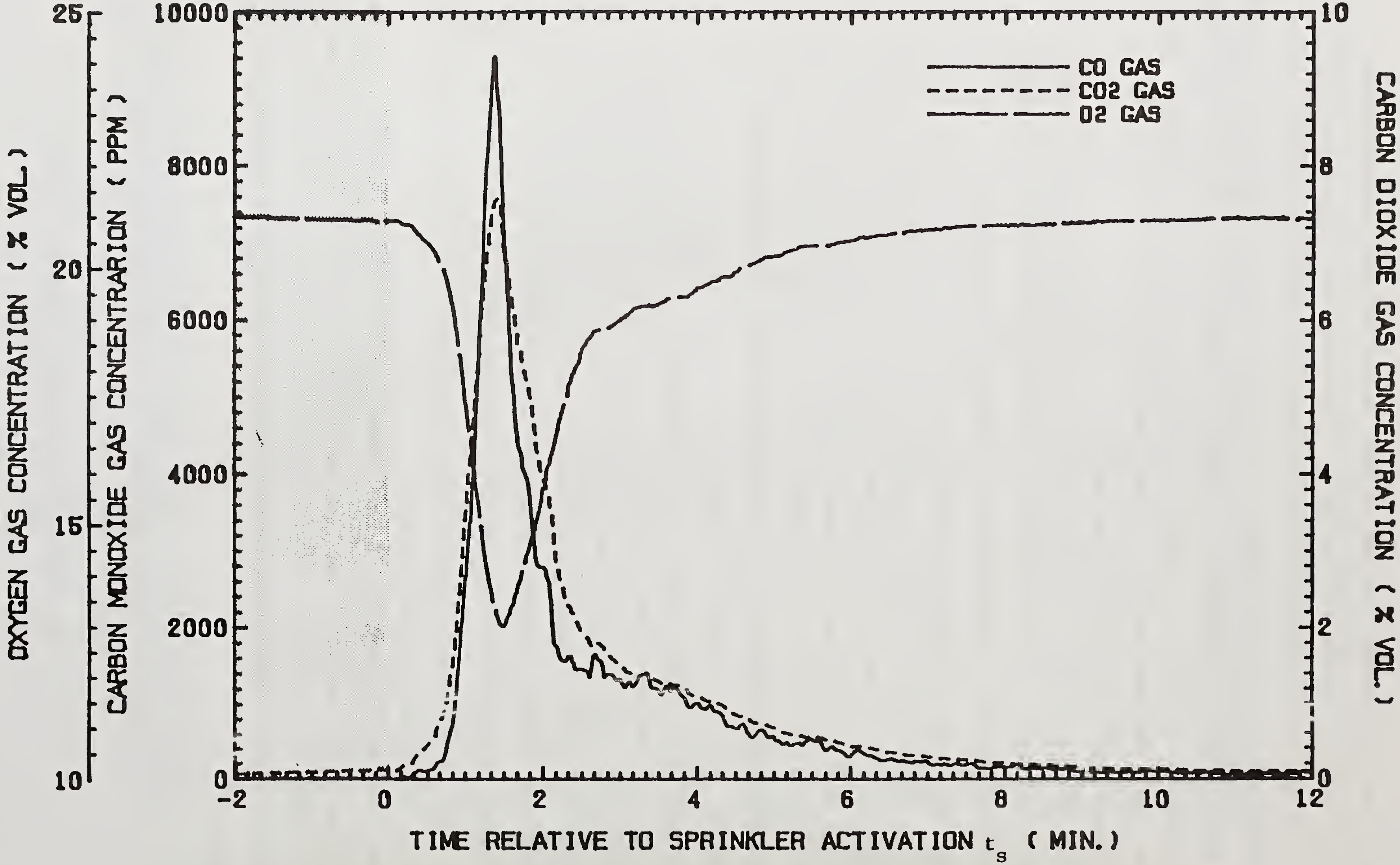

FIGURE 22 GAS CONCENTRATIONS OF CO, CO_2 AND O_2 AT EYE LEVEL - TEST 4

were 9400 ppm, 8.0 percent, and 8.9 percent respectively. Based on measurements of CO, CO_2 and O_2 concentrations, the environment in the room of fire origin is deemed nonsurvivable.

Figure 23 shows the CO gas concentrations at eye level for Tests 5 and 6. In both tests, the CO concentration had not exceeded 280 ppm.

For Tests 4, 5, and 6, eye-level gas temperature and ceiling surface temperature above ignition are shown in Figures 24 and 25 respectively. The maximum ceiling surface temperature for Test 4 exceeded the adopted critical value for evaluation of property protection. For both Tests 5 and 6, all the maximum values of CO concentration, eye-level gas temperature, and ceiling surface temperature were considerably smaller than the critical values. Therefore, a manufacturer's prototype sprinkler, activated by a 15.1-sec time-constant link rated at 136°F, delivering 0.035 gpm/ft^2 of w_c over the fire source in the corner of the room and 0.012 gpm/ft^2 of w_v to the wall above the chair has been demonstrated to be effective in controlling such a high-challenge, fast developing fire and capable of providing adequate life-safety and property protection in the room of fire origin.

VII CONCLUSIONS

Performance of pendent sprinklers as affected by sprinkler response time and sprinkler water distribution has been investigated in several typical, residential fire scenarios involving flaming fire starts. A commercially available sprinkler link, representative of the most sensitive on the market, was employed for sprinkler activation in a nonventilated small-bedroom fire. Due to the small room size (12.3 ft x 8.8 ft), hot ceiling gases descended quickly to eye level. At the time of sprinkler activation, the eye-level gas temperature near the center of the room had already reached 241°F, exceeding the adopted critical value for eye-level gas temperature. In order to maintain a survivable environment in the room of fire origin throughout this fire, it was concluded that the sprinkler should respond at an earlier stage of the fire; in other words, the sprinkler link must be even more sensitive than the commercially available link.

In the living room fire tests, combustibles were located in the northeast corner of the room; fire first spread to the left side of a reclining chair, and

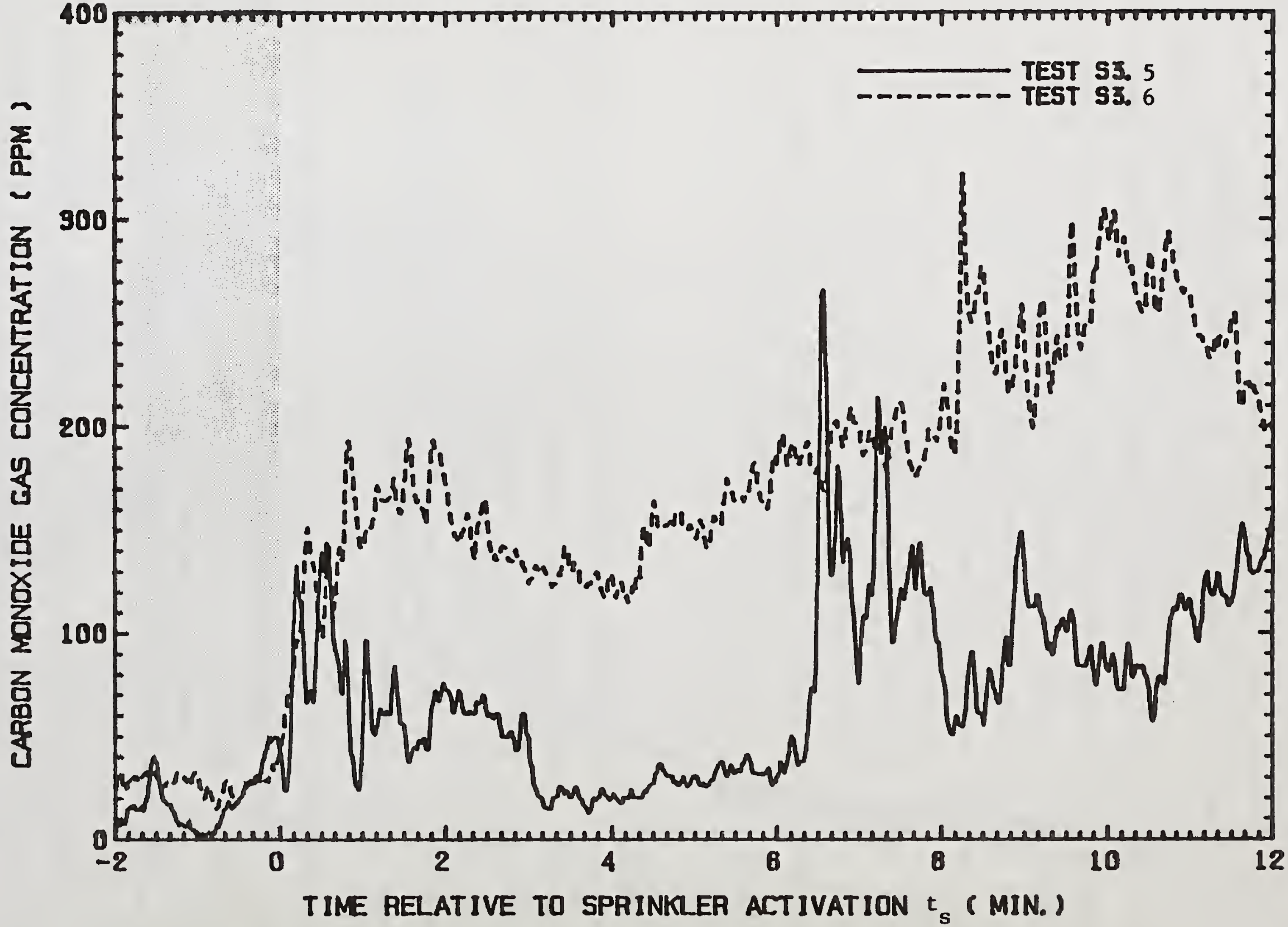

FIGURE 23 CO GAS CONCENTRATIONS AT EYE LEVEL - TESTS 5 AND 6

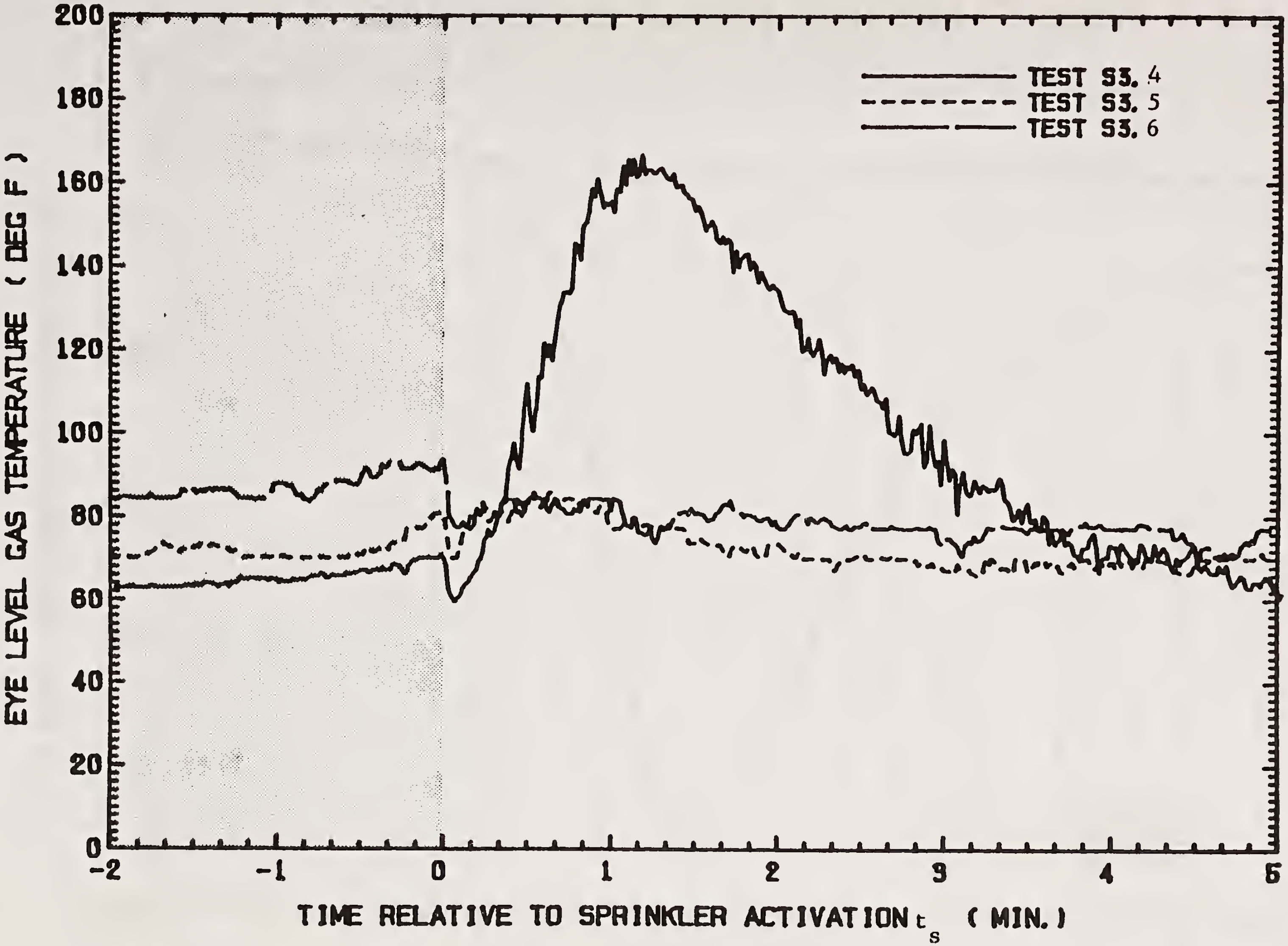

FIGURE 24 GAS TEMPERATURE AT EYE LEVEL - TESTS 4, 5, AND 6

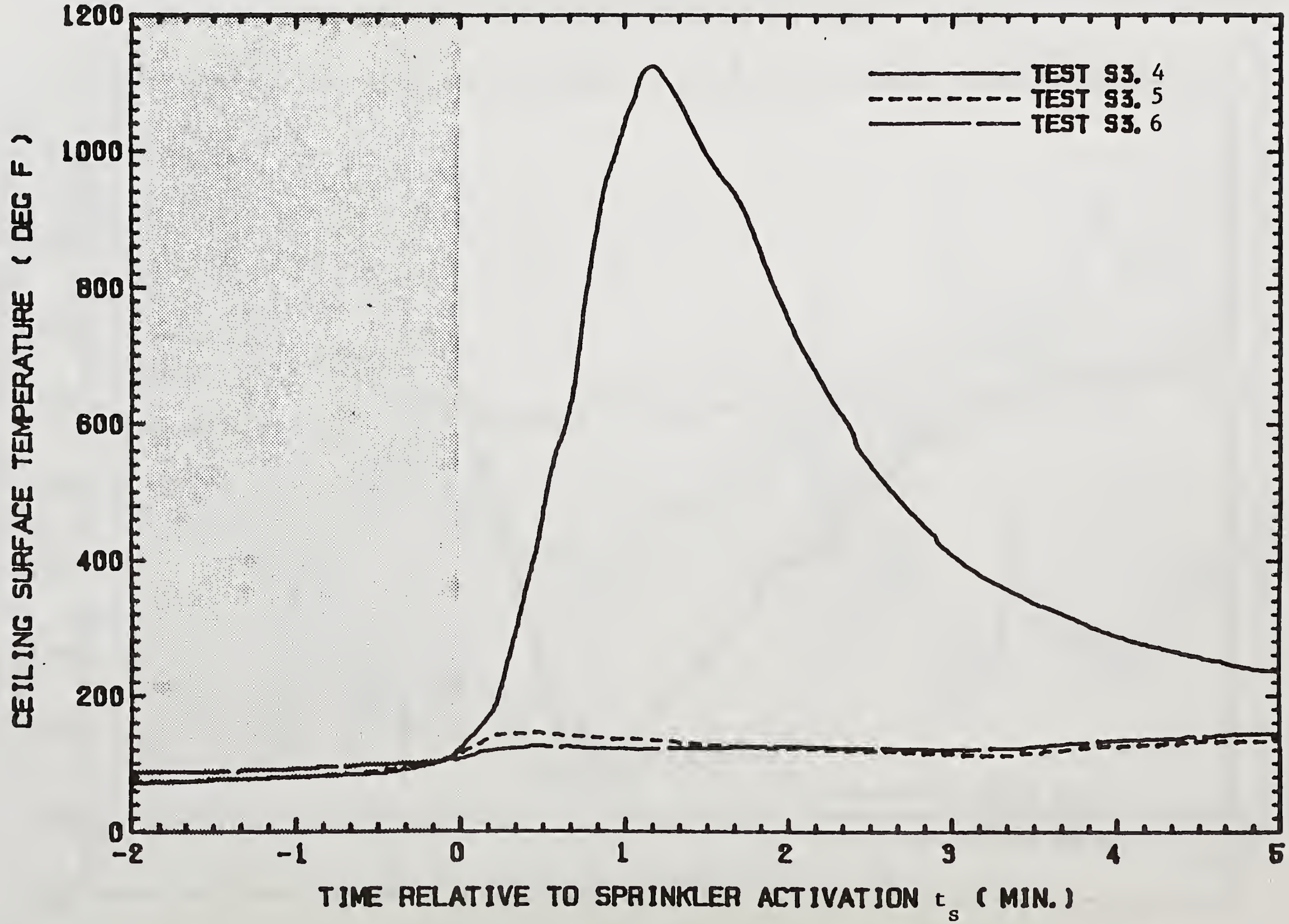

FIGURE 25 CEILING SURFACE TEMPERATURE OVER IGNITION POINT - TESTS 4, 5, AND 6

then to the curtains behind the chair. Fire on the left side and backside of the chair was shielded from direct sprinkler water impingement. In order to suppress such a challenging fire and cool the fire gases, considerably more water was required over the fire source than in the small-bedroom fire. An average water application density, w_c, over a 5-ft x 5-ft floor area in the corner of a 15-ft x 15-ft coverage area without walls was used to indicate the amount of sprinkler water delivered to the corner of the living room. The vertical application density, w_v, over the 1-ft wide x 2.5-ft high area on the wall above the chair indicates the amount of water delivered to protect the wall from igniting by the source fire.

In the ventilated living room fire tests with noncombustible walls and ceiling, it was demonstrated that a sprinkler activated by a 16.9-sec time constant link rated at 140°F, delivering an application density, w_c, of 0.015 gpm/ft^2, was capable of providing adequate life-safety and property protection in the room of fire origin. However, a value of w_c of 0.015 gpm/ft^2 was not sufficient to suppress the fire and cool the fire gases to prevent excessive sprinkler openings in the hallway and the kitchen outside the living room.

In the ventilated living room fire tests with combustible walls and ceiling, manufacturer's prototypes with a link of 15.1-sec time constant rated at 136°F were investigated. The critical value of the application density, w_c, was found to be 0.035 gpm/ft^2 in order to suppress the fire source in the corner and prevent plywood panels and the combustible ceiling above the fire source from igniting. In addition, sufficient wetting of the combustible walls was also essential in preventing fire spread from the fire source to the walls. A vertical application density, w_v, of 0.012 gpm/ft^2 on the wall from 3.5 ft to 6 ft from the floor was demonstrated to be adequate to prevent fire jump from the backside of the chair to the wall.

In the tests in which the manufacturer's prototype 2 sprinkler was demonstrated to be successful in controlling such a challenging ventilated fire, only one sprinkler was activated and the sprinkler discharge rate was 15 gpm covering a 12-ft x 12-ft area. Further, the prototype discharges a rather uniform pattern in the angular distribution so that, even if a fire starts behind the arms of the sprinkler frame, an adequate amount of water can be expected to be delivered to the fire source.

In conclusion, significantly more sensitive links than the commercial link representative of the most sensitive on the market are essential in providing adequate life-safety and property protection in residential fires. The required sprinkler operation conditions for control of such a typical high-challenge, fast-developing residential fire have been determined in terms of water distribution associated with a link (rated at 136°F) five times as sensitive as the commercial link.

The results obtained in the program will 1) serve as a guide for the development of residential sprinklers, 2) establish a foundation for new installation standards of residential sprinkler systems, and 3) lead to new evaluation standards for approval and listing by recognized laboratories.

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Discussion of Presentations on Sprinkler Technology

O'Neill Presentation

Handa: I understand the use of fast response sprinklers which has a large amount of water sprinkling, but I do not understand the use of the slow response sprinkler.

O'Neill: In this paper we looked at standard U.L. listed sprinklers which are currently available. For the mattress and bedding fires, they were relatively slow in responding for the conditions that we were looking at and given the gas temperatures that occurred in the vicinity of the sprinklers.

Handa: I think we are primarily talking about residential sprinklers. In my opinion, in this case, more numbers of sprinkler heads and more water will be more useful. I do not understand for what case the slow response sprinkler would be used.

O'Neill: We specifically addressed the patient room arrangement of a hospital. Dr. Kung will talk about the fast response for residential fires later in the program.

Handa: What do you mean by slow response?

O'Neill: In terms of the thermal inertia, it is the length of time difference from the time that the gas temperature near the sprinkler reaches its actuation point, (the nominal actuation rating) compared to the actual time of response. To explain further, for example in this case with this fire the gas temperature near the sprinkler has reached 200°C before the sprinkler actuated although the sprinkler was rated at 74°C.

Handa: What is the relationship of the sprinklers to detectors? Did you use detectors in the test series?

O'Neill: Yes we did. However because of the limited time on the agenda today, I have not discussed the response or results of the detector phase. They are contained in another report which we can make available to Prof. Handa.

Unoki Presentation

Quintiere: How important is the problem of disturbance of the smoke layer by the sprinkler.

Unoki: Any obscuration by smoke would be detrimental for the escape of the occupants. As I mentioned in my presentation, in Japan the buildings where sprinkler systems are mandatory in order to save human lives, they must install automatic fire alarms as well. So, up to now the thinking has been for escape of the occupants, they would have to depend on the automatic fire alarm system. When you have to examine the usefulness of the sprinklers installed above the escalators, or staircases, we still have to find out if sprinklers are really helpful or detrimental for people to escape.

Emmons: A few remarks in connection with the last question by Dr. Quintiere may be worth noting. The effects of the sprinkler involve two things. The water spray coming down from the sprinkler drives the gases down with it. This tends to mix the obscuring particles into a larger volume, a little less density perhaps, but it increases the obscuration for a short time at least. It puts the he fire out, but it does spread the obscuring particles. However, it also cools the gas, and when you cool the gas it contracts and more fresh air coming in from outside. These two effects have contradictory effects: outside it becomes a little less obscure; inside it becomes a little worse. This makes it very complicated to know for certain whether you are better or worse with the sprinklers. It will also complicate the matter of fire modeling, as I believe Dr. Quintiere was concerned with, in attempting to predict whether sprinklers are better or worse.

Clarke: When was the date of the regulation requiring installation of sprinklers in the buildings. Referring to you paper it was 1976, but I may have missed it, if it was actually written down. I am impressed with the remarkable rate at which sprinklers are being installed in buildings, in which I guess previously did not have sprinklers.

Unoki: The regulation date was roughly twenty years ago. Of course in those twenty years this problem of installation has expanded greatly. Before the regulations went into effect, there was some sprinklers installed but very few. One exception, the very famous Mitsukashi department store in Tokyo installed its sprinkler system even before War World II.

Clarke: Are metal, iron piping required in all sprinklers in Japan. Especially in retrofitting, in installing sprinklers after the building is constructed, are lighter weight piping materials permissible in any cases?

Unoki: A building that is mandated to install a system must use iron piping. Neither plastic nor copper piping has been used as yet.

Benjamin: I would like to congratulate Dr. Unoki for his very fine presentation. I now know far more about sprinklers in Japan than I did before. Two features that are used in this country are what we call water flow alarms which actually sound a gong alarm when the water in the sprinkler is activated; and also sprinklers are required to be tied into the alarm system so that when a sprinkler head activates the alarm system is also activated. I wonder if the Japanese practice also has these features?

Unoki: The building which has an automatic alarm system will sound the alarm when the sprinkler is activated. In other buildings we recommend installation of an alarm system in the middle of the building. There was an example, of an accident in a large storage building. In the middle of the night a sprinkler system went off without any fire by false alarm. The local bell sounded but it did not reach the control center and the accident was recognized after the consumption of 30 minutes of water storage.

O'Neill: Was the need for a change in the previous sprinkler spray distribution test, the single head distribution test, enhanced or necessitated by poor fire experience or was it justwas perceived to be the problem with the void coverage?

Unoki: I do not believe that it was because of past fire experiences. It was because Japanese rooms are small and each room seems to have one or two heads. The reason the change occurred was to avoid any space where water does not cover.

Kung Presentation

Handa: I am interested in how you developed the highly sensitive link. I think you might lower the heat capacity. Is this a corporate secret?

Kung: By reducing the mass and increasing the surface area to correct the heating, you increase the sensitivity.

Handa: I assume the air content has very little heat. On the other hand, the sensor is metal.

Kung: It takes much less heat to heat that element up than the standard sprinkler link.

Emmons: What fraction of the heat actuation of the link comes from the gas directly by convective heat transfer as opposed to radiation from the flame? Does radiation contribute significantly?

Kung: We have not done an exercise to determine what fraction comes from convection or what fraction comes from radiation. However, we assume that transport is by convection. Then we use the heat transport equation to predict that link thermal response and compare the prediction with the measured value of the link temperature. The predictions are very close. I imagine before the sprinkler activates, the fire is not of such a big size. The fire was about five or six feet tall.

Unoki: I remember you said only one sprinkler head activated, but do you have two sprinklers that you installed for the test?

Kung: In the test we installed four sprinklers.

Unoki: Are there any figures describing where these sprinklers are installed?

Kung: Yes, it is in the report.

Unoki: For your test described today, was there only one head installed?

Kung: This was a condensed version.

Unoki: One thing I noticed in your presentation was that no measurements of smoke obscuration were mentioned. Why?

Kung: The obscuration measurments were included in the report.

Unoki: I remember in Mr. O'Neill's report the obscuration was bad. Were similar conditions reached in your experiment?

Kung: Yes.

Chaiken: The prototype link that you developed had a one second or two second response; you also had a 135°F burn height capability. What would you expect the false alarm rate to be in a house with the heating system or out west where you have some high solar energy. Do you have any ideas?

Kung: I think this concern has been taken care of in the new proposed standard which requires that the fusing temperature at the link be at least 35°F above the maximum temperatures in that locality. So, I don't really know when they would have to use 165°F temperature rating.

Quintiere: What was the nature of the distribution of the spray? Do you feel that that has been optimized with regard to the residential environment of a relatively small room compared to industrial sprinkler applications?

Kung: I do not feel that the spray pattern from the phototype sprinklers are necessarily optimized. Next week at the Annual Conference, I will shed some light on the pattern of spray distributions found in more extensive studies.

Miyama: I assume the residential sprinkler will become popular and the standard test for these sprinklers may become important. One suggestion is to standarize the dimension of the test room and the type of burning fuel material and its quantity.

Kung: I think the new approved standards, specifically for residential sprinklers, are being developed by Factory Mutual and Underwriters Laboratories. The sprinklers used in residences will be only the residential sprinklers and would not be standard sprinklers. In the approved test standards we will try to formulate some standard fire tests to evaluate the performance of sprinklers.

Saito: From what point of view did you decide the permissible levels of CO concentration of 1500 ppm and temperature of 200°F?

Kung: We did not mean them as permissible levels. We just chose these values. As experts you probably could provide better values for these.

Saito: I am glad to hear this. If these values are approved, our work in toxicity has been completed. In relation to those two factors, CO concentration and the temperature, I believe the use of the sprinkler usually raises the amount of humidity. The humidity is another factor affecting human conditions. I suggest that humidity should be taken into consideration.

Kung: I hope NBS would take this into consideration.

5. FIRE MODELING

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Laminar Wake Flame Heights

One important measure of material fire hazard is the flame height a given polymer produces upon burning in a specified ambience. Six systems are considered here—two fuel geometries: wall-mounted and free standing; and three flow fields: forced, free and mixed-mode. In each case, the extent of the combusting gas downstream of a pyrolyzing slab is obtained as a function of the fuel's thermochemical properties. The flow is modeled as a steady, laminar, two-dimensional, nonradiative boundary layer. The combustion is described by a single Shvab-Zeldovich energy-species equation assuming unit Lewis number and a fast one-step overall gas phase reaction. Numerical methods are employed due to the abrupt change in boundary conditions at the end of the pyrolyzing slab. However, an approximate similarity solution is found for forced flow which yields explicit flame heights. Based on these results, explicit functional fits to numerical flame heights are obtained for free and mixed-mode flows. Comparisons between theory and experiment indicate quantitative agreement.

Introduction

The development of laminar, forced, free, and mixed-mode convection flames above both wall-mounted and free-standing vertical burning surfaces is examined. This study is a natural extension of previous investigations of laminar combusting boundary layers [1–7]. The limits of pure forced and pure free flow combustion downstream of vertical pyrolyzing surfaces have been examined by Pagni and Shih [4] and by Faeth and co-workers [5, 6], while mixed-mode diffusion flames adjacent to a burning fuel slab have been analyzed by Shih and Pagni [7]. The present investigation extends the analysis of mixed-mode combustion into the region above the fuel source and provides accurate explicit expressions for flame heights in all six cases considered. Good agreement is obtained with experiments.

The six systems analyzed are illustrated schematically in Fig. 1. The two geometries given in Figs. 1(*a*) and 1(*b*) are: (1*a*) combustion adjacent to an inert, adiabatic, vertical extension above the fuel slab, referred to as "wall-wake" or "wall-plume" combustion, and (1*b*) combustion above a free-standing fuel slab referred to as "wake" or "plume" combustion. Three flow regimes are considered for each geometry: (1) forced flow: $\xi_x \ll 1$, (2) free flow: $\xi_x > 1$, and (3) forced and free mixed-mode flow: $\xi_x = 0(1)$. In each case a uniform stream of oxidizer approaches the vertical fuel plate and reacts with pyrolyzed fuel in a thin diffusion flame.

All systems have two regions: a pyrolysis zone where energy transfer to the fuel produces mass transfer into the flow and partial fuel consumption occurs, and an extended flame zone where pyrolysis ceases and the combustion process is completed. The abrupt change in boundary conditions between these regions disallows similarity; hence, numerical techniques are employed. For pure forced flow combustion, however, an approximate similarity model is developed which yields flame heights in terms of known combustion parameters. The analyses are presented in order of increasing complexity, viz., pure forced, pure free, and then mixed-mode combusting flow.

Forced Flow Combustion

Analyses. The boundary-layer equations which govern two-dimensional, laminar flows with fast kinetics are well known, hence the mathematical treatment is abbreviated. Making the usual Shvab-Zeldovich and boundary-layer assumptions, the continuity, momentum, and coupled energy-species equations for forced flow combustion, neglecting dissipation and radiation, are, in turn,

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0$$
$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) \quad (1)$$
$$\rho u \frac{\partial J}{\partial x} + \rho v \frac{\partial J}{\partial y} = \frac{\partial}{\partial y}\left(\rho D \frac{\partial J}{\partial y}\right)$$

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in which J is the normalized energy-species variable. The stoichiometry is given by an assumed single-step overall chemical reaction,

$$\nu_f \text{ fuel} + \nu_{ox} \text{ oxidizer} \rightarrow \nu_p \text{ products} + Q \quad (2)$$

where Q denotes the energy released by ν_f moles of fuel in the reaction.

At the pyrolyzing surface, the streamwise velocity vanishes, the enthalpy is specified and energy and fuel balances yield the transverse velocity and the wall fuel concentration:

$$\rho_w v_w = \frac{\lambda}{c_p L} \frac{\partial h}{\partial y}\bigg|_w, \; x \leq \ell$$

and

$$\rho_w v_w = \frac{\rho D}{Y_{fw} - Y_{ft}} \frac{\partial Y_f}{\partial y}\bigg|_w, \; x \leq \ell. \quad (3)$$

The boundary conditions downstream of the pyrolyzing surface, $x > \ell$, depend on the specific system under consideration. For wall-wake combustion, the velocity vanishes at the adiabatic, inert wall along with the enthalpy and fuel gradients, whereas, for wake combustion, the transverse gradients of streamwise velocity, enthalpy, and fuel are zero along the axis of symmetry as is the transverse velocity. In

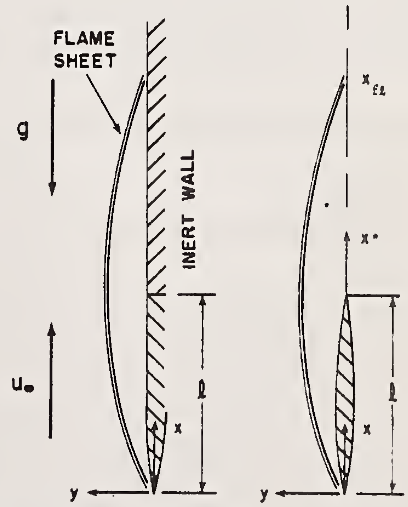

Fig. 1 System schematic of steady, laminar, mixed-mode combustion above a burning vertical fuel slab: (*a*) wall-wake combustion; (*b*) wake combustion

all instances, the streamwise velocity, enthalpy, and oxidant approach their prescribed values in the free stream.

The following dimensionless variables are appropriate:

$$X \equiv \frac{x}{\ell},\ Y \equiv \frac{\mathrm{Re}_\ell^{1/2}}{\ell}\int_0^y \frac{\rho}{\rho_\infty}\,dy,$$

$$U \equiv \frac{u}{u_\infty},\ V \equiv \frac{\mathrm{Re}_\ell^{1/2}}{\rho_\infty u_\infty}\left(\rho v + u\int_0^y \frac{\partial \rho}{\partial x}\,dy\right) \tag{4}$$

in which $\mathrm{Re}_\ell \equiv u_\infty \ell/\nu_\infty$ is the slab Reynolds number. Assuming constant Pr and $\rho\mu$, the governing equations become

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0,$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = \frac{\partial^2 U}{\partial Y^2}, \tag{5}$$

$$U\frac{\partial J}{\partial X} + V\frac{\partial J}{\partial Y} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 J}{\partial Y^2}.$$

In the pyrolysis region, $X \leqslant 1$, the boundary conditions, assuming $Y_{\mathrm{ox}_w} = 0$, are

$$U = 0,\ V = -\frac{B}{\mathrm{Pr}}\frac{\partial J}{\partial Y}\bigg|_w,\ J = 1 \text{ at } Y = 0 \tag{6}$$

$$U = 1, J = 0 \quad \text{as } Y \to \infty \tag{7}$$

where the mass transfer number is defined as

$$B \equiv [QY_{\mathrm{ox}\infty}/\nu_{\mathrm{ox}}M_{\mathrm{ox}} - h_w]/L \tag{8}$$

In the extended flame region, $X > 1$, equation (7) continues to apply, while equation (6) is replaced with

$$U = V = \frac{\partial J}{\partial Y} = 0 \text{ at } Y = 0, \tag{9}$$

for wall-wake combustion and

$$\frac{\partial U}{\partial Y} = V = \frac{\partial J}{\partial Y} = 0 \text{ at } Y = 0 \tag{10}$$

for wake combustion.

Temperature and species fields are readily obtained from $J(X, Y)$ using the flame-sheet approximation, i.e., fuel only exists inside and oxidizer only outside the flame. At the flame, $Y_f = Y_{\mathrm{ox}} = \beta = 0$, and $J_{f\ell}(X_{f\ell}, Y_{f\ell}) = r/(1+r)$, which implicitly identifies the flame location. The mass consumption number, r, [4] is defined as the ratio of the relative available oxygen to the stoichiometrically required oxygen,

$$r \equiv Y_{\mathrm{ox}\infty}\nu_f M_f / Y_{fu}\nu_{\mathrm{ox}}M_{\mathrm{ox}}. \tag{11}$$

The surface fuel concentration, for $X \leqslant 1$, is known *a priori* [7] as

$$Y_{fu} = [Y_{f\ell}B - Y_{\mathrm{ox}\infty}(\nu_f M_f/\nu_{\mathrm{ox}}M_{\mathrm{ox}})]/(1 + B) \tag{12}$$

The flame height is that downstream location where all of the pyrolyzed fuel is consumed, here approximated as where the reaction sheet intersects $Y = 0$. Thus the flame height, $X_{f\ell}$, is implicitly given by

$$J_w(X_{f\ell}, 0) = J_{f\ell} = r/(1 + r). \tag{13}$$

Approximate Solution for Downstream Forced Flow. While the abrupt change in boundary conditions renders the flow field non-similar near the trailing edge of the fuel slab, it is likely that the combusting system again approaches self-similarity far downstream. An approximate profile of the Shvab-Zeldovich variable, J, in the extended flame zone is now found by coupling the pyrolysis zone similarity solution with a downstream similarity solution for $X \gg 1$. The assumption that the flame extension is large compared to the fuel slab length suggests the similarity variable,

$$\eta \equiv Y/2X^{1/2}. \tag{14}$$

The stream function, $\psi = f(\eta)X^{1/2}$, is defined by

$$U \equiv \frac{\partial \psi}{\partial Y} \text{ and } V \equiv -\frac{\partial \psi}{\partial X}. \tag{15}$$

The downstream velocity is then $U = f'(\eta)/2$. If it is assumed that $J/J_w(X)$ is only a function of η, i.e., $J/J_w(X) \equiv \theta(\eta)$, then

$$\theta'' + \mathrm{Pr}[f\theta' - 2f'\theta(J_w'X/J_w)] = 0 \tag{16}$$

is obtained by substituting these definitions into the energy-species equation (5). Primes denote differentiation with respect to the independent variables of $f(\eta)$, $\theta(\eta)$, and $J_w(X)$. To determine if a similarity solution can be found, i.e., if $J_w'X/J_w$ is independent of X, consider the integral form of the energy-species equation downstream of the fuel slab for an inert, adiabatic wall or symmetric wake:

$$\frac{d}{dx}\int_0^\infty \rho u J dy = 0, x > \ell. \tag{17}$$

Substituting θ, f' and equations (4) and (14) into equation (17) shows that indeed $J_w'X/J_w = -1/2$.

The downstream energy-species equation is now

$$\theta'' + \mathrm{Pr}(f\theta' + f'\theta) = 0 \tag{18}$$

subject to

$$\theta(0) = 1, \theta'(0) = 0, f(0) = 0. \tag{19}$$

The solution is simply

$$\theta(\eta) = \exp\left(-\mathrm{Pr}\int_0^\eta f(\eta)\,d\eta\right) \tag{20}$$

where $f(\eta)$ is obtained from the transformed momentum equation,

Nomenclature

B = mass transfer number, $(QY_{\mathrm{ox}\infty}/\nu_{\mathrm{ox}}M_{\mathrm{ox}} - h_w)/L$
c_p = specific heat
D = species diffusivity
D_3 = dimensionless heat of combustion, $QY_{\mathrm{ox}\infty}/\nu_{\mathrm{ox}}M_{\mathrm{ox}}h_w$
f = similarity stream function
Gr_x = Grashof number, $g(T_w - T_\infty)x^3/\nu_\infty^2T_\infty$
g = acceleration of gravity
h = specific enthalpy, $\int_{T_\infty}^T c_p\,dT$
J = normalized Shvab-Zeldovich variable, $(\beta - \beta_\infty)/(\beta_w - \beta_\infty)$ or $(\gamma - \gamma_\infty)/(\gamma_w - \gamma_\infty)$
L = effective latent heat of pyrolysis
ℓ = fuel slab length
M_i = molecular weight of specie i
Pr = Prandtl number
Q = energy released by combustion of ν_f moles of gas phase fuel
Re_x = Reynolds number, $u_\infty x/\nu_\infty$
r = mass consumption number, $Y_{\mathrm{ox}\infty}\nu_f M_f/Y_{fw}\nu_{\mathrm{ox}}M_{\mathrm{ox}}$
S = total flux of J in extended flame zone
U = dimensionless streamwise velocity
u = streamwise velocity
V = dimensionless transverse velocity
v = transverse velocity
X = dimensionless streamwise coordinate
x = streamwise coordinate
Y = dimensionless transverse coordinate
y = transverse coordinate
Y_i = mass fraction of specie i
β = $Y_f/\nu_f M_f - Y_{ox}/\nu_{\mathrm{ox}}M_{ox}$
γ = $-h/Q - Y_{ox}/\nu_{\mathrm{ox}}M_{ox}$
η = similarity variable
θ = Shvab-Zeldovich variable
λ = conductivity
μ = viscosity
ν = kinematic viscosity or stoichiometric coefficient
ξ_x = mixed convection number, $\mathrm{Gr}_x/\mathrm{Re}_x^2$
ρ = density
ϕ = enthalpy ratio, h/h_w

Subscripts

f = fuel
$f\ell$ = flame
ox = oxidizer
t = transferred gas
w = fuel surface
∞ = ambient

Superscripts

* = measured from the downstream edge of the fuel slab

$$f''' + ff'' = 0 \tag{21}$$

with the boundary conditions,

$$f(0) = 0, f'(\infty) = 2$$

and

$$f'(0) = 0 \text{ or } f''(0) = 0 \tag{22}$$

for wall-wake or wake combustion, respectively. For wall-wake combustion, the system is identical to the Blasius problem for flow over a flat plate and although no closed-form expression for $f(\eta)$ exists, numerical solutions are well known [8]. For wake combustion, the solution for $f(\eta)$ is

$$f(\eta) = 2\eta. \tag{23}$$

These results are simply the two asymptotes for $X \gg 1$, i.e., flat plate flow for wall-wake combustion and uniform flow for wake combustion.

In the pyrolysis region, the energy-species equation in integral form is

$$\frac{d}{dx}\int_0^\infty \rho u J dy = \rho_w v_w J_w - \rho D \left.\frac{\partial J}{\partial y}\right|_w, \; 0 < x < \ell. \tag{24}$$

Substituting equations (4) and (6) into equation (24) and integrating along the length of the fuel slab yields

$$S \equiv \int_0^\infty UJdY = \left(\frac{1+B}{B}\right)\int_0^1 V_w dX \text{ at } X = 1. \tag{25}$$

Equation (17) indicates that S remains constant throughout the extended flame zone; i.e., J is conserved. J is generated along the pyrolyzing surface and is never consumed in the flow field. The extended flame region is effectively coupled to the pyrolysis region through a single source of J, with strength S, located at the trailing edge of the slab.

