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NATIONAL BUREAU OF STANDARDS

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Fire Safety Research

Proceedings of a Symposium
Held at the National Bureau of Standards
Gaithersburg, Md., August 22, 1973

Mary Jo Butler and James A. Slater, Editors

Programmatic Center for Fire Research
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

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ABSTRACT

A Symposium on Fire Safety Research was held at the National Bureau of Standards (NBS), on August 22, 1973. The Symposium's participants were NBS staff as well as outside contributors affiliated with the NBS fire program including representatives from private industries, universities, government agencies, and the National Fire Protection Association. The papers covered topics in hazard analysis, standards development, flame chemistry, fire modeling, fire detection, physiological effects of fire, fire services, effect of fire on building materials, and field investigation methods for firefighters. Specifically included were papers dealing with the development of the Children's Sleepwear Flammability Standards and mandatory sampling plans, mechanisms of flame retardants, flame spread and radiant panel test methods, contribution of interior finish materials to fire growth, a field study of non fire-resistive multiple dwelling fires, the Research Applied to National Needs (RANN) Program of NSF, and other related topics.

Key words: Apparel fires; carbon monoxide; concrete beams; field investigation; FIFI; fire; fire buildup; fire detection; fire engines; fire growth; fire research; fire retardants; fire safety research; firefighter training; flame inhibition; flame spread; flames; flammable fabrics standards; hazard analysis; injury severity; interior finishes; mandatory standards; modeling; multiple dwelling fires; oxygen; physiological effects of fire; polymeric materials; radiant panel; RANN; red oak; smoke; standards; test methods; textile testing; thermal decomposition; toxic effects of fire.

Contents

WELCOME

Richard W. Roberts, Director
National Bureau of Standards, Washington, D.C.

Fire might be characterized as one of man's most important discoveries; it is also one of our most useful tools. We use it to heat our homes and our offices, to generate electricity, to power most forms of transportation, even though the bicycle is starting to make inroads, and we use it most in industrial processes. I think it is a fair statement to say that life as we know it today could not exist without fire; but along with all of these beneficial aspects of fire come some very serious side effects.

In 1971, 12,000 Americans were killed by fire and over 100,000 were desperately injured by fire-related accidents. Fire takes a tremendous economic toll in the United States. In fact, it is estimated that $2.8 billion worth of property damage occurred in 1971. Now to put these statistics in perhaps a little more concrete terms, this means that by tomorrow morning, there will be 1,500 families without a home because they suffered a fire.

The Bureau has been involved in fire research for a long period of time and I think has made many significant contributions. I think the program today will reveal many of these and perhaps point new directions for future activities.

INTRODUCTION

F. Karl Willenbrock, Director
Institute for Applied Technology
National Bureau of Standards, Washington, D.C.

The problem of destructive fire continues to plague our nation. Each year, at least 12,000 people are killed, many more seriously injured or crippled for life, and billions of dollars in property lost. The need for fire protection has become a public demand. We, at the National Bureau of Standards (NBS), believe that technology can provide the public with a more fire-safe environment, one that is more fail-safe to human carelessness.

For sixty years, NBS has conducted a building fire program which has provided the technical base for many fire safety codes and standards. In the past several years, however, NBS has acquired more responsibility for reducing fire losses. The Fire Research and Safety Act of 1968 greatly broadened the NBS authority. Under this legislation, NBS developed a more extensive fire program including technical support of the fire services. As a result of the 1967 amendment of the Flammable Fabrics Act, NBS, in 1968, established a flammable fabrics program and assisted in the development of a number of mandatory flammability standards such as carpets and rugs, children's sleepwear and mattresses. Although the responsibility for the development of standards under the Flammable Fabrics Act was reassigned to the Consumer Product Safety Commission by the Consumer Product Safety Act of 1972, this Act specifically directs the Commission to use NBS for research in fabric flammability and for technical assistance in developing product flammability standards. We are, therefore, working closely with the Commission in carrying out these responsibilities.

Our several fire activities are unified to assure integration of building fire safety, fire services, product flammability test development, fire research, and analysis of fire accident data. We have organized these activities into programs based on the chain of events which lead to fire losses, namely, exposure of ignitable material to an ignition source; ignition of the material; and spread of fire. To minimize fire losses, we must interrupt this chain of events. Therefore, our fire programs, which are aimed at breaking the fire chain at each juncture, consist of three major elements: fire prevention, fire control, and fire suppression; with foundation activities in research and hazard analysis. The foundation activities for these programs are based on understanding real world fire problems through analysis of fire accidents (hazard analysis activity) and through research on the physical characteristics of fire, to learn why and how fire hazards exist. These activities provide a sound basis for outputs to activities such as building fire codes, fabric flammability standards, and performance criteria for fire equipment.

Fire Prevention: Fire prevention is a prime area in which a major impact in saving human lives and property is possible. We have projects directed towards: encouraging the fire services to assist home owners in voluntary inspections; exploring new designs for common ignition sources, such as kitchen ranges, matches, and lighters; and providing the technical basis to the Consumer Product Safety Commission for mandatory national standards on the flammability of clothing and interior furnishings.

Fire Control: Fire control can be accomplished through reduction of fire loads in buildings, through early detection and suppression of fire, and through minimization of smoke and fire movement in burning buildings. NBS has received funding to conduct a nation-wide survey of fire loads in office buildings from which a representative picture of fire loads will be developed. Once the nature of these fire loads has been more accurately determined, we will be better able to design buildings that resist the spread of fire. In automatic fire control, NBS is emphasizing smoke detectors. We have analyzed many commercial smoke detectors and recommended design changes which some manufacturers have already incorporated, producing more effective fire detectors. We are also developing recommended performance criteria for residential detectors, and exploring new approaches to early detection of fire, as well as measuring unique fire signatures to reduce false alarms. The use of sprinklers in life safety applications for residences is being explored as a further extension of the automatic detection and control concept. In addition, we are developing design criteria and flammability tests for building materials and systems leading to viable building standards for fire-safe buildings. Under development are building design standards for smoke control based on the results of full scale tests on several multi-story buildings, fire safety standards for day care centers, and a new flammability test for carpets aimed at more fire-safe corridor exits.

Fire Suppression: Our fire suppression activities are in direct support of the fire services. We have tested the effectiveness of clothing and equipment for firefighters and discovered some inadequacies in protective coats, helmets, and ladders which may help reduce the dangers associated with firefighting which is one of the most dangerous of the professions. To help correct these inadequacies, we are developing performance specifications to aid firemen in selecting safe and effective equipment. We are also developing guides to enable optimum use and placement of firefighting resources, to balance specific local needs. We are also conducting a project to develop analytical tools with which a local fire chief can analyze the injuries his firefighters suffer. Based on this analysis, the Chief can decide how to modify his firefighting tactics, training, or equipment so as to reduce injuries.

Research: Research can provide valuable new solutions to old problems. The NBS approach is to work on those fire problems in which new knowledge in science and technology can make a contribution to saving lives and property. Our investigation of the chemistry and physics of combustion processes could lead to improved fire retardant materials or improved fire extinguishers. The exploration of the dynamics of fires could lead to improved fire detectors and fire-safe building design.

Hazard Analysis: Accurate accident data are needed on which to base our priorities and to monitor our progress. This information must be detailed enough so that its analysis can clearly indicate the cause of fires. We have, therefore, contracted for the design of a national fire loss data system which will collect data from various state and local sources to provide a true picture of the nature and causes of fire loss. As a model, the NBS Flammable Fabrics Accident Case and Testing System (FFACTS), which includes detailed data about thousands of fires involving fabrics, has guided priorities in the development of fabric flammability standards. What is the future of the fire programs at NBS? The report of the National Commission on Fire Prevention and Control, "America Burning," has resulted in the introduction of several legislative proposals in Congress for an expanded fire program. Recent hearings before the Subcommittee on Science, Research and Development of the House Committee on Science and Astronautics indicate that the Department of Commerce and NBS will be called upon to play a larger role in future fire safety programs. A new fire research laboratory is now under construction at the NBS Gaithersburg site. When completed, this laboratory will provide a modern facility for conducting large scale fire experiments. NBS is preparing for an expanded role in reducing the nation's fire losses.