The flame height is obtained by considering the variation of J_w for $X > 1$ or $X^* > 0$. From equation (25),

$$J_w(X^*) = S/(X^{*1/2}\int_0^\infty f'\theta d\eta) \tag{26}$$

where X^* is the streamwise coordinate measured from the trailing edge of the fuel slab. The flame height is the X^* at which $J_w = J_{f\ell}$; i.e.

$$X^*_{f\ell} = S^2/(J_{f\ell}\int_0^\infty f'\theta d\eta)^2. \tag{27}$$

Numerical integration of equations (20, 21) yields $\int_0^\infty f'\theta_{(\text{wall-wake})}d\eta \approx 1.5\,\text{Pr}^{-0.6}$, while equations (20) and (23) give analytically $\int_0^\infty f'\theta_{(\text{wake})}d\eta = (\pi/\text{Pr})^{1/2}$; so that

$$X^*_{f\ell(\text{wake})}/X^*_{f\ell(\text{wall-wake})} \approx 0.72\,\text{Pr}^{-0.2}, \tag{28}$$

i.e., wake flame heights are ~3/4 (wall-wake flame heights).

The B number dependence of $S(\text{Pr}, B)$ can be made explicit by fitting total pyrolysis rate computations,

$$S \approx 0.56\,\text{Pr}^{-0.6}B^{-1.15}(1+B)\,\ell n\,(1+B),\; 0.5 \le B \le 5,\; 0.5 \le \text{Pr} \le 2 \tag{29}$$

Since the generation of J by diffusion decreases with increased blowing, the B dependence of S is weaker than the B dependence of the total pyrolysis rate, as shown by the pre-integral factor in equation (25). Substituting equations (13) and (29) and the $\int_0^\infty f'\theta d\eta$ fit into equation (27) yields an approximate explicit expression for the wall-wake flame height,

$$X^*_{f\ell(\text{wall-wake})} \approx 0.14\,[(1 + r^{-1})(1 + B^{-1})\,B^{-0.15}\,\ell n\,(1+B)]^2 \tag{30}$$

for $0.5 \lesssim B \lesssim 5.0$, $0.5 \lesssim \text{Pr} \lesssim 2.0$ and all r. As examples, equation (30) gives $X^*_{f\ell} = 19$ and 1.9 respectively for polystyrene ($r = 0.14$, $B = 1.3$) and cellulose ($r = 0.59$, $B = 0.8$). Equation (30) also fits the numerical $X^*_{f\ell}$ shown in Fig. 2 within 15 percent for $0.1 \le r \le 0.5$. The dominant parameter in equation (30) is r which entered only through $J_{f\ell}$. $X^*_{f\ell}$ increases strongly as r decreases, since small r implies that much fuel is available relative to that which is required by stoichiometry and thus long flames are produced.

Additional Results. Numerical solutions were also obtained using the Patankar-Spalding finite difference method (GENMIX) [9, 10] which employs streamwise marching integration. The computations were initiated near the leading edge of the pyrolyzing slab ($X = 0.01$) assuming standard, cubic, forced-flow profiles for U and J. Mass transfer (blowing) effects at the pyrolyzing surface were included. Employing 50 cross-stream grid nodes, the step-by-step procedure traversed the pyrolysis region and continued into the extended flame zone. The ratio of the streamwise step size to the current boundary-layer thickness was initialized at 0.01 and gradually increased along the length of the plate. At the trailing edge of the slab, the step size ratio was reset to 0.01 and again progressively increased downstream. As a check on the numerics, the surface gradients on the pyrolyzing slab at the trailing edge gave agreement with similarity results [11] within one percent. Detailed profiles and surface fluxes were calculated; flame height results are emphasized here.

Fig. 2 presents flame heights measured from the downstream edge as functions of B parameterized in r for (a) wall-wake and (b) wake combustion obtained with equation (27) and S from similarity solutions, an integral approach [4], and GENMIX. Good agreement between this approximate solution and GENMIX is observed for flame heights in excess of one slab length. It appears that the simple model based on conservation of J and large X asymptotic profiles is valid for synthetic polymer fuels. For short flames, this approximate solution overpredicts flame heights, as expected, since large $X^*_{f\ell}$ is an

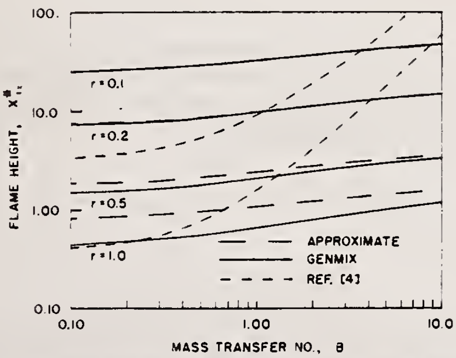

Fig. 2(a) Dimensionless flame height in a wall-wake measured from trailing edge of fuel slab versus mass transfer number parameterized in mass consumption number for Pr = 0.73

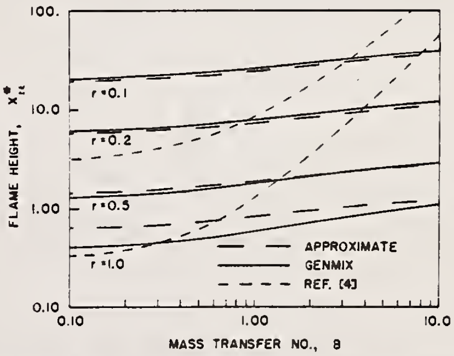

Fig. 2(b) Dimensionless flame height in a wake measured from trailing edge of fuel slab versus mass transfer number parameterized in mass consumption number for Pr = 0.73

essential model assumption: indeed, the accuracy as low as $X^*_{f\ell} \sim 1$ is surprisingly good. The previous approach [4] shows agreement with the GENMIX results only for short flame heights, $X^*_{f\ell} < 1$, typical of natural polymer fuels.

Many trends agree with those obtained from the previous integral analysis [4], namely: flame heights increase with increasing B number and decreasing r number, wall-wake flames are longer than wake flames, and the dimensionless flame height is independent of Reynolds number. Quantitative differences are obvious, however; the present analysis shows a much weaker dependence of flame height on B number. Briefly, the integral analysis assumed polynominal profiles for fuel and velocity fields normalized on wall/centerline values which had to be obtained as functions of X from local elemental balances. While the approximate polynomials might suffice in the integral equations, they are not adequate to determine proper wall/centerline values from differential expressions. Such an approach can only succeed when the flow is similar. The poor representation of the detailed profiles in the non-similar region led to loss of conservation of the total flux of fuel which became worse the further the flame extended beyond the pyrolysis zone. The excess pyrolyzate results reported [4] for the end of the pyrolysis zone were correct. Here S is held constant throughout the extended flame zone, $X^* \geqslant 0$. This emphasis on S, the total flux of the Shvab-Zelovich energy-species variable J, is responsible for the agreement with the numerical solution and for the difference from the previous approximate integral approach.

The constancy of the total flux of the Shvab-Zeldovich variable downstream of the fuel slab demands that a balance be maintained between velocity and J in the extended flame zone. Any decrease in average velocity is thus accompanied by an increase in J; a longer distance is then required for J to decay down to $J_{f\ell}$. Thus longer flames result whenever the velocity is retarded, as in the case of the wall-wake, Fig. 2(a), compared with the wake, Fig. 2(b). The approximate solution for wake combustion neglects the velocity defect that may exist for some distance downstream of the slab. This velocity defect will produce longer flames, therefore the slightly larger GENMIX results in Fig. 2(b) are expected even at large $X^*_{f\ell}$. The approximate flame height ratio given by equation (28) is thus a lower bound. The overprediction at short $X^*_{f\ell}$ is primarily caused by placing the source in the approximate model, S, at the trailing edge of the fuel slab rather than upstream in the pyrolysis region. A simple procedure for more accurately locating the source is not obvious.

Comparisons with Experiment. Flame heights in the wall-wake of PMMA samples burning in O_2/N_2 mixtures were measured in a small wind tunnel 12 cm wide by 5 cm high. Slabs of PMMA of lengths 1.3 and 1.6 cm and width 9.0 cm were approximately flush mounted in the martinite floor of the test section. Y_{ox_∞} was varied from 30 to 100 percent producing B numbers from 2.0 to 8.0 and r numbers from 0.25 to 0.65 [12]. Data were taken at two free-stream velocities, 85 cm/s and 170 cm/s, determined by corrected volume flow rate measurement. Gas and wall temperatures were monitored. Steady-state flame heights were recorded with an 8 mm movie camera. Fig. 3, which plots the dimensionless flame height, $X^*_{f\ell}$, versus free stream oxygen mass fraction, Y_{ox_∞}, shows good agreement between theory, equation (30), and experiment. Radiation is probably responsible for the experiments slightly exceeding predictions. Though thin, these flames are very luminous. Net radiation to the pyrolyzing surface would, by decreasing L, increase B, and through the B dependence of Y_{fw} decrease r and thus increase $X^*_{f\ell}$. The data confirm that larger r numbers, produced by higher ambient oxygen concentrations, yield shorter flames and that the dimensionless flame height is independent of Reynolds number.

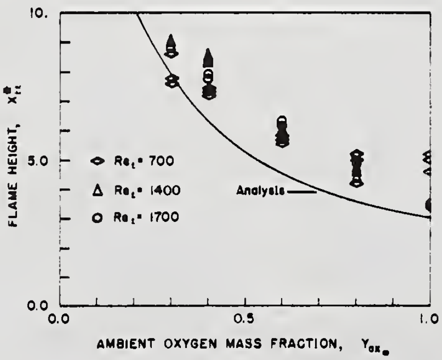

Fig. 3 Comparison of experimental and theoretical dimensionless flame heights for PMMA in wall-wake combustion as function of ambient oxygen mass fraction

Free Flow Combustion

Analyses. The equations which govern free flow combustion near an upright burning surface are identical to the forced flow relations, equation (1), with the obvious modification of a buoyancy term in the momentum equation,

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) + g\,(\rho_\infty - \rho). \tag{31}$$

Here the appropriate dimensionless variables are

$$X \equiv \frac{x}{\ell},\; Y \equiv \frac{Gr_\ell^{1/4}}{\ell} \int_0^y \frac{\rho}{\rho_\infty} dy$$

$$U \equiv \frac{u\ell}{Gr_\ell^{1/2}\nu_\infty},\; V \equiv \frac{\ell}{Gr_\ell^{1/4}\rho_\infty\nu_\infty}\left(\rho v + u \int_0^y \frac{\partial \rho}{\partial x} dy\right) \tag{32}$$

in which $Gr_\ell \equiv g(T_w - T_\infty)\ell^3/\nu_\infty^2 T_\infty$, is the slab Grashof number. The natural convection momentum equation then becomes

$$U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = \frac{\partial^2 U}{\partial Y^2} + \phi \tag{33}$$

where, assuming uniform mixture specific heat and molecular weight across the boundary layer, ϕ is the enthalpy ratio, h/h_w, which in the flame-sheet approximation is

$$\phi = D_3 + (1 - D_3)J,\; Y \leqslant Y_{f\ell}$$

and

$$\phi = (1 + D_3/r)J,\; Y \geqslant Y_{f\ell}. \tag{34}$$

Equations (34) introduce the single new parameter needed to describe free flow combustion,

$$D_3 \equiv \frac{QY_{ox_\infty}}{\nu_{ox}M_{ox}h_w}, \tag{35}$$

a dimensionless heat of combustion. The transformed continuity and energy-species equations are identical to equation (5) while the boundary conditions are given by equations (6–10) with the exception that

$$U = 0 \text{ as } Y \rightarrow \infty. \tag{36}$$

The strong coupling between velocity and thermal fields in combusting plumes makes it more difficult to formulate simple approximate solutions, however, using the forced flow results, equations (28) and (30) as guides, the following fits, accurate to 10 percent, were obtained from GENMIX results:

$$X^*_{f\ell(\text{wall-plume})} \approx 0.24[(1 + r^{-1})r^{-0.16}(1 + B^{-1})B^{-0.06}\ell n(1 + B)D_3^{-0.03}]^{4/3} \tag{37}$$

and

$$X^*_{f\ell(\text{plume})}/X^*_{f\ell(\text{wall-plume})} \approx 0.9 \tag{38}$$

for $0.1 \leq r \leq 0.5$, $0.5 \leq B \leq 5$, $2 \leq D_3 \leq 60$, and $Pr = 0.73$.

Results. Numerical computations were performed by GENMIX using natural convection profiles as initial conditions for the marching process [13], the details of which closely parallel the forced flow calculations. The combined body force and pressure gradient term, ϕ, was treated as an apparent pressure gradient in the finite difference code. The surface gradients at the trailing edge of the pyrolyzing slab

Conclusions

In summary, from the detailed steady, laminar, two-dimensional, nonradiating, combusting boundary layer analyses of six systems (wall-wake, wake, wall-plume, plume, mixed-mode wall-wake and mixed-mode wake), emphasizing the constancy of the flux of the Shvab-Zeldovich energy-species variable J in the extended flame region, the following conclusions are drawn:

1 For forced flow, $X^*_{f\ell}(r, B, \mathrm{Pr})$ and is independent of Re_ℓ. Explicit expressions are presented which quantify the strong increase in $X^*_{f\ell}$ as r decreases and the moderate increase in $X^*_{f\ell}$ as B increases. The Pr dependence is very weak. Good agreement with experiment is obtained.

2 For free flow, $X^*_{f\ell}(r, B, \mathrm{Pr}, D_3)$ and is independent of Gr_ℓ. Explicit fits to numerical results are given which quantify the r and B dependence as in forced flow. The dependence on D_3 and Pr is weak. Free flow flames are generally shorter than forced flow flames for the same fuel and ambience. Reasonable agreement with experiment is obtained.

3 For mixed-mode flow, $X^*_{f\ell}(r, B, \mathrm{Pr}, D_3, \xi_\ell)$ with the forced and free limits approached at $\xi_\ell \lesssim 10^{-2}$ and $\xi_\ell \gtrsim 1$ respectively. The mixed-mode case appears to be a simple superposition of forced and free flow.

4 Wall-mounted flames are longer than free-standing flames for the same fuel and ambience. This difference depends on flow type and Pr, i.e., wall-wake flames are ~30 percent longer than wake flames, wall-plume flames are ~10 percent longer than plume flames.

Future effort will be directed at extending these analyses to include radiation and turbulence. More experimental results for comparison would be valuable. It is hoped that flame height measurement under controlled conditions will become one of the standard procedures for assessing material fire hazard.

Acknowledgments

Mr. R. Beier obtained the experimental data reported in Fig. 3. The authors appreciate support from the Products Research Committee and from the National Bureau of Standards—Fire Research Center. The conclusions are those of the authors and not of the Products Research Committee nor the National Bureau of Standards.

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The Computer Fire Code

The calculation of the growth of a fire in a building via computer has progressed slowly since the last meeting of this committee. The updated version, Computer Fire Code IV, has itself been replaced by Computer Fire Code V. This latest version in Fortran is available on tape, and is accompanied by a "Users' Guide."

The most important aspect of such a code--beyond its ability to calculate a fire correctly--is the ease with which it can be used. Thus, Computer Fire Code V has a completely revised input system. The program is able to handle a fire in a room of any size containing up to five objects, one of which is initially ignited. The others will be heated as the fire progresses, and will ignite at a user-specified ignition temperature (default 740°K).

After they ignite, their gases rise in a plume into the hot layer, and their fires radiate to each other to provide the expected energy feedback. The room can have one to five rectangular vents anywhere in the vertical walls.

To supply the required room and object dimensions, and the thermal and fire properties of the walls and objects in the room, an interactive input program has been developed. This program asks questions on the console, and the user supplies the requested information.

The program itself contains a standard room with two objects--one ignited, the other a target. The first question asked by the computer is: (underlined items are printed by the computer)

STANDARD GEOMETRIC AND PHYSICAL PARAMETERS (NO = 0, YES = 1)?

On the console there then appears:

ROOM NUMBER 1:

    0) CHANGE NOTHING (CONTINUE)
    1) LENGTH IS NOW: 3.6580E+00
    2) WIDTH IS NOW: 2.4384E+00
    3) HEIGHT IS NOW: 2.4384E+00
    4) NUMBER OF OBJECTS IS NOW: 2
    5) PRESENT AMBIENT TEMPERATURE: 3.0000E+02

IF ALL THE ABOVE INPUT IS SATISFACTORY, THEN HIT 0 (FOLLOWED BY <NL>).* IN ORDER TO CHANGE ANY (OR ALL) OF THE ABOVE, TYPE IN THE APPROPRIATE LINE NUMBERS ABOVE, EACH ON A NEW LINE. END WITH <NL>, <NL>.

Suppose we wanted to study a room 8 × 15 × 10 meters high. The computor would type:

1.
2.
3.
<NL>,<NL>

The dialog would proceed as follows.

1. ROOM LENGTH?	15	<CR> (<CR> is carriage return)
2. ROOM WIDTH?	8	<CR>
3. ROOM HEIGHT?	10	<CR>

The computer then responds by retyping the list of 5 items above with the new chosen values in their correct place, and asks if you wish to make any further changes. (No = 0, Yes = 1).

Following this, the computer lists, in turn, all of the other adjustable characteristics of the program with their default values, and asks if you wish to change them as described above for the room. The adjustable characteristics are:

Room 1 Object 1 (Geometric Properties)

x coordinate, y coordinate, height above floor, thickness, initial burning radius, object radius, maximum burning radius, input length and width instead of above radii.

Room 1 Object 1 (Physical Properties)

This object is burning, air fuel ratio, stoichiometric ratio, thermal

---

*i.e., new line

conductivity, specific heat, density, emissivity of surface, fraction of combustion heat released, heat of combustion, heat of vaporization, initial fuel mass, ignition temperature, pyrolization temperature, mass ratio CO_2/fuel, CO/fuel, smoke/fuel, gas flow rate if object is a gas burner.

These same questions are asked for all remaining objects up to the number chosen by the computor under "geometric properties."

Vent 1

width, height, transom depth, Side 1 is Room 1, Side 2 is Room 0 (0 is at present the atmosphere). Each vent desired is similarly covered.

Wall 1

thickness, thermal conductivity, specific heat, density.

Other variables

specific heat of air, flame radiative mean free path, ambient temperature (outside), maximum heat transfer coefficient to ceiling, minimum heat transfer coefficient, heat transfer coefficient to top of horizontal surface, plume entrainment coefficient, vent flow coefficient.

The results of the calculations are made available in one of two forms. The user may have any eight physical quantities printed out vs. time in a nine-column tabular form at user-chosen time intervals (default 10 sec.), or as a block of all thirty seven general variables plus about ten variables for each object at chosen time intervals (default 10 sec.).

The quantities made avilable by the computer are:

Properties of the hot layer

depth, energy, mass, temperature, composition [CO_2, CO, O_2, smoke], rate of energy increase, rate of mass increase, net rate of heat loss by radiation, rate of heat loss by convection to ceiling.

Pressure at the floor of the room (in meters of ambient air)

For each object

surface temperature, remaining mass, rate of mass loss, feedback radiative heat flux from the layer, heat flux from the walls, radiative heat loss.

For each vent

total mass outflow, total energy outflow, total lower inflow.

For the walls (and ceiling) adjacent to the hot layer (inside the room)

net radiative heat flux from the layer, convective heat flux from the layer, radiative heat flux from the flames, the surface temperature plus the same four quantities on the walls outside the room.

The new piecewise linear vent flow calculation mentioned at the last UJNR meeting in Tokyo has been implemented and incorporated in CFC V. A fairly simple one-page Fortran code is able to separate and calculate all seventy vent cases described at that time.

The CFC V still has occasional numerical troubles. In spite of that fact, three different routines with decreasing time-step are tried automaticcally and in succession if the fastest method fails to converge to a relative error of 3×10^{-4} in thirty iterations.

The Hasimi Diagram for the Computer Fire Code is shown in Fig. 1. Various results are shown in Figs. 2 through 6. Only a few of the fifty output variables are shown. The results shown illustrate some of the fire physics not yet adequately understood. Figure 4 shows the failure to predict sufficiently high radiation flux. This is believed to be an underestimate caused by the absence of burning of the fuel in the hot layer. The lack of knowledge of the products of combustion when flames burn in fire-vitiated air is the cause of the failure to predict the carbon monoxide concentration by an order of magnitude as shown in Fig. 5.

However, the flexibility of the program in predicting a range of conditions is shown by the predicted effect of lowering the top of the door all the way from the ceiling to 25 cm from the floor.

Where do we go from here?

Although not sufficiently developed to be included in CFC V, two developments are well advanced.

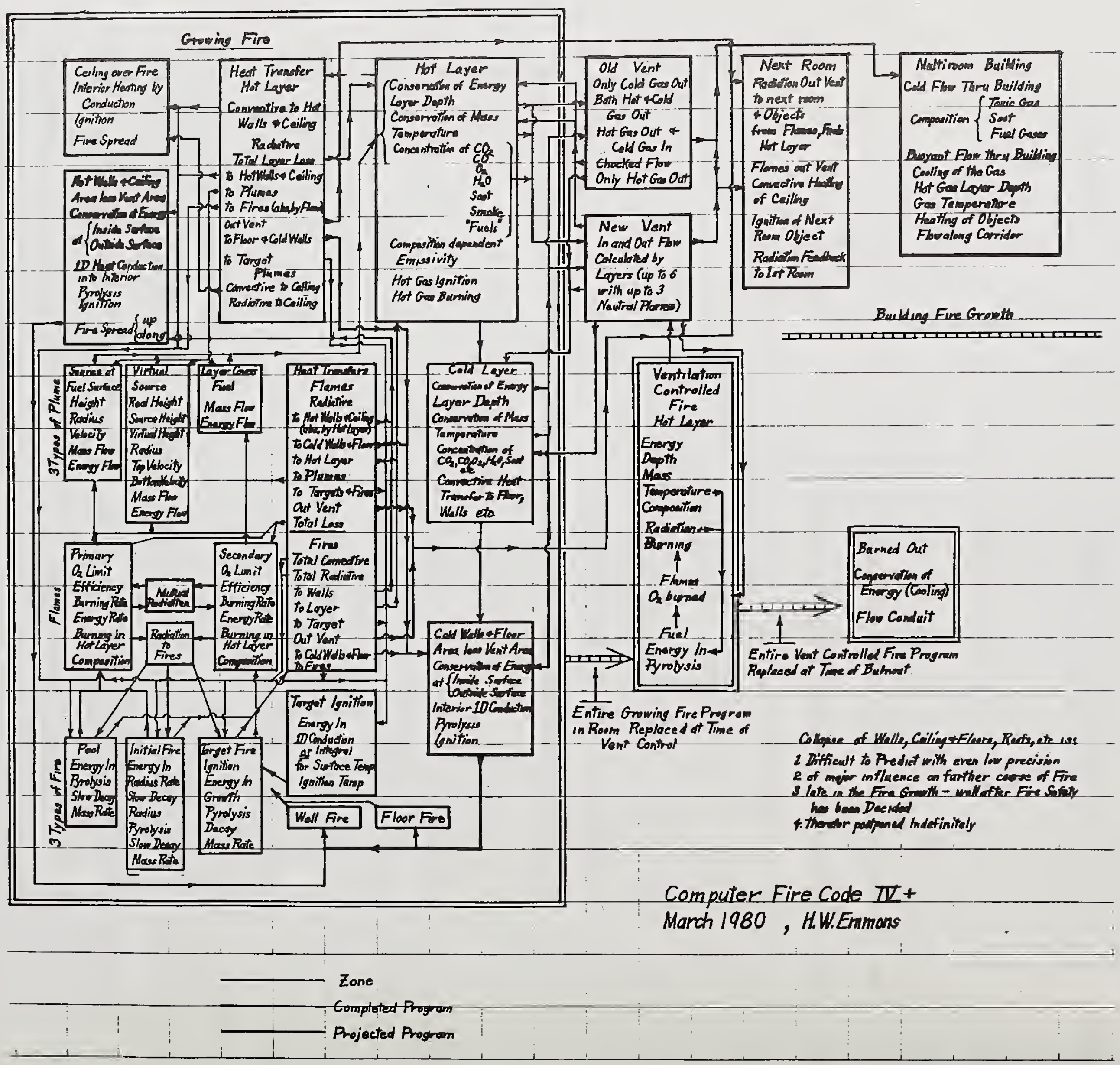
I. The new piecewise linear solution of flow through a vent is being used on various multi-room cases. It appears to give results which we believe to be correct, but which seem to differ somewhat from the results obtained previously by Tanaka. We hope to clarify the differences during this meeting.

II. Most fire codes have written the physical equations, simplified them by algebraic manipulation, and then computer-coded the result. This technique results in relatively few (less than a dozen for one room) equations to be solved. It has, however, a serious disadvantage, since it requires that the equations must be rederived and recoded each time any change is made in our knowledge of fire physics.

We have avoided this algebraic manipulation in the Computer Fire Code so as to maintain greater flexibility, but at the cost of a large number of equations and unknowns. Mr. John Ramsdell has examined this problem by use of graph theory. He has developed a method by which the number of essential independent variables can be reduced to a minimum, and a program by which the computer can determine the numerical minimum and put the subroutines in the correct order to use this minimum. We expect this will offer some improvement in computing time for a single room, and will be extremely important when a one-hundred-room building is being considered.

In separate experimental studies, the detailed composition of a flame at various levels and the burning of a flame in a ceiling layer are being measured, so as to supply this vital information for incorporation into the Computer Fire Code.

The Harvard Home Fire Project is supported under a Grant from the National Bureau of Standards, Washington, D.C.



Growing Fire
Ceiling over Fire Interior Heating by Conduction Ignition Fire Spread
Hot Walls + Ceiling Area less Vent Area Conservation of Energy at {Inside Surface Outside Surface 1D Heat Conduction into Interior Pyrolysis Ignition Fire Spread {up along
Heat Transfer Hot Layer Convective to Hot Walls + Ceiling Radiative Total Layer Loss To Hot Walls + Ceiling To Plumes To Fires Out Vent To Floor + Cold Walls To Target Plumes Convective to Ceiling Radiative to Ceiling
Hot Layer (Conservation of Energy Layer Depth Conservation of Mass Temperature Concentration of CO₂ CO O₂ H₂O Soot Smoke "Fuels" Composition dependent Emissivity Hot Gas Ignition Hot Gas Burning
Old Vent Only Cold Gas Out Both Hot + Cold Gas Out Hot Gas Out + Cold Gas In Chocked Flow Only Hot Gas Out
New Vent In and Out Flow Calculated by Layers (up to 6 with up to 3 Neutral Planes)
Next Room Radiation Out Vent to next room + Objects from Flames, Fuels Hot Layer Flames out Vent Convective Heating of Ceiling Ignition of Next Room Object Radiation Feedback To 1st Room
Multiroom Building Cold Flow Thru Building Composition {Toxic Gas Soot Fuel Gases Buoyant Flow thru Building Cooling of the Gas Hot Gas Layer Depth Gas Temperature Heating of Objects Flow along Corridor
Building Fire Growth
3 Types of Plume
Source at Fuel Surface Height Radius Velocity Mass Flow Energy Flow
Virtual Source Real Height Source Height Virtual Height Radius Top Velocity Bottom Velocity Mass Flow Energy Flow
Layer Covers Fuel Mass Flow Energy Flow
Heat Transfers Flames Radiative To Hot Walls + Ceiling (abs. by Hot Layer) To Cold Walls + Floor To Hot Layer To Plumes To Targets + Fires Out Vent Total Loss Fires Total Convective Total Radiative To Walls To Layer To Target Out Vent To Cold Walls + Floor To Fires
Cold Layer Conservation of Energy Layer Depth Conservation of Mass Temperature Concentration of CO₂, CO, O₂, H₂O, Soot etc. Convective Heat Transfer to Floor, Walls etc.
Ventilation Controlled Fire Hot Layer Energy Depth Mass Temperature Composition Radiation Burning Flames O₂ burned Fuel Energy In Pyrolysis
Burned Out Conservation of Energy (Cooling) Flow Conduit
Entire Vent Controlled Fire Program Replaced at Time of Burnout
Flames
Primary O₂ Limit Efficiency Burning Rate Energy Rate Burning in Hot Layer Composition
Mutual Radiation
Radiation to Fires
Secondary O₂ Limit Efficiency Burning Rate Energy Rate Burning in Hot Layer Composition
Cold Walls + Floor Area less Vent Area Conservation of Energy at {Inside Surface Outside Surface Interior 1D Conduction Pyrolysis Ignition
Entire Growing Fire Program in Room Replaced at Time of Vent Control
3 Types of Fire
Pool Energy In Pyrolysis Slow Decay Mass Rate
Initial Fire Energy In Radius Rate Slow Decay Radius Pyrolysis Slow Decay Mass Rate
Target Fire Ignition Energy In Growth Pyrolysis Decay Mass Rate
Target Ignition Energy In 1D Conduction or Integral for Surface Temp Ignition Temp
Wall Fire
Floor Fire
Collapse of Walls, Ceiling + Floors, Roofs, etc. is:
1 Difficult to Predict with even low precision
2 of major influence on further course of Fire
3 late in the Fire Growth – well after Fire Safety has been Decided
4 Therefor postponed Indefinitely
Computer Fire Code IV +
March 1980 , H.W. Emmons
Zone
Completed Program
Projected Program

FIG I.

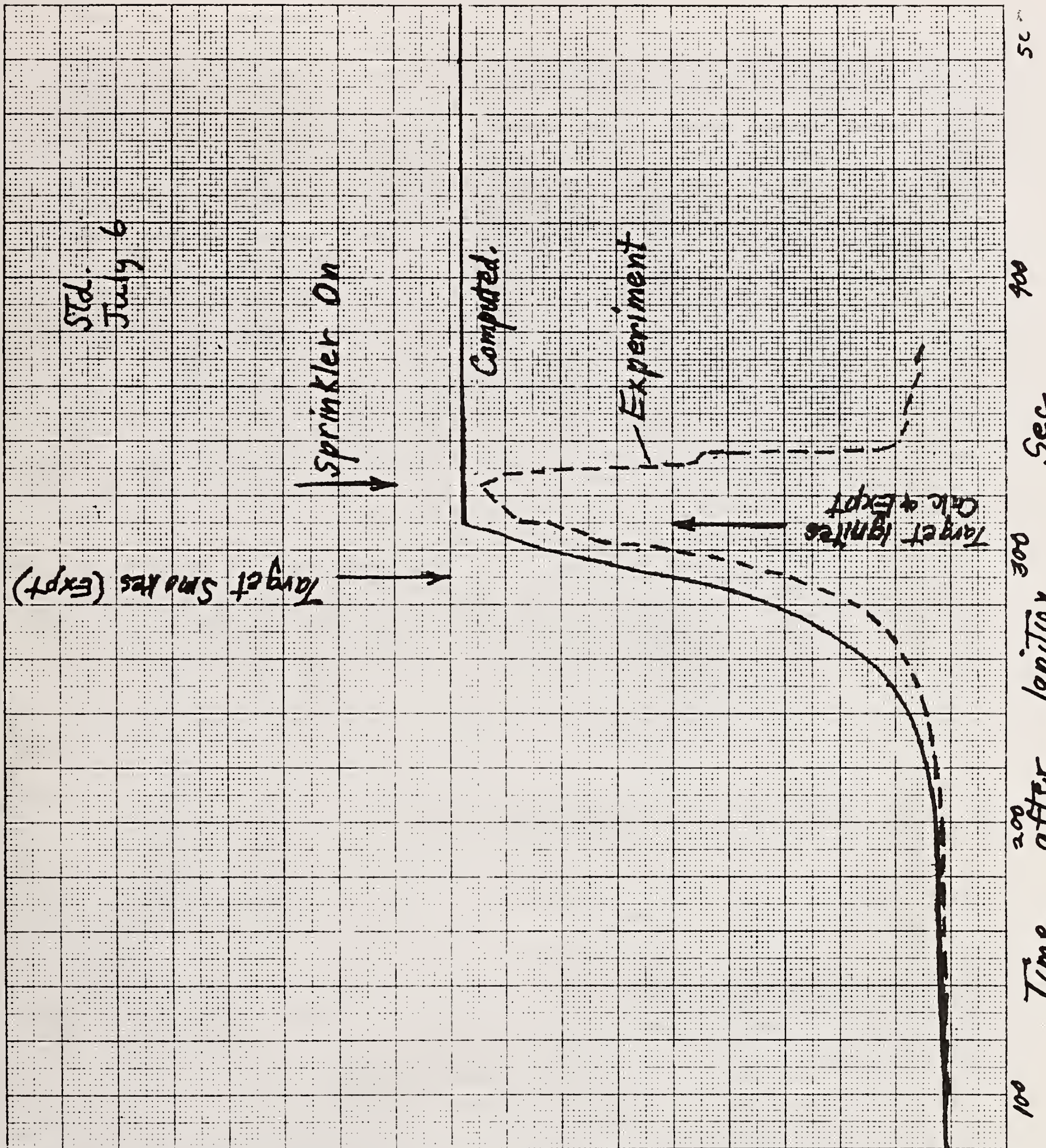

STd.
July 6
Sprinkler On
Computed.
Experiment
Target Smokes (Expt)
Target ignites
Calc & Expt
Time after ignition Sec
0
100
200
300
400
500
Target Surface Temp °K
300
400
500
600
700
800
900

Fig. 2

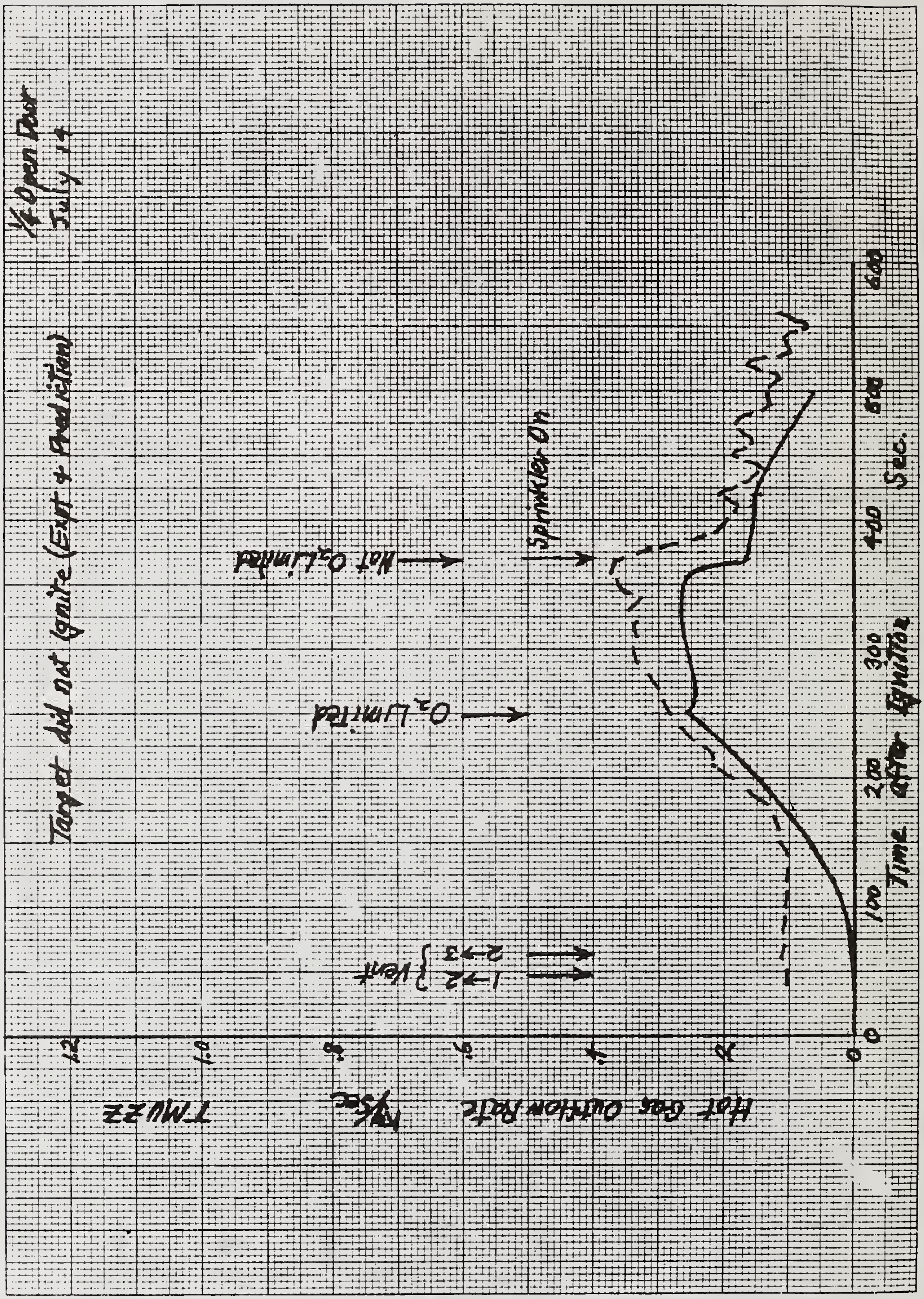

Target did not Ignite (Expt + Prediction)
1/4 Open Door
July 14
Hot Gas Outflow Rate
1.2
1.0
.8
.6
.4
.2
0
0
100
200
300
400
500
600
Time After Ignition Sec.
1→2
2→3
Vent
O_2 Limited
Not O_2 Limited
Sprinkler On

Fig. 3

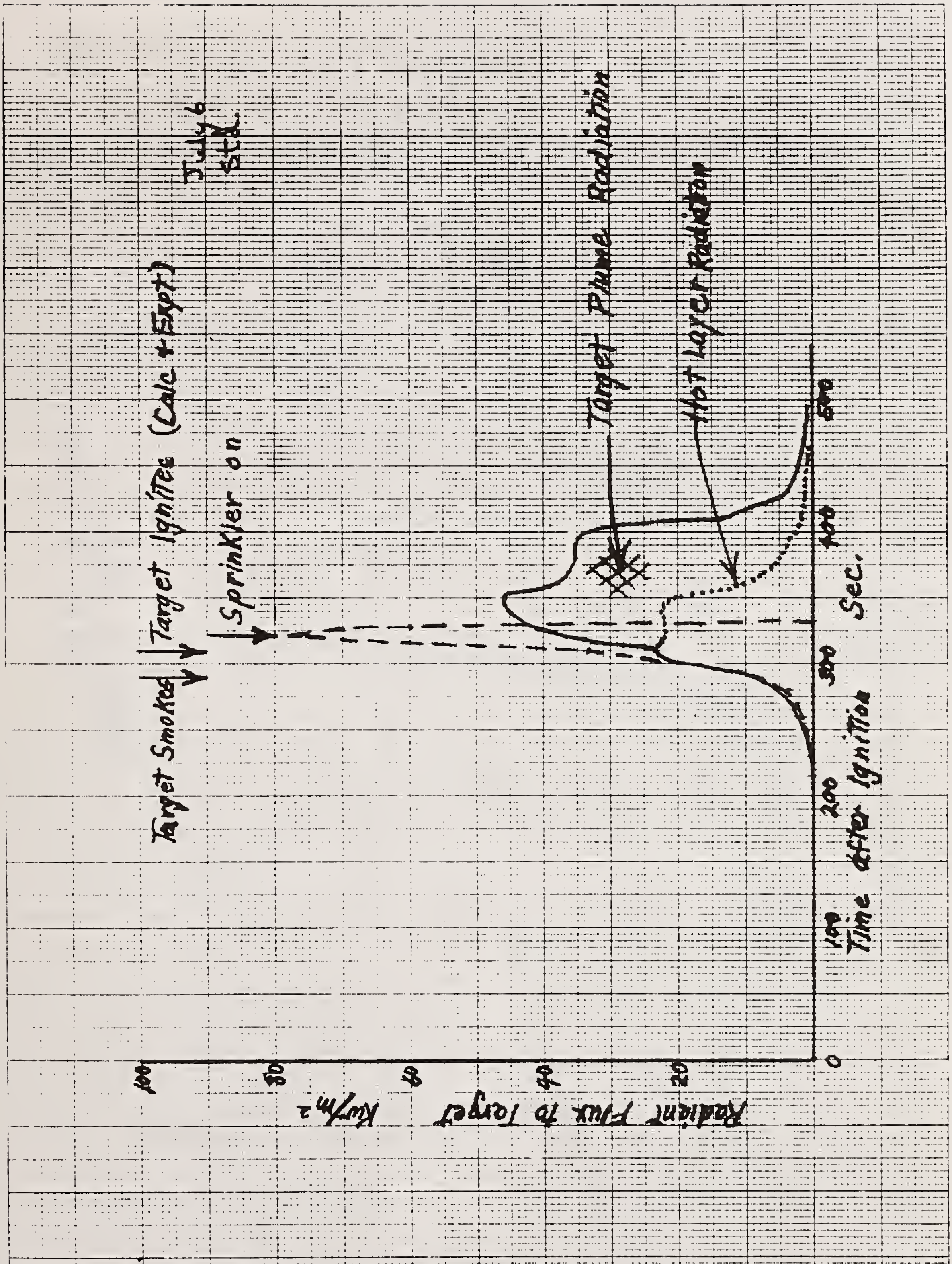

Target Smoked
Target Ignites (Calc + Expt)
Sprinkler on
July 6 std.
Target Plume Radiation
Hot Layer Radiation
Time after Ignition
Sec.
0
100
200
300
400
500
Radiant Flux to Target Kw/m2
20
40
60
80
100