The papers that follow appear in the order in which they were presented at the Symposium. May I take this opportunity to express my appreciation to the authors of these papers and other participants who contributed toward making the Symposium a success, to Dr. Radford Byerly who was instrumental in the direction and initiation of the Fire Safety Research Symposium, to Dr. Clayton Huggett who graciously accepted to host the Symposium, to Mrs. Sara Torrence and Mrs. Mary Jo Butler for their help with the coordination of the Symposium, and to Mr. James Slater and Mrs. Mary Jo Butler for editing and managing the production of the Proceedings. Special thanks is due to Mrs. Carol Thompson and Mrs. Evelyn Granger for their editorial and production skills.

NATIONAL BUREAU OF STANDARDS SPECIAL PUBLICATION 411, Fire Safety Research, Proceedings of a Symposium Held at NBS, Gaithersburg, Md., August 22, 1973, (Issued November 1974)

A COMPARISON BETWEEN POTENTIAL HAZARD REDUCTION FROM FABRIC FLAMMABILITY STANDARDS, IGNITION SOURCE IMPROVEMENT AND PUBLIC EDUCATION

Benjamin Buchbinder and Allan Vickers
National Bureau of Standards, Washington, D.C.

Mandatory standards have been and are being promulgated for flammable fabric item types (e.g., children's sleepwear, mattresses, upholstered furniture) to reduce the fire hazard inherent in the use of common ignition sources (e.g., matches, cigarettes, kitchen ranges). Trade-offs should be made between potential hazard reduction from fabric item standards and from design changes or improved quality control in ignition source fabrication. Public education is a third approach to the reduction of certain hazards.

Key words: Cigarettes; education; fabric; fire; flammability; hazard; ignition source; kitchen ranges; matches; mattresses; sleepwear; standards; upholstered furniture.

The hazard represented by fabric fire accidents may be studied from many points of view. In this paper we will look at the kinds of considerations involved in addressing the reduction of the fabric fire hazard by means of three approaches: fabric flammability standards, improved safety in ignition sources and effective public education.

First, our source of data, the Flammable Fabrics Accident Case and Testing System, which we call FFACTS, provides the data for fabric fire studies at the National Bureau of Standards' (NBS) Fire Technology Division. FFACTS is a computerized data base now containing 2,660 cases, rich in detail, with over 130 data elements for each case. These data are derived from detailed case history investigations of fabric fire accidents, performed largely by Consumer Product Safety Commission contractors and Food and Drug Administration field investigators, augmented by laboratory analysis, at NBS, of fabric samples submitted with the reports. The detailed data in FFACTS permit the identification of patterns of accident parameters which define different accident types. These parameters encompass both fire characteristics and human involvement.

In this paper, four FFACTS data elements have been used, namely fabric item first to ignite, ignition source, age of victim and sex of victim, to examine the kinds of considerations inherent in choosing a course of action for hazard reduction.

Other Fire Technology Division studies encompass additional FFACTS data elements including victim's activity prior to ignition and reaction after ignition, injury and economic loss and test data from fabric sample laboratory analysis. The purposes of these studies range from the development of hazard related test methods for flammability standards to an investigation of the causal relationship of human activities to injury severity.

In order to discuss the pros and cons of the three approaches to hazard reduction, let us first define several hazards in terms of our four data elements. For purposes of this discussion, a hazard is defined as a combination of ignition source, human involvement and flammable material with a high probability of injury.

Table 1, based on the data base level of 1,964 cases, shows the number of cases in FFACTS for which sleepwear, shirts and blouses and upholstered furniture were the first fabric item types to ignite. (This "first-to-ignite" criterion is useful in determining the most important item involved in a fire accident, when more than one fabric item is involved.) The incidence of sleepwear cases was primarily among females, the shirt/blouse category incidence was

Table 1. Incidence of FFACTS[a] Cases For Selected Item Types (First-to-Ignite), By Sex of Victim

Item Type	Number of Cases		
	Male	Female	Total
Sleepwear	79	253	332
Shirts/Blouses.	193	49	242
Upholstered Furniture . . .	52	57	126[b]

[a]Based on a data base of 1,964 cases.
[b]Total includes 17 cases with sex of victim unknown or not applicable.

primarily male; and both sexes were involved almost equally in upholstered furniture cases. Table 2 shows the number of cases in FFACTS for which matches, cigarettes, cigars and pipes, kitchen ranges, and open fires were the ignition sources. Matches and cigarettes involved both sexes, kitchen ranges involved more females, and open fires involved more males. Neither the item type/sex classification of incidents such as in table 1 nor the ignition source/sex classification of table 2 is sufficient for our hazard definitions.

Table 2. Incidence of FFACTS[a] Cases For Selected Ignition Sources By Sex of Victim, Where Item First to Ignite Is Known

Ignition Source	Number of Cases		
	Male	Female	Total
Matches	145	124	269
Cigarettes, Cigars & Pipes.	123	117	240
Kitchen Ranges.	78	204	282
Open Fires.	99	40	139

[a]Based on a data base of 1,964 cases.

The categories of table 3 further define hazards by a cross tabulation of numbers of cases by item type and ignition source. Sex is used to modify the item type classification only where the involvement of that item is primarily for one sex. Age is introduced in the first two item type classes, to more specifically define particular problem areas. For our purposes today, the data in table 3 are adequate to provide examples of hazards. We will return to these data to discuss seven different hazards and the potential effectiveness of item type flammability standards, ignition source safety improvement and public education in addressing them. First, let us define generalized criteria for assessing the potential effectiveness of each remedial approach, in terms of a series of questions. These questions fall into three categories -- state-of-the-art, public acceptance and protection of some at the expense of others -- and these questions will be addressed relative to each of our three approaches in turn.

First, for fabric item flammability standards:

Does state-of-the-art technology permit the development of flame retardant material, and does potential industry capacity exist for production of sufficient material?

Will the properties and the cost of the new product meet public acceptance? (If not, will public rejection in favor of homemade items or substitutes counter the intent of the standard?)

Does the standard protect one group at the expense of others?

Table 3. Incidence of FFACTS Cases By Item Type First to Ignite and Ignition Source

Item Type	Ignition Source					
	Match	Cigarette[a]	Range	Open Fire	Other	Total
Female Sleepwear (21+)[b]. . .	25	-	54	4	46	129
Children's Sleepwear (0-12)[b]	46	-	60	12	47	165
Dresses (Female)[b].	22	-	30	7	34	93
Shirts (Male)[b]	46	-	36	32	79	193
Pants (Male)[b].	15	-	5	29	33	82
Upholstered Furniture. . . .	5	94	-	-	27	126
Mattresses and Pads.	10	38	1	-	16	65
Others	100	108	96	55	171	530
Total.	269	240	282	139	453	1,383

[a]Includes cigars and pipes.
[b]This item type primarily involved a specific age group or sex. Only the indicated data have been included to more specifically identify the particular hazard.

Improvements in ignition source safety may be made in production quality control to reduce the incidence of defective products, and in product re-design to reduce the hazard inherent in its normal use (or misuse). In terms of the three categories above, we ask relative to ignition source safety improvement:

Does state-of-the-art technology permit enough improvement to be made to significantly reduce the hazard, and will the changes impair the primary function of the product or inadvertently introduce new safety hazards?

Can the changes be made within the constraints of cost and public acceptance?

Will the changes protect one group at the expense of others?

Public education does not require increased industrial capacity or tradeoffs between safety and product performance. However, we ask:

Is the state-of-the-art in educational programs adequate both to reach the intended audiences and to significantly influence behavior?

Is education cost effective?

Returning to table 3, let us examine in turn the hazards represented by adult female sleepwear, male shirts and pants, female dresses, upholstered furniture, mattresses, kitchen ranges, and cigarettes. They were chosen to illustrate the potential effectiveness of the three approaches to hazard reduction, rather than necessarily to reflect the greatest hazards.

First, consider hazards potentially addressable by item type standards. The hazards related to upholstered furniture and mattresses are suggested for this category, for the following reasons:

1. State-of-the-art technology permits the development of the required materials.

2. Although a single ignition source category, cigarettes, cigars and pipes, is involved in 75 percent of upholstered furniture cases and 59 percent of mattress ignitions, it is not likely that improved safety in these ignition sources can easily be obtained.