Fig. 4

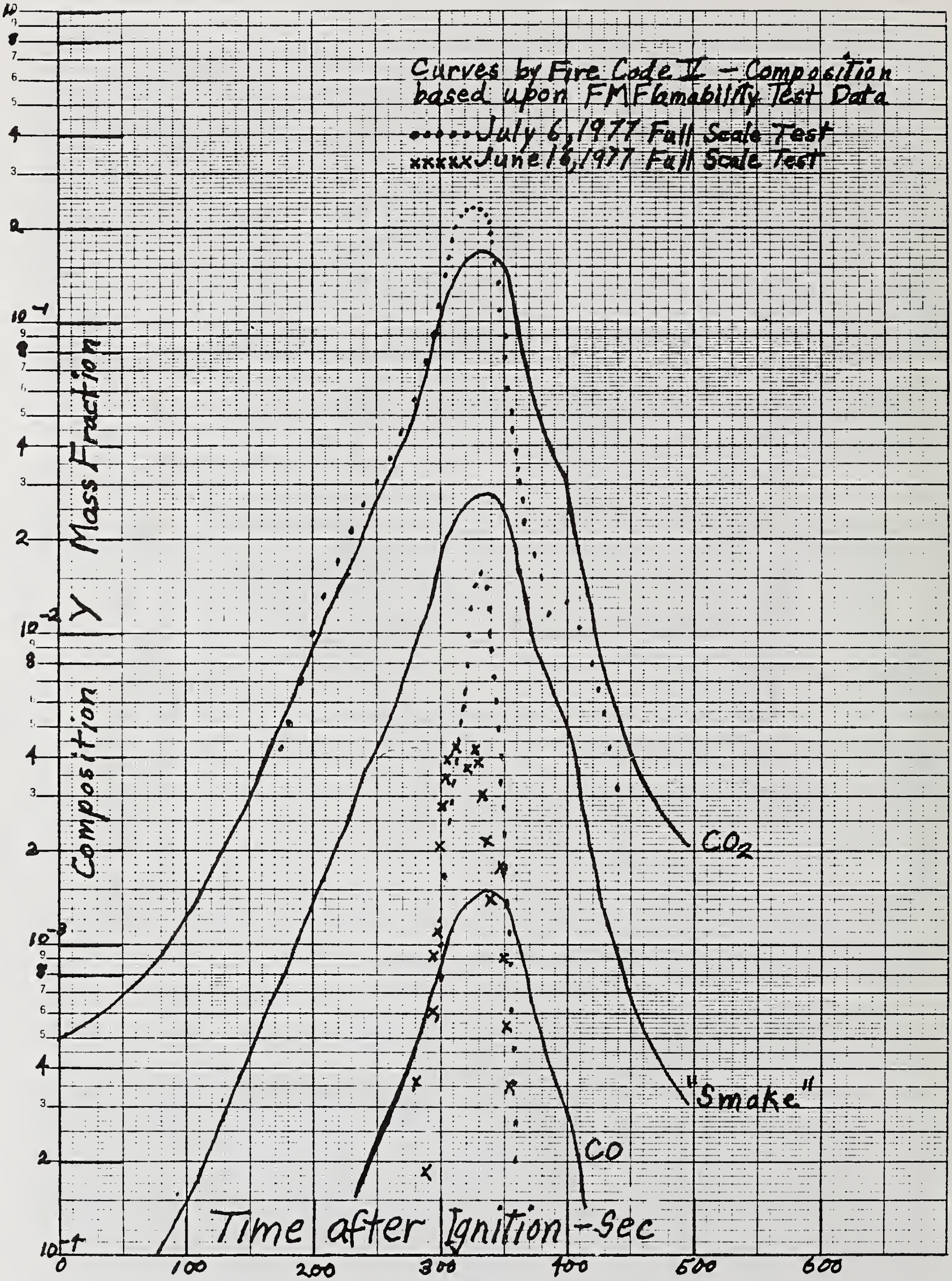

Curves by Fire Code II - Composition based upon FM Flamability Test Data
•••••July 6, 1977 Full Scale Test
xxxxxJune 16, 1977 Full Scale Test
Composition Y Mass Fraction
Time after Ignition - Sec
CO_2
"Smoke"
CO
0
100
200
300
400
500
600

Fig. 5

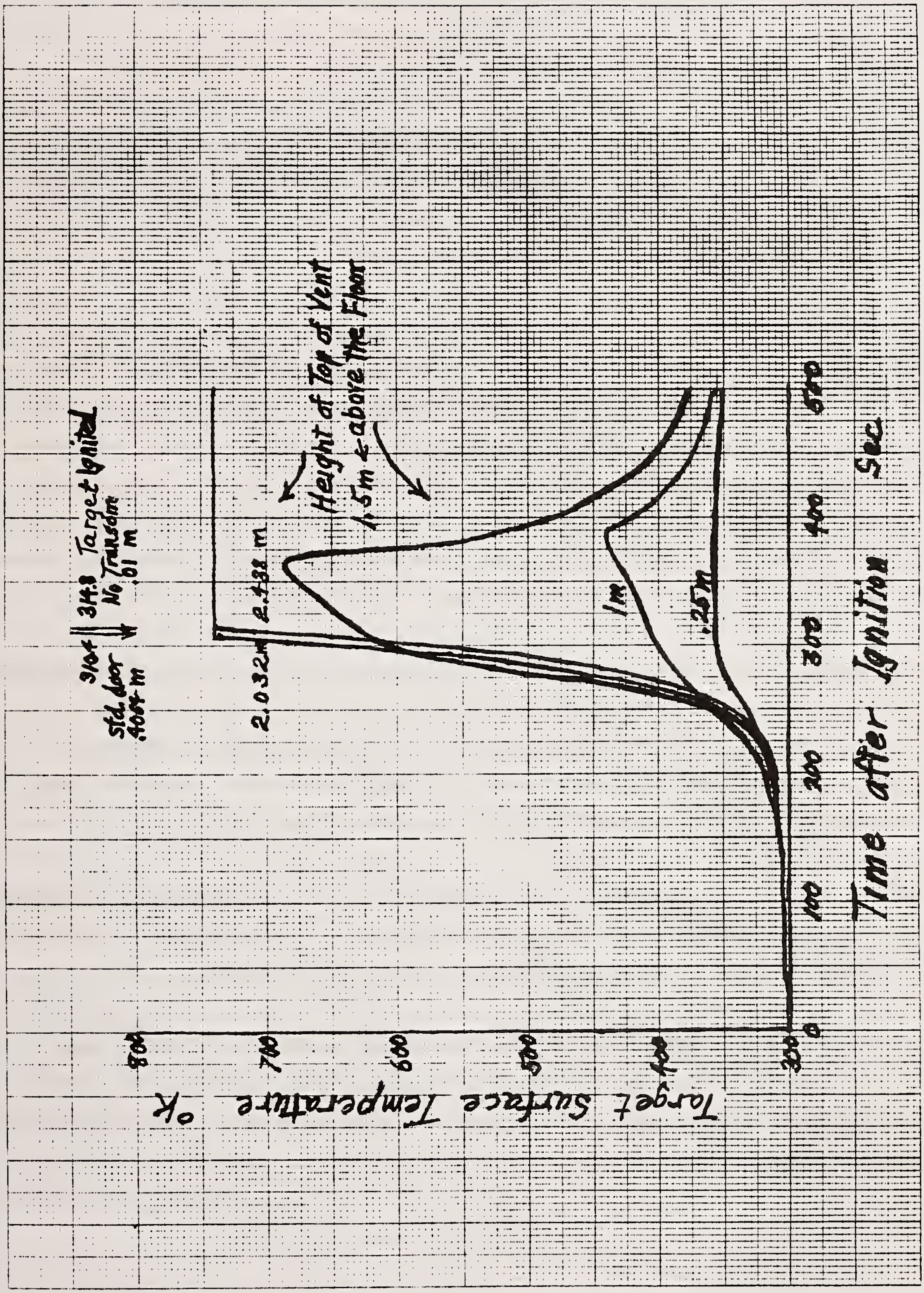

Target Surface Temperature °K
Time after Ignition Sec
Height of Top of Vent
1.5m & above the Floor
310.4
Std. door
.4064 m
314.8
No Transom
.61 m
Target Ignited
2.032m
2.438 m
1m
.25m
800
700
600
500
400
300
0
100
200
300
400
500

Fig. 6

RECENT U. S. PROGRESS IN MATHEMATICAL MODELING OF FIRE ENCLOSURES

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September 1980

Abstract: Current modeling progress at Notre Dame, the University of Dayton Research Institute, the National Bureau of Standards, and IITRI is described. The Harvard Computer Fire Code is discussed in a companion paper. In addition, certain experimental studies useful for testing enclosure fire models which were done at Notre Dame, at NBS, and at NASA/JSC are summarized. Some investigations at Factory Mutual of key model elements, especially radiation, turbulent plume structure, and effect of oxygen deficiency, are referenced.

Introduction: Since the last UJNR Joint Conference in February 1979, development of models to describe fires in compartments has continued in the U. S. The progress made with the Harvard Computer Fire Code by H. W. Emmons, H. Mitler, and colleagues is reported in a companion paper. In this paper, short summaries will be provided of other relevant U. S. work.

I wish to point out that the overall program is being conducted at a relatively modest level of effort, considering the complexity of the problem, and progress is relatively slow. However, definite advances are occurring.

University of Notre Dame - The key personnel are J. R. Lloyd, K. T. Yang, K. Satoh, and N. P. Lynch. They have developed a finite-difference computer code designated UNDSAFE-II which is based on a field model. There are three recent publications (1, 2, 3).

The calculations were originally limited to two dimensions, but recently (3) they have extended the model to three dimensions, using 12 x 12 x 12 cells in a finite-difference grid. This model can take into account transients, strong buoyancy, turbulence, compressibility and smoke diffusion. They currently feel that adequate quantitative overall flow behavior except immediately above the heat source may be obtained by using a turbulence viscosity which is 20 times the laminar viscosity.

In a recent study of ventilation and smoke-layer depth (3), they have assumed a cubic room with a central heat source and a door-like opening of variable size in one wall. For a doorway of given height but progressively increasing width, and a given heat source, they find that the steady-state ventilation flow at first increases proportionally to door width. However, for widths greater than a critical value, which appears to decrease with increasing door height, the ventilation decreases to less than half of the maximum value corresponding to the critical width. Simultaneously the smoke neutral plume rises very substantially. Figures 1 and 2 show this behavior. The results are compared with earlier predictions of Thomas et al., (4). A physical explanation of the phenomenon is provided which is in agreement with the numerical results.

In another computer study, a two-dimensional compartment is analyzed with an opening in the floor and another (offset) opening in the ceiling. The fire is represented by a constant heat and smoke source. The computational grid was 16 cells high and 48 cells wide. The heat source strength and the locations of the heat source and the ceiling vent were varied.

The results were presented in a plot of a dimensionless ventilation parameter vs. a modified Grashof number. The modification of the buoyancy-driven flow by the flowresistance of the compartment can be discerned by examining the trends in the data. The steady-state smoke distributions are also plotted for the 6 cases studied. In two of the cases the long-time behaviors were oscillatory in nature and the authors say that they can be explained by the developing flow patterns in the compartment.

The other recent study by the Notre Dame group (1) is an experimental program to obtain data with a growing methane fire in a room adjacent to a corridor. Temperatures and velocities were measured and flow visualization techniques were used. The data for the first minute after ignition were found adequate to characterize conditions when adiabatic walls were assumed. The data were specifically selected to be useful for evolution and development of transient fire models.

National Bureau of Standards - The center for Fire Research has recently organized a section of its Fire Safety Engineering Division entitled "Fire Modeling", under the leadership of J. G. Quintiere. Other members are H. Baum, M. Harkleroad, D. Corley and K. Steckler. In addition, J. Rockett, Senior Scientist at the Center, has a major interest in computer models of fire. Furthermore, their Exploratory Fire Research section, headed by R. Gann, is concerned with refining the physical knowledge of various processes which must be considered in an accurate fire model.

Quintiere (5) has recently outlined a framework for modeling vertical wall fire spread in a room, using a two-layer zone methodology. He discusses the inputs but apparently has not yet obtained numerical results. He suggests functional expressions for the dependences of burning rate and of spread on incident radiant heat flux and local oxygen concentration. He considers the primary transient process to be the fire growth and spread, and suggests that some fluid-mechanical transients, such as the time to fill the upper room with combustion products may be ignored. However transient conduction into the wall should be included. He concludes that the calculating scheme is far from complete for the wall fire problem, primarily because of uncertainties in fire growth equations and inconsistencies between actual non-uniformities in wall temperature near the fire vs. assumed uniform wall temperature in each zone of a zone model.

Quintiere and McCaffrey (6) have carried out a series of tests with cribs burning in a room with an open doorway. The door was either 1/4 open, 1/2 open, or fully open. The number of cribs in the room was varied from one to four. Two types of cribs were used: sugar pine and polyurethane foam of nearly the same density. Mass loss, temperatures, velocities, CO_2, O_2, and CO were measured. The data were correlated; for example it was found that the mass loss rate varied with the 5/4 power of the number of cribs in the room, suggesting radiative interactions. The crib burning rates in the room were either smaller (0.8 times) or larger (1.3 times) than the free burning rates depending on whether the door was 1/4 open or fully open, demonstrating both ventilation effects and radiant feedback effects. Results were compared with a mathematical model which ignored transients. The equations (seven non-linear algebraic equations) were solved numerically; in some ranges complete convergence was not achieved. When the model output was compared with the data, "the agreement may be considered fair to good," according to the authors.

In another N.B.S. study related to modeling, K. D. Steckler has accurately measured flow coefficients for room openings with fire-induced flows, and will shortly issue a report.

Factory Mutual Research - FMRC has a long-range goal to develop a mathematical model of a sprinklered fire in a building. As a preliminary step, Alpert and Mathews (7) have developed a computer program which computes the axisymmetric flow field induced by entrainment of air into a sprinkler discharge. The model includes a ceiling and a floor but no walls. Droplet drag and evaporation are included. Calculated profiles of induced air velocity agree reasonably well with measurements. The work is currently being extended to include the interaction of a buoyant, upward-moving fire plume with the downward-moving flow caused by sprinkler entrainment, including cooling of the fire gases.

In other programs, FMRC scientists have been developing quantitative descriptions of fire properties as inputs for fire models. de Ris (8) has reviewed the state of knowledge of fire radiation. He concludes that, for fires of moderate scale, the radiation can be adequately approximated by representing the flame as a homogeneous volume with an effective flame temperature and gray emission-absorption coefficient. For large-scale fires, he is concerned that there is significant blockage of radiation by pyrolysis vapors rising from a horizontal combustible surface. There is as yet no way to treat this effect quantitatively. He provides 42 references.

Work done at Factory Mutual, including that of Markstein (9, 10), Orloff (11), Santo and Tamanini (12), Modak and Mathews (13) and Grosshandler and Modak (14) have provided theoretical approaches and experimental data for calculating the radiant flux emitted by a fire. The experimental work involves measurements of polymethyl methacrylate, polystyrene, polypropylene, and polyoxymethylene turbulent pool fires. Consideration is given to flame size and shape, variations of radiative properties from point to point within a flame, and means of finding equivalent overall radiative properties for use in a model. In one of these studies (13) a mathematical model is presented for calculating the radiation from non-isothermal regions containing variable concentrations of soot, water vapor, and CO_2.

In addition, Santo and Tamanini (12) specifically explored for the first time the quantitative effect of reduced oxygen on diffusion flame radiation, using nitrogen dilution. Tewarson et al., (15) measured the effect of reduced or increased oxygen on pool fires of various plastics and methanol, observing changes of burning rate and combustion efficiency. Perhaps the reader will be surprised to learn that luminosity always increases with increasing oxygen.

Tamanini (16) has developed a relatively simple one-dimensional integral model of a turbulent fire plume which assumes top-hat profiles and gives flame-shape results close to those of more elaborate two-dimensional k-ε-g treatments. He has also (17) developed a model for turbulent wall fires which predicts structure and burning rate. Heskestad (18) has found a new means of correlating flame height and structure of buoyancy-controlled turbulent fire plumes.

University of Dayton Research Institute - C. D. MacArthur and co-workers for some years have been developing a computer model of a growing fire in an aircraft cabin, called DACFIR. No reports have been issued since the last UJNR Conference. However interim progress is summarized below.

(1) The concept of the recirculation zone and the zone of uncontaminated air (see Fig. 3) have been merged into a single idealized region now given the name "recirculation zone". The mathematical formulation of the governing equations for this region include, in addition to the usual continuity and energy equations, a momentum equation for the purpose of computing the vertical component of velocity. The effects of horizontal gas motion, due to entrainment by the flames and plume and flow through vents (doors) to the exterior, is modeled by including artificial mass source or sink terms to the recirculation zone equations. The size of these terms are determined by the entrainment rate and the buoyant and/or pressure driven flow through the vents.

(2) A flame and plume model has been developed as an extension of the integral models of Steward (19) and Fang (20) which admits variable external conditions and uses a variable entrainment coefficient. To incorporate variable external conditions, that is, changes in the ambient gas temperature or composition with height, the equations are integrated numerically rather than in the approximate analytical manner of Steward and Fang. An expression for the entrainment coefficient as a function of fuel mass fraction was taken from work by Tamanini (21) on the k-ε-g modeling of turbulent diffusion flames.

The flame and plume model shows some improvement over the earlier integral methods in predicting the vertical development of temperature and the flame length but its main usefulness is in its compatibility with the recirculation zone model, according to MacArthur. Work is still needed to obtain better flame length predictions and to include flame radiation in a more fundamental fashion.

(3) A ceiling jet model has been formulated which is compatible with the flame/plume and recirculation zone models and takes into account, albeit very approximately, the effect of the end walls. In this model the horizontal flow is specified by prescribing its value on a grid of points running along the cabin length just below the ceiling. Physical constraints determine the velocities at the outflow of the plume impact region and at the end walls; between these limits interpolation is used to set the values. The conservation equations are then used at each grid point to compute the amount of downward flow into the recirculation zone. Convective losses to the ceiling and walls are included and radiation from the jet will be added next.

(4) The full-scale cabin mock-up fire test program at NASA/JSC has been completed and the data are now being analyzed and prepared for comparison to the updated version of the model, DACFIR.3. NASA will publish a report on just these tests probably near the end of the year or in early 1981. The report on the comparison of DACFIR.3 to these tests should be ready at about the same time.

MacArthur also plans to modify the model further to include the possibility of a spill fire outside the cabin entering through a door or other vent and to add the capability of compartmenting the cabin.

IITRI. R. Pape and T. Waterman have been developing a computer model of a fire in a room, called RFIRES, which was described at the last UJNR conference in some detail. The program has not been active since that time. However a computer program documentation and users manual was issued (22). The authors, with T. Eichler, are now preparing a final report on their modeling of burning furniture items, with emphasis on a plume model.

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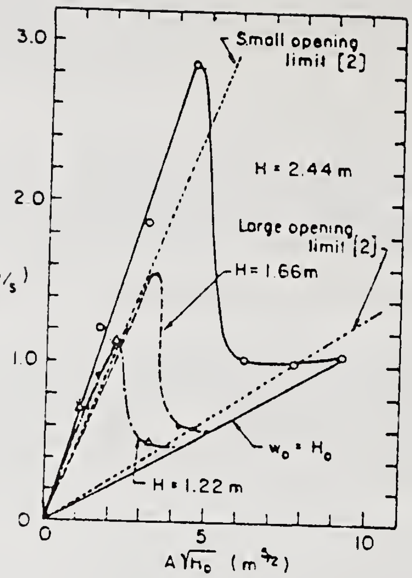

Figure 1. Ventilation Characteristics.

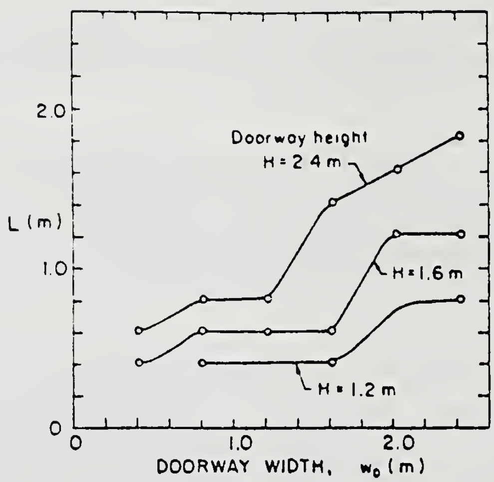

Figure 2. Height of Smoke Neutral Plane.

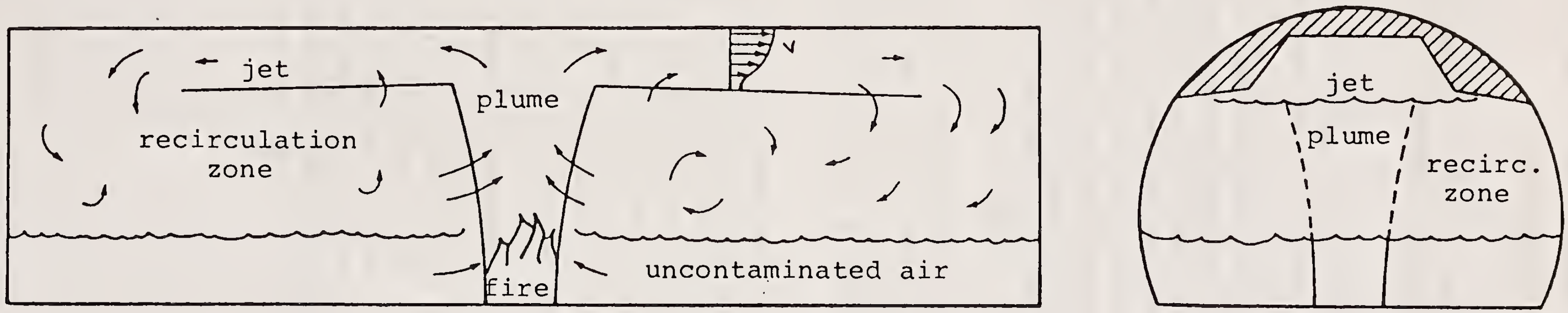

Figure 3. Flows and Zones in the Refined Gas Dynamics of DACFIR A semi-gaussian velocity profile is assumed for the ceiling jet.

Discussion of Presentations on Modeling

Pagni Presentation

Chaiken: Could you comment on the affects of charring solid, particularly one with wood which achieves sizable surface temperature during combustion.

Pagni: I would like to respond with two comments. One primary effect of char is to reduce the ability of the heat to get to the virgin material. This has the effect of increasing the latent heat of the material causing more energy to be provided to produce a gram of fuel into the gas phase. We would expect charring materials to behave in a more acceptable way than non-charring materials. However, it makes it difficult for the analyzer of the model. As the char layer grows these properties become time dependent. I could only hope that quasisteady approximations would be valid and if the property at each instant of time is known, I could apply this analyses to the system. But this is much more information than one needs about a material whose property doesn't change with time.

Quintiere: We have a potential apparatus that could measure equivalent properties, such as heat of combustion or heat of vaporization. What is your opinion as to the viability of such an approach for measuring equivalent like properties in applying models to evaluate those materials.

Pagni: ... One has to be careful to have, in the apparatus in which the property is measured, the condition in which the material will exist in full scale and that is a major difficulty. There are three techniques that I think are valuable in getting the laboratory scale equipment to appear to the material like a full scale fire. Those techniques are: first, external radiant panels which would simulate the effect of radiation from other materials to this sample; second, is the technique of pressuring modeling which was first described by Prof. Williams theoretically and tested by the group at Factory Mutual by Dr. Alpert; and the third possibility would be to change the oxygen concentration in these pressure modeling tests--the difficulty appears to be that the radiation isn't scaled in the same way as the production. But the radiation is due to soot and as we change the oxygen concentration, we might be able to change the soot concentration in the appropriate way. But this addresses the major long range to the modeler, which is to provide the transition from small scale tests to large scale experiments. We could only hope for eventual success.

Hasemi Presentation

Pagni: That was quite an amount of material covered in a short time. Going back to your own work in modeling and flashover, is there any simple way of distinguishing cases where flashover occurs.

Hasemi: We are still studying. One problem is in calculating the model for practical purposes since our mathematical model is becoming more and more complex.

Emmons: This is a comment rather than a question. I was interested in the solution of Mr. Matsushima which you showed. I believe that is the same problem that was studied both experimentally and analytically here at the National Bureau of Standards by the Research Associates from the Factory Mutual Corporation in 1965 or 1966. Mr. Torrence worked out the solution to what I think is the same problem. It would be interesting for Mr. Matsushima to make the comparison.

Emmons Presentation

Hasemi: What kind of input information is needed for this model?

Emmons: The program is in Fortran 4 and will operate on a considerable range of different computers. But each different computer has its own special properties and sometimes our program doesn't run because of some difference between our computer and another one.

Hasemi: Who are the users: firefighters, fire researchers, building architects?

Emmons: The use is rather limited at present because of the limited numbers of fires that one can calculate. As an illustration, I am currently using this program in fire soot. The question of importance is when did the detector detect the fire. By supposing that the detector is one of the objects, (the detector will not burn, it will just heat) I can predict the time after the begining of the fire when the detector responded.

Hasemi: How do you calculate the burning rate? Do you actually calculate burning rate from heat feedback, or use as specified input?

Emmons: The burning rate was one that was ignited and spread. The spread rate and the per unit of the area burning rate, pyrolysis rate, were taken in the following way from an experiment performed in the open. The measured radius rate and the measured pyrolysis rate were interpreted as related to the radiant energy input from the open flame. This means that when the object was burned inside of a room and had a different radiation rate, it would spread and vaporize differently.

Chaiken: How long does this computation take?

Emmons: The computation takes of the order of the actual fire time, actually slightly faster than the real fire.

Friedman: Your last slide, does that refer to the second object of target materials?

Emmons: In examining the effect of the heat of vaporization, I did not have a target.

Quintiere: Was that for a spreading fire?

Emmons: Yes.

Friedman Presentation

Hasemi: Is there any cooperation or coordination among your research studies?

Friedman: There is a mathematical modeling committee of which Dr. R. Levine is the Chairman. Perhaps he would care to comment.

Levine: I will give a short report of our last committee meeting. We used the Hasemi diagram of the interactions in a computer program on fire in order to try to start a discussion on which algorhythms should be used for each of these interactions. There were perhaps fifty people at our meeting and we were not successful. We have decided for next year, to hold four workshops--each one on a different phenomenon. In each case we will have a few people selecting the workshops, almost all of them are people who are doing active research on that particular phenomenon. In addition, Prof. Emmons, Dr. DeRis who works with Dr. Friedman, and Dr. Quintiere will be present. We hope we can arrive at the best algorithm and best input/output statements for the computer in each case. We will then hold another large meeting of the overall committees and discuss where we go from there.

DISCUSSION ON MATHEMATICAL MODELING SESSION

General Comments

Friedman: In my presentation earlier, I neglected to mention the work that Dr. Baum is doing here at the National Bureau of Standards on mathematical modeling.

Baum: I will confine my remarks to advertising a talk that Dr. Rehm and I will give during the informal session later in the program. We are calculating field equation models of bouyant flow enclosures and the transport and coagulation of smoke. We are now in the process of trying to integrate these two phenomena into a single computer program.

Emmons: I would like to make a few remarks that I feel are important with respect for fire modeling.

A number of people have observed questions with respect to steady burning in the various models. Dr. Quintiere, NBS, Dr. Thomas of England and Dr. Hasemi have looked at various phases of this question. These are important mathematical studies of the nature of the steady burning in enclosures. It appears to me, however, that a very important nonsteady question must still be answered. At any instant of time the nonsteady development of fire will be developing towards the steady state. It has been interpreted by the authors that the discontinuity is evidence of flashover. Flashover is not a well-defined term. There are a number of physical phenomena that at various times has been called flashover. It is not clear to me that the new work called flashover is the same as one of those already defined, or is the new definition. Perhaps more important towards immediate modeling studies, is the question of whether or not the occurrence of such discontinuities in equilibrum states have an affect on the nonsteady development of the fire. Nonsteady development tending first towards one equilibrium then towards the other, as the point exists in my program, has never showed itself. I have seen no evidence of such a change. In any complex development of this kind, the computer program behaves beautifully sometimes and other times for no reason it behaves badly. It is very important to further study these discontinuities as related to the numerical model, as well as their relationship to possible physics.

6. SMOLDERING

Modeling of Smoldering Combustion Propagation

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Introduction

This paper is concerned with self-sustaining, heterogeneous oxidation processes in organic materials. When such a process occurs in a fire safety context, it is called smoldering combustion. Such processes do occur in other contexts such as underground coal gasification and we will mention results from that field when they are pertinent.

Nature of smoldering combustion phenomena. Smoldering, like flaming, is a combustion process which spreads through a fuel when heat released by oxidation is transferred to adjacent elements of the fuel. The central role of heterogeneous oxidation (i.e. direct attack of oxygen on the fuel surface) as the principal heat source in the smoldering of polymeric materials has only recently been closely examined (1,2); it appears analogous to, but more complex than, pure carbon oxidation (3). Since oxygen attack on the fuel surface is paramount, access of the surface to this attack plays a major role. It will be seen, furthermore, that the relative directions of movement of oxygen and reaction zone can have a major impact on the smoldering process.

Dominance of heterogeneous oxidation does not preclude some heat release via gas phase oxidation. However, this dominance does generally lead to a combustion process considerably different in quantitative terms from the more familiar gas phase dominated flaming process. While spread of smoldering and flaming both occur through coupled heat release and heat transfer mechanisms, smoldering typically yields less complete oxidation of the fuel, lower temperatures and much slower propagation rates. All of these smolder characteristics can vary widely with oxygen supply. Stable smoldering is possible in some circumstances at equivalence ratios only a few percent of stoichiometric. At the opposite extreme, a strong oxygen supply can raise the intensity and temperature of smolder to such a degree that gas phase reactions become dominant and flaming propagation takes over.

Fire safety hazards involving smoldering. Only rather recently has smoldering been recognized as a major fire safety hazard in the United States. Clarke and Ottoson (4) found cigarette ignition of bedding and upholstery materials to be the single largest cause of residential fire deaths. The cigarette, itself a smoldering cellulosic fuel, is nearly ideal as a smolder initiator in susceptible fabric and filling materials. In such materials, a self-sustaining smolder process can often be established well before the cigarette is consumed. This particular problem is coupled to both fabric and filling response to heating. Once established in this manner, smoldering becomes a steadily growing generator of carbon monoxide and other toxic gases as the size of the reacting region enlarges. This smoldering process may spread stably for an hour or so then abruptly transition to flaming combustion. The hazard is thus two-fold--toxic gases during smoldering and rapid destruction following flaming transition. Which of these is most responsible for the observed death toll is unclear; both undoubtedly contribute.

The increasing interest in residential energy conservation has resulted in a strong demand for effective insulating materials, particularly for attics where heat losses are greatest. Cellulosic loose-fill insulation is quite effective and comparatively inexpensive. It is essentially ground wood, being made mainly from recycled newsprint, reground to a fibrous, fluffy form that is blown into place. The oxidation chemistry of wood clearly renders this material combustible. A variety of additives, typically in fine powder form, are included in an effort to control this combustibility. They are rather effective in suppressing flaming but are much less so for smoldering. When the insulation is improperly installed, heat sources such as recessed light fixtures can cause smolder initiation. Once started, this smolder becomes self-sustaining, spreading through an attic space and posing the same toxicity and flaming-potential hazards as in the above case.

The two problem areas above, upholstery/bedding and cellulosic insulation smoldering, probably comprise the two most widespread and common hazards from this form of combustion in the United States today. They are also the most extensively studied in some respects. There are numerous other problems, however. For example, wood and certain other low permeability building materials (particleboard sheathing and some types of rigid foam insulation) can be induced to smolder in configurations where surface heat losses are suppressed. Spontaneous heating and ignition, usually to smoldering combustion, have long been a problem with a variety of natural products, usually cellulosic in nature. In industries which process oxidizable materials in finely divided form there is danger not only from dust explosions (a flaming problem) but also from smoldering ignition of dust layers accumulating within or on top of hot processing equipment. These industrial problems have been extensively reviewed in a book by K. N. Palmer (46) and will not be examined here in any depth.

<u>Some experimental characteristics of smolder propagation</u>. Table I is a brief summary of the smolder behavior observed for a variety of fuels in several configurations. The list of results is by no means complete but it gives a representative picture for smolder in organic materials. The study by Palmer (5) presents the most complete parametric examination of smolder behavior for configurations that are rather complex but realistic. The study by Lucca (12) is the first systematic comparison of configurations simple enough to be modeled in detail. (The forward/reverse terminology is explained below.)

Cellulosic materials show up most frequently in Table I because they are so common and nearly all of them smolder. (It is interesting to note that pure cellulose does not smolder, at least in small masses; it requires alkali metal contamination to sustain smolder (6,7).) There are, of course, numerous other materials with the potential to smolder but both the material and the way it is used must be favorable to smoldering in order for it to emerge as a fire safety hazard.

The various results in Table I generally justify the description of smoldering as a slow, low temperature combustion phenomenon that responds with increased vigor when the oxygen supply is enchanced. The slowness is apparent in the magnitude of the smolder velocities. It is interesting to note that these do not vary greatly (except for a cigarette during a draw) in spite of wide variations in fuel type and configuration. This probably reflects the oxygen-supply-limited character of the process; a kinetically-limited process would be expected to vary more with various materials. The low temperatures generally reflect the fact that smoldering causes quite incomplete oxidation of the carbon and hydrogen in the fuel. Part of this incompleteness is probably a consequence of the detailed nature of the surface reactions but part is also a result of how various configurations minimize or preclude gas phase oxidation of surface-derived molecules (pyrolytic or oxidative). One feature of smoldering that is not evident in Table I is the variability of the air to fuel-consumed ratio as air supply is changed. Smoldering, at least in some configurations, achieves an extra degree of tenacity because it can adapt to very weak air supplies by varying its effective equivalence ratio (11).

General factors favoring smoldering combustion. All of the fire safety problem areas noted previously do not have a unique set of common factors but certain chemical and physical factors can be discerned to be conducive to smoldering. First, access of the fuel surface to oxygen attack clearly enhances heat generation by heterogeneous reactions. The low diffusivity of oxygen in liquid or solid fuels effectively limits oxidation reactions to the interfacial region between fuel and gas phase. The reaction rate of unit volume of fuel can be increased many orders of magnitude if that fuel is permeated with pores or is in a finely divided form. Second, this access of oxygen to the surface must be retained as the fuel increases in temperature due to self-heating or external heating. The reaction will be effectively suppressed if the fuel melts or forms a liquid product whose surface tension causes contraction and loss of the extended interfacial area. Formation of a solid product or the presence of an extended area support material thus can favor smoldering; this preserves reactable surface and/or provides an insulation for the reaction zone.

Third, the fuel clearly must be amenable to exothermic attack by oxygen but the rate of that attack can vary widely. What counts is the reaction rate under the thermophysical conditions at which the material is used. Smolder initiation depends on a competition between heat generation rate and heat loss rate. This also implicates a fourth factor--conditions which retard heat losses from the reaction zone thereby lessening the requisite reaction rate for smoldering. In the case of smolder initiation, at least, heat losses can be influenced not only by the conductivity and thickness of the fuel but also by the initiating heat source. If that source is sustained in duration for a time sufficient to thoroughly pre-heat all adjacent fuel, the losses from the reaction zone are further diminished. Sustained sources of intensity insufficient to cause fuel ablation or flaming are thus conducive to smoldering.

Note that char formation *per se* was not listed as a prerequisite factor in smoldering. A char is an ill-defined material and one has to be cautious about the meaning of the word. The blackened solid product formed by heating many organic materials is rarely pure carbon; its chemical make-up and its physical properties are usually dependent on the total history of its formation. It is deceptive to say that "char" is the true fuel for smoldering combustion. The tendency to form a solid product (by oxidative or inert pyrolysis) frequently means the extended surface area of the condensed phase is preserved or even enlarged; as noted above, this is a smolder enhancing factor. If there is a persistent solid organic phase, there can be a continuum of exothermic surface reactions available to drive smolder and some of these may start while the fuel is only slightly discolored. While the term "char" is useful (and is used here), one should be careful about what it is meant to imply.

There is, of course, an interplay among these factors that ultimately determines the smolder hazards of a particular usage of a particular material. Note that the hazard of a material is very much dependent on the context of usage. Some situations bring together a particularly undesirable set of factors. In the upholstery smolder problem, two smolder-susceptible materials (cellulosic fabric and polyurethane foam or cotton batting) are juxtaposed and then exposed to an already smoldering source (a cigarette). In cellulosic loose-fill insulation, a thick, heat-preserving layer of a high surface area wood product sits atop a a prolonged heat source like a recessed light fixture. The great potential for trouble in such circumstances should be more widely recognized. This recognition would come more easily if the smolder hazard could be more readily quantified. Unfortunately this quantification depends on the specifics of all the above factors and only very limited studies have as yet been made.

In the present overview of modeling efforts, we will first examine a general classification scheme for smolder propagation problems. Following this, we will survey the modeling efforts currently in the literature and try to decide where further work is most needed.

Smolder Configurations

Conditions favorable to smolder may be encountered in a wide variety of fuel configurations; the resulting propagation process will vary quantitatively and, to a lesser extent, qualitatively with such configurations (so also will the likelihood of smolder initiation). By configuration we mean here the macroscopic and microscopic details of fuel geometry and air supply that dictate how oxygen and fuel come together to react.

Characteristic Lengths. In examining the question of smolder configuration, it is useful to keep several characteristic lengths in mind. There are, first of all, certain physical dimensions that are relevant:

ℓ_{FP} - characteristic dimension of fuel particle

ℓ_{FE} - characteristic dimension of effective fuel element

ℓ_{FB} - characteristic dimension of array or bed of fuel elements

Note that in most problems ℓ_{FE} equals either ℓ_{FP} or ℓ_{FB}. There are also certain lengths characterizing the smolder process or component parts of it:

ℓ_{SW} - characteristic thickness of propagating smolder wave

ℓ_{REAC} - reaction zone length $\simeq t_{REAC} \cdot V_S$

$\ell_{CONV,B}$ - convective heat transfer length in fuel array $\simeq \dot{m}_G \phi\, C_p / hA_V$

Also for each of the three physical scales above (particle, element, array), we have characteristic diffusion and conduction lengths since each scale carries a different diffusivity:

ℓ_C - conduction length $\simeq (K\ t_{SW})^{1/2}$

ℓ_D - diffusion length $\simeq (D\ t_{SW})^{1/2}$

In the above diffusion lengths, t_{SW} is the smolder wave passage time ($t_{SW} = \ell_{SW} \cdot V_S$); V_S is the smolder propagation velocity; K and D are thermal and molecular diffusivities, respectively. Also t_{REAC} is a characteristic reaction time (reciprocal of characteristic reaction rate).

The thermophysical smolder configuration depends on relative values of these various characteristic lengths. Since there are several lengths, the number of permutations is obviously large and we shall not attempt to consider all possibilities here. However, some useful distinctions can be made; some of these are summarized in Figure 1.

The first pertinent length we consider, that of the effective fuel element ℓ_{FE} is roughly defined as the largest fuel aggregate not permeable to airflow under the conditions of the problem in which it appears. This permeability question is quantified further below. Note that, in virtually every smolder problem in the fire safety field, there will be a flow of air whether forced or buoyantly induced. We are concerned with what scale of fuel mass this flow penetrates (if at all) since this bears on the complexity of the problem.

With the above definition, the value of ℓ_{FE} for the same array of fuel can change with the factors that dictate the airflow through or around the array. For example, a bed of loose-fill insulation is made up of wood fibers. When such a bed is smoldering under the influence of a forced flow of air that passes through the bed of fibers, ℓ_{FE} equals the effective fiber diameter ℓ_{FP}. However, when only buoyancy is present, it is insufficient, as will be shown below, to provide the dominant oxygen supply. Rather, it is diffusion from the exterior of the bed that supplies most oxygen; the smolder wave then behaves as if ℓ_{FE} is the characteristic fuel bed dimension ℓ_{FB} (e.g., its thickness). As another example, a cigarette alternates between these two cases: when it is being consumed by buoyant convection, ℓ_{FE} equals the cigarette diameter (ℓ_{FB}); when the smoker draws on the cigarette, ℓ_{FE} equals the tobacco particle size ℓ_{FP} in the forced flow smolder region. For single pieces of low permeability materials such as wood or closed cell polymeric foams there is no ambiguity; ℓ_{FE} is equal to the characteristic macroscopic dimension of the piece ($\ell_{FE} = \ell_{FP}$). If, on the other hand, the problem involves an array of such pieces, one must examine the flow permeation through the array just as in the insulation case mentioned above.

To these physical dimensions we want to compare the characteristic lengths associated with internal aspects of the smolder process. The overall thickness of the propagating smolder wave ℓ_{SW} typically is roughly equal to the sum of the reaction zone thickness ℓ_{REAC} and a pre-reaction zone dominated by transport processes (of length ℓ_{CB} or ℓ_{DB} for conductive or diffusive dominance in an array or bed of fuel elements; if convective heat transfer dominates, the pre-reaction length is of order $\ell_{CONV,B}$; for mixed convection and conduction, this length is of order (λ_B/M_{NTM}) where M_{NTM} is the net thermal mass flux in the two phases; if radiative transfer dominates, as in very porous materials, it is of order $1/\alpha_B$, the radiative path length).

<u>Smolder wave many elements thick</u>. If the smolder wave thickness ℓ_{SW} is large compared to the effective fuel element size ℓ_{FE}, we have one major subdivision of smolder problems as shown in Figure 1. We implicitly assume in this subdivision that there is a large fuel array of size $\ell_{FB} >> \ell_{FE}$ and $\ell_{FB} >> \ell_{SW}$. This subdivision encompasses such problems as forced flow smolder through loose-fill insulation, a cigarette during a draw and at least some problems of coal or oil shale gasification where the starting material is finely particulated.

In this first subdivision, many fuel elements are encompassed by the smolder wave and we have the possibility of a macroscopically one-dimensional (1-D) propagation process. That is, gradients of temperature and species on the scale of ℓ_{SW} may only be significant in the direction of smolder wave propagation. This is not likely to occur in practice without some intentional efforts but it is a welcome simplification useful in qualitatively simulating the smolder problems just mentioned.

Tractable detailed models of such smolder propagation require a further simplication as well, that of microscopic one-dimensionality. This requires

$$(\ell_{CE}/\ell_{FE}) >> 1; \; (\ell_{DE}/\ell_{FE}) >> 1 \qquad (1)$$

These conditions imply that there are no gradients of temperature or species within each effective fuel element. The second of these two conditions is usually the hardest to satisfy because of low species mobility in micropores of the fuel element, especially if $\ell_{FE} = \ell_{FP}$ and the fuel element is a low porosity solid like coal or a char. If the conditions in Equation (1) are satisfied, the smolder propagation process can be simulated by a fully 1-D model that only considers gradients on the scale of ℓ_{SW}. The simulation will only be qualitative, of course, if the real smolder problem of interest is 2-D on the scale of ℓ_{SW}. If the conditions in Equation (1) are not satisfied, modeling is still possible but it becomes much more expensive; this problem is being confronted in the underground coal gasification field.

Simpler limiting cases. As noted in the upper part of Figure 1, there are two limiting cases that are macroscopically (and possibly microscopically) 1-D, depending on the relative directions of air and smolder wave movement. Forward smolder is the term applied to the case where both air and smolder zone move in the same direction. (This is also called counter-current smolder; an observer moving with the reaction zone sees fuel and air enter it from opposite sides.) Reverse smolder (co-current smolder) applies when the smolder zone moves toward the incoming air. These distinctions are important because they can have considerable effect on the character of the smolder process. Forward smolder tends to move more slowly and to completely consume the fuel. The fuel heat up zone ahead of the wave is devoid of oxygen; this can strongly affect the amount of char formed as well as affecting the composition of the smoke. Reverse smolder is faster for the same air flow and less complete (to a varying degree), proceeding at a rate greatly dependent on heat transfer (like a deflagration wave). The fuel heat up zone is highly oxygenated since the wave moves toward the air flow.

In general, real problems are neither purely forward nor purely reverse smolder in character since the air supply and the reaction zone are not usually constrained to be collinear. The above limiting cases are of interest both because some of their character can be seen in more complex problems and because they are more tractable than the arbitrary cases; we thus can obtain information pertinent to the most general three dimensional cases indicated in Fig. 1 by examining the simpler limiting cases.

Smolder wave comparable to fuel element. If the smolder wave thickness ℓ_{SW} is less than or comparable to the effective fuel element ℓ_{FE}, the propagation is multi-dimensional in character on the scale of ℓ_{FE}. We then have the second major subdivision of smolder problems as shown in the lower half of Fig. 1. (There is, in principle, a 1-D limit to configurations, such as that suggested in Fig. 1, when $\ell_{DE} >> \ell_{FE}$ and $\ell_{CE} >> \ell_{FE}$ but this does not appear to be pertinent to any real smolder problem.) The smolder wave tends to spread over the outer surface of the fuel element and penetrate inward by consumption of the outer layers. If there is only one such fuel element involved, this confinement of reactions to the outer surface will inhibit smolder because of heat losses. Survival of smolder in these circumstances requires either very favorable chemistry or inhibition of the heat loss by an ash, for example. Many cellulosic materials seem to have both of these survival factors.

There is, of course, a classic heterogeneous oxidation problem that falls in this category, that of the consumption of a single char particle in a furnace environment. This problem area is extensively reviewed in ref. 20; many of the thermophysical phenomena discussed there are pertinent here as well.

If the heat losses from a single fuel element preclude its smolder when it is isolated, the inclusion of another (or many more) fuel element(s) may change this. The sketch in the lower half of Figure 1 suggests two slab-like fuel elements forming an air gap (this could be a wall cavity);

heat losses from the inner surface of each are mutually cancelling. Effects such as this enhance the smolderability of charcoal briquets or logs in a fireplace.

Once again, in the lower half of Figure 1, there exist two limiting cases in the relative direction of movement of air and the smolder wave. The qualitative differences between these limiting cases should be essentially the same as in the previously discussed case.

Assessing fuel permeability. Recall that we have defined the effective fuel element as the largest fuel aggregate not permeable to airflow. It is pertinent then to attempt to assess what conditions permit airflow permeation through a fuel aggregate. We compare convective air flow-through to diffusive O_2 supply from the exterior of the fuel mass under consideration to discern when that convective supply can be dominant.

Consider a flat layer of smolderable fuel of thickness ℓ and width much greater than ℓ. Assume the convective flow through the fuel is supplied by buoyancy generated in the smolder wave and that this buoyancy is balanced by the drag the flow experiences in passing through the permeable fuel mass. Then we have

$$a_D \left(\frac{\mu}{\mu_R}\right) V_g = g\rho_R \frac{\left(T-T_R\right)}{T} \qquad (2)$$

The symbols are defined in the Nomenclature Table. The term on the left in Eqn. (2) is the laminar drag, proportional to gas viscosity and flow velocity; the term on the right is the buoyancy force measured in the peak temperature zone of the smolder wave. The proportionality constant a_D is a measure of the fuel permeability to gas flow. This equation can be solved for the gas velocity and from this we get an approximate measure of the convective oxygen flux

$$\dot{m}_{OC} \simeq \rho_M Y_{OXA} V_G \qquad (3)$$

This ignores the increased gas mass flux due to fuel gasification. For this convective flux to dominate over diffusive oxygen supply, at least when the reaction zone is a mid-depth in the fuel mass, we require that it be, say, ten time larger than the diffusive flux at that point. The diffusive flux at mid-depth may come from both bounding surfaces of the fuel

$$\dot{m}_{OD} \simeq 4\bar{\rho}\bar{D}\left(\frac{Y_{OXA}}{\rho}\right) \qquad (4)$$

where we have assumed that Y_{OX} goes to zero in the reaction zone. This expression ignores the effect of convective counter-flow on the diffusive flux from one bounding surface. Both Eqn. (3) and Eqn. (4) tend to overestimate their respective fluxes.

From the requirement that $\dot{m}_{OC}$ be at least 10 $\dot{m}_{OD}$, we can solve for the upper limit on the gas permeability constant that satisfies our criterion for dominance of convective oxygen supply.

$$a_D \leq \left(\frac{\ell}{40\bar{\rho}\bar{D}}\right)\left(g\rho_R\rho_M\right)\left(\frac{\mu_R}{\mu}\right)\left(\frac{T-T_R}{T}\right) \qquad (5)$$

This is an approximate guideline for the range of fuel mass permeabilities that will permit dominant convective supply to the fuel mass interior. If fuel mass in question satisfies Eqn. (5), we look at the next lower scale of fuel mass to discern if it dictates ℓ_{FE}, as defined above since the scale just examined does not. For highly porous fuels such as flexible polyurethane cushioning materials, a_D can vary widely from about 1.0 to 100 g/cm^{3}sec (13); for a typical cellulosic, loose-fill insulation, a_D is approximately 10 g/cm^{3}sec. For typical smolder conditions, Eqn. (5) reduces to $a_D \leq 10^{-2}\ \ell$; since ℓ for these fuels is 10-30 cm, typically, they will not meet the criterion for high permeability. An exception might be cellulosic insulation in a vertical wall cavity where ℓ could be much greater.

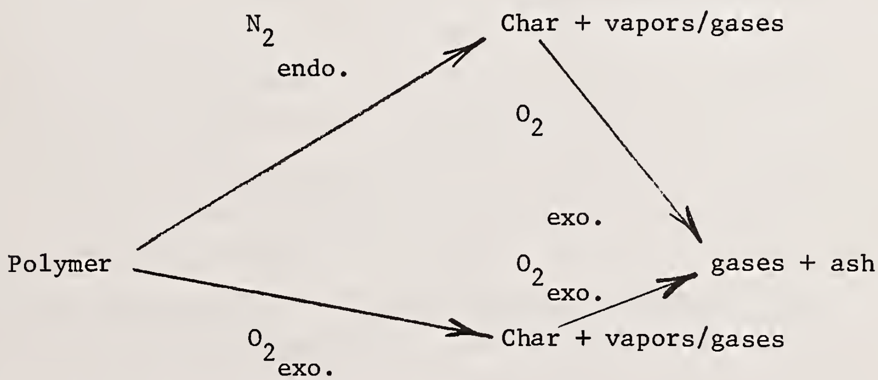
This conclusion only holds when natural convection provides the oxygen supply. Forced convection may be pertinent to realistic smolder hazard problems. For example external winds penetrating vent holes or internal home ventilation could result in forced air flow through loose-fill insulation. Then the right side of Eqn. (2) is replaced by the pressure gradient $\Delta P/\ell$ and Eqn. (5) is replaced by a calculation of the minimum imposed pressure force for convective dominance. Thus a given fuel mass scale may dictate the effective fuel element size ℓ_{FE} in one set of conditions but in another, ℓ_{FE} may be less (i.e. $\ell_{FE} = \ell_{FB}$ or $\ell_{FE} = \ell_{FP}$).

Other considerations. It is worth noting that the varying configurations in Fig. 1 will affect not only smolder propagation but also the ease with which smolder can transition into flaming combustion. For example, smolder within a porous fuel mass is not likely to transition unless there are large air gaps (presumably larger than a flame quench distance). The available data on the transition process are meager (5,17,27,28). The distinctions in Fig. 1 are not as important for smolder initiation, however. Since a moving front does not yet exist during ignition, the forward and reverse distinction does not apply. Fuel permeability is pertinent primarily because it affects the extent of oxygen depletion during ignition. Smolder initiation in high permeability fuels can be treated as a problem in thermal ignition theory (14,15,16); smolder initiation in low permeability fuels has received only limited study (17).

It appears that virtually every established smolder process quickly becomes oxygen-limited (i.e. oxygen concentration goes to zero in the reaction zone). If so we can make the following qualitative inferences about smolder spread. Once smoldering is fully initiated on some part of the outer boundary of a fuel, it will undergo a transient spreading process and the smolder wave may arrive at a steady or quasi-steady shape that then consumes the remaining fuel. (Since this evolution takes time, the steady state may never be reached with small fuel masses.) The transient evolution of the smolder wave is due to heat transfer but the rate at which heat is evolved and made available for transfer is dictated by the rate of oxygen supply. Thus the relative rate of smolder penetration into the bulk of the fuel versus spread over the outer surface is dependent on the fuel permeability considerations discussed above. The one factor that can always override this oxygen-limited spread process is heat loss. If heat losses from some region of the spreading front become excessive, the local temperature will be suppressed to the point where the kinetics of oxidation, rather than the rate of oxygen supply, limit the heat evolution rate. This will slow or stop spread into that region. A steady-state is finally achieved when (and if) a stable balance of heat generation rate versus heat transfer rate is achieved at each element of the smolder wave. The shape of the steady state wave will be largely determined by oxygen transport processes to the reaction zone.

<u>Smolder Chemistry</u>

During the passage of a smolder wave, the fuel, which typically consists of a complex polymer or mix of polymers, is degraded and gasified by both heat and oxygen. Even when the fuel is a single polymer, this degradation/gasification process will involve large numbers of series and parallel reaction paths. Some of these will be endothermic, others exothermic. About all that can be stated for certain about this overall process is that it must have a net exothermicity, otherwise self-sustaining smolder could not occur. In broad overall terms, most polymeric fuels can be at least approximately described by a degradation/gasification scheme like the following.



This glosses over tremendous complexity; each "reaction step" in this scheme is the composite result of numerous reactions of unspecified nature. For example, for cellulose, the pyrolytic pathway (N_2) has been under investigation for years but it is not fully clarified. Again for cellulose, the initial oxidative reaction paths have examined to some extent (18) and the char oxidation is also just beginning to be investigated (1,2). For other smolderable fuels the underlying chemistry is even less clear. What is termed "char" in the above scheme has to be operationally defined since it has no definite composition (and probably differs whether formed in the presence or absence of oxygen).

Much of what happens to the polymeric fuel during smolder is qualitatively analogous to the fate of coal during devolatilization and oxidative gasification. There is an extensive literature in the coal field (19,20,21) which can provide insights into the smolder problem, especially physical processes bearing on the above degradation scheme, but the results cannot be directly applied here.

Even though the above type of scheme is only a crude representation of reality, it can be quite useful if it can be quantified properly. A tractable smolder model could handle four overall reactions; from the model one can then learn what factors affect which of these overall stages. This can in turn help pinpoint what aspects of the underlying chemistry might best be further examined in efforts to retard or suppress smolder.

Since each step in the above scheme is a composite of several reactions having, in general, different activation energies, quantification of the scheme should ideally be done in the same conditions of atmosphere and heating rate as occur in smolder. Otherwise, the apparent kinetics of any given composite reaction step can change. In practice this can only be approached at present, especially because heating rates in smolder (1/2 °C/sec and up) frequently exceed present instrumental capabilities. Thermal analysis (thermogravimetry and differential scanning calorimetry) are the best techniques presently available for quantifying the overall rate laws for each step in the above scheme. Typically this requires sample runs at two or more heating rates and several oxygen levels (21% to 0%). Techniques are available for fitting rate equations to the data (22,23).

A further important consideration pertains to matching the above scheme to actual overall smolder chemistry. Physical factors affect the degradation process as well as chemical factors. Oxidation occurs on the available surface of the fuel, pyrolysis in the bulk of the fuel. The available surface of the fuel may involve micropores either initially or after some extent of reaction. The oxidative/pyrolytic competition depends on the surface to volume ratio, among other factors, and that ratio may change as degradation/gasification progresses. The physical form of the sample should be the same as that occurring in real smolder so that the physical interactions with the chemistry are the same. One should recognize that the "kinetic rate law" derived for any overall reaction step may be describing physical as well as chemical changes; thus it is dangerous to assign any mechanistic significance to the apparent activation energy.

Smolder chemistry is in a rather primitive state; there is much to be learned that could have a large impact on the smolder hazard problem. Until the situation improves, schemes such as that above can be applied to carefully limited sets of conditions.

Smolder Propagation Models

The number of smolder models in the literature is rather small, reflecting the underdeveloped state of this field. They can conveniently be broken into two categories which will be called simple and complex. The simple models typically are applied to rather complex configurations where a detailed description quickly becomes intractable from the solution standpoint. The main value of the simple models is in providing a qualitative prediction of the effect of pertinent parameters on smolder propagation characteristics. Potentially they can draw together a set of experimental measurements, rationalize their main features and provide an approximate extrapolation of behavior to other sets of conditions. The more complex models begin, at least, with simple configurations, impose fewer assumptions about controlling factors, and let the model solution tell the story of what factors(s), in what conditions, govern(s) the output of interest. The complex model is, in effect, another experimental tool for examining the parameters that influence smolder characteristics; it is a tool more easily manipulated and probed than the laboratory smolder system. Of course, no model is better than the physics and chemistry that go into it.

1. Simple Models

Cohen and Luft (Ref. 8). This is a phenomenological model of lateral smolder spread through a thin bed of fuel particles; oxygen supply is by natural convection. This is a 1-D model of a 2-D propagation process. Here $\ell_{FE} \approx \ell_{SW}$ and both are comparable to the fuel layer thickness; the problem falls in the general category of the lower half of Fig. 1 since the smolder wave may be mixed forward/reverse in character. The model begins with the 1-D approximation that convective and conductive heat fluxes from and to the virgin material where the smolder wave is moving are in balance.

$$(1-\varepsilon)\lambda_B \frac{\left(T_M - T_R\right)}{\ell_s} \approx (1-\varepsilon)\tilde{\dot{m}}_F C_F \eta \ (T_M - T_R)$$

where

$$\eta - 1 = \left(\frac{C_A \varepsilon \ \dot{m}_A}{C_s (1-\varepsilon)\dot{m}_s}\right)$$

is the thermal capacitance ratio of air to solid entering the reaction zone. There are four unknowns here, T_M, ℓ_s, $\dot{m}_s$, $\dot{m}_A$. Further approximate relations are introduced specifying peak temperature, air velocity and fractional conversion of the solid. These are all utilized, together with some of the experimental smolder measurements, in a manner not sufficiently explained; some of the intermediate steps and results are subject to question. The peak temperature is thermodynamically determined on the assumed basis of CO formation only (not examined experimentally). Air supply is taken to be dictated by a drag/buoyancy balance in the particulate fuel bed; oxygen diffusion, which can be shown to be of the same magnitude, is ignored. The authors calculate fractional conversions of the solid which are implausibly low (2% in some cases). They seem constrained by an attempt to justify measured temperatures which themselves are implausibly low (see Table I, for example). The general approach has merit as a basis for correlating experimental trends on thin fuel layers but would benefit from a few additions as noted. Comparison with the more extensive experimental data of Palmer (5) would be beneficial.

Kinbara, Endo and Sega (Ref. 9) This is a 1-D model of 2-D downward smolder propagation in single, low permeability fuel cylinders. Air flow is due to natural convection. Again $\ell_{FE} \simeq \ell_{SW}$ and the problem falls in the lower subdivision of Fig. 1. (Also $\ell_{FE} = \ell_{FP}$ = cylinder diameter.) Downward propagation against upward buoyant air flow around the cylinder gives the problem a 2-D reverse smolder character. The model is based on the 1-D heat conduction equation for the solid fuel; estimates are made of heat production and heat loss terms in this equation. The development seems somewhat forced in an attempt to match experimental trends for the effect of ambient temperature and fuel cylinder radius. Heat production rate on the fuel surface is taken to be oxygen-supply limited; the rate of O_2 supply is assumed proportional to the temperature difference between the surface and ambient (assumes mass and heat transfer numbers are equal). The heat production rate is also proportional to the reacting surface area but here the actual conical shape is ignored and a "correction" for effective surface area is applied. Finally, heat production rate is assumed inversely proportional to the difference between ambient temperature and a measured instantaneous ignition temperature. Heat loss from the surface is Newtonian; the effective heat transfer coefficient and the surface area "correction" are obtained from separate experiments. The resulting steady-state energy conservation equation is the following.

$$\lambda_F \frac{d^2T}{dx^2} + \dot{m}_F C_F \frac{dT}{dx} + 2\left(\frac{1}{r_c} + \frac{\Delta}{r_c^2}\right)\left(\frac{q}{T_i - T_o} - h\right)\left(T - T_o\right) = 0$$

This equation has solutions of exponential form that involve a parameter grouping called β. The authors offer a rather obscure argument that $\beta=0$; this leads directly to

$$V_s^2 = \left(\frac{8\lambda_F q}{C^2 \rho^2}\right)\left(\frac{1}{r_c} + \frac{\Delta}{r_c^2}\right)\left(\frac{1}{(T_i - T_o)} - \frac{h}{q}\right)$$

This is the same form as that in which their experimental data on the effects of r_c and T_i are correlated. The unknowns q and Δ are inferred from this match and appear plausible. The same development is applied to rectangular cross-section materials and leads to a very similar expression which again correlates their experimental data. Here there is some apparent conflict with the data of Palmer (5) on fiberboard strips; he found a linear relation (rather than V_s^2) between smolder velocity and sample dimensions (perimeter/area). The range in dimensions for both studies is too narrow to settle this definitively.

Sega (24,25) has extended both the experimental and theoretical work on downward smolder propagation in low permeability fuels to other geometries including a hollow cylinder. The results are correlated similarly. The model is developed in a somewhat different fashion that accounts for the non 1-D geometry of the reacting surface. The final correlating equations for smolder velocity in terms of sample dimensions and temperature are similar to that above. This work has not been translated to English so detailed comments cannot be made at present.

Williams (Ref. 26). This development is couched in very broad terms in the midst of a general discussion of fire spread mechanisms; it is intended only as a phenomenological description of smolder spread mechanisms. The author notes that oxygen-limited smolder is more probable because kinetically-limited propagation is often unstable. This leads to the interesting rough criterion for a smolder extinction limit:

$$Y_{ox}^{n} \; A \exp (E/RT_M) < \rho_{ox} D_{ox} / \ell_G$$

This says that extinction can be expected when the kinetic oxidation rate of the fuel drops below the diffusive oxygen supply rate (ℓ_G is a characteristic length for oxygen diffusion). Applying this in practice, of course, calls for more detailed analysis of a specific configuration.

For a permeable fuel in a forward smolder mode (eg, a cigarette smoldering upward with a buoyant/diffusive O_2 supply), Williams equates an oxygen-limited heat generation rate to the fuel heat-up enthalpy to get a rough expression for smolder velocity:

$$V_s = Q_{ox} \rho_{ox} D_{ox} / \ell_G \rho_F C_F (T_M - T_o)$$

If the fuel is not permeable, the reaction is confined to the surface and a configuration-dependent heat loss must be subtracted from the heat generation rate. (In fact, heat losses must also be included in the permeable forward smolder case, otherwise regenerative reactant heating precludes the assumed steady state.) If ℓ_G is assumed proportional to a lateral dimension of the fuel, the resulting expression will look roughly like that of Kinbara, et al, above but it is linear in V_s, not quadratic. The expected dependencies here are qualitative only since no realistic configurational details are included.

Moussa, Toong and Garris (Ref. 27). This is a 1-D model of a 2-D lateral smolder spread along a horizontal cellulosic roving (in effect a porous cylinder made up of fibers); air is supplied by natural convection/diffusion. The problem is also qualitatively quite similar to a horizontal cigarette smoldering under natural convection conditions; the model has also been applied to horizontal smolder spread along blocks of polyurethane foam wrapped with a cellulosic fabric (28). For all these cases we have again $\ell_{FE} \simeq \ell_{SW}$ with both approximately equal to the lateral dimension of the fuel mass (a general case in the lower half of Fig. 1). This theory is substantially more complete than any of the preceding models since it includes fuel pyrolysis as well as oxidation and attempts, also, to predict extinction limits for smoldering.

The cellulose is assumed to undergo two simultaneous degradation reactions, one forming a char and the other forming volatiles that disappear from the system; the oxidation of the char drives this system. This is analogous to the overall reaction scheme given above but it assumes no char is formed by the pyrolytic route (N_2); this is an approximation. Note that the amount of char available for oxidation will depend on the balance between competing reactions.

A planar interface is assumed to divide the cellulose heat-up and degradation zone from the char oxidation zone; heat from the latter zone, less heat losses to ambient, must balance the heat requirements of the former zone in order for a steady smolder solution to exist. If not, the particular set of conditions falls in an extinguishment region (transient smolder might exist but is not considered).

With the problem thus split into two parts, the parts are analyzed separately. The heat-up/degradation zone is treated rather more accurately than the char oxidation zone. For the former, a 1-D model (neglecting surface heat losses and radiative transfer) for temperature and species is solved numerically with various imposed heat fluxes at the artifical interface. The reaction heats are found to have only a 20-30% effect on these results so that an analytical solution for zero heat effect is ultimately used instead. The output is interface temperature and char fraction versus imposed flux. To match this and select a unique smolder velocity, one needs the available feedback flux from the char oxidation zone versus interface temperature. Here it is assumed that the char oxidation zone is isothermal at the interface temperature in spite of the experimental observation that temperature here varies over a 100-200°C range. This is the roughest approximation in the model. Heat generation in this isothermal region can be limited by O_2 supply, oxidation kinetics or both. The oxidation rate is deduced from the carbon literature

$$r = FP_{ox,s}^{1/2} \exp(-E/RT_s)$$

Oxygen arrives at the char surface by diffusion through a natural convection boundary layer

$$J_{ox} = 2.2 \cdot 10^{-5} \sqrt{\frac{T_m}{\delta}} \left[\frac{P_{02,\infty} - P_{02,s}}{P_T} \right]$$

where δ is the boundary layer thickness, taken from the literature. The char is treated as though it is non-porous (on macroscopic & microscopic scales) and the total heat generation rate is deduced by multiplying the above reaction rate by an imposed char surface area (estimated from experiment). The partial pressure of oxygen at the char outer surface is obtained from the steady state assumption that the above two expressions specify equal oxygen fluxes. The char reaction rate specifies oxygen via a stoichiometric coefficient, taken as that for carbon oxidation to CO_2; the reaction heat is also that of this reaction. Finally, the net heat flux available for feedback is the chemical heat minus radiative and convective losses as well as a loss through the ash end, rather crudely estimated. As indicated, this is matched to the pyrolysis zone to get smolder velocity and peak temperature.

This is a quite reasonable qualitative model of smolder propagation for this type of over-oxidized configuration (i.e, where there is an infinite reservior of oxygen available to the smolder zone). It has more real physics in it than any preceding model though it still has some major approximations. One might expect that its prediction of trends would carry over to the cigarette problem mentioned above or to a smoldering fabric or, in fact, to the system studied by Kinbara, et al.

The authors give predictions of the variation of smolder velocity and peak temperature with oxygen mole fraction and oxygen partial pressure. They also predict minimum values of these two external parameters which will yield smolder extinction. The prediction of experimental trends is good in all cases. In certain cases the quantitative agreement between model and experiment is quite good; in view of the numerous approximations, this must be viewed as fortuitous.

Another interesting prediction of the model is that for essentially all conditions not near an extinction limit the smolder process is oxygen supply limited. Oxidation kinetics limit only in a narrow zone before extinction; this is in qualitative agreement with Williams suggested limit criterion above.

General Comments. From the fire safety viewpoint, the ultimate goal and justification for modeling of a smolder process is to learn how to eliminate it; short of reaching this ambitious goal, one at least wants to know how to lessen the impact of smolder as a cause of fire deaths and injuries. The above models are only a tentative first step in this direction. They correlate experimental results, providing an approximate but plausible rationale for the observed behavior. Only in the last model, however, is there enough detail for one to begin to discern a route to a lesser smolder tendency. The amount of char formed is a variable calculated by the model; lessening the amount of char should shift the extinction limit so that a lesser domain of conditions permits smolder. Qualitatively, this is an old idea, of course; the model, however, can quantify the relation between extinction and char formation. This gives the chemist a quantitative guideline for how much the char versus volatiles competition must be altered. This is an example of how smolder propagation, which all models show to be oxygen supply limited rather than chemically limited, is really a chemical problem. Most solutions to smolder problems will ultimately be chemical in nature. Another example is in the chemistry of the char oxidation.

The model of Moussa, et al. essentially says it affects only the position of the extinction limit but this is an important relation to quantify; to close the loop, the chemist must learn how to alter the chemistry of char oxidation (as well as its formation).

With regard to the char oxidation process, the model of Moussa, et al. is really rather rough, though less so than the preceding models. The problem in all of the above cases, however, is that this part of the problem is non 1-D in character because of the conditions of oxygen supply. Detailed treatment of a 2-D problem would be premature, at present; the 1-D cases have not been fully exploited or analyzed.

The 1-D configurations are those limiting cases of forward and reverse smolder indicated in Fig. 1. Fuel bed permeability is high (due to a very porous structure or an imposed forced flow) so that air and product gases flow through the fuel. These cases are thus not "overoxidized" in the sense used above; oxygen reaches the reaction zone from one side at a rate dictated by buoyancy or by an imposed pressure differential. The 1-D nature of the reaction/propagation process makes a more detailed treatment feasible though certainly not trivial.

2. Complex Models

The forward and reverse 1-D configurations are at uneven states of development. That the models exist at all is mainly a consequence of specific smolder problem areas demanding study. The forward smolder models, in particular are thus very specialized.

Specialization is also a difficulty in applying to smolder the literature results from other fields. There are a variety of related problems, some of which have received very extensive treatment but the differences from smolder in specific physical and chemical details typically preclude anything more than some qualitative transferral of trends. Johnson, et al. (29) present an analytical solution to the 1-D problem of carbon burn-off from a bed of catalyst particles. This is essentially a forward smolder problem with a very low fuel loading and a high "ash" content. However, the analytical solution is made possible by de-coupling the reaction rate from the temperature; species and heat diffusion are also neglected. The model is qualitatively instructive in that it shows succinctly how forward smolder, in the absence of heat losses, is inherently unsteady, with a monotonically increasing peak temperature. Physically this is a consequence of regenerative heating of the reactants: gas and solid pass over each other in opposite directions when leaving and entering the reaction zone. Heat transfer between them is always such as to feed heat from both sides back into the reaction zone where it accumulates. This is one of the factors making forward smolder quite different from reverse smolder.

The underground coal and oil shale gasification field is currently undergoing intensive development. Typically the fuel seam is permeable, or is made permeable by drilling or explosives, and an exothermic reaction zone is driven through the fuel, gasifying a substantial fraction of it. Forward and reverse propagation schemes are used and the heat to drive the wave comes from partial oxidation of the fuel. The analogy with smolder propagation is apparent; only the names and the fuels are different. The logical starting point for models of these processes has been 1-D descriptions in which the conditions of Equation (1) are assumed to apply (not necessarily a good assumption in this problem). The modeling goals are generally quite different than they are with smolder. The rate of propagation versus air supply is of some interest but the major concern is with the composition and energy content of the product gases. This leads to models which contain rather extensive descriptions of coal-related chemistry, having as much as a dozen chemical reactions. Because of specific conditions in such problems, species diffusion is typically neglected and radiative transfer is included only as a minor correction to solid-solid conduction; these approximations are not necessarily good in smolder problems. Typical reports of model development and results can be found in references 30 to 36. This field continues to proliferate and bears close watching for qualitative results that may shed light on the smoldering problem. The models most likely to provide insights of a useful nature are those less specialized such as ref. 31 or the general performance analyses such as those of wavefront stability (ref. 33). There has been much less activity directly applied to the question of smoldering combustion as will be seen.

Egerton, Gugan and Weinberg (Ref. 10); Forward Smolder. This model was posed as a first step in the description of smolder propagation in cigarettes. We have noted previously that the cigarette problem oscillates in character, falling in the upper half of Fig. 1 during the smoker's draw and in the lower half between draws. The model proposed is not complete and it was never solved; nevertheless, the paper in which it was presented was a pioneering effort and had a strong impact on this field. Arguing from their partial model and from their experimental results, the authors independently discovered the regenerative heating effect in forward smolder, qualitatively demonstrated the impact of switching from forward to reverse smolder, noted the rate-limiting effects of oxygen supply on smolder and showed that this has powerful effects on the shape and behavior of this smoldering system, leading ultimately to an instability in its behavior that precludes uniform propagation. This was a substantial contribution to the understanding of smolder propagation.

Summerfield, Ohlemiller and Sandusky (Ref. 37); Forward Smolder. This is a specialized 1-D model of 2-D forced forward smolder in a cigarette; as noted above it falls in the upper half of Fig. 1 since ℓ_{FE} equals the tobacco particle size and $\ell_{SW} >> \ell_{FE}$(marginally in some conditions). The peripheral paper behavior makes it 2-D. The model is transient, encompassing ignition but the air flow is constant. Air flow values are 5-60 cm/sec so that convection is the dominant heat and mass transport mode; diffusion and conduction are neglected. The model is further specialized by the fact that it includes a moving step decrease in side wall flow resistance coupled to the moving thermal wave. This is a simulation of burn-back of the peripheral cigarette paper, a process which lets some of the incoming air bypass the oxidation zone. It also lets essentially all air enter the sides of the cigarette, not the end, decreasing the regenerative heat transfer effect. This sidewall entry of air causes strongly 2-D behavior at the base of a real cigarette coal; this model simulates it qualitatively in a 1-D fashion.

This is the first model to attempt a description of the complete smolder wave structure, albeit for specialized circumstances. The fuel chemistry, derived from thermal analysis experiments (heating rates 100X less than cigarette), includes one step pyrolysis followed by one step char oxidation (essentially the lower pathway in the above reaction scheme).

Char oxidation can be kinetically or oxygen-transport controlled. The model assumes that the conditions in Equation (1) hold, a marginal assumption for the heating rates and fuel particle sizes involved. Gas and solid energy equations are considered separately allowing local temperature differences; this is necessary in forced cigarette smolder. Radiative transfer between solid particles is described approximately using the forward-reverse approximation. Radiative losses from the periphery are included so that the indefinite (and here, unrealistic) build-up of peak temperatures does not occur. The coupled set of ten differential equations describing the variable profiles is solved numerically.

Figure 2 shows a typical set of variable profiles in the reaction region at a time when smolder propagation is nearly steady. The large local differences in gas and solid temperature are a consequence of the highly forced smolder and the relatively small specific surface area of the fuel. Consideration of the direction of heat transport between gas and solid that these differences imply, together with relative directions of movement of fuel and gas, should clarify the regenerative heat transfer effect, always present to some extent in forward smolder. Because of it, one cannot deduce a peak smolder temperature from a simple overall energy balance, even in the absence of heat losses.

The oxygen profile in Fig. 2 is peculiar because of the peripheral air inflow noted above. In the absence of this effect, the oxygen profile would resemble a mirror image of the gas mass flow profile in Fig. 2, going to zero near the temperature peaks. Unfortunately, all of the solutions presented in the above reference include peripheral air inflow.

The model is reasonably successful in predicting the overall behavioral trends in this system such as smolder rate variation with air inflow rate or inflowing oxygen level. The reference shows rather good quantitative agreement with experimental data but this is fortuitous. The model predictions are quite sensitive to the details of peripheral air inflow and the 1-D simulation of this 2-D effect is rough. This model can be viewed as being qualitatively instructive about the details of forward smolder but there is a need still for a less specialized forward smolder model that incorporates diffusive effects dominant under conditions more pertinent to the fire safety field.

Though it is not so apparent from this model study, forward smolder has another factor inherent in it, in addition to regenerative heat exchange, that makes it greatly different from reverse smolder. This is a consequence of oxygen entry from the char side of the smolder zone. The oxygen first encounters hot char and reacts with it, possibly being fully consumed by the char alone. This would leave no oxygen for the fuel heat-up zone which can greatly affect the chemistry there. It also implies that the forward smolder propagation rate is largely dictated by the stoichiometry of char oxidation. As will be seen, reverse smolder propagation is dominated by other factors. A detailed model is needed to investigate these questions and their implications.

<u>Muramatsu, Umemura and Okada (Ref. 38); Natural convection cigarette smolder</u>. This is a 1-D detailed model of part of a 2-D smolder problem, i.e., smolder propagation along a horizontal cigarette with a natural convection air supply. The problem is qualitatively the same as that of Moussa, et al. above but the goals and treatment are different. The authors are ultimately interested in the details of smoke formation in a cigarette; in this model they consider only the pyrolytic/evaporative smoke formation region of a cigarette.

The model is essentially a much more detailed calculation of the same pyrolysis zone prior to the matching interface considered by Moussa et al. above. The loop is not closed, however, by a prediction of char oxidation heat feedback. Instead, smolder velocity is an imposed parameter specifying the rate that virgin tobacco enters the evaporation/pyrolysis zone from the cold side. The model of this zone is steady-state and requires the simultaneous solution of seven differential equations. The conditions in Equation (1) are assumed to hold. Tobacco pyrolysis is described by four parallel gasification reactions whose kinetic parameters are derived from low to high heating rate thermogravimetry experiments. The reaction heats are taken as zero as in the model of Moussa, et al. though the justification is less clear. Water evaporation prior to pyrolysis is included by employing a semi-empirical rate expression; it is the only vapor species followed. Gas and solid temperature are taken as equal; the single energy equation allows heat convection and conduction plus radiative and convective losses from the periphery. For some unclear reason, sensible heat carried out by vaporized species from the tobacco is ignored. Radiative transfer is implicit in a temperature dependent thermal conductivity. The model equations are integrated numerically from the cold end and the resulting temperature and total density profiles compared with experiment. Something akin to the cold boundary difficulty (39) is encountered here but is not fully discussed. In the zone treated, density falls to about 35-40% of its starting value and temperature rises from ambient to about 600°C; all vaporization reactions are essentially followed to completion.

Agreement between experimental and calculated density profiles is generally quite good. The effects of model parameters on these profiles is intuitively plausible. This is a successful model as far as it goes but the authors will have to add considerable complexity to reach their ultimate goal of smoke formation analysis in forced draw conditions.

Ohlemiller, Bellan and Rogers (Ref. 40); Reverse Smolder. This is a 1-D, time dependent model, of downward smolder through a flexible polyurethane foam material against a buoyant or forced air upflow. It is essentially a model of the fully 1-D reverse smolder limiting case shown in the upper half of Fig. 1. The model is suggested by the 2-D process of smolder spread through upholstery or bedding. A nearly 1-D region of spread would exist along the centerline of downward/outward spreading hemispherical smolder zone in a thick bed of fuel. The total problem of smolder in upholstery or bedding falls into the lower half of Figure 1 since ℓ_{FE} equals the cushion or mattress thickness and $\ell_{FE} \simeq \ell_{SW}$. Experimental comparisons are actually with 1-D forced flow configurations

(11); in this case ℓ_{FE} is of the order of the cell size in the polyurethane and the problem clearly falls in the upper half of Fig. 1.

The behavior of the polyurethane fuel is rather problematical. Both conditions in Equation (1) are assumed to hold in the model but there are indications that the second (pertaining to diffusion) fails at certain stages. Char formation in this material requires oxygen but this gas has very limited penetration into the original polyurethane "particles" which have no pores. Thus, char forms on the exterior while the interior pyrolyzes and vaporizes; the final porous char is open enough to satisfy both conditions in Equation (2) when it oxidizes. No attempt was made to account for the complex details of the initial char formation/ pyrolysis process since this would have required a 2-D treatment of the condensed phase. An approximate kinetic description in terms of two overall steps (char formation, char oxidation) was obtained on the same physical foam structure using thermogravimetry; it fits a limited set of conditions that do not fully match the smolder situation. The most likely consequence is an incorrect calculation of the amount of char formed (overestimated).

Another difficulty with the chemistry is treated heuristically. Thermal analysis gives no information on the oxygen stoichiometry of the overall reaction stages. Moussa, as well as Sandusky, essentially solved this by treating the char as carbon; no other reactions consumed oxygen. Here both overall reactions are exothermic as measured by differential scanning calorimetry and both consume oxygen. In the absence of better information, the char oxidation stoichiometric coefficient was taken as (Q_2/Q_1) times the char formation stoichiometric coefficient, where Q is the reaction heat. The char formation stoichiometric coefficient was adjusted until the overall equivalence ratio from the model solution at one condition was in the right domain. This assumes constant heat output per gram of oxygen which is an approximation, at best, for smolder.

Physically the model is fairly complete. Air flows up toward the descending reaction zone as a result of buoyancy or forced convection. Oxygen convects and diffuses toward the reaction zone. The gas phase is taken to be quasi-steady because its characteristic time is much less than the condensed phase; this approximation would distort rapid transients only. The gas and solid temperatures are locally equal, a very good approximation for reverse smolder in a high specific surface area fuel. Heat from the reactions can accumulate, be convected, conducted or transferred by radiation; this last is treated with the forward/reverse approximation. The set of nine time and space dependent differential equations is solved numerically.

The model is semi-quantitatively successful in predicting observed reverse smolder trends and parameter values. Smolder velocity is of the right magnitude; it and peak temperature increase with air flow or O_2 level at approximately the correct rate. Another correct prediction by the model is that the oxygen/fuel equivalence ratio of the smolder zone increases with O_2 supply; this is a distinctive feature of reverse smolder that allows it to adapt to very low O_2 supply rates. The model has definite deficiencies; it substantially underestimates total fuel gasification and peak temperatures are some 75°C below experimental values. Part of this is due to the inadequate description of the polyurethane chemistry; the model will be tested further by the author on a cellulosic system with fewer complications in the chemistry.

Figure 3 shows some of the variable profiles at a particular time when the system is fully ignited and is propagating under the diminishing influence of the igniting heat flux at $x = 0$. In comparing this reverse smolder wave structure with the specialized forward smolder case in Fig. 2, one should recall the differing relative directions of movement of smolder zone and gas flow inherent in the two configurations. Quantitative comparisons of peak temperature or smolder velocity are deceptive because of drastically differing air supply rates, about 150X greater in the forward smolder case. Comparative experiments for the same fuel and air supply (12) show that forward and reverse smolder temperatures are comparable but that forward smolder propagation is an order of magnitude slower.

Note in Fig. 3 that the oxygen is now present on the fuel heat-up side of the wave, affecting the chemistry there. Its presence there has another consequence. As soon as an element of fuel reaches a reactable temperature, it will do so. This cuts off some oxygen to the remainder of the reaction zone and, in effect, moves the zone toward the oxygen supply. In other words, this reverse smolder wave propagates at a rate determined by heat transfer to the virgin fuel and it can leave behind a varying amount of unburned material. The rate at which heat is generated and made available for transfer is dictated by the oxygen supply so, ultimately, this smolder process is also oxygen controlled.

An important consequence of the tendency for reverse smolder to leave fuel behind is that it provides insulation to the reaction zone. When one looks for a domain of non-self-sustaining smolder, the bounds of the domain depend on the duration of the igniting heat flux. If the flux is sustained long enough, the reaction zone manages to propagate inward and insulate itself more and more, finally becoming self-sustaining. This kind of realistic complication to the question of extinction limits cannot be handled by simpler steady-state smolder models.

Conclusions

Smoldering combustion is not a well-characterized process. Certain salient features, such as its oxygen limited character, are widely recognized and reasonably described though almost always in highly specialized models. While such models are always of value if they correlate a set of observations, in general there has been too much attention devoted to devising a model describing some very limited set of parameter studies and very little attention devoted to ascertaining what aspects of the process might be exploited in efforts to control it. As with flaming combustion, the most practical means of control will very likely be chemical in nature. This implies two things. First, much more will have to be learned about the chemistry of smolder--what governs char formation and reactivity, what is the nature of low temperature exothermic reactions in polymeric fuels, what are the key details of char oxidation. Second, models incorporating tractable descriptions of these chemical processes need to be developed and studied in an effort to clarify the context in which this chemistry occurs and to quantify the sensitivity of the overall smolder process to changes in individual chemical "steps". It may well be that inhibition of one "step" in the process, e.g., char formation, is more effective than inhibiting another such as char oxidation. That is, modeling can help focus chemical efforts on the most productive approaches to smolder suppression.

As the various models above imply, the context in which the chemistry is expressed (i.e., the temperature range, heating rate, oxygen level) varies with the problem at hand; this, of course, affects the chemistry. Models inclusive enough to help clarify some of these overall chemical effects must inevitably be physically simplified. The two fully 1-D limiting cases of Fig. 1, i.e., 1-D forward and reverse smolder, are the logical starting points. While they do not necessarily bracket the full range of behavior that might be exhibited in realistic multi-dimensional smolder problems (especially those that fall in the lower half of Fig. 1), they do represent opposing poles of a sort which can be identified to varying degrees in real world problems. A comparative study of forward and reverse smolder for the same fuel under the same conditions would provide an excellent qualitative base from which to assess the interaction of chemical and physical aspects of smolder in realistic configurations. A preliminary experimental study along these lines of overall smolder characteristics will soon be available (12). The 1-D reverse smolder model discussed above is available, although possibly in need of some refinements; a forward smolder model adapted from it is being developed (41).

There is a need for more information on the physical, thermal and chemical structure of propagating smolder waves in realistic problem configurations. Since the early work of Palmer (5) and Egerton et al. (10) there has not been a great deal of work in this area. A notable exception is the work of Baker (43,44) which has had great impact on the cigarette smolder field.