3. Looking at the cigarette column of table 3 we see that 94 plus 38, or 132 cigarette ignitions, 55 percent of the total of 240 cases, involved the two item types, upholstered furniture and mattresses. This indicates that these two item type standards would also address 55 percent of a major ignition source hazard.

Second, let us consider hazards addressable by improved safety in ignition sources. There are two categories of item types in table 3 which present hazards not directly addressable by item type standards. Adult female sleepwear is the first item type. Non-flammable material is not at present available in sufficient quantity to produce flame resistant sleepwear for all adult women. The hazard is most severe for elderly women, but unlike the situation with regard to children's sleepwear, there is no size difference to permit a distinction to be made between elderly female sleepwear and other adult female sleepwear. Even if sufficient fabric were available for an overall female sleepwear standard, a large portion of the population would be unnecessarily subjected to the higher cost and changed product characteristics of flame resistant sleepwear. The second item type not directly addressable by an item type standard is dresses, for similar reasons. It appears that the improvement of safety in kitchen ranges offers good potential for the reduction of kitchen range accidents in general (20 percent of all first-to-ignite cases involve ranges), and for the reduction of the adult female sleepwear and dress hazards as well. Table 3 shows that 54 adult female sleepwear cases (42 percent of the total) and 30 dress cases (32 percent of the total for dresses) involve ranges.

Finally, consider hazards partially addressable by public education. The hazard represented by male shirt and pants ignitions is at present not completely addressable by either item type standards or improved ignition source safety, for the following reasons:

1. Of the 193 cases in which male shirts were first to ignite 135 (70 percent) involved males age 16 and older. This indicates that the shirt fire hazard is largely an adult problem, and at present sufficient flame resistant shirt fabric is not available.

2. Even if technological considerations permitted a standard to be promulgated, a large portion of the hazard would not be addressed. This is because the fabric fire hazard to adult males is strongly related to flammable liquid involvement. Forty-four percent of male shirt and pants ignitions involved flammable liquids. Even a flame retardant fabric will support combustion if it is soaked in gasoline.

3. There are many ignition sources involved with shirt and pants ignitions; therefore, improved ignition source safety would require effort in many areas.

For these reasons, public education should be explored, perhaps in concert with the other two approaches, to fully address the male shirt and pants hazard.

The examples given above are intended to illustrate the complexity of the fabric flammability problem. The item type standards now in force and in various stages of development address obvious hazards. The voluntary actions of the kitchen range and book match industries, which are currently considering ways to make their products safer, address another segment of the problem. Public education is a third approach which should be explored, because the magnitude and complexity of flammable fabric hazards make it necessary to use all available approaches to reduce these hazards.

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DEVELOPMENT OF THE STANDARDS FOR THE FLAMMABILITY OF CHILDREN'S SLEEPWEAR

Emil Braun, James H. Winger and James A. Slater
National Bureau of Standards, Washington, D.C.

The general methodology used in the development of a mandatory flammability Standard is presented. An illustrative summary is given of the hazard analysis of the accident data and the subsequent test development and laboratory investigations conducted in the development of the children's sleepwear flammability standards (DOC FF-3-71 and DOC PFF-5-73). Some of the problems encountered in the development of a mandatory standard and the resolution of those problems are discussed.

Key words: Children; flammable fabrics; sleepwear; standards development; statistics.

1. INTRODUCTION

In 1967, Congress issued amendments to the 1953 Flammable Fabrics Act [1] that directed the Secretary of Commerce[1] to issue mandatory standards for limiting the flammability of fabrics, wearing apparel, and interior furnishings in those areas where "unreasonable risk" has been shown to exist. The act further stipulated that all standards must be reasonable, appropriate, and technologically practicable. In an effort to insure that standards comply with these criteria, they must logically be developed from a careful study of accident data and laboratory experiments. The end product of this study is a mandatory flammability standard that removes "unreasonable risk" from the market place.

Flammability standards are a synthesis of three distinct elements. First, there is the basic test method that must, as far as possible, relate small scale performance to real world performance. Then there is the acceptance criterion that sets the level of performance desired; and, finally, a sampling plan that insures that an allowable level of statistical risk to the consumer is not exceeded. In this paper we will concern ourselves only with the development of the first two points - the test method and the superimposed acceptance criterion.