Figure 4 is an example of some recent results obtained by the author on the thermal structure of a 2-D smolder wave propagating horizontally through an 18 cm layer of cellulosic insulation (wood fibers). This is the problem of Cohen and Luft on a larger scale.) This system is still under study but it appears to be driven by the combined exothermicities of char formation and char oxidation and is largely forward smolder in character; this last is due to predominant, but not exclusive, O_2 supply by diffusion from above. The point to note here is that real 2-D or 3-D problems do introduce considerable additional complexity and ambiguity of interpretation. The concepts to be quantified by the 1-D models discussed above do indeed seem qualitatively applicable here but this is an underdeveloped area and one must move with caution. The caution is increasingly needed as diffusive transport processes in the fuel element become more difficult. Little is known in the area of smolder propagation in fuels where the conditions in Eqn (1) fail completely; available data (9,17,24) are suggestive only. The only complex model the author is aware of which resembles this case assumes zero fuel permeability (45) and a single reaction at the gas/solid interface. It is idealized in other ways as well but could provide some insights for such problems as wood smolder. Any further modeling efforts here should be preceded by experiment.

Another key aspect of the smolder problem is largely unexplored, i.e., transition from smolder to flaming. It is a frequent end result of the increasing intensity of smolder with increasing air supply as was noted by several investigators (5,13,17,27,28). Exactly what conditions are necessary for a switch from the dominance of heterogeneous oxidation to the dominance of gas phase oxidation is essentially unknown at this point. Since the transition can lead to a sudden loss of life and property, it requires close study.

Nomenclature

A - pre-exponential factor

a_D - laminar flow drag constant

C - heat capacity

D - diffusivity

d_F - effective fuel "particle" size

E - apparent activation energy

F - pre-exponential factor

g - acceleration due to gravity

h - convective heat transfer coefficient

J_{OX} - flux of oxygen to superficial fuel surface

ℓ - fuel thickness

ℓ_C - conduction length; $\ell_C = \sqrt{\alpha t_w}$ where α is thermal diffusivity of fuel mass and t_w is the smolder wave passage time

ℓ_D - diffusion length; $\ell_D = \sqrt{D_F t_w}$ where D_F is the effective diffusivity of gases in fuel mass

ℓ_s - smolder wave width (Cohen and Luft)

$\dot{m}$ - mass flux

M_{NTM} - thermal mass flux = $[\dot{m}_G\ C_G \varepsilon \pm \dot{m}_F\ (1-\varepsilon)\ C_F]$

$P_{OX,S}$ - oxygen partial pressure at superficial surface of fuel

P_T - total pressure

q - constant with units of heat flux (Kinbara, et. al.)

Q_{OX} - heat release/unit weight of oxygen consumed

R - universal gas constant

r - fuel reaction rate/unit superficial area

r_c - fuel cylinder radius

T - temperature

v_G - gas velocity

V_S - smolder velocity

Y_{OXA} - ambient oxygen mass fraction

δ - boundary layer thickness

ε - fuel bed porosity (fractional free volume)

λ_B - fuel bed thermal conductivity

μ - gas viscosity

ρ - density

sub-scripts

A - air
F - fuel
M - condition at max. temp.
m - mean of surface and ambient (Moussa, et. al.)
OC - oxygen convection
OD - oxygen diffusion
OX - oxygen
R - reference or ambient state

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TABLE I

EXPERIMENTAL CHARACTERISTICS OF SMOLDER PROPAGATION

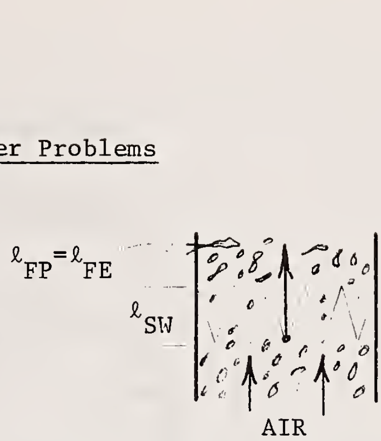
Ref. No.	Fuel	Fuel/Smolder Geometry	Air Supply condition/rate	Smolder Velocity, $\frac{cm}{sec}$	Maximum Temp. (°C)	Comment
8	coal dust (<104μ)	1 cm thick layer/ horizontal spread	natural convection/ diffusion	$1.7 \cdot 10^{-3}$	460	bulk density not given
8	sawdust (75-150μ)	1 cm thick layer/ horizontal spread	natural convection/ diffusion	$4.0 \cdot 10^{-3}$	(170)*	smol. vel. increased with layer depth; *(temp. dubious)
5	cork dust (<65μ) (0.18 g/cc)	1.65 cm thick layer/ horizontal spread, forward smolder	flow over top of layer/50-700 $\frac{cm}{sec}$	7.10^{-3}-$1.8 \cdot 10^{-2}$	790 at 200 $\frac{cm}{sec}$ 840 at 600 $\frac{cm}{sec}$	smol. vel. increased monotonically w. air vel.
5	cork dust (<65μ) (0.18 g/cc)	1.65 cm thick layer/ horizontal spread, reverse smolder	flow over top of layer/75-800 $\frac{cm}{sec}$	5.10^{-3}-6.10^{-3}	not given	smol. vel. independent of air vel. above 400 cm/sec
5	vegetable fiber board (0.27 g/cc)	1.3 cm thick board/ upward spread	natural convec./diffus.	$4.5 \cdot 10^{-3}$	not given	smol. vel. ~2X less if board is horizontal
9	rolled paper	0.4-0.8 cm dia. cylin./ downward spread	natural convec./diffus.	8.4-$5.0 \cdot 10^{-3}$	not given	smol. vel. increased with decreasing diam.
10	tobacco shreda	cigarette, 0.8 cm dia.	intermittent nat'l convec./diffus. and forced draw $\frac{15\ cm^3}{sec}$	$4.5 \cdot 10^{-3}$ (nat'l convec.) $\leq .15$ (periphery during draw)	820°C (nat'l convec.) $\leq$1200°C (draw)	highly transient behavior
7	cellulose fabric +3% NaCl	double fabric layer 0.2 cm thick/horiz. spread, weakly forward smol.	flow over exterior, 10 $\frac{cm}{sec}$	$1.0 \cdot 10^{-2}$	770	smol. vel., temp. dependent on additives
11	flexible polyurethane foam	nearly 1-D/reverse smolder	uniform flow through foam/0.15-0.45 $\frac{cm}{sec}$	1.0-$1.8 \cdot 10^{-2}$	430-475	smol. vel. also increased with increasing % O_2
12	cellulosic loose-fill insulation (wood fibers)	1-D/reverse smolder	uniform through fiber bed/0.04-0.75 $\frac{cm}{aec}$	$4.5 \cdot 10^{-3}$ to $3.7 \cdot 10^{-2}$	430-640	smol. vel., temp. increased monotonically w. air flow
12	cellulosic loose-fill insulation (wood fibers)	nearly 1-D/forward smolder	uniform through fiber bed/0.15-0.48 $\frac{cm}{sec}$	1.0 to $2.5 \cdot 10^{-3}$	535-595	smol. vel., temp. increased monotonically w. air flow

<u>Figure 1</u>

<u>Classification of Smolder Problems</u>

$\ell_{FE} << \ell_{SW}$
(effective fuel element much smaller than smolder wave thickness)

<u>Limiting Case</u>:
Air flow and smolder wave parallel (<u>forward smolder</u>)



fully 1-D if $\left(\frac{\ell_{CP}}{\ell_{FP}}\right),\left(\frac{\ell_{DP}}{\ell_{FP}}\right) >> 1$

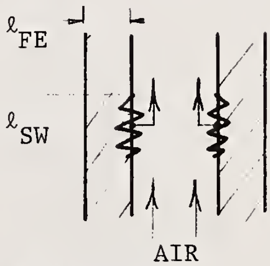
<u>General Case</u>:
Airflow & smolder wave intersect at arbitary angles; no restrictions on ℓ_{CP}, ℓ_{DP} except that they are $\lesssim \ell_{FP}$ (eg., cigarette during draw)

<u>Limiting Case</u>:
Air flow and smolder wave anti-parallel (<u>reverse smolder</u>)

same

$\ell_{FE} \gtrsim \ell_{SW}$
(effective fuel element comparable to or larger than smolder wave thickness)

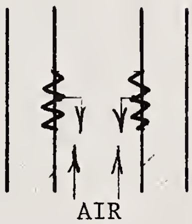
<u>Limiting Case</u>:
Airflow and smolder wave parallel (<u>forward smolder</u>)



usually 2, 3-D since $\left(\frac{\ell_{CE}}{\ell_{FE}}\right),\left(\frac{\ell_{DE}}{\ell_{FE}}\right) \lesssim 1$

<u>General Case</u>:
Airflow and smolder wave intersect at arbitary angles; no restrictions of ℓ_{CE}, ℓ_{DE} except that they be $\leq \ell_{FE}$ (e.g., horizontal spread in a layer of loose-fill insulation)

<u>Limiting Case</u>:
Airflow and smolder wave anti-parallel (<u>reverse smolder</u>)



same

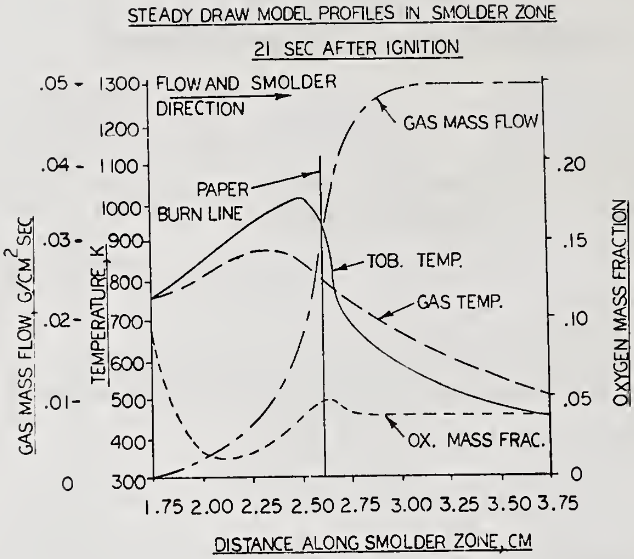


Figure 2. Calculated profiles in forward smolder zone of a cigarette with steady draw air flow of 32 cm/sec; smolder velocity = 0.15 cm/sec.

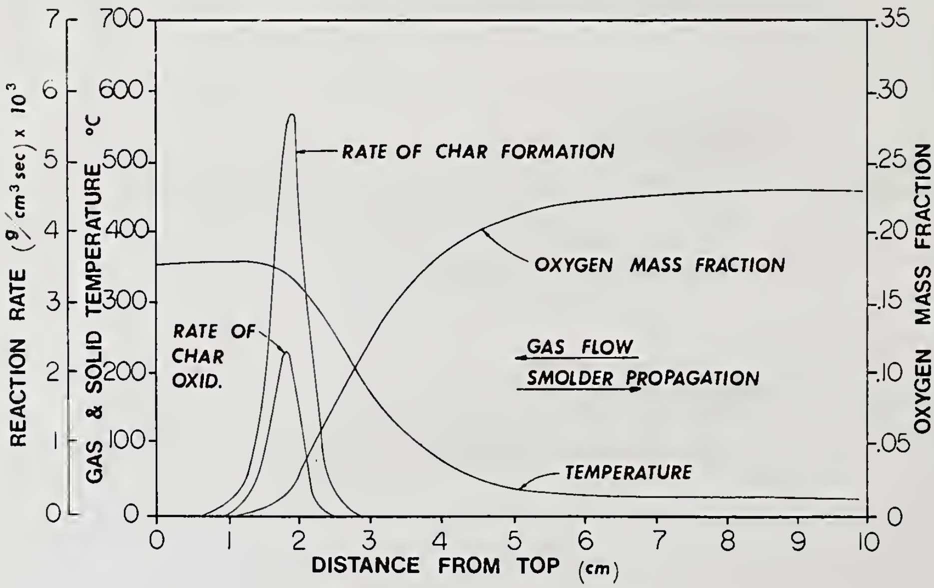


Figure 3. Calculated profiles of a reverse smolder zone propagating through a flexible polyurethane. Air flow velocity = 0.2 cm/sec; smolder velocity = 9.8 x 10^{-3}cm/sec. Radiative flux of 0.20 cal/cm^{2}sec persists at top of fuel (left end in figure).

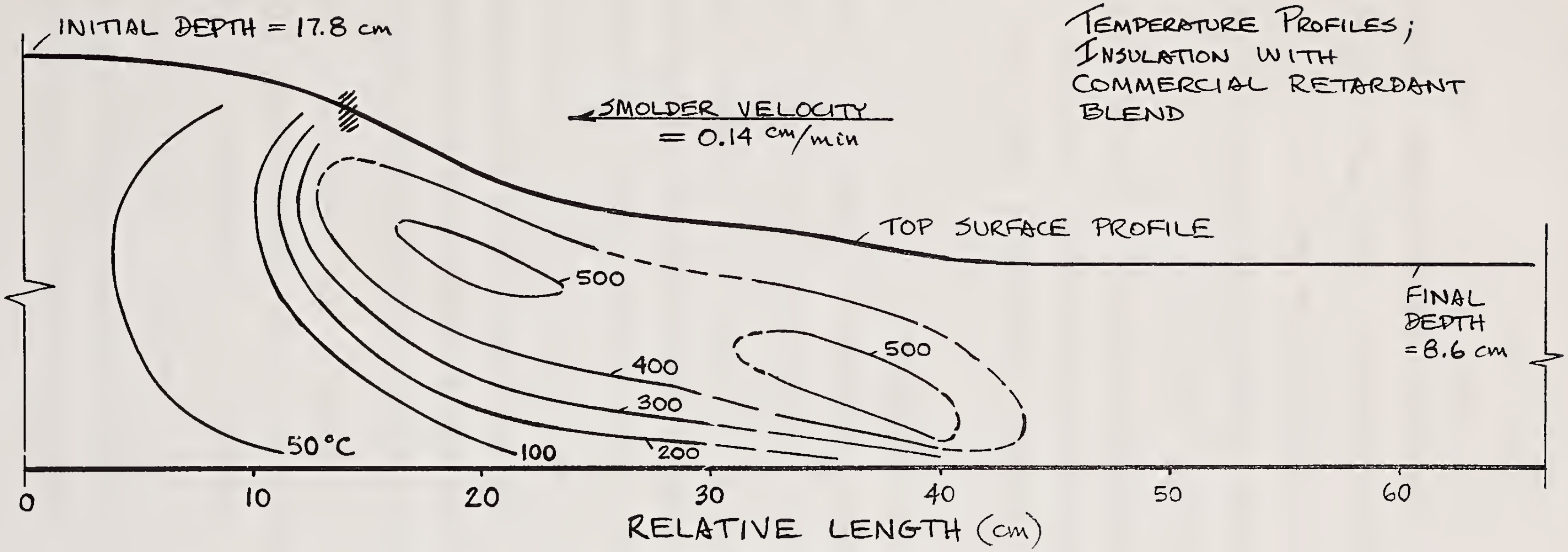


Figure 4. Experimental results for lateral 2-D steady-state smolder propagation through a horizontal layer of cellulosic insulation; air flow is natural convection/diffusion. Temperature isotherm profiles superimposed on cross-sectional view of fuel bed depth versus distance.

THERMAL PROCESSES IN THE SMOLDERING OF WOOD

by

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ABSTRACT

The oxygen consumption of wood was studied in correlation with its structural change due to thermal relaxation of the hydrogen bond network supporting the system. From X-ray diffraction and visco-elastic studies, it was found that the thermal motion in the amorphous part of wood fibril was optimally activated at around 190°C and the collapse of wood structure through thickening of fibril occurred at around 220°C due to the thermal relaxation of interlamellar bonds. It was also found that there was a linear correlation between the elongation in crystallite part and that in amorphous part toward L-direction i.e. approximately along fibril axis, but a break at around 220°C with regard to R-direction. The latter change brought about a critical break in the relation of oxygen consumption rate with elongation of size toward both directions. Therefore, the regime of temperature governing the reaction can be said to be dual demar-cated at around 220°C. Lignin was found to play the single most

significant role for the oxygen consumption in the first regime. There was also an indication of an approximate coincidence in the values of the apparent activation energies between oxygen consumption rate and disclosure of hided sites with a correspondence to the weight loss rate. The disclosure of hided sites in the second regime above 220°C must be governed by a delay in the amorphitization of crystallite part with temperature resulting in an indication of a quasi first order or first order rate in the kinetics of weight loss reactions. Therein, both values of apparent activation energies in the first regime may be sustained with a correspondence to the weight loss rate in the temperature range 130-280°C provided that oxygen consumption occurred only by the disclosure of hided sites in the amorphous part which was extented by a collapse of crystallite part. Secondly, the effect of moisture in reducing the hazard for the spontaneous ignition of wood during its thermal aging was discussed with regard to the role of lignin and the state of arts of moisture in wood. Finally, the calculations were made on the basis of the first order reaction rate utilizing the revised equation. Thereby, it was assumed that the weight loss proceeded in a complex way through the formation of char(1) which was made from cellulose by a transfer of nascent oxygen from the thermal decomposition of the oxygen adducts of active ingredients in lignin at higher temperature.

INTRODUCTION

We have studied so far on the thermal change in the physical properties of wood-polymer alloys in correlation with those pertinent to wood itself[(1)-(8)]. The objective of these studies was originally from different prospect for the confrontation with the deformation and rupture of the irradiated products by thermal strain due to internal heat evolution in the graft-copolymerization of synthetic monomers with lumber or a heap of fluffy cotton by γ-ray processing. A critical change occurred in the tangential direction of wood dimension at around 220°C associated with an indication of a significant break in its dynamic modulus which was originated from the initiation of molecular motion in the amorphous region at around 180°C leading to the scission of cellulose chains in cellulosic fibrils at a high temperature. Abe and Hirata have pursued the performance of fire retardants in wood system[(9)(10)]. As a related study, Hirata reported on the thermal scission of molecular chains of genuine cellulose in vacuo elucidating the mechanism in the possibility for the scission of molecular chains even at a temperature lower than 220°C[(11)]. Hence, we may allow to propose that the thermal relaxation of the tight hydrogen bond network supporting the wood system must incur the penetration of oxygen into the cellular system and as a consequence, will accelerate the chain scission besides the genuine thermal process producing levoglucosan. Kosik et al. reported that the oxygen consumption revealed at around 150°C[(12)(13)]. We also probed the situation in the oxygen consumption in connection with the thermal deformation of wood and cellulose structure covering the range of temperature from 100°C to 220°C with regard to the preparation of thermoresistive wood and base panel of printed circuit.

This is firstly because of the doubt as to whether the genuine thermal process had really dominated the phase of thermal deterioration of wooden and cellulosic materials in this range of temperature or the specific oxygen-affinity attributed to the chemical character of some ingredient governed the phase by making a cause for the preferential break of the tight hydrogen bond network and secondly, as to whether the latter character can really be one of the important causes for the incidence of the spontaneous smoldering burn at around the center of a pile of wood tips and saw dusts, and even in wood cores far below their nominal ignition temperature after exposure to hot environments with a long lapse of time.

The present paper deals first with the correlation between the thermal processes and the oxygen consumption revealing in wood and secondly, with the spontaneous smoldering ignition of thermally aged wood core.

EXPERIMENTALS

(1) Materials

Veneers used in the study were of rotary-cut beech 0.65mm thick which were carefully selected from factory products of similar quality. Filter paper (Toyo Filter Paper No.2), cellulose film (Cellulose Tubing by Visking Company), avicel SF, xylan, and lignin were used as the reference materials of wood. All samples were oven-dried in vacuo at 80°C for 30 hr, and then maintained in the desiccator with phosphorus pentoxide in vacuo..

(2) Delignification of wood

Delignified wood was prepared by the sodium chlorite method. The detailed procedures were as follows: ca. 30ml of distilled water ca. 0.1ml of acetic acid, and ca. 0.3g sodium chlorite per 1g of wood were added to the specimens. Then, the system was heated at 70-80°C for 1 hr. After then, another ca. 0.1ml of acetic acid and ca. 0.3g of sodium chlorite were added to the system per 1g of wood. The heating was continued at 70-80°C for another 1 hr. After 6 times of chloriting processes at maximum in total, the treatment was washed with cold water and then dried in vacuo.

(3) Measurements

The dynamic modulus E' and the loss modulus E" of the specimens were measured by Vibron DDV-II. The measuring temperature was raised from room temperature to 300°C at the rate of 1°C/min. Although E' and E" of specimens were measured in air, the contribution of a slight amount of moisture to E' and E" was not recognized during measurement at the higher temperature range over 100°C.

X-ray diffraction patterns of the pulverized specimens were measured at room temperature for the range from 5° to 35° values of 2θ using Ni-filtered Cu-Kα radiation at 35kV and 20mA.

The moisture content (M.C.) of the specimens was controlled in desiccators over two weeks at room temperature under different standardized relative humidity (R.H.) using several kinds of solution of inorganic salts. The M.C. of the system was adjusted to be kept almost constant during measuring excluding the effect from the environmental humidity. Thereby, those data within the allowable deviation of M.C. below 0.2% between before and after the measurement were only adopted particularly for those samples with an extremely low and high M.C. For the samples within the allowable deviation of moisture, the averages of M.C. before and after the measurement were taken in specifying the M.C. samples. The instrument for the measurement of the dielectric properties was equipped with a bridge type transformer TRS-10C (Ando Electric Co., Ltd.) and an electrode which was capable to cover the measuring temperature range from -196°C 0°C. The dielectric constant ε' and the loss factor ε" were measured along the radial direction of the specimens at each measuring frequency from 30Hz to 1MHz.

Oxygen consumption of samples was determined according to the procedure of W.L.Hawkins et al.[14][15] in which the amount of oxygen reacting with the samples was measured volumetrically. The pressure of oxygen inside the line was controlled at 760 mmHg by meas of a manometer. Samples weighting 0.5g were placed in glass tubes along with 10g of Molecular Sieve, Type 5A.

RESULTS AND DISCUSSION

(A) Oxygen Consumption and Thermal Deformation of Wood Structure

(a) Oxygen Consumption Below the Nominal Ignition Temperature

The situation in the oxygen consumption of wood and its ingredients were studied covering the range of temperature from 100°C to 220°C in connection with the thermal deformation of wood structure. The test specimens were beech veneers (Fagus crenate Blume) which we used in the measurements of the dynamic and the dielectric properties of wood. Thereby, L-, T-, and R-samples meant those veneers which were cut out with size of 50 x 5 x 0.65mm and 34 x 34 x 0.65mm by taking the longest perimeter toward the corresponding direction of wood respectively. It should be noted hereby that the beech wood is consisted of cellulose, hemicellulose, and lignin approximately in a weight ratio of 2:1:1. Fig.1 shows the time-dependent variation in the oxygen consumption of wood, delignified wood, and some of those ingredients comprising the wood system at 200°C in the genuine oxygen atmosphere. It is obvious that lignin possesses the highest affinity with oxygen being subjected to the high reactivity of its unstable components. Handa et al. elucidated that those unstable components of lignin on the inner surface of vessels had extensively terminated the propagating radicals of growing polymer chains from irradiated radicals in the interior of wood cell through recombination process in the manifacturing of wood-polymer alloys under the electron beam irradiation[16]. The next are mannan and xylan in hemicellulose comprising the amorphous regions of wood fibrils in combination with cellulose whereas the cellulosic system either highly crystalline (Avicel) or lowly crystalline (Visking tube) only exhibited a poor reactivity with oxygen in this range of temperature. There was an indication of a fair coincidence of the observed amount of oxygen consumption in wood with the calculated one on the basis of those in lignin, delignified wood, mannan and xylan taking the weight ratio of cellulose, hemicellulose, and lignin as 2:1:1. Therefore, it can be said that about 75% of oxygen consumption in wood was occupied by lignin leaving about 80% of the rest 25% for hemicellulose. Therefore, it is suggested that although there must be another kind of scission endorsed by oxygen, almost of all scission of cellulose chain below this temperature must be initiated by a genuine thermal process producing levoglucosan. Fig.2 shows the situation in the oxygen consumption of wood with hot bath temperature. The Arrehnius plot of the initial rate of oxygen consumption vs 1/T gave approximately a straight line. Its slope value of ca. 24kcal/mol was given as the apparent activation energy of oxygen adsorption in the genuine oxygen atmosphere. A similar value of ca. 27kcal/mol was also given for that in air with a decrease in frequency factor. Those values laid close to the value of 26.1kcal/mol given by Kinbara as the activation energy of the weight loss rate of saw dusts in its spontaneous smoldering burn(17). However, being evaluated with the same value of frequency factor, the latter value in air converted to ca. 30kcal/mol. Fig.3(a) shows the effect of intermixed nitrogen in oxygen consumption at 200°C. There was an indication of an approximately linear relation between oxygen consumption rate and oxygen partial pressure. Fig. 3(b) shows the correlation between the oxygen consumption and the weight loss of the samples at 200°C in the genuine oxygen atmosphere. There was an indication of a linear correlation between the weight loss and the amount of initial consumption. Accounting for the atomic ratios of C and H to O in the gasified fraction on the basis of the lost weight of H, C and O as a sum of the weight of each atom in the lost-fraction and adsorbed oxygen, it was found that the atomic composition ratio in the gasified fraction were uniquely of $H_{12}C_5O_8$ irrespective of reaction time. Thereby, the contents of H, C and O in wt% were 5.4%, 47.8%, and 46.8% for the untreated samples, 5.0%, 49.2%, 45.9% and 4.4%, 50.2%, 45.4% for the samples exposed to oxygen for 4 and 12 hr, respectively. The content of carbon in the exposed sample increased scarcely with time whereas the contents of hydrogen and oxygen decreased.. As a result, it can be said that in a sense, the oxidative degradation proceeded uniformly irrespective of an indication of the breaking in the variation of the oxygen consumption with time. Hence, we may allow to infer that only lignin reacted with oxygen and there must be a delay of time between the adsorption of oxygen and its release in the gasified fraction. That delay seems to be enhanced in the oxygen consumption at a temperature lower than 180°C with an indication of a scarce recovery in the oxygen contents of the systems and the increase of carbonyl groups in the infrared spectra.

Fig. 4 shows the pronounced pattern of such delay as reflected in the differential weight loss which was promoted in the higher range of temperature under oxygen-rich environment. Thereby, a fair faster elevation rate of hot bath temperature of 2.5°C/min was taken. As a result from the decomposition of the ΔW-Temperature diagram by curve resolution, five phases appeared in the change of ΔW vs temperature of the thermal decomposition of wood in the nitrogen atmosphere containing scarce oxygen. Therein, ΔW_{ij} was a difference between the sample weight W_i at a temperature T_i and W_j at T_j namely $\Delta W_{ij} \equiv W_i - W_j$ and ΔW-T diagram was prepared by taking always $\Delta T_{ij} = 4°C$. The first phase must be concerned with the thermal decomposition of hemicellulose, the second and third ones with cellulose, the fourth one with lignin, respectively and the fifth one is presumed to be from the charred residues. Similarly, five phases appeared in the oxidative thermal decomposition in air. Particularly, the second and third phases are suggested to come from the decomposition of cellulose in the scheme as Dr.Roger and Prof. Dr.Ohlemiller proposed[18]. It seems likely that as the oxygen partial pressure increased, the oxidative decomposition was promoted and the diagram revealed apparently to be consisted of two major peaks by the shift of third, fourth and fifth peaks to the lower temperature side due to the accelerated charring of the oxidized products of lignin to promote the scission of cellulose chain by the supply of nascent oxygen from the decomposition of the former under the oxygen-rich atmosphere.

(b) Thermal Change in Wood Structure

It is generally accepted that the thermal change in wood structure can be attributed first to the local relaxation of the tight hydrogen bond network consisted of interlamellar, inter and intra fibrilar hydrogen bonds to thermal relaxation and secondly, to the scission of cellulosic chains due to strain coming from thermal deformation of structure. As the complex pattern in the thermal changes of wood structure is well reflected on the changes in various physical properties of wood, it is not too far saying that we can know the extent to which a certain change occurs by detecting the change in the corresponding physical properties.

Fig.5 shows the dilatometric change of wood dimension with temperature along the longer direction of test specimens which were cut out by taking the longest perimeter toward L-, and T-direction of rotary-cut beech lace veneers, respectively. There was an indication of the system for the inflexion of the thermal expansion toward R-direction at around 220°C and also the compensated inflexion to promote the elongation toward L-direction at around 230°C respectively being in overall resulted in a serious contraction of volume above 220°C.

Fig.6 shows the thermal changes in (002) spacing of the cellulose crystallite and the half width angle of (002) with hot bath temperature by X-ray diffraction[5]. Thereby, the latter represents changes in the fibril orientation suggesting that the thickening of fibrils occurs at around 220°C in a way to take the maximum fibril angle due to the thermal relaxation of interlamellar hydrogen bond system. Comparing the macroscopic dilatometric change in Fig.4 with the microscopic one in Fig.5, it was found that there was an excellent linear correlation between the dimensional change in the crystalline part as represented by the elongation of (002) spacing and that in amorphous part as represented by the elongation of sample toward L-direction. However, there was a revelation of break at around 210°C in the linear correlation with regard to T-direction. Further, the elongation of the (002) spacing was particularly promoted above 230°C being corresponded with the enhanced elongation toward L-direction. The promoted elongation must be caused by the random scission of cellulosic chains revealing eminiently above 230°C even in vacuo with an indication of levelling off degree of polymerization (DP_∞) of ca. 600 after 3 hr at around that temperature and DP_∞ of ca. 200 after 2 hr at around 260°C. Thereby, it should be noted that the split fractions must be recrystallized into microcrystallites by cooling because of an indication of the elevation in the crystallinity index of the test specimens after the exposure to repeated cycles of heat cure below 220°C(19). Above 250°C, the enhanced stretching occurs toward L-direction in a way so as to reduce the fibril angle by the dislocation leading to the rupture of crystallite due to the thermal strain from the peeling motions of the defolded tails which are entangled with the chains in the amorphous part. The thermal motions of those molecules consisting the amorphous part of wood are activated optimally at around 190°C as will be referred to in the succeeding discussion.

Fig.7 shows the correlation between the oxygen consumption and the dilatometric change in wood dimension. Remembering that the initial rate of oxygen consumption illustrated a linear plot vs 1/T and the cellulosic material either highly or lowly crystalline exhibited a poor oxygen consumption at 200°C, the revelation of anomalous break at around 210°C in the increase of oxygen consumption with the elongation of size either toward both L- and T-directions suggests that the corresponding increase in the specific internal area occurred by the disclosure of hided sites of lignin and hemicellulose due to an extensive relaxation of interlamellar hydrogen bonds sustaining cellulosic fibrils in the temperature range 210-230°C.

The predicted rupture of hydrohen bond network of cellulosic fibrils in that temperature range can be said to be substantially reflected in the break of the dynamic modulus of wood in the temperature range 210-250°C with revelation of the loss modulus peak at around 220°C for T-samples and the at around 240°C for L-samples respectively. The thermal behaviors of the dynamic modulus E' and the loss modulus E" for T-samples at the measuring frequency of 110Hz, 35Hz, and 11Hz are shown in Fig.8. Approximately the same pattern was also observed with regard to the measurement in terms of the vibrating method. Similar patterns were observed in the thermal dispersion of the dynamic shear G' and the loss modulus G" which were measured by torsion pendulum in vacuo at a measuring frequency of ca. 0.3Hz for L- and T-samples of oven-dried beech veneers. Fig.9 shows the variation in the temperature dispersion of E' and E" with grain angle. The peculiar shift of the indicated temperature of E" peak is based on the anisotropic character of the thermal relaxation conforming to the spatial angle between grain and fibril. Fig.10 shows the temperature dispersion of E' of delignified T-samples. The delignified samples indicate a higher crystallinity index than that of the ordinary ones by X-ray diffraction. The temperature dispersion of E' and E" looks like that of the ordinary

T-sample. This indicates that although the oxidation of lignin proceeded considerably in the range of temperature lower than 220°C, lignin itself was not authentically involved in this phase of structural change. Fig.11 shows the overall change of dynamic modulus and the loss modulus of wood (L-sample) at a measuring frequency of 110Hz and in N_2 containing scarce oxygen covering the range of temperature from 30°C up to 320°C which is nominated as decomposition temperature of cellulose by DTA study. An intense decrease in E'_L and the corresponding rise of E''_L revealed suggesting the collapse of fibril system.

As a result, togather the results so far[5][8], eight E" bands revealed in overall as pertinent to wood (M.C.=1%). They are summarized in Fig.12 and are assigned as follows: Band(a) at around 300°C comes supposedly from the defolded and zig-zag bridged short chains of dehydrated cellulose due to the thermo-oxidative scission of chain and cross-linking. Band(b) at around 250°C comes from the decrystallizing structural change to stretch fibrils being accompanied by the shrinkage along the T-direction. Band(c) at around 220°C comes from the degradative structural change to thicken fibrils due to the thermal relaxation of the interlamellar hydrogen bonds. Band(d) at around 190°C comes from the transition in the molecular motion of amorphous cellulose and hemicellulose. The magnified revelation of this loss band was confirmed by the lower temperature shift of band(b) and band(c) in the decrystallized samples[6]. Band(e) at around 135°C comes from the deformation in the fibril orientation by the disorder in its conformation close to the surface of the cell wall. It was confirmed that a magnified activation of this loss band revealed due to the thermal perturbation by polymer produced outside the cell wall in polymer-wood alloys[3][4][6][8]. Band(f) at ca. 100°C comes from the dehydration of movable water associated with the hydrogen bond in wood. Band(g) at ca. -50°C for ordinary sample (M.C.2%) consists of dual bands. Band(g_1) comes from the relaxation of hydrogen bond involved in the local mode motion of wood system due to moisture and Band(g_2) comes from the intrisic mode of cellulosic segments etc. Band(h) at ca. -120°C must come from the rotational motion of the methylol (CH_2OH) groups in wood. Therefore, it is allowable to conclude that eight step-wise transitions occur in structural change and transition of wood. The apparent activation energy for the thermal relaxations of hydrogen bond system attributed to bonds(a), (b), (c), (d), (e), (g), and (h) are estimated to be ∞, 440, 160, 80, 25-30, 16, and ca. 9 kcal/mol, respectively. Those for the thermal relaxations pertinent to bonds (a), (b) and (c) are anomally high. Hence, it is suggested that the thermal scission of the glucosidic linkage must occur involving the chemical reaction (dehydration cross-linking and oxidation) before the system decomposes into single cellulosic chains. Fig.13(a), (b) shows the similar changes in the temperatur dispersion of dielectric constant (ε') and the loss factor (ε") for the oven-dried R-sample. It may be allowable to presume the low measuring frequency (110Hz) represents the rotational motion of CH_2OH groups with an indication of the loss peak for the rotational motion of CH_2OH groups at a temperature close to -110°C (oven-dried) and the high frequency (1MHz) rather responds with the motion of OH groups. The former motion begins to be activated thermally at around 135°C whereas the latter motion begins to be activated at around a temperature higher than 200°C. The revelation of another ε" peak was confirmed at around -40°C due to hydration for R-samples with M.C. of 1.2%[20][21]. Fig.14 reveals the higher temperature shift of the ε" peak coming from the rotational motion of CH_2OH groups for the heat cured samples at 240°C for 1 hr. The increase in the value of the activation from 9.4kcal/mol to 12.8kcal/mol associated with the higher temperature shift of that ε" peak suggests the possibility for the formation of cross-linking among cellulosic chains in fibrils which promotes the restriction on the rotational motion of CH_2OH groups exposed to the channel among the folded chains in the lamella. Fig.15 shows the corresponding changes in DTA thermogram. Curve(a), curve(b), and curve(c) represent the thermogram of beech veneers in air, N_2 with a trace of oxygen and the well known endothermic ones in genuine Ar environment, respectively. The dotted line associated with curve(a) means the change in the ratio of CO to CO_2 in weight i.e. Wco/Wco_2 with temperature. It was assigned by many authors that the exothermic peak which revealed at around 400°C in curve(a) came from the combusion of oxidized lignin whereas the shoulder and peak at around 280°C and 310°C came from the hemicellulose and cellulose. From the change in Wco/Wco_2 with temperature and our foregoing results in the oxygen consumption of each gradient at 200°C, it is evident that lignin was oxidized in the lower range temperature and the oxidized products must be decomposed vigorously at a high temperature around 400°C. As shown by curve(c), the thermal decomposition of wood in Ar is authentically endothermic throughout the process. Curve(b) suggestes the initiation of oxidation due to the scarce present of oxygen at around 150°C corresponding to the relaxation of hydrogen bond in the amorphous parts. The exothermic peak at around 150°C in the dotted curve associated with curve(b) in rigid line represents the estimated heat possibly issumed by the oxygen consumption of lignin which was located close to the surface of cell wall. The cross-over from endothermic to exothermic of curve(b) revealed at around 225°C by the penetration of oxygen due to the aforementioned thermal relaxation of hydrogen bond network in fibrils corresponding to the E" band(b) and (c) in the thermal change of E" in Fig.14. The higher temperature exothermic peaks at around 300°C in the dotted curve must come from the oxidation of hemicellulose and cellulose. It is evident that the oxidation accompanied by an evolution of heat occurred even at a temperature lower than 150°C with an indication of a scarce loss in weight. On the basis of the analytical values of oxygen content in the heat cured product, it is suggested that some chemical changes, say, oxygen bridge involving the formation of peroxide with unstable components in lignin must be occurred at a lower temperature besides the oxidation during the slow elevation of the environmental temperature.

(B) Spontaneous Smoldering Ignition of Wooden Materials

It is evident that only lignin and some igredients comprising hemicellulose can adsorb oxygen and react with it at a temperature lower than 180°C. This lower temperature oxidation must be a cause for the incidence of smoldering burn of wood materials after exposure to hot environments for a long time in a shape of a bulky matter or being placed in a state of thermal insulation. Since long time ago, the spontaneous smolderings of a pile of fiberous materials, coals, saw dusts and tips have been matters of a well known discussion, the theoretical elucidation of which was given by Frank-Kamenetzkii. Also, I should like to remember that Dr. Robertson in

National Bureau of Standards had made an extensive contribution to this area of research. The point taken up in this paper is the effect of moisture on the spontaneous smoldering burn. Moisture can participate in the hydrogen bond network and confront with the oxidative degradation of wood system by shielding the penetration of oxygen into the cell system. As reported previously, even a small amount of M.C. in an order of 1-3% can reform the authentically deformed wood fibrils and gave a closest packing structure with an indication of the maximum value of E' vs moisture[20]. Fig.16 shows the state of moisture contained in wood from the dielectric aspect of study on the temperature dispersion of loss factor for samples equilibrated to various R.H. below moisture content (M.C.) 10%, the moisture participates in the cooperative local motion of hydrogen bonds and above M.C. of 10%, some part of moisture is free from the system with an indication of the presence of ice at -40°C[21]. Moreover, it consumes heat in the vaporization. The samples used in the experiment were spherical cores of Japanese cedar wood with diameters of 5, 10, 15 and 20cm, respectively. The hot bath (100cm x 100cm x 150cm) was equipped with electric heaters in quartz-glass tubes on every wall, ceiling and floor being shielded by asbesto plates so as to reject the direct exposure to radiation from heaters. The temperature of hot bath was adjusted multiply by a controller system of the heater voltage. The temperature defference between ceiling and bottom remained within 0.5°C.

The calculation on the temperature in wood was made on the basis of the following equations and boundary values:

(i) equation of energy

$$\rho C_p \frac{\partial T}{\partial t} = \lambda_\perp \frac{\partial^2 T}{\partial x^2} + \lambda_{//} \frac{\partial^2 T}{\partial y^2} + \delta \rho Q A \exp(-E/RT) - \rho_v Q' K_1 (\rho_v^\circ - \rho_v)$$
$$+ \rho_v Q' K_2 (\rho_v^\circ - \rho_v) \quad \text{where } K_1 = 1.25 K_2 (\rho_v^\circ - \rho_v)/\rho_v \qquad (22)$$

(ii) equation of moisture diffusion

$$\frac{\partial \rho_v}{\partial t} = D_\perp \frac{\partial^2 \rho_v}{\partial x^2} + D_\perp \frac{\partial^2 \rho_v}{\partial y^2} + K_2 (\rho_v^\circ - \rho_v)$$

(iii) boundary condition between wood(I) and mortar(II) or glass-wool(II)

$$\lambda_{\perp(I)} \frac{\partial T}{\partial x}\bigg|_{x=x(I)} = \lambda_{(II)} \frac{\partial T}{\partial x}\bigg|_{x=x(II)} , \quad T_{(I)} = T_{(II)}$$
$$\lambda_{//(I)} \frac{\partial T}{\partial y}\bigg|_{y=y(I)} = \lambda_{(II)} \frac{\partial T}{\partial y}\bigg|_{y=y(II)} \quad \text{for all boundaries}$$

λ is the heat conductivity, D is the diffusion constant, ρ is the density of wood, Cp is the specific heat, ρ_v is the density of moisture, A is the pre-exponential factor, E is the activation energy for the weight loss rate, Q is the heat evolution per gram of sample, Q' is the heat of vaporization, K_1 is the adsorption rate of moisture, K_2 is the desorption rate of moisture, and δ is decomposition ratio of the system at an arbitrary weight W in a quasi first order decomposition of wood.

As the hot bath temperature was generally adjusted in the range lower than 200°C and the heating rate was so slow staying in the range 0.2°C-0.4°C/min, we adopted the present representation in the equation with regard to the contribution from internal heat generation, assuming that some part of oxygen which was adsorbed by active components of lignin was rather stored in the system than completely released back to environment in the gasified fractions. Even if we adopted the first order rate equation, assuming a faster rate (2-3°C/min), there was no an indication of any obvious difference in the behavior of the center temperature except some changes in the values of activation energy and pre-exponential factors being located close to those value which many authors estimated covering the higher range of temperature under a faster heating rate. The experiments revealed two distinctive results, smoldering-ignition and non-ignition, depending on the balance between the size of spherical wood core and the environmental temperature. There were indications of stationary values being extended from 80°C to 110°C in the elevation of the center temperature. Fig.17 shows the example for the non-ignition result with regard to the wood sphere of 10cm in diam. being placed in the hot bath with a slow heating rate and the levelling off of the elevation in hot bath temperature at around 150°C. The curves (I) and (II) with rigid lines are the observed values of the surface and center temerpature respectively, while the curve with dotted line is the calculated one. There was an indication of a symptom for some stationary values in the range from 80°C to 90°C with the elevation of the center temperature. However, it should be noted that the same system ignited under a more slower heating rate with a higher levelled-off temperature and a less moisture content. Fig.18 shows the example for the spontaneous smoldering ignition at an environmental temperature far lower than the nominal ignition temperature of wood. The wood sphere of 10cm in diam. enwrapped by glass wool was used. Curve(I), curve(II) and curve(III) with rigid lines represent the temperature in the hot bath, boundary between glass-wool and wood sphere, and the center of sphere, respectively. The curve(II') curve(III') with dotted lines represent the calculated values, respectively. There was also an indication of some stationary values for the elevation in the center temperature due to the effect of moisture. Fig.19 shows the relation between the critical environmental temperature to induce the spontaneous ignition of wood sphere and the diameter of wood sphere with regart to the calculation on the basis of the observed values of surface temperature taking the activation energy as 35.5kcal/mol for the thermal decomposition of wood issuing the heat ganeration. Therein, the rigid circles are the observed values and open circles are the calculated values. Fig.20 shows the shift of ignition site in the spherical wood core of 10cm in diam. with the elevation in the surface temperature. The ignition site moves from the center to the surface with a route as shown in the figure because of the anisotropy in the heat conductivity and diffusion coefficient of moisture in wood. Fig.21 and Fig.22 shows the examples for the revelation of obvious stationing of the temperature rise due to moisture with regard to the spherical wood core of 10cm in diam. enwrapped by a layer of mortar with 2.5cm width and the spherical saw dust blocks of 40cm in diam. The latter samples contained moisture 0.2099kg/m^3 and 0.4000kg/m^3, respectively. There was indication of obvious stationary values extended from 80 to 100°C in the elevation of center temperature for wood sphere enwrapped by mortar because of the moisture hydrated in mortar and no indication of any symptom for the spontaneous smoldering ignition being prevented by a greater heat conductivity of mortar. After 15 hr, every temperature at the center inner boundary and surface levelled off and converged to the hot bath temperature of ca. 150°C. The time-dependent variation in the observed values

for the decomposed fraction δ is shown in Fig.23. It is suggested that most of the weight loss was occupied by those of hemicellulose and lignin considering the weight ratio of cellulose, hemicellulose and lignin, approximately being 2:1:1. Typical examples for the stationing due to moisture revealed in the elevation of center temperature of moistened saw dust block with an indication of a long terrace of stationed temperature exceeding 80 hr. Thereby, we used Kinbara's value of 26.1kcal/mol in the computation as the activation energy for the thermal decomposition of saw dusts[17]. The numerical values used in the computation are summarized in Table 1.
Next, we revised the previous equations extending the regime of temperature in the reaction by assuming two stepwise decomposition of wood;

$$[\text{wood}] \longrightarrow m_1[\text{char}(1)] + l_1[\text{gases}]$$

$$[\text{char}(1)] \longrightarrow m_2[\text{char}(2)] + l_2[\text{gases}]$$

Following equations were provided:

(i) equation of continuity

$$-\frac{\partial \rho}{\partial t} = (1-m_1)R_{n_1} + (1-m_2)R_{n_2}$$

(ii) equation of energy

$$\rho C\frac{\partial T}{\partial t} = \lambda_{//}\frac{\partial^2 T}{\partial x^2} + \lambda_{\perp}\frac{\partial^2 T}{\partial y^2} + Q_1 R_{n_1} + Q_2 R_{n_2}$$

(iii-a) mass fraction of wood

$$\rho\frac{\partial W_0}{\partial t} = \left[(1-m_1)W_0 - 1\right]R_{n_1} + \left[(1-m_2)W_0\right]R_{n_2}$$

(iii-b) mass fraction of char(1)

$$\rho\frac{\partial W_1}{\partial t} = \left[(1-m_1)W_1 + m_1\right]R_{n_1} + \left[(1-m_2)W_1 - 1\right]R_{n_2}$$

where $R_{n_1} = \rho W_0 A_1 e^{-E_1/RT}$, $R_{n_2} = \rho W_1 A_2 e^{-E_2/RT}$

It should be noted hereby that we excluded the effect of moisture utilizing the oven-dried wood sphere of 20cm in diam. Fig.24(a) shows the coincidence of the calculated result with the observed one with regard to the time-dependent variation of temperature at the center of sphere. Fig.24(b) shows the time-dependent variation of the calculated values for the density of wood, mass fraction of char(1) and wood at the center. Fig.25(a) and Fig.25(b) show calculated results on the time-dependent variations in the distribution profiles of temperature and density along the radial direction of sphere. The numerical values of parameters used in the calculation are summarized in Table 2. We feel, it is really our great honor and privilege that we could borrow the numerical values estimated by Dr.Roger and Prof.Dr.Ohlemiller for the thermal decomposition of cellulose in air. Thereby, we assumed; the thermal decomposition proceeded in a complex way in that the thermal decomposition of cellulose to char (1) occur due to the transfer of nascent oxygen by the thermal decomposition of oxygen adducts coming from the reaction of oxygen with the active ingredients in lignin and hemicellulose in the range of 200-240°C. It should be noted that the calculated value on the ultimate value of density after thermal aging coincidenced approximately with the observed one.

CONCLUSION

Smoldering combusion of wood can be characterized to be promoted by thermal processes in the relaxation of hydrogen bond system lead-

ing to the collapse of its fibril structure with genuine or oxidative scission of cellulosic chains. The function of temperature governing the reaction is distinctively divided into two regime demarcated at around 220°C. The oxygen consumption of lignin plays the most significant role in the first regime below 220°C being subsidiarily endorsed by that of hemicellulose. It is suggested that those oxygen consumption are promoted above 150°C depending on the extent to which the hided sites of lignin and hemicellulose in the amorphous part are disclosed on the inner surface of cell walls along the vessel of wood. There was an indication of an approximate coincidence in the value of the activation energy of the oxygen consumption with that of the activation of the thermal motion of fibril tails on the surface of vessels with a correspondence to weight loss.
It is suggested that the long time accumulation of heat issued from those oxygen consumptions must be the most significant cause for the spontaneous smoldering ignition of bulky wood materials far below the nominal ignition temperature of wood under a faster heating rate. The role of moisture contained in wood in reducing the possibility for that type of spontaneous ignition due to oxidation of the components in lignin must be the rejection of the oxygen adsorption being hydrated in the hydrogen bonds in those site as well as taking off heat due to evaporation. The smoldering process in the second regime above 220°C must be proceeded mostly through the disclosure of hided sites in the amorphous part of wood depending on the extent to which the crystallite part binding the fibril structure is descrystallized due to the genuine scission of folded chains. Thereby, the weight loss must occur through disclosure of hided sites with a correspondence in activation energy and a delay

in the amorphitization of crystallites. Comparing the results of the simulation, it is likely that the decomposition reaction proceeds in a first order rate under the faster heating rather than in a quasi-first order rate.

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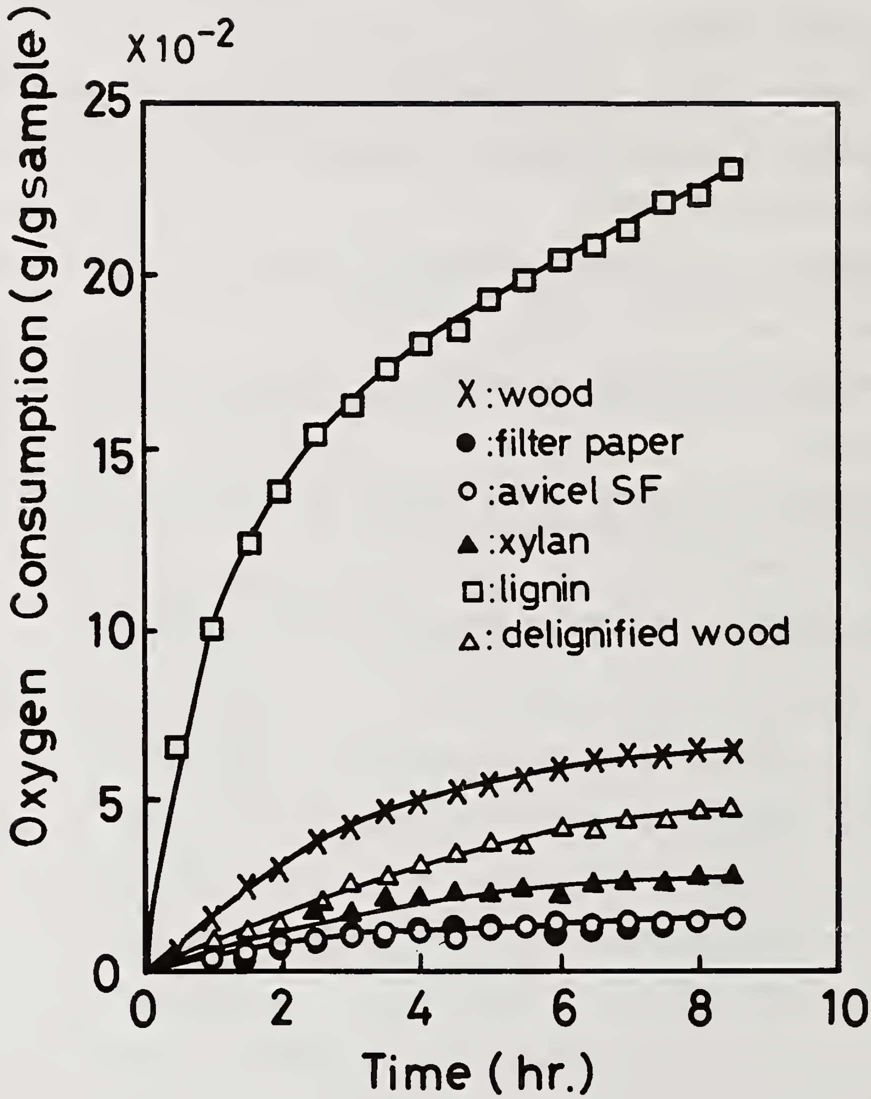


Fig.1 Variation in the oxygen consumption on heating of wood and its ingredients at 200°C.
x, wood; •, filter paper; o, avicel SF; ▲, xylan;
□, lignin; △, delignified wood.

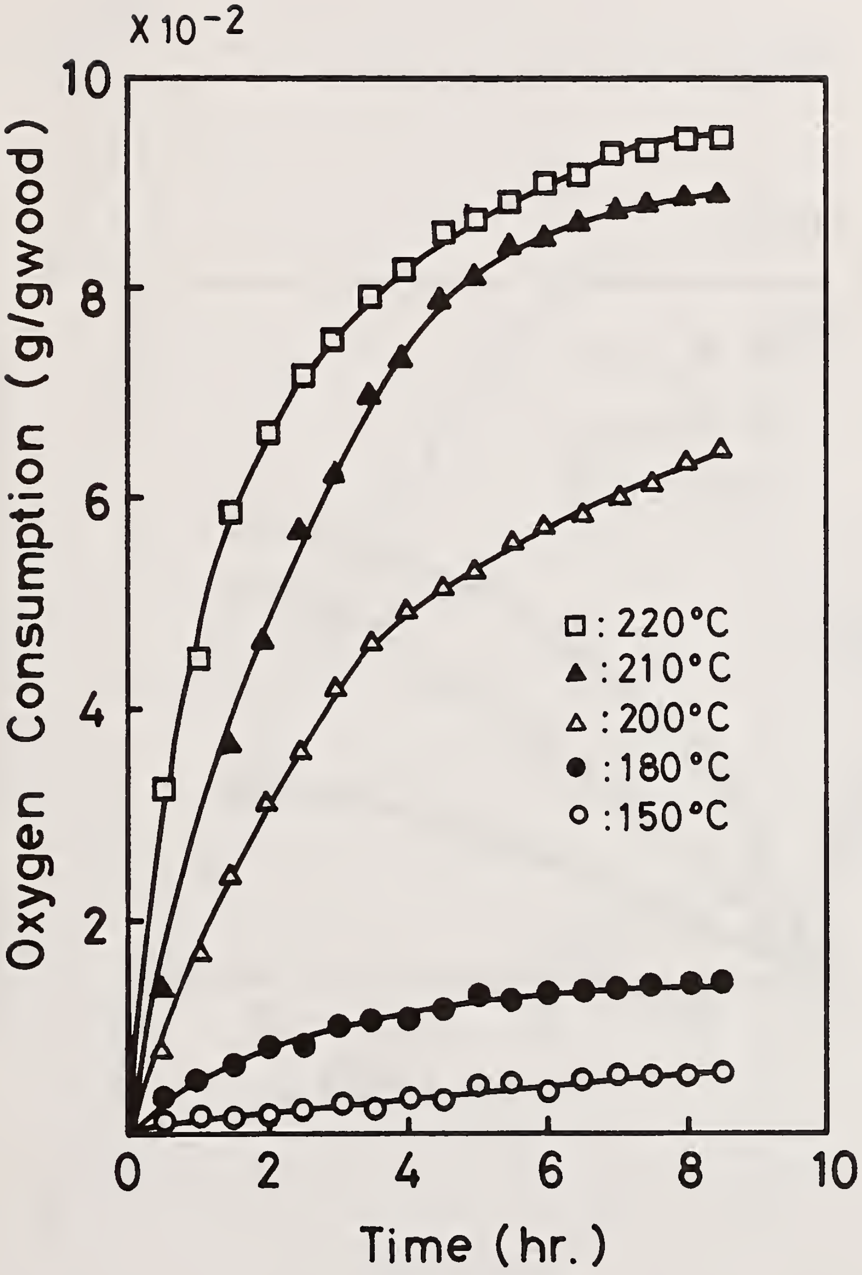


Fig.2 Variation in the oxygen consumption on heating of wood at virious temperature from 150°C to 220°C.
o, 150°C; ●, 180°C; Δ, 200°C; ▲, 210°C; ◘, 220°C.

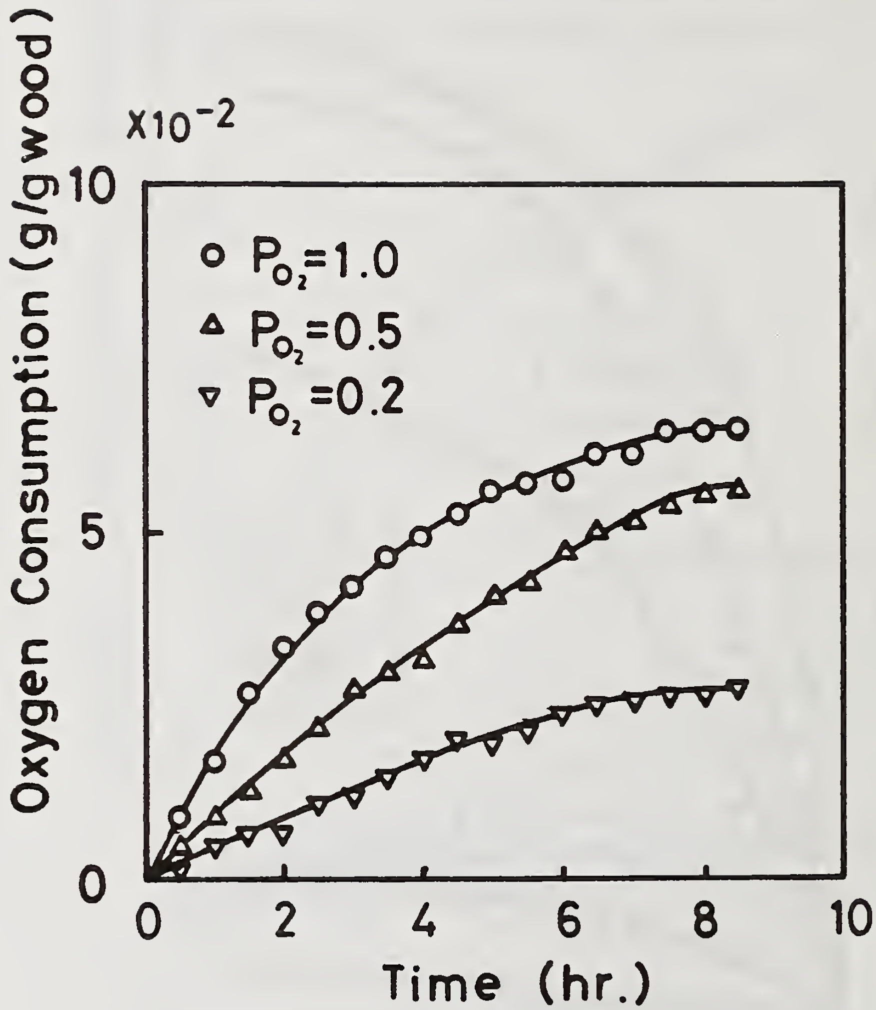


Fig.3(a) Effect of oxygen partial pressure on the variation in the oxygen consumption on heating of wood at 200°C.

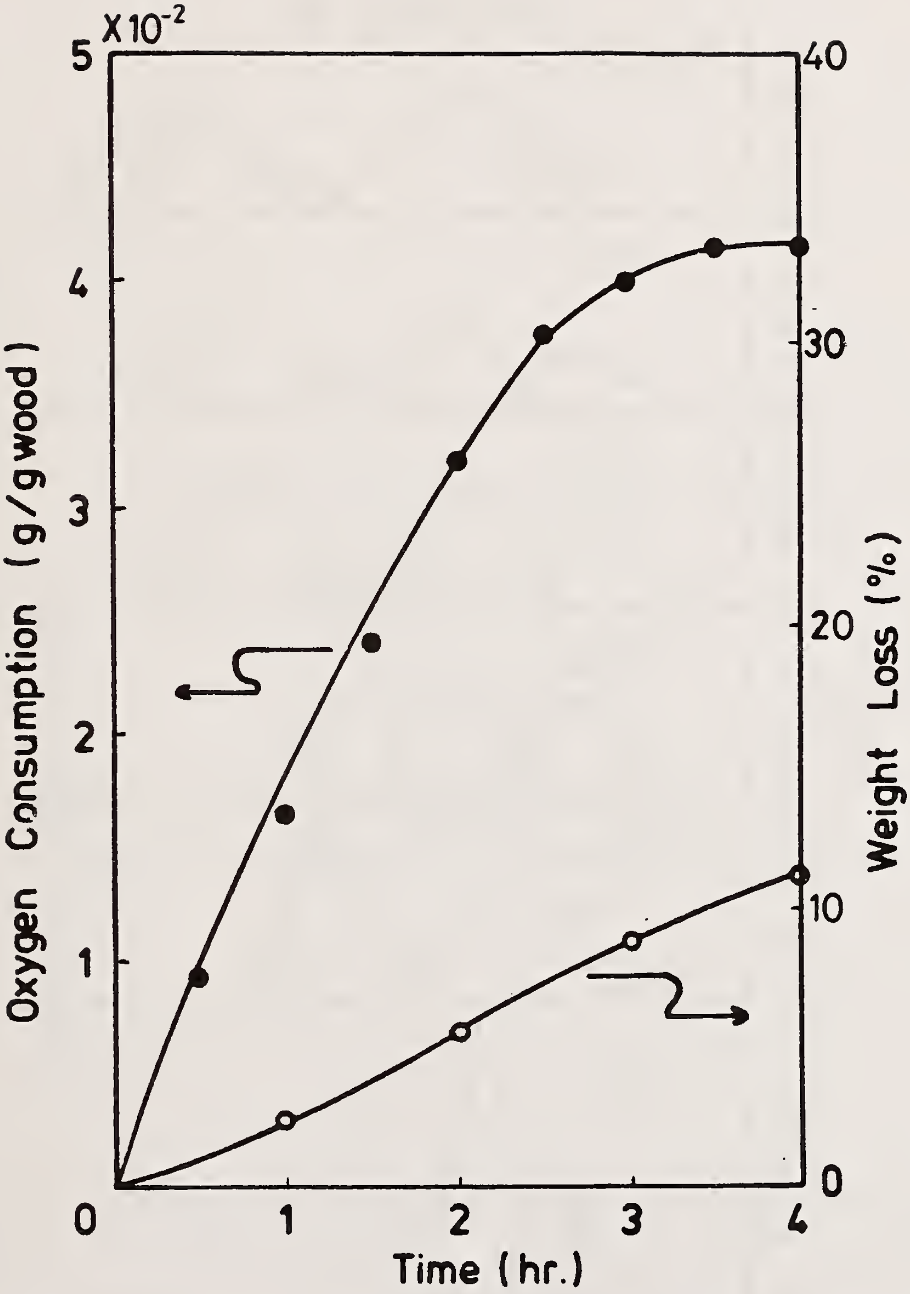


Fig.3(b) Weight loss of wood corresponding to the oxygen consumption on heating at 200°C.

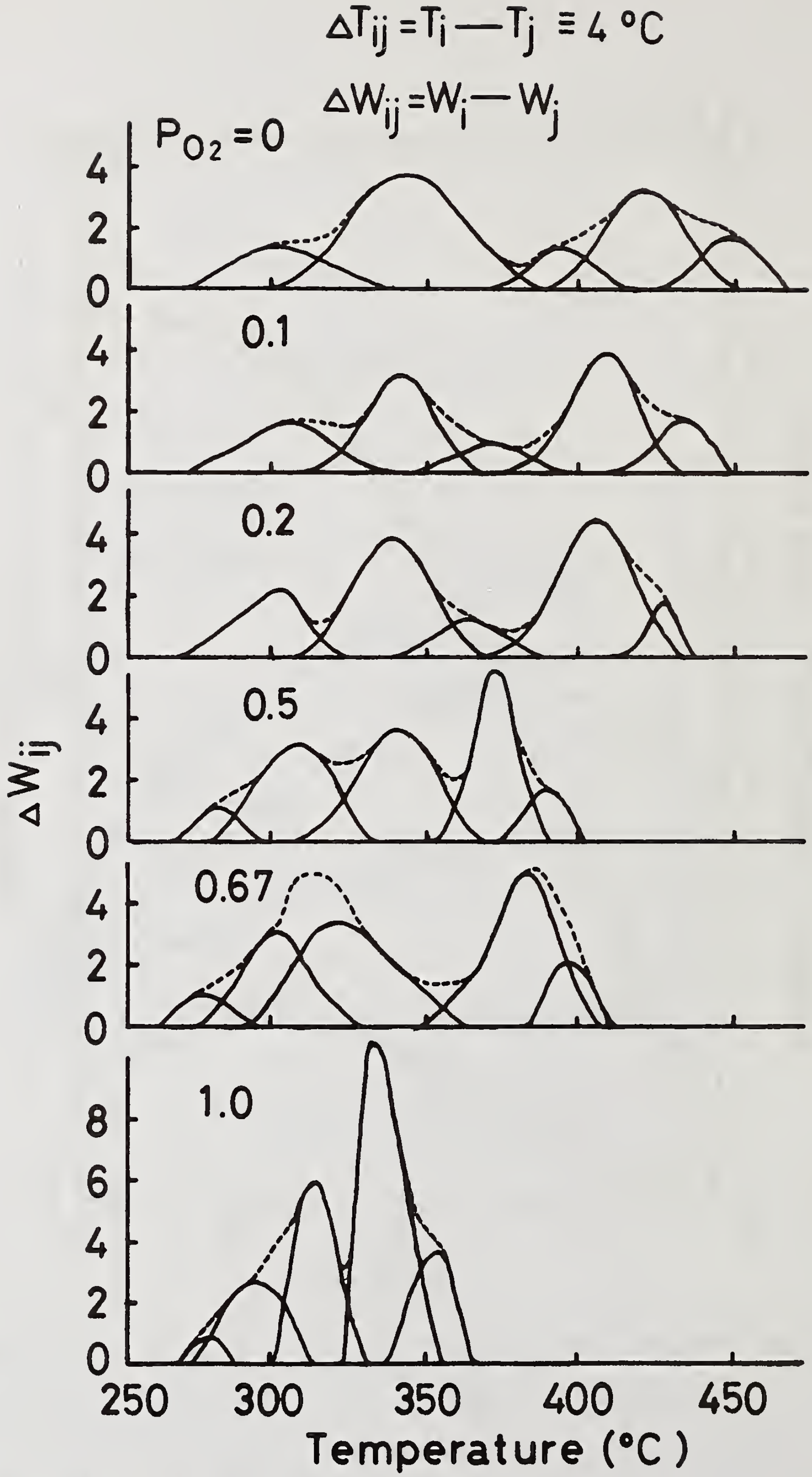


Fig.4 Effect of oxygen partial pressure on the variation in the weight loss rate on heating of wood on the rate of 2.5°C/min.

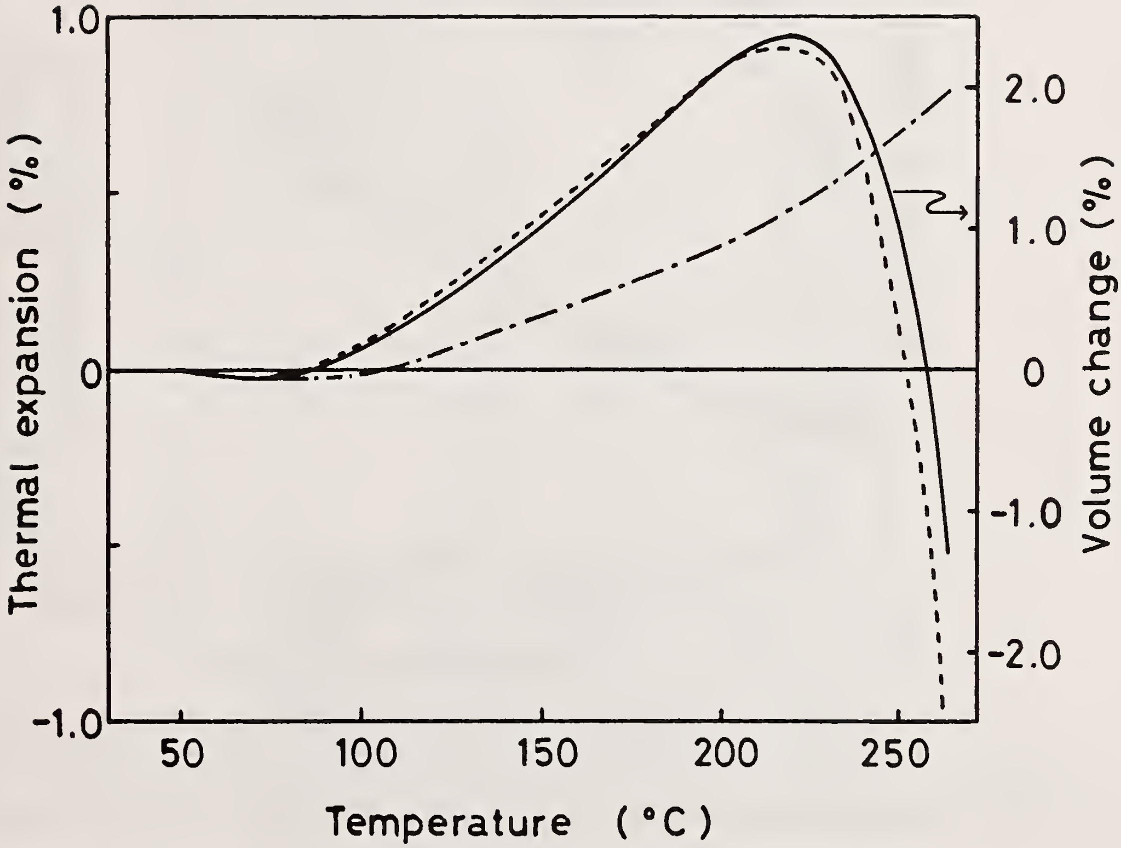


Fig.5 Temperarure dependences of the thermal expansion of wood.
—-—, L-direction of wood; -----, T-direction of wood;
——, volume of wood.

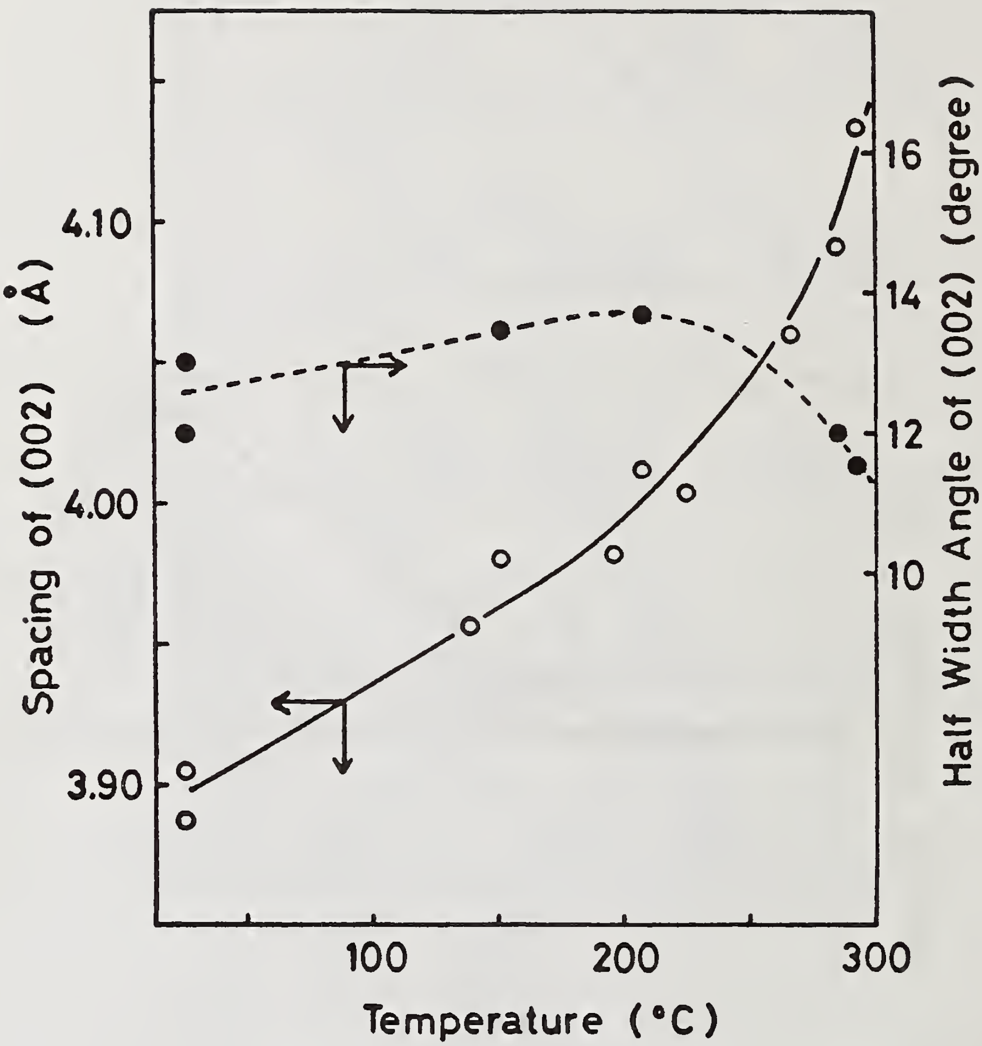


Fig.6 Temperature dependences of spacing of (002) in cellulose crystallite and the half angle of (002) representing cellulose fibril orientation in site at the corresponding temperature. o, spacing of (002); •, the half value angle of (002).

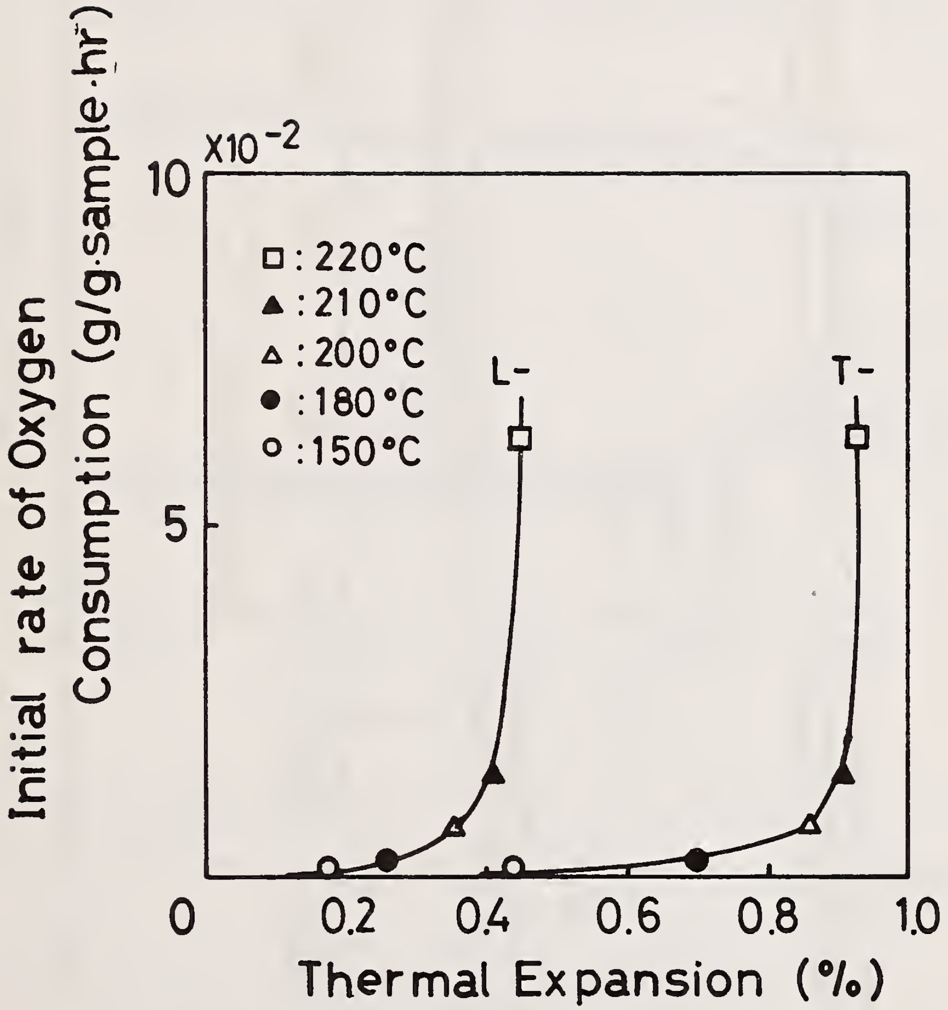


Fig.7 Correlation between the initial rate of oxygen consumption and the dilatometric change of wood.

——, L-direction of wood; -----, T-direction of wood.

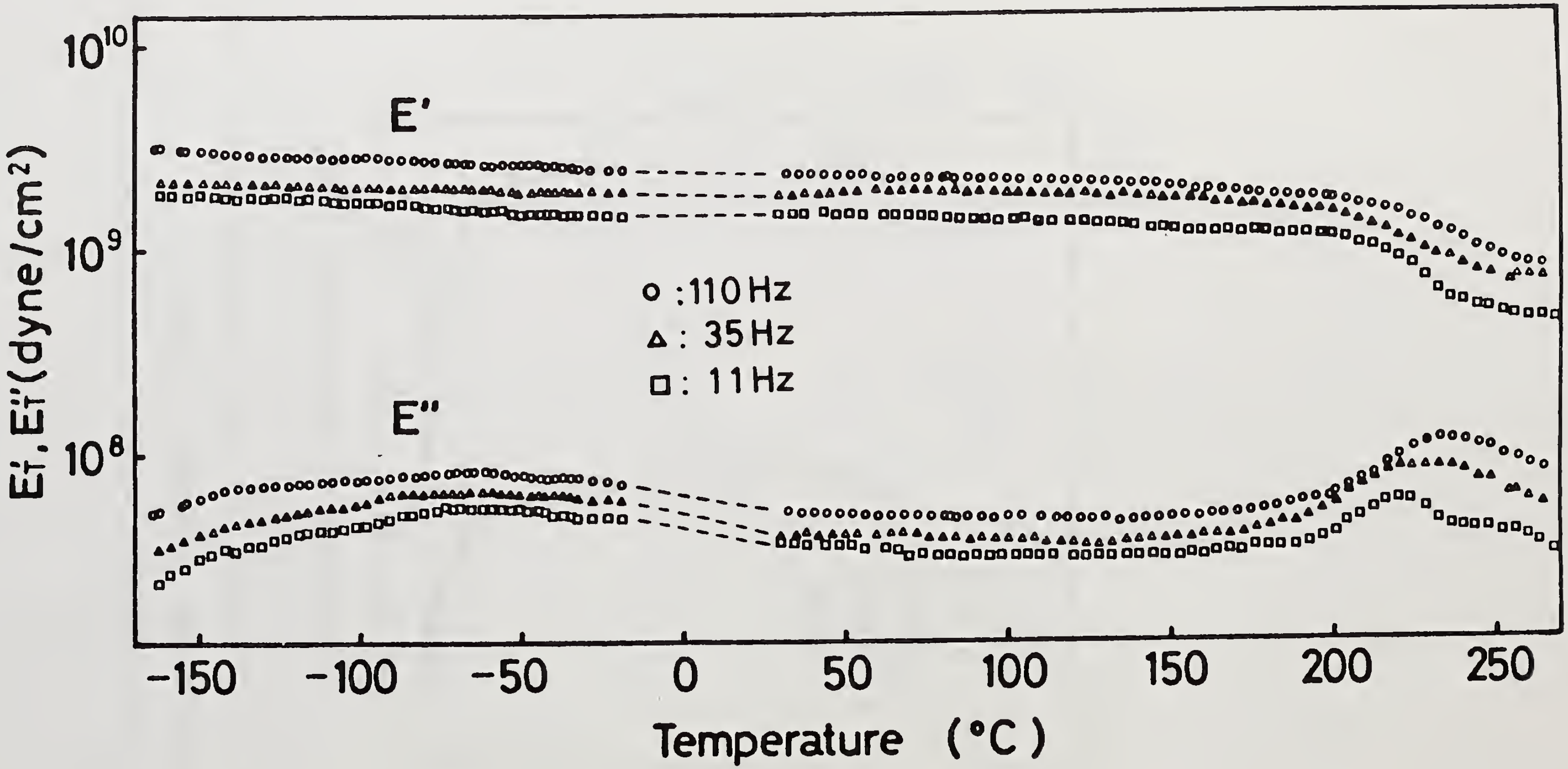


Fig.8 Temperature dependences of the dynamic modulus E' and the loss modulus E" at various measuring frequencies for T-direction of wood.

measuring frequency: o, 110Hz; Δ, 35Hz; □, 11Hz.

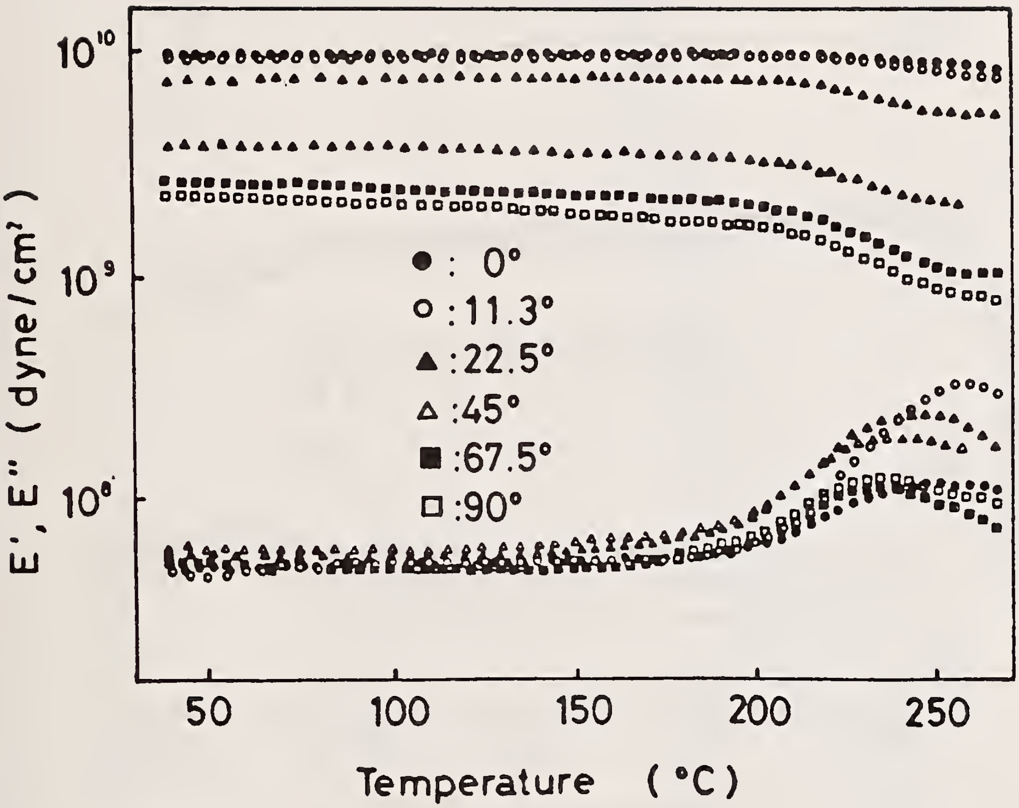


Fig.9 Temperature dependence of the dynamic modulus E' and the loss modulus E" at 110Hz as a function of grain angle of wood.

grain angle: ●, 0°(L); o, 11.3°; ▲, 22.5°; Δ, 45°; ■, 67.5°; x, 90°(T).