The Proposed Children's Sleepwear Standard [2] for ages 6-12 years old, and the manner in which it differs from the Children's Sleepwear Standard [3] for ages 0-5 years old will provide illustrative examples of the evolutionary history of a test method and the acceptance criterion that form the foundation upon which a mandatory flammability standard is built. These standards will also serve to illustrate the direct relationship between the analysis of accident statistics and the finding of need for a standard, its scope, and the appropriateness of the test method employed.

2. TEST METHOD

A flammability test method is effectively determined by specifying four interrelated parameters: the variable to be measured, the source of ignition, the specimen configuration, and the preparation of the specimen prior to testing. Each item must be carefully defined so that the end result is a test that is repeatable and reproducible, as determined by an interlaboratory evaluation, and that reflects real life performance as far as is consistent with the requirements of a practical test method.

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[1]The Consumer Product Safety Act of 1972 has since transferred the standards setting responsibilities to the Consumer Product Safety Commission effective May 14, 1973.

2.1. Variable to Be Measured

There are several different variables that can be used to describe the relative degree of the flammability of a fabric. One could measure the time to ignition, the burn rate, or both simultaneously - as is done in CS-191-53 (Flammability Standard For General Wearing Apparel). The tendency of a fabric to self-extinguish before it is consumed could also be measured or the rate of heat transfer to a known substrate. Procedures have already been developed to measure any one of these variables. The question that first must be answered is which procedure is appropriate for children's sleepwear?

Accident data[2] [4], tables 1 and 2, indicate that children between 0 and 12 years old are more prone to flammable sleepwear injuries than any other age group. Table 1 is a percentage breakdown of all sleepwear cases in the National Bureau of Standards' Flammable Fabrics Accident Case and Testing System (FFACTS) [5]. Table 2 is a normalization of table 1 based on the actual percentage of the population [6] represented by each age group. Table 2 shows tha as a subtotal of the entire U.S. population, children 0 to 5 years old and 6 to 12 years old are found in the data base far in excess of what would be expected from population figures - 2.7 and 1.7 times, respectively. From this information along with data from other sources [4], it was concluded that children under age 13 are exposed to sleepwear fires more frequently than other segments of the population or are less capable of correctly initiating a protective reaction at the first sign of danger.

Table 1. Age and Sex Distribution of Persons Involved in All FFACTS First-to-Ignite Uncontaminated Sleepwear Incidents

Age	Female (%)	Male (%)	Total (%)
0-5	16	11	27
6-12	19	5	24
13-20	3	1	5[a]
21-45	12	1	13
46-65	13	2	15
66+	13	3	16
Total	76	24[a]	100

[a]Independently rounded.

Table 2. Ratios of Persons Involved in FFACTS Sleepwear Incidents[a] to Corresponding U.S. Population Totals By Age Group

Age	Female	Male	Total
0-5	3.2	2.2	2.7
6-12	2.7	0.7	1.7
13-20	0.4	0.1	0.3
21-45	0.8	0.1	0.4
46-65	1.3	0.2	0.8
66+	2.2	0.8	1.6

[a]For incidents in which a fabric item involved was the first item ignited and was not contaminated by flammable liquids.

[2]Accident statistics are based on a FFACTS data file containing 1,964 cases.

In addition, full scale mannequin studies of fabrics similar to those found in FFACTS, have shown that massive involvement of a child's garment occurs very rapidly - on the order of 20-30 seconds after ignition. This, of course, should have a direct bearing on the appropriateness of a test method and its ability to protect against the hazards for which the test is supposedly designed.

The measured variable in a test must be one that provides maximum protection in order to significantly reduce deaths and injuries. The requirement of maximum protection immediately eliminates burn rate and rate of heat transfer to the body as possible alternatives for test methods. Both of these variables implicitly assume that, given a finite amount of time, the victim can rapidly extinguish or remove a burning garment. Research has also removed ignition time as a viable alternative. It has been shown that ignition of a fabric usually occurs before the wearer experiences thermal pain [7].

It follows from the concept of maximum protection that the use of a test that measures a fabric's ability to self-extinguish is the only appropriate selection. This insures that thermal