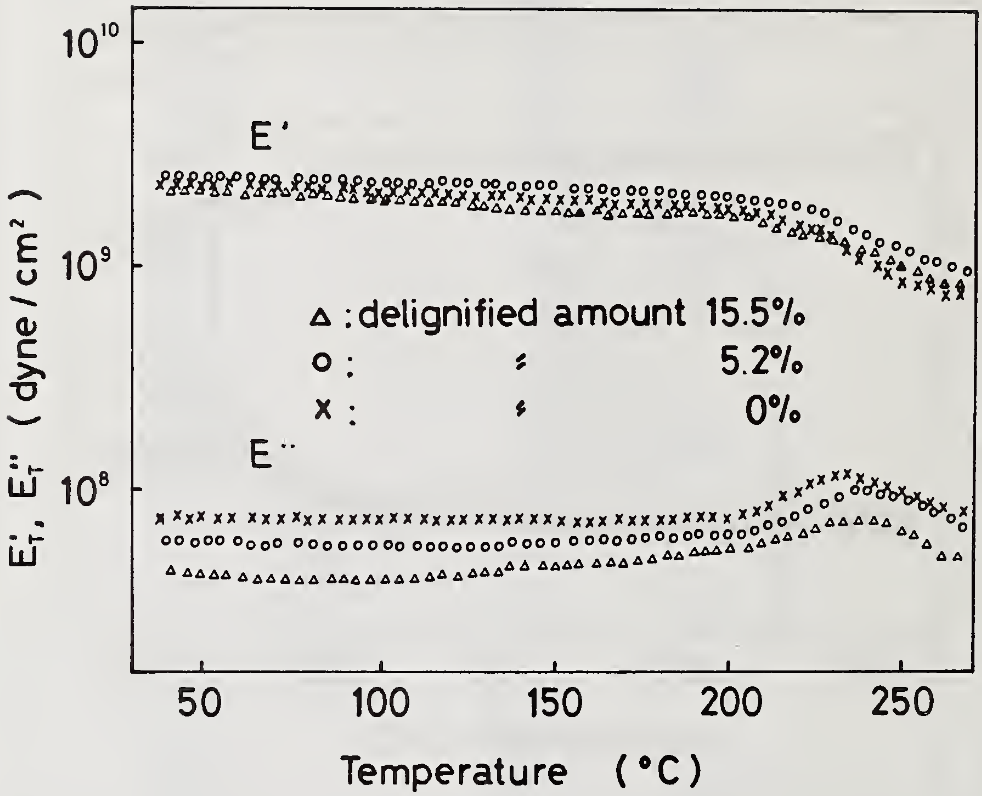


Fig.10 Temperature dependences of E' and E" at 110Hz of the delignified wood.
delignified amount: x, 0%; o, 5.2%; Δ, 15.5%.

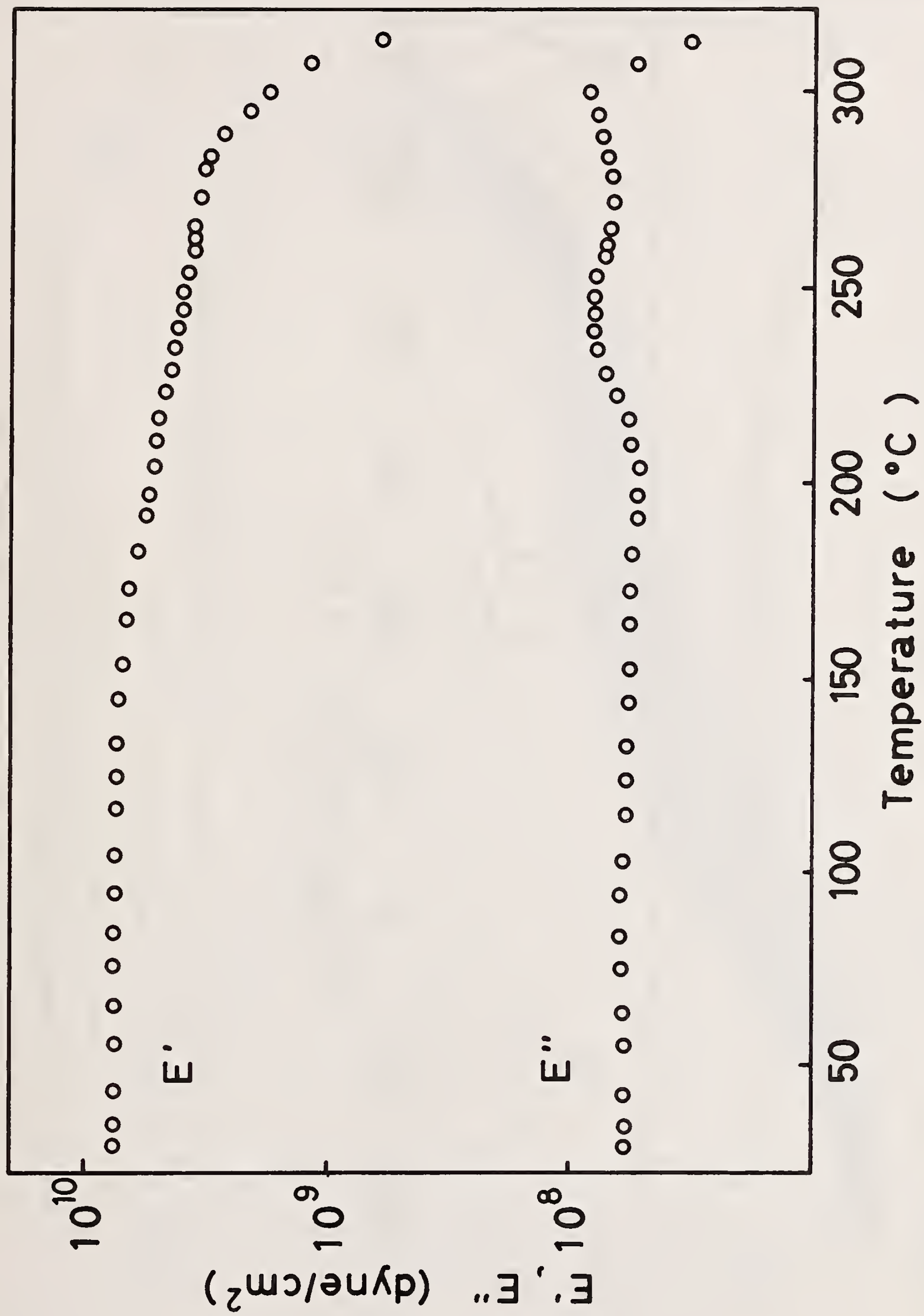


Fig.11 Temperature dependences of E' and E'' at 110Hz of the L-direction of wood.

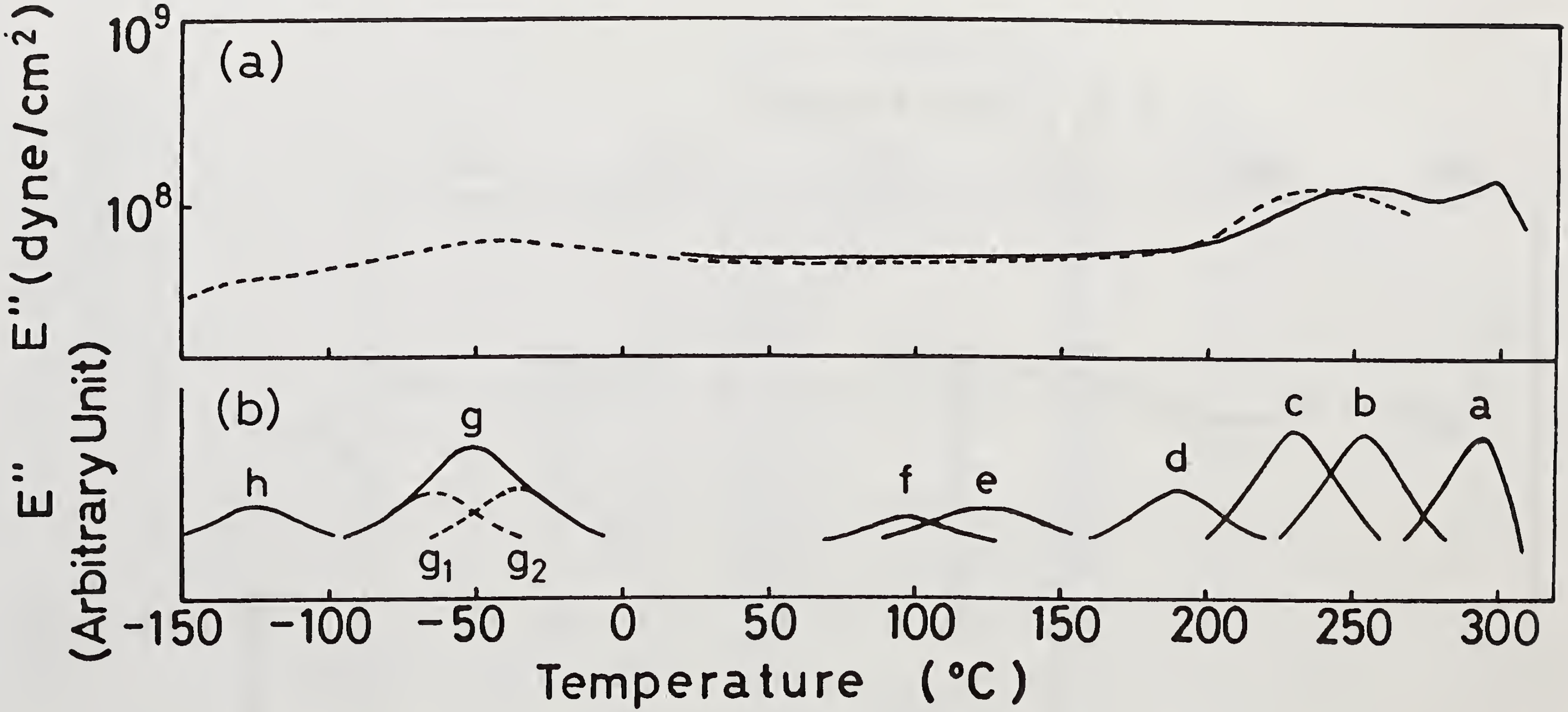


Fig.12(a) Temperature dependence of the loss modulus E" at 110Hz for L- and T-direction of wood.
——, L-direction; ----, T-direction.
(b) Schematic diagram characterizing E" bands isolated from the temperature dependence of the loss modulus.

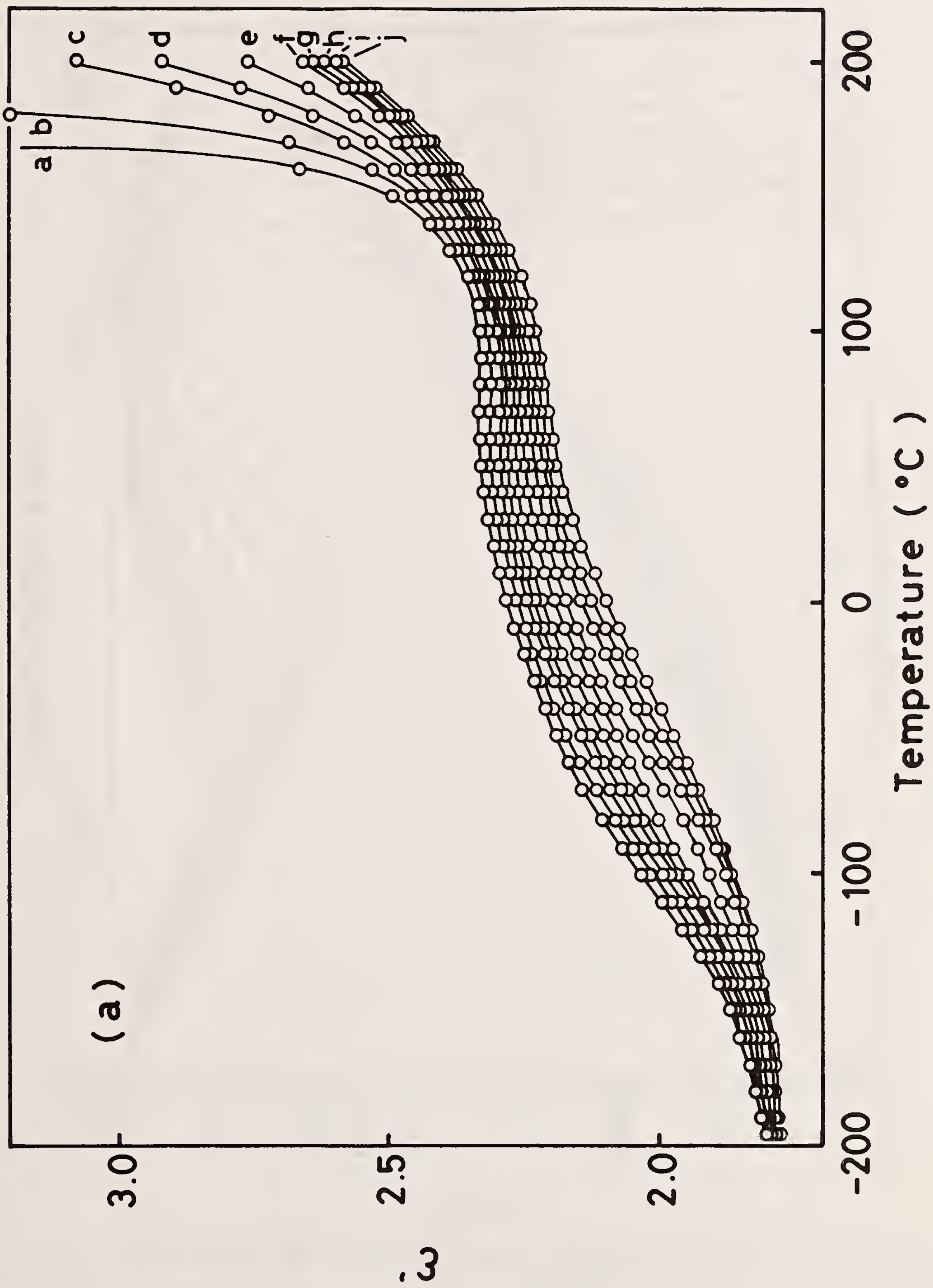


Fig.13(a) Dielectric constant ε' for R-direction of oven-dried wood as a function of temperature at respective frequency.

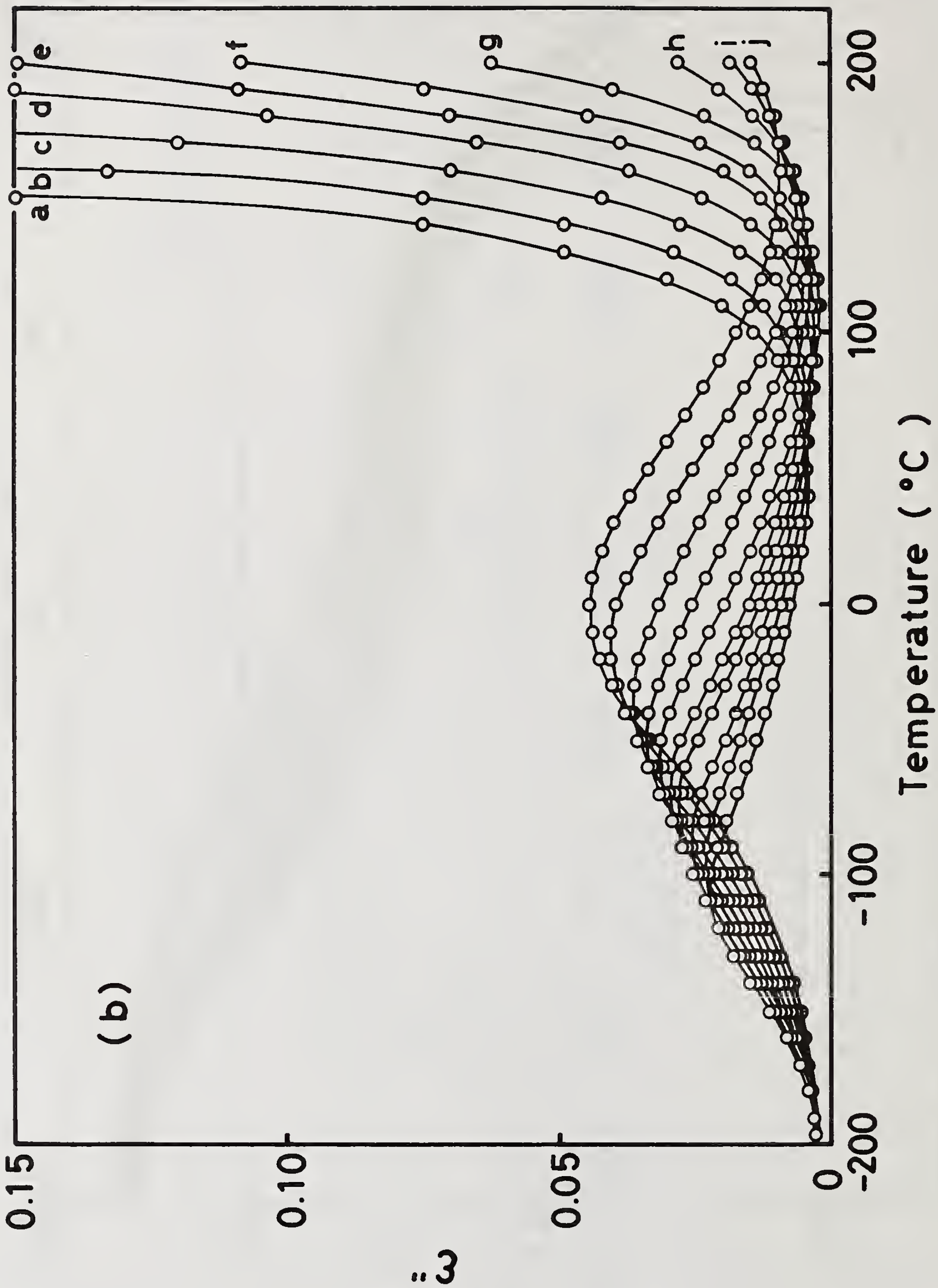


Figure 13 - (b) Dielectric loss factor ε" for R-direction of oven-dried wood as a function of temperature at respective frequency. a, 30Hz; b, 110Hz; c, 300Hz; d, 1kHz; e, 3kHz; f, 10Hz; g, 30kHz; h, 100kHz; i, 300kHz; j, 1MHz.

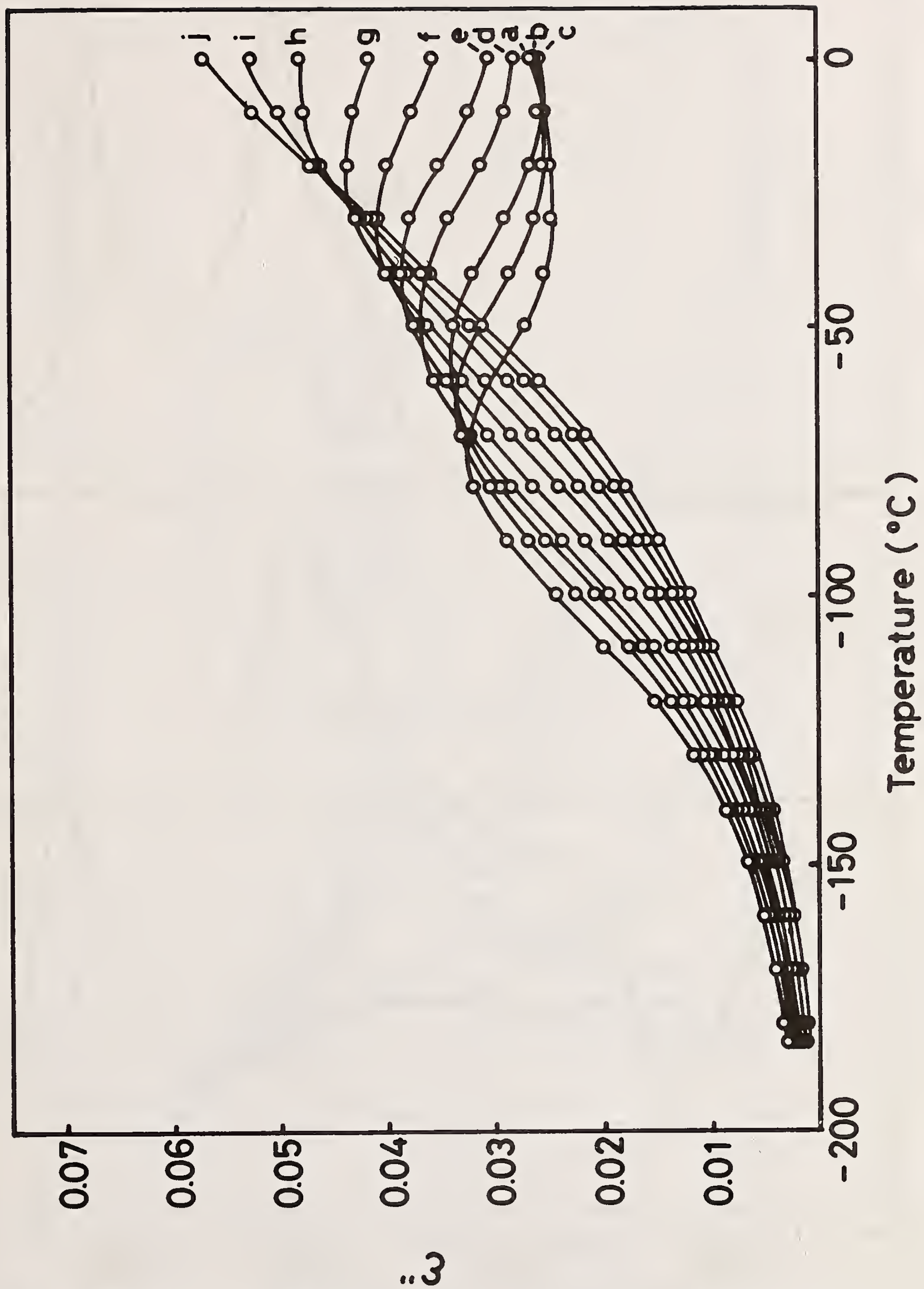


Fig.14 Temperature dependence of the dielectric loss factor ε'' for R-direction of oven-dried heat-treated at 240°C.
a, 30Hz; b, 110Hz; c, 300Hz; d, 1kHz, 3kHz; f, 10kHz; g, 30kHz; h, 100kHz; i, 300kHz; j, 1MHz.

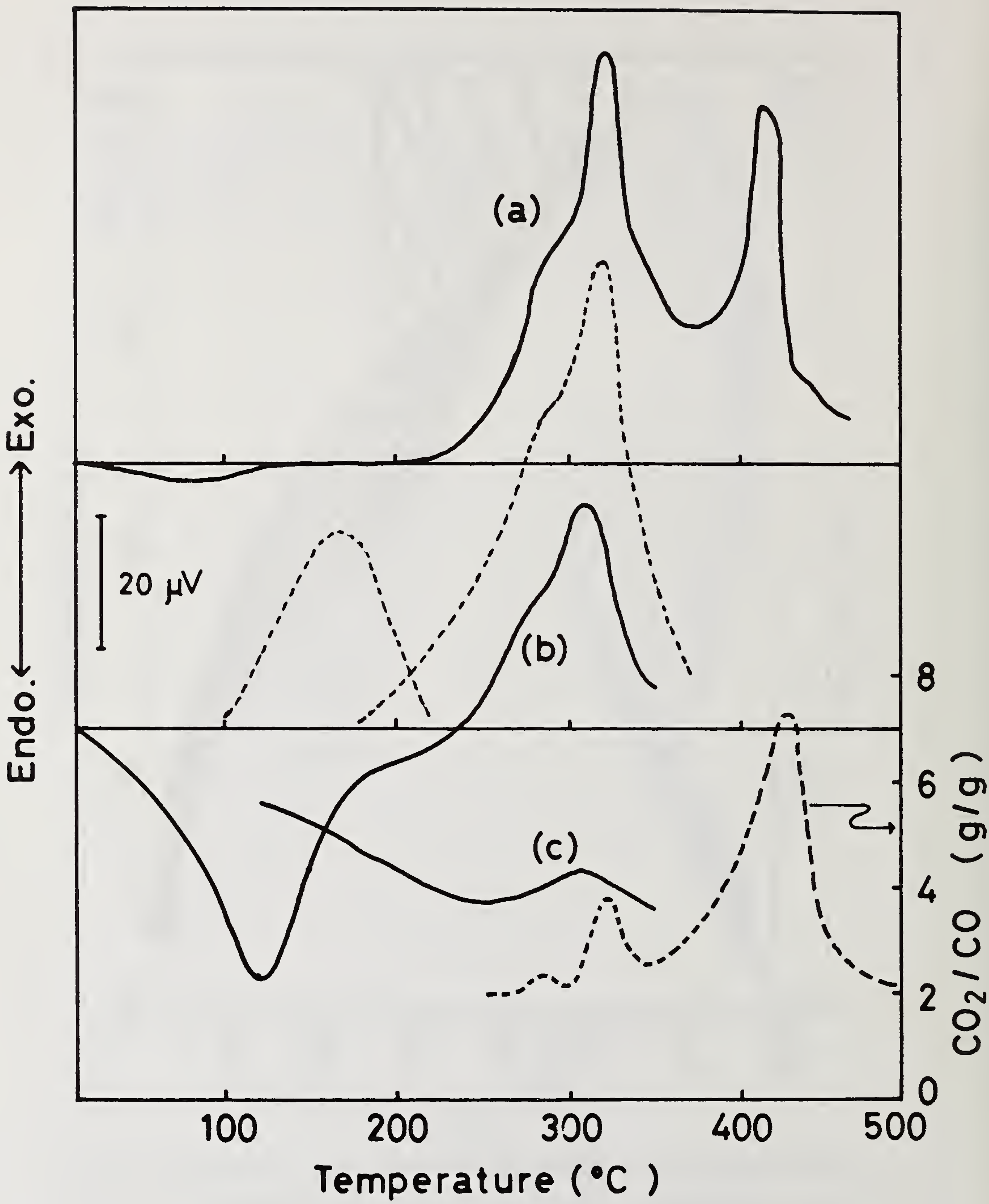


Fig.15 DTA thermograms of wood.

a, in air; b, in N_2 with a trace of O_2; c, in Ar.

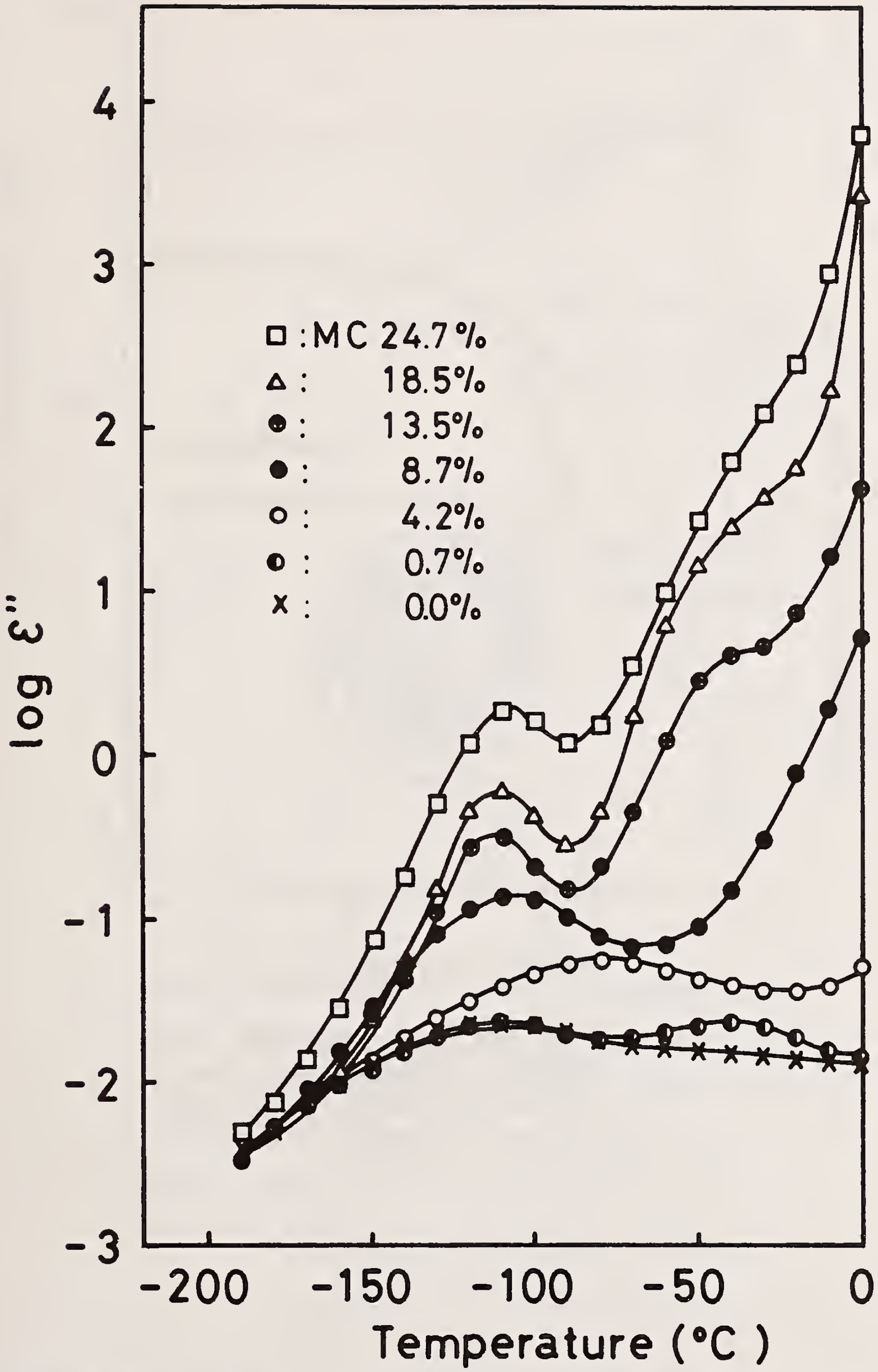


Fig.1·6 Temperature dependence of log ε'' at 30Hz for R-direction of wood containing various amounts of moisture.
x, oven-dried; ◐, 0.7%; o, 4.2%; ●, 8.7%; ⊕, 13.5%; Δ, 18.5%; □, 24.7%.

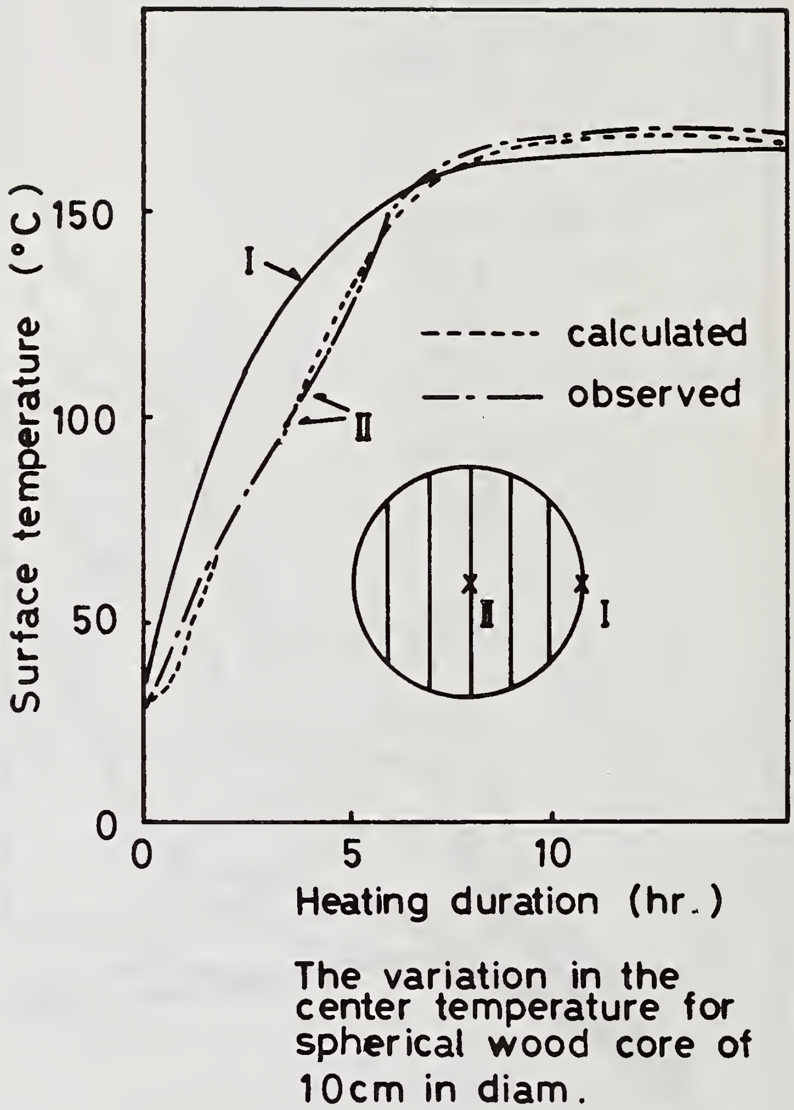
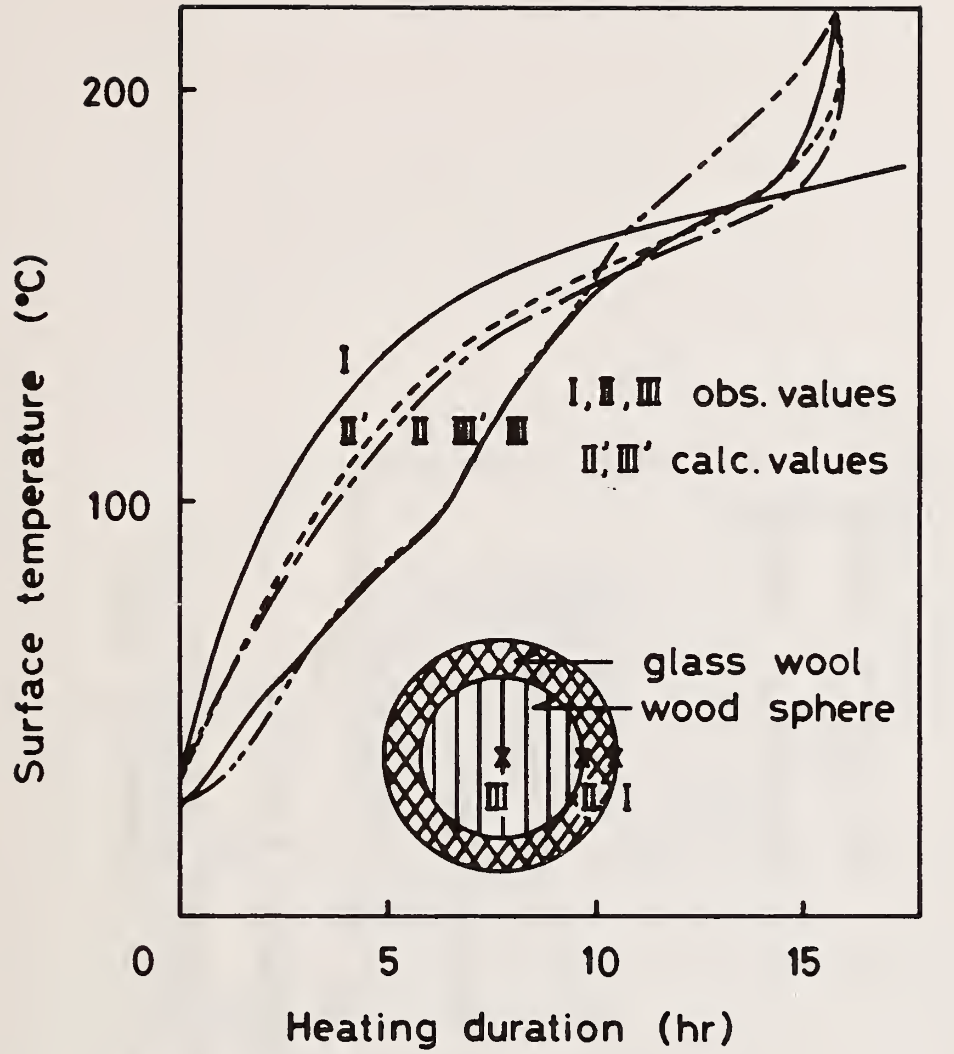
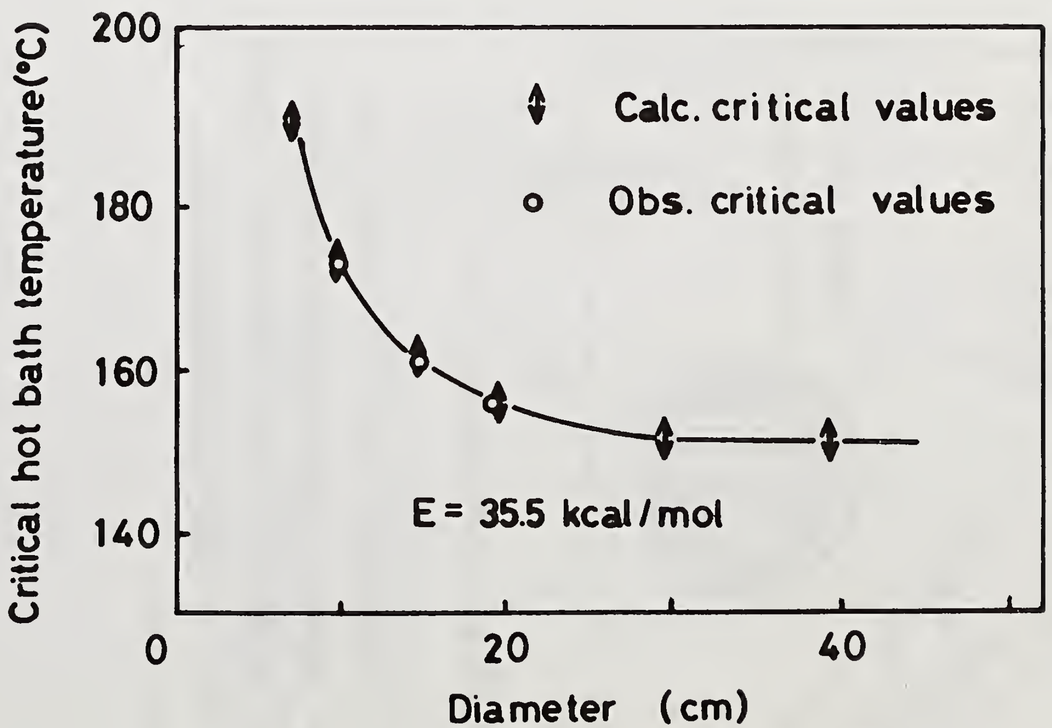


Fig.17 Variation in the center temperature for spherical wood core of 10cm in diameter.



The temperature rise at center of wood sphere and boundary between wood and glass wool for wood sphere of 10cm in diam. enwrapped by glass wool.

Fig.18 Temperature rise at center of wood sphere and boundary between wood and glass-wool for wood sphere of 10cm in diameter enwrapped by glass-wool.



The correlation between critical hot bath temperature and the diameter of wood sphere.

Fig.19 Correlation between critical hot both temperature and the diameter of wood sphere.

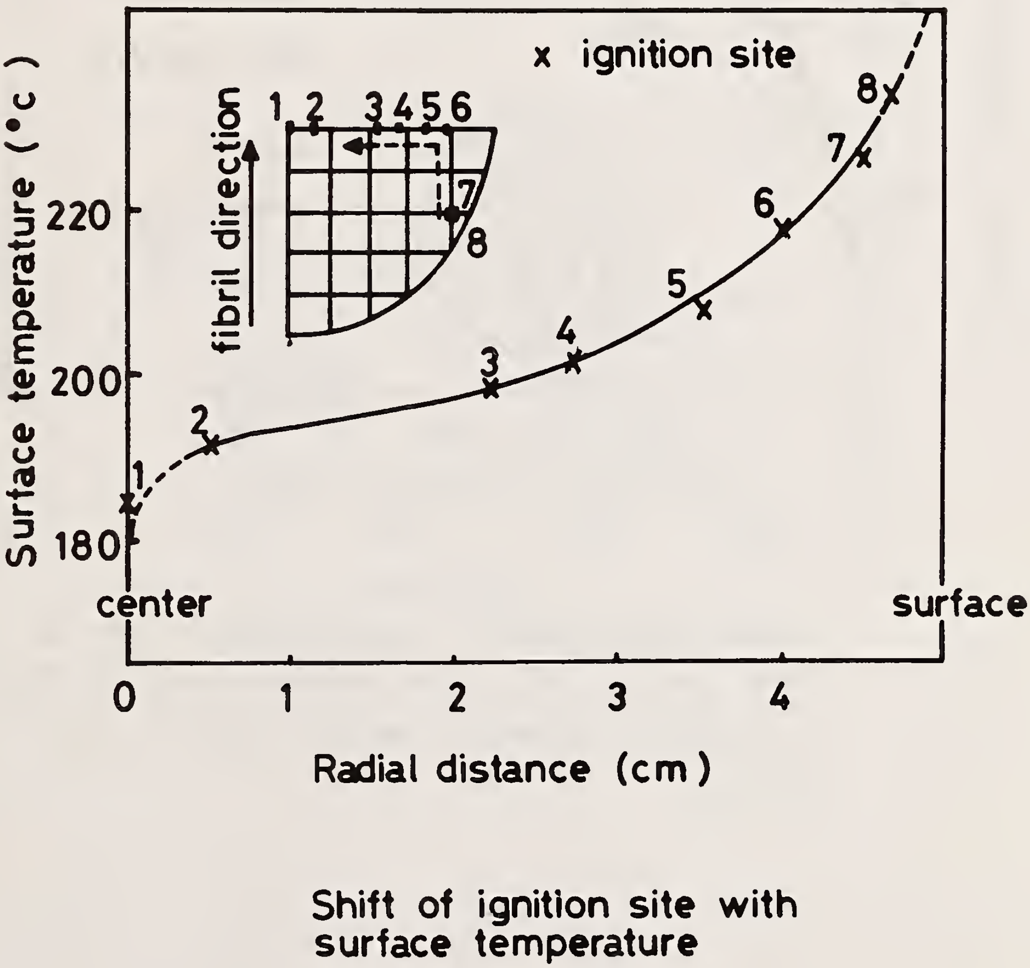
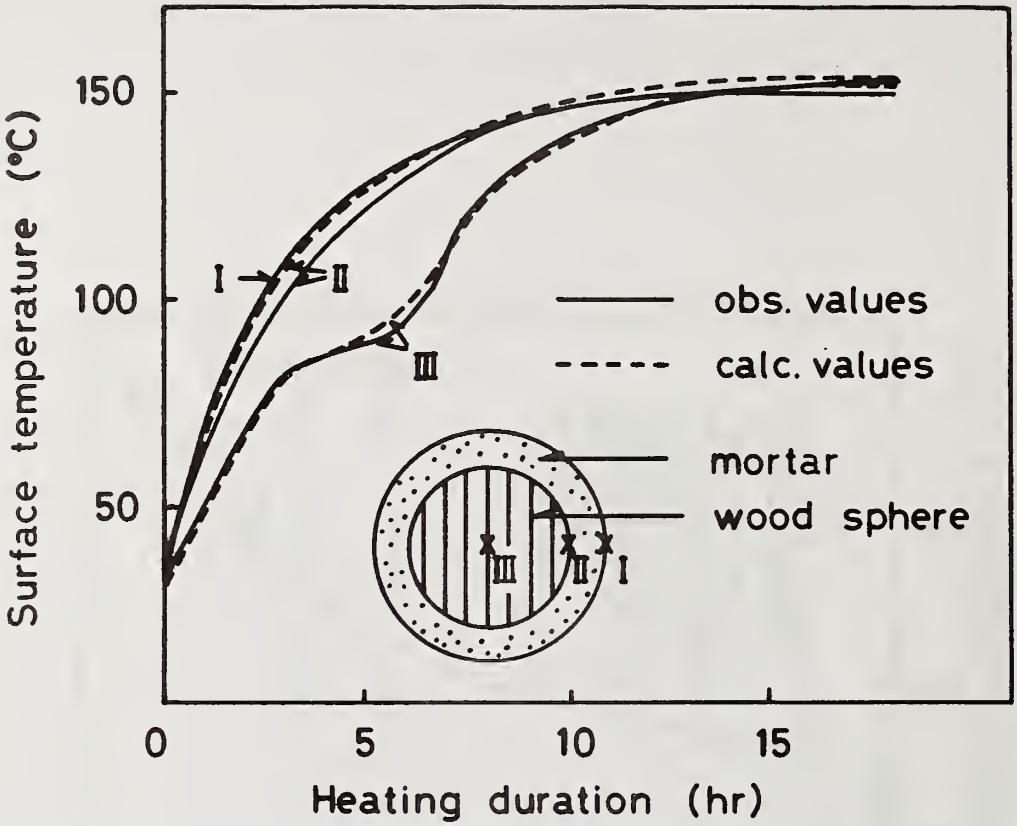


Fig.20 Shift of ignition site with surface temperature.



Time-dependence temperature rise at the center of wood sphere and in the boundary between wood sphere and mortar.

Fig.21 Time-dependent temperature rise at the center of wood sphere and in the boundary between wood sphere and mortar.

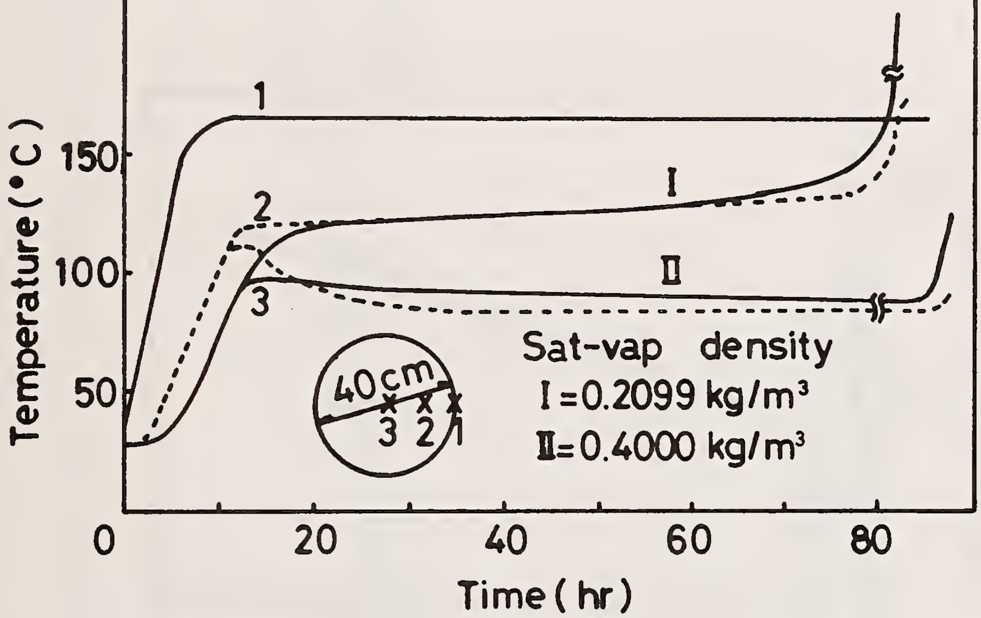


Fig.22 Thermal diagram of the wood sphere for the case of the arbitrary size as illustrated in figure.

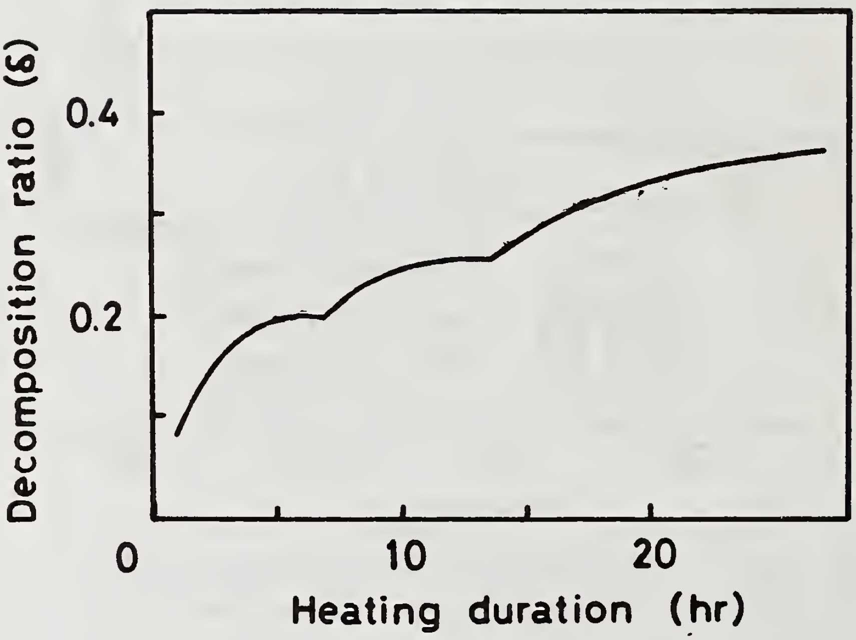


Fig.23 Variation in decomposition rate of wood with heating duration.

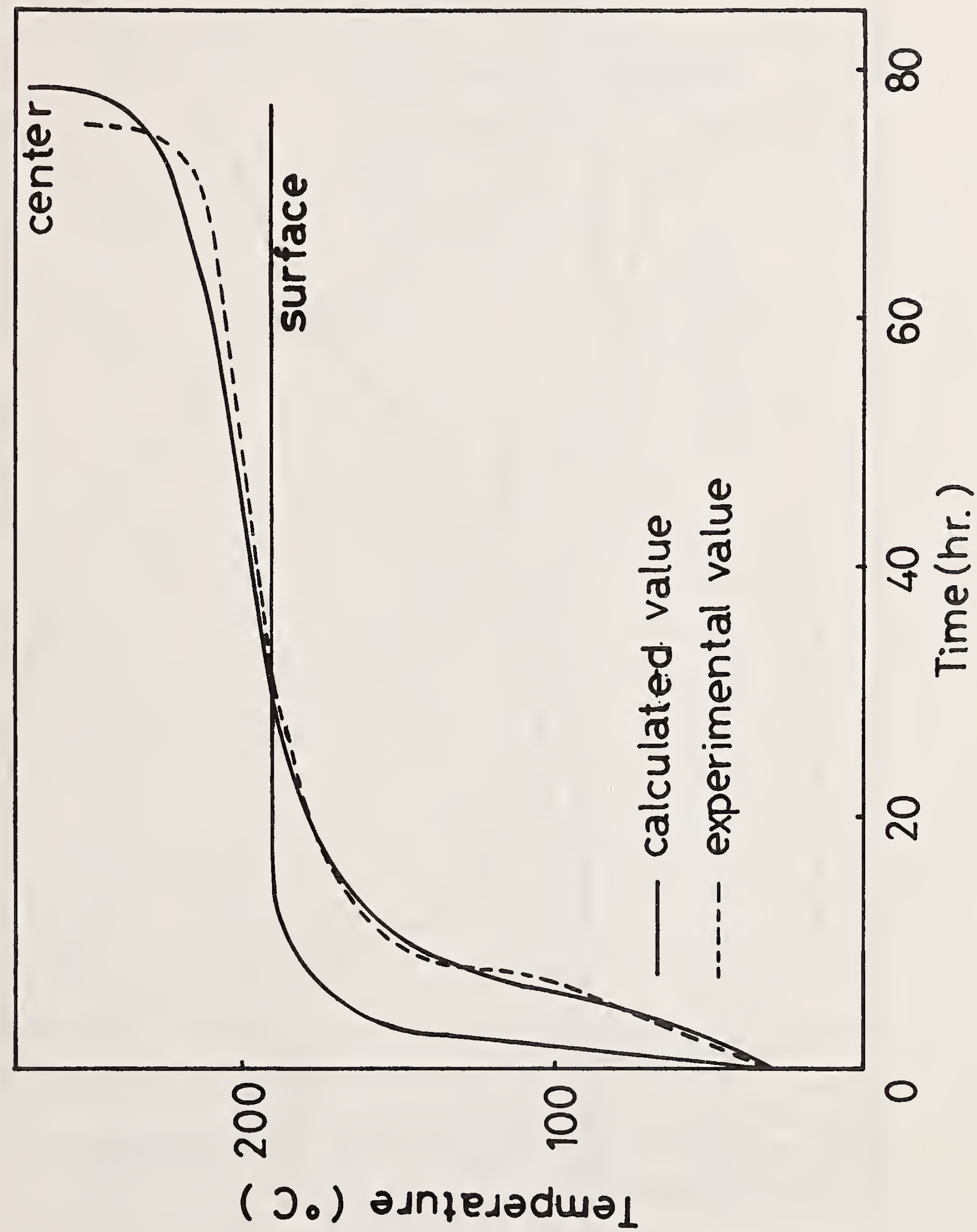


Fig.24(a) Time-dependent variation of temperature at the center of sphere.

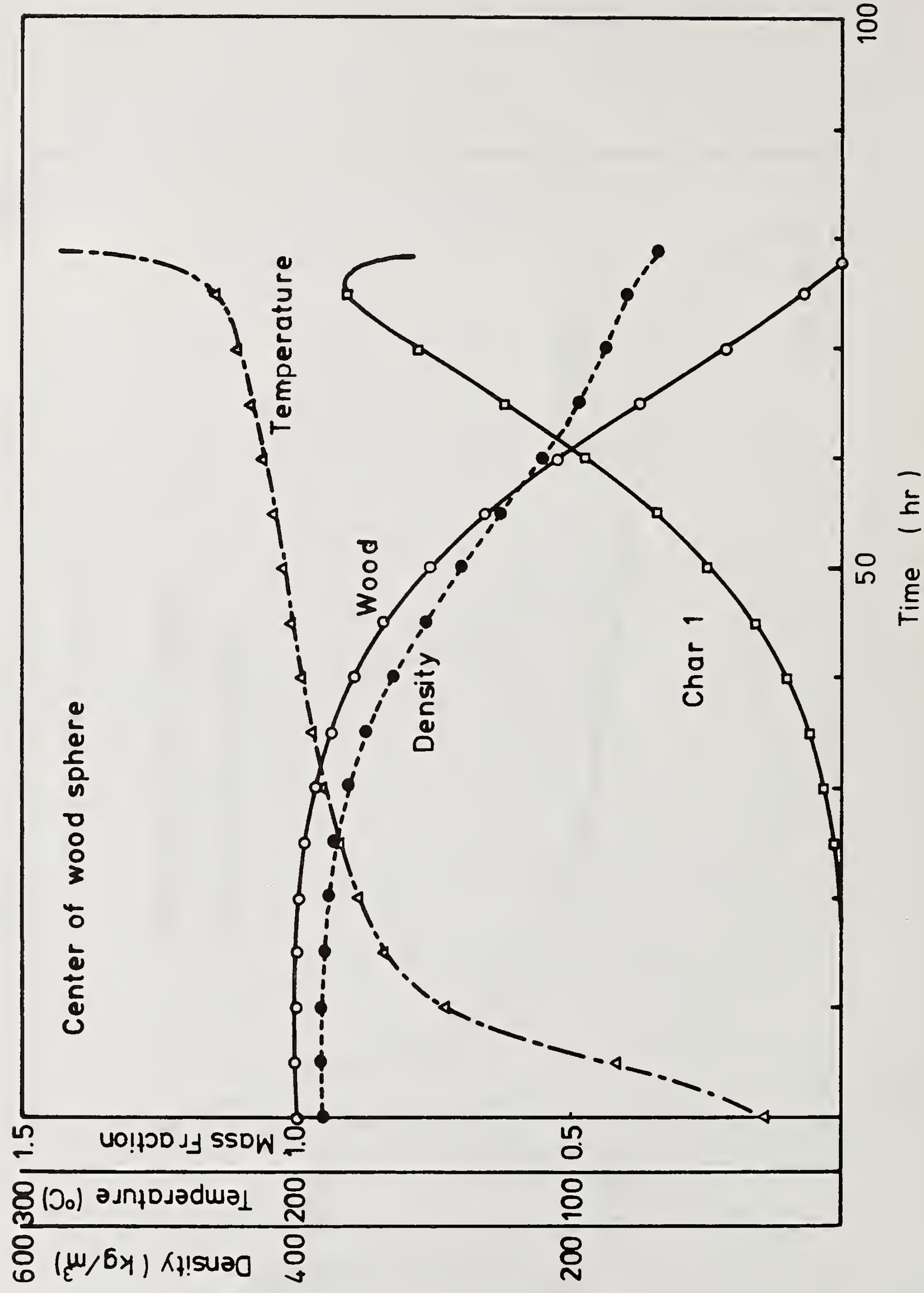


Fig.24(b) Time-dependent variation of calculated values for the density of wood, mass fraction of char(1), and wood of the center.

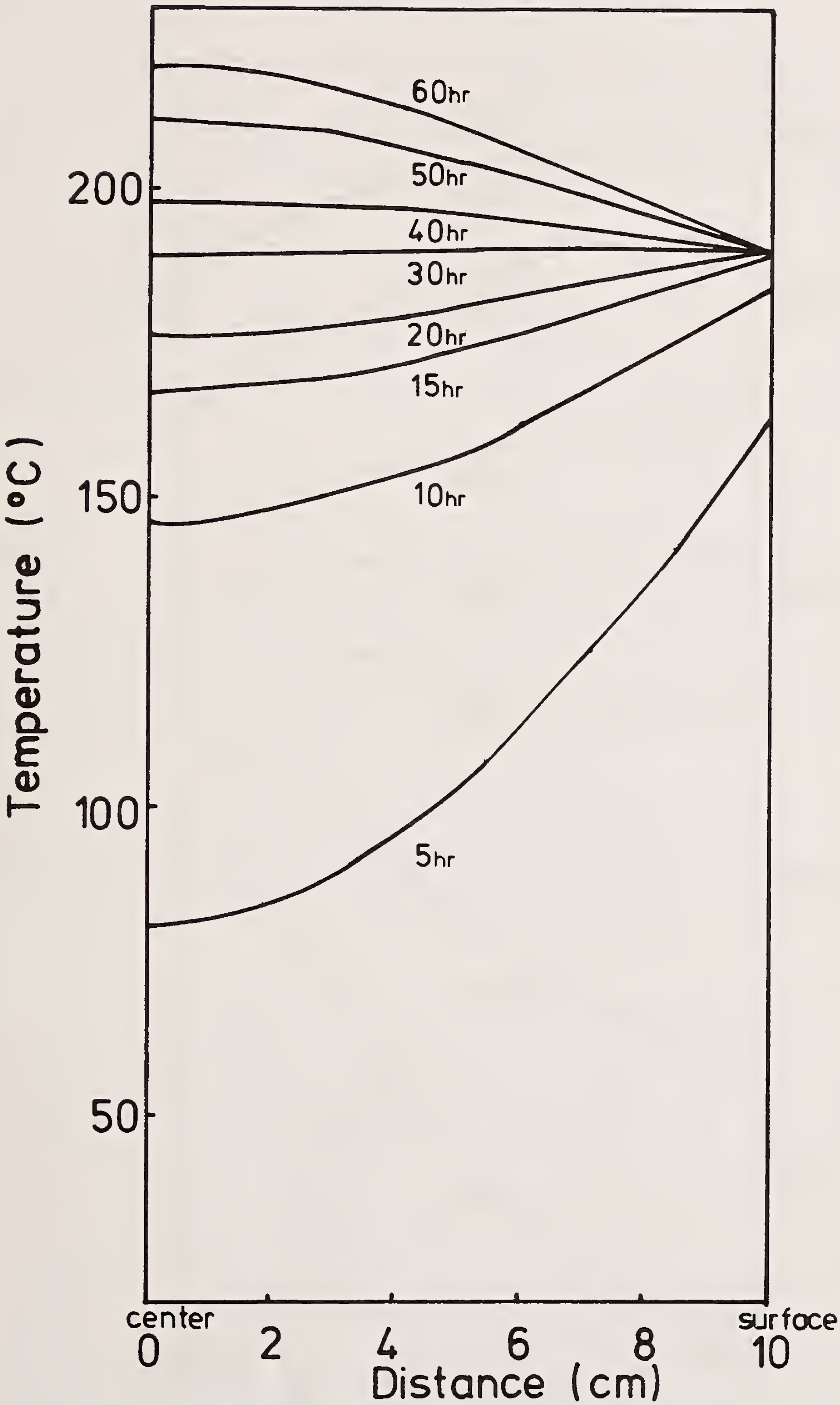


Fig.25(a) Distribution profiles of temperature along the radial direction of sphere.

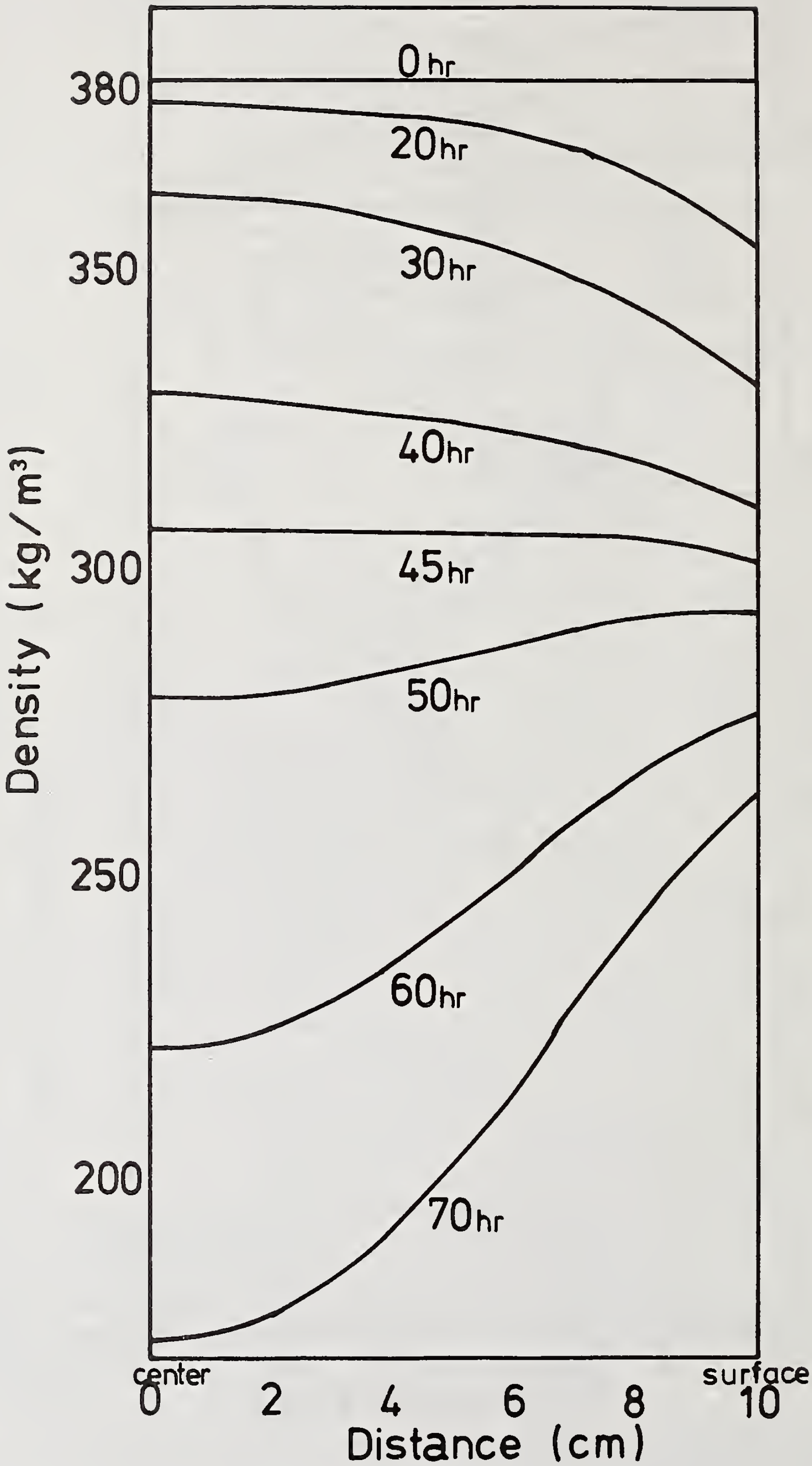


Fig.25(b) Distribution profiles of density along the radial direction of sphere.

Table 1. The values of coefficients used in the calculation.

NOMEN CLATURE (SYMBOL)	UNIT	MORTAR	GLASS-WOOL	WOOD	SAW DUST
Diffusion Constant (D)	m^2/hr	10.03×10^{-3}	10.80×10^{-2}	// 15.20×10^{-3} ⊥ 12.40×10^{-2}	90.00×10^{-3}
Heat Conductivity (λ)	kcal/m.hr.deg	12.60×10^{-1}	36.00×10^{-3}	// 75.00×10^{-3} ⊥ 15.00×10^{-2}	50.40×10^{-3}
Specific Heat (C_p)	kcal/kg.deg	25.00×10^{-2}	20.00×10^{-2}	41.00×10^{-2}	44.00×10^{-2}
Density (ρ)	kg/m^3	$21.00 \times 10^{+2}$	$20.00 \times 10^{+1}$	$38.00 \times 10^{+1}$	$14.00 \times 10^{+1}$
Adsorption Constant (K_2)	1/hr	80.00	$10.00 \times 10^{+1}$	$12.00 \times 10^{+1}$	$12.00 \times 10^{+1}$
Activation Energy (E)	kcal/mol	------------	------------	35.50	26.10
Pre-exponential factor (A)	1/hr	------------	------------	$36.00 \times 10^{+15}$	$36.00 \times 10^{+12}$
Heat Evolution (Q)	kcal/kg	------------	------------	32.00	96.00×10^{-1}
Desorption Constant (δ)	---------	------------	------------	38.00×10^{-2}	38.00×10^{-2}
Heat of Vaporization (Q')	kcal/kg	------------	------------	$62.00 \times 10^{+1}$	$62.00 \times 10^{+1}$
Moisture Density (ρ_v)	kg/m^3	*	20.99×10^{-2}	20.99×10^{-2}	20.99×10^{-2}
Gas Constant (R)	kcal/mol.deg	19.90×10^{-4}	19.90×10^{-4}	19.90×10^{-4}	19.90×10^{-4}
Heat transfer Coefficient (h)	$kcal/m^2.hr.deg$	-------------	------------	(72.00)	------------

* by the equation of Clausius-Clapeyron

Table 2. Thermal parameter for the computer simulation

Specific Heat (kcal/kg.deg)	c	0.41
Thermal Conductivity (kcal/m.hr.deg)	$\lambda_{\parallel}$ $\lambda_{\perp}$	1.5×10^{-1} 7.5×10^{-2}
Stoichometric Coefficient	m_1 m_2	0.40 0.20
Heat of Evolution (kcal/kg)	Q_1 Q_2	48.0 375.0
Frequency Factor (1/hr)	A_1 A_2	3.6×10^{16} 1.8×10^{13}
Activation Energy (kcal/mol)	E_1 E_2	39.5 37.5
Density (kg/m^3)	ρ_o	380.0

Discussion of Presentations on Smoldering

Handa Presentation

Earl: Were studies on crystallinity index used? Did you see any changes in the crystal form? In other words, did you see a change from cellulose 1 to cellulose 2?

Handa: Yes. However, without figures it is very distorted and hard to understand.

Earl: But you see no cellulose 2.

Handa: We tried to get some but we failed.

Emmons: In Table 2, you had two values of various quantities. What does 1 and 2 signify? M1 and M2, Q1 and Q2 -- what is 1 and 2?

Handa: Char 1 and Char 2.

Emmons: What is the difference between Char 1 and Char 2?

Ohlemiller: This is the thermal decomposition of cellulosic insulation and it falls more or less into two stages of degradation. The first one is oxidative pyrolysis, and the second one is the char oxidation process.

Chaiken: Just a comment. Much faster heating and degradation of wood is found using a laser. We are of the opinion now that the water that is in the wood, as well as the water that is formed during the composition, actually proceeds ahead of the thermal wave. At least the charring wave plays a very important role in the progress of the degradation.

We haven't looked in detail in terms of the precursor oxidation reactions which might be subject to water. But from the viewpoint of simply altering the thermal gradiants within the sample as water is formed in the thermal wave, a water front is actually moving ahead of the thermal wave, this supplies a good heat conduction mechanism for heating wood entering the reaction zone. This would be interesting from the viewpoint of your results which say that water can possibly react in terms of some precursor reaction.

Emmons: You indicated that the oxygen uptake by various compounds is related to the thermal expansion in various directions.

Handa: I mean oxygen uptake might be by lignin; it absorbs most oxygen around 200°C when fission of the chain occurs thermally. Above 230°C, other processes suggested by Dr. Ohlemiller may occur.

Emmons: Does this imply that if the expansion is due to stress, there is also an increase oxygen uptake.

Handa: Yes.

Friedman: I have a question on experimental detail. You state that you measure the oxygen uptake by a decrease of pressure of the oxygen, but if the wood is liberating gases at the same time, how does that work?

Handa: We use several kinds of molecular sieve to analyze the gases.

FINAL SESSION REPORTS

REPORT OF TECHNICAL SESSION ON PROGRESS REPORTS

F. Clarke, Chairman

The first technical session was devoted to progress reports on: fire retardance, building design and smoke control, human behavior in fires, and fire protection.

Dr. Saito reported on the use of fire retardant chemicals in Japan, giving approximate amounts of use and numbers of manufacturers of various kinds of fire retardants. A large amount of data was presented on smoke generation of urethane and polyvinylchloride, treated with various additives and fire retardants. The relationship between flashover and heat content of cellulosic materials was discussed, as was the flame profile as a function of location and size of pool fire.

For the American side, Dr. Clarke reported on several promising techniques for the elucidation of molecular process in the pre-combustion and early combustion phases. These include solid phase nuclear magnetic resonance spectroscopy; a laser reduced particle ionization technique which is effectively a time-of-flight mass spectrometer for incipient soot particles and the opposed flow diffusion burner, useful for a variety of flame phenomena.

Dr. Morishita presented the Japanese progress report on Building Systems and Smoke Control for himself and Dr. Wakamatsu. He reported briefly on several papers on building design, including advances in the field of state transition modeling and network systems previously reported. Other optimization techniques, and the contribution the components of fire environment to the overall fire hazards, were reviewed as well. In the smoke control field, Dr. Morishita described the new experimental test facility in Tsukuba, which has been used for over 80 experiments so far this year. He also reported on "cold smoke" studies in two large office buildings in Tokyo. For one of the two buildings, the Shinjuku Center Building, the smoke control system was found to perform effectively. Measurement difficulties made performance of the other building systems difficult to evaluate.

The American work on smoke control was presented at the "Annual Conference" during the second week of the program. Dr. Klote of NBS reported on smoke control modeling techniques for analysis of pressurized stairwells and on refinements of the ISI smoke movement model. The progress for developing a smoke control manual was also reviewed. Smoke movement studies at California Institute of Technology were reported by Dr. Zukowski. Emphasis in this work is on room-to-room flow of smoke and hot gases in the early stages of a fire. Other American work on building design is closely related to human behavior, and was covered in the session on human behavior at the Annual Conference.

Dr. Jin reported on Human Behavior in Fires for the Japanese side. He presented a proposed new exit symbol now under study in Japan. The symbol may offer more legibility and clarity than a proposed ISO symbol. Work on human vision through smoke was also extended over that reported in earlier conferences.

Prof. Vreeland of the University of North Carolina reported at the Annual Conference on the actions of occupants caught in a simulated residential fire. Dr. Levin of the NBS discussed fire safety for the handicapped and some of the implications which that carries for building design.

Dr. Stahl of NBS and Prof. Francis of University of Florida, both discussed the modeling of human behavior in fire situations. Dr. Stahl concentrated on modeling the decision process which potential fire victims undertake, while Francis concentrated on the description of people movement in building evacuation.

Mr. Benjamin from the U.S. side discussed smoke detection status in the United States. He estimated that as many as 50% of U.S. homes are now covered by smoke detectors. Studies on the audibility of smoke alarms were reported by Prof. Nober of the University of Massachusetts. He reported that the 55db alarm level seems adequate as long as air conditioning and other interferring noises are not present.

Prof. Miyama reported on Japanese work on smoke detection. He discussed developments of criteria for performance of beam-type smoke detectors. He also presented findings that visible light, when used in photoelectric smoke detectors, is attenuated substantially less than infrared light under the same experimental conditions.

REPORT OF TECHNICAL SESSION ON ARSON AND FIRE INVESTIGATION

I. Benjamin, Chairman

Mr. Karchmer presented a paper discussing some of the possible reasons for an increase in arson in the United States. He then went into detail on several of the early warning systems which had been set-up to attempt to predict where arson will occur.

Mr. Kawamura gave some statistics on arson in Japan indicating that it is not as serious a problem as in the United States, and does not appear to be substantially growing. He also presented some data from a supplemental report by Mr. Murakami which analyzed in detail psychological and sociological aspects of arson that had occurred in Japan.

A brief discussion was held on what might be the reason for differences between growth of arson in the United States and Japan. Several plausible explanations were suggested but no definite conclusions were reached.

REPORT OF TECHNICAL SESSION

TOXICITY OF COMBUSTION PRODUCTS

J. Bryan, Chairman

The session on Toxicity consisted of three segments with presentations in the UJNR meeting on October 16, 1980. In addition, an informal session was held on October 20. The final session relating to Toxicity was presented at the Annual Conference on Fire Research on October 23.

Dr. F. Saito, Building Research Institute, presented the paper entitled "Basic Concepts on Toxic Hazards in Building Fire," written by Kishitani and Saito. He emphasized that the burning condition of the sample controlled the level of toxicity of combustion products. Therefore, the detailed measurements of temperature and amount of air supply to the sample in full size experiments are needed to define the burning condition for the toxicity measurement. Also, he recommended that the question of rapid acting toxicants should be included for the evaluation of toxicity of combustion products.

Prof. Y. Nishimaru, Yokohama City University, reported on the study of the toxic gas generated by the combustion of artifical turf. The specimen samples were ignited in chamber test situations with eight mice exposed in each test situation. The use of occupancies such as ball parks and golf courses for areas of refuge during earthquakes motivated the concern for this study. The relationship between amounts of COHb and CO_2-Hb in blood and incapacitation time of mice was also reported.

Dr. M. Birky, Center for Fire Research, reported on the development of the proposed modeling procedure for the determination of toxic combustion products which was introduced to the Panel at the 1978 meeting. He reported on the seven laboratory evaluation projects, involving twelve materials. Dr. Birky also presented the results of the project to correlate the small test chamber results to a full scale room situation for both a polyurethane and a cotton material. The analytical comparison of the two situations was most significant while the toxicological comparison indicated areas for further study.

The session on Toxicology during the Annual Conference on Fire Research was chaired by Dr. Birky. Dr. Barbara Levin, CFR, presented the data on the seven laboratory evaluation study presented by Dr. Birky to the Panel. Ms. Maya Paabo, CFR, presented the results of the small scale to large scale test comparisons also previously presented by Dr. Birky.

Dr. S. Packham, a consultant, presented a review of the published tenability time limits for CO and HCN from the Harvard School of Public Health, National Academy of Sciences and National Bureau of Standards. He emphasized that tenability limits vary with time and the total time concentration curve must be considered in the evaluation of materials.

Professor Y. Alarie, University of Pittsburgh, reported on their studies to determine the time-concentration effects of toxic products which involved large scale comparisons with the products of combustion from the wall panels exposed in a room corner test. The study exposed four groups of rats of four animals each, with varying smoke concentrations. Alarie agreed with Packham rather intently that the entire time concentration curve must be utilized, and these curves are well established.

Dr. Z. Annau, Johns Hopkins University, reported on the effects on rats relative to the learned shock-avoidance responses when exposed to an injection of ethanol, ten minutes prior to a thirty minute exposure to 1500 ppm of CO, with a thirty minute observed recovery period. His data indicated significant changes in the responses produced and shocks endured. He indicated his study did not evaluate the additional influence of thermal exposure which should be considered.

Dr. R. Meyers, Maryland Institute for Emergency Medical Services, University of Maryland Hospital, Baltimore, reported on development of a cognitive-perceptive clinical test procedure to evaluate the need for the treatment of patients with suspect COHb levels, in the hospital hyperbaric oxygen chamber. The results of the test use were presented with the plans for improvement. Nurse Jones presented a Minico CO analyzer which is being field tested as a diagnostic procedure to enable EMT, CMT, and Paramedics to determine if a patient requires hyperbaric oxygen chamber treatment. It was reported that FM radio transmissions and alcohol breath both affect the instrument. The instrument is currently being field tested on fire department personnel in the Baltimore area.

Dr. G. Hartzell, Southwest Research Institute, reported on the study supported by the U.S. Fire Administration, to determine the combustion atmosphere in buildings encountered by fire department personnel. Ten sampling boxes are being utilized by San Antonio, Texas, fire fighters to collect samples for determination of levels of HCN, HCL, CO CO_2, O_2, Benzine, Acrolein and Acetyaldehyde. The collection area consists primarily of single family, frame dwellings. This is a followup study from the Harvard University - Boston Fire Department study.

The discussions at all of these sessions appeared to be enlightening and informative.

REPORT OF TECHNICAL SESSION

ADVANCES IN SPRINKLER TECHNOLOGY

T. Jin, Chairman

Presenting a paper, "Life Safety Factors Involved in the Use of Sprinklers," Mr. O'Neill has reported on full-scale fire tests in a patient room and mentioned as follows: "A dynamic heating measurement of the sprinkler, in addition to the temperature rating of the sprinkler, may be a primary design variable in future sprinkler criteria. For life safety, a more rapidly responding sprinkler than conventional sprinklers is necessary, but the benefit of it may not be so significant for very rapid developing, shielded fires, such as fires inside combustible clothing wardrobes."

Presenting a paper, "Sprinkler Technology and Design in Japan," Mr. Unoki reported on mandatory installation of sprinklers in Japan and mentioned as follows: "The heads used in these systems are designed to meet the standards which are characterized by the following: the water distribution test is to be conducted using a single head, and the relationship between the permanent and the elastic elongation of the frame is to be defined. The proposal on time constant as the requirement of heat response of heads is also being discussed."

Presenting a paper, "Advances in Residential Sprinklers," Dr. Kung has reported on full-scale fire tests in a living room and mentioned as follows: "Links considerably more sensitive than the commercial link are essential in providing adequate protection in residential fires. The required sprinkler operation conditions have been determined in terms of sprinkler water distribution associated with a link five times more sensitive than the commercial link."

Through these reports, the sensitivity of link, the water distribution, the smoke obscuration problem, etc., have been discussed.

REPORT OF TECHNICAL SESSION

FIRE MODELING

T. Handa, Chairman

Prof. P. Pagni presented a report entitled, "Diffusion Flame Analyses with Fire Safety Application." This was a clear review using classic diffusion flow studies to assess the potential fire hazard of synthetic polymers in fire. Flame heights produced by various materials were shown to depend primarily on the mass consumption number, r, and secondarily on the mass transfer number, B, when using an approximate quasi-steady model for laminar diffusion flames. This emphasis on the mass consumption number is new.

Mr. Y. Hasemi presented an excellent condensed review of the manuscripts regarding recent advances in Japanese fire research including the mathematical modeling of fire (Tanaka, Matsushima), flashover as critical instatiblity (Takeda, Hasemi), the extinction of infrared radiation by smoke (Jin), the remote imaging of flames (Kawagoe), statistical view on flashover occurrence (Morishita), and criteria on simulated model experiments (Saito).

Prof. Emmons presented a report entitled, "Computer Fire Codes," an overview of the current status of the Harvard Fire Code, which emphasized the significance of numerical mathematical modeling in the practical prediction of fire.

The presentation of a report entitled, "Recent United States Progress in Mathematical Modeling of Fire Enclosure," was postponed to the afternoon session. Dr. R. Friedman gave a comprehensive review of the many computer programs in the United States which address components of the compartment fire problem.

REPORT ON TECHNICAL SESSION

SMOLDERING

R. Friedman, Chairman

Dr. T. Ohlemiller of the National Bureau of Standards, Center for Fire Research presented a survey paper entitled, "Modeling of Smoldering Combustion Propagation." He divided smoldering into various regimes, depending on low vs high permeability, and forward smoldering vs reverse smoldering (oxygen approaching from the burned vs the unburned side of the reaction zone). He discussed the significance of ratios of various characteristic lengths. He concluded that there is need for more study of the smoldering problem, and especially on transition to flaming combustion.

Prof. T. Handa of the Science University of Tokyo described work by himself and his colleagues (S. Yoshizawa, M. Moria, M. Fukuoka, H. Tsuhima, Y. Hashizume, and T. Nakamura), entitled, "Thermal Processes in the Smoldering of Wood." Wood samples were heated in various oxygen-containing environments. Measurements were made of weight loss, oxygen consumption, X-ray diffraction, viscoelastic properties, thermal analysis. In another series of tests, spheres of wood of various diameters were exposed to heat over long periods, and conditions for runaway thermal behavior were found. A collapse of the structure near 220°C was related to the kinetics of oxidations in the amorphous part of the wood. The tendency to thermal runaway was shown to be dependent on moisture content.

Following these papers, some general comments on modeling were made. Prof. Emmons of Harvard University made a point with regard to studies of flashover by making stability analyses of equations derived by assuming that the fire may be represented by a series of steady states at successive times. Quintiere, Thomas, and Hasemi have made such analyses. Emmons commented that his numerical solutions of the full set of time-dependent equations had not yet revealed any sudden transitions as suggested by the stability analyses, and recommended that an attempt be made to study more closely the relationship between the two modes of analysis.

After the modeling discussion, Prof. Handa described some work on "Current-Voltage Characteristics of Pt Dispersed SnO_2 Wafer," which is relevant to detection of various fire gases, including carbon monoxide, by a device which functions at room temperature.

RESOLUTIONS

RESOLUTIONS

The members of the UJNR Panel on Fire Research and Safety are very happy with the results of the Fifth Joint Panel Meeting held in Washington, D.C., October 15-24, 1980. The progress reports on the many topics of concern to fire safety were very instructive. The workshops on special topics held on Monday and Tuesday proved to be especially valuable for all participants. The limited topics in each of the simultaneous sessions together with the more informal atmosphere lead to more intimate and detailed exchange of information on the special topics.

The Panel Members herewith resolve:

1. That the next (6th) meeting of the UJNR Panel on Fire Research and Safety be held in Tokyo, Japan, for five working days in May 1982.

2. That the format of the meeting be as follows:

   a) The first two days be devoted to progress reports on all phases of fire safety: human behavior, fire modeling, toxicity, sprinklers, detectors, fire and smoke retardants, fire investigation techniques and building systems and smoke control.

   b) The next two and one-half days be devoted to workshops on building systems and smoke control, human behavior, fire modeling and toxicity with simultaneous sessions as appropriate.

   c) The last one-half day of closing session contain session reports, and adoption of resolutions.

3. That the meeting be held in several different laboratories on different days, but that all sessions on any one day be held all at one place.

4. That some cooperative fire research programs be started. These will be especially valuable where the facilities are somewhat different in our two countries.

5. That the working personnel exchange be pursued more vigorously. One NBS employee, Dr. Mulholland, spent a valuable month in Japan. The U.S. is looking forward to the visit of Dr. Tanaka for a year beginning in the near future. It is hoped that someone from the U.S. can be sent to Japan for an extended period of research in the not so distant future.

6. That the toxicity tests by mice (Japan) and rats (U.S.) be correlated by the testing by each country by their respective methods of common samples. This would perhaps be best done by each country submitting to the other for tests, samples of materials already tested in the home country.

7. That Panel Members be encouraged to exchange information of interest through the respective Chairmen between meetings. A few such exchanges occured during the past year, but there should have been many more. Reports should be submitted in the original language with an abstract in the other language.

8. That to improve communication during meetings, especially the first two days of formal progress reports, copies of all the relevant reports be sent in time to be received in the other country by one month ahead of the meeting.

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The Fifth 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, MD, from October 15 through 24, 1980. The meeting consisted of in-depth technical sessions on arson and fire investigation, toxicity of combustion products, advances in sprinkler technology, and fire modeling. Progress reports briefly covered fire retardance, building design, smoke control, human behaviors in fires, and fire protection. Two days of informal sessions were held on toxicity, human behavior, detection and smoke properties, sprinklers, smoldering, and fire modeling. This meeting was held in conjunction with the Center for Fire Research's Annual Conference which included United States presentations of related technical subjects. The proceedings include the technical papers presented at the UJNR meeting along with the ensuing discussion and the summary reports prepared by each session chairperson.

The first meeting of the UJNR Panel on Fire Research and Safety was held in Washington, DC, 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 resolved that the sixth meeting, to be held in Tokyo, would cover the following topics in-depth: (1) building systems and smoke control, (2) human behavior, (3) fire modeling, and (4) toxicity. Progress reports will be submitted in the areas of human behavior, fire modeling, toxicity, sprinklers, detectors, fire and smoke retardants, fire investigation techniques, and building systems and smoke control.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

arson; building design; combustion products; fire investigation; fire modeling; fire protection; human behavior; smoke control; smoldering; sprinkler systems; toxicity.

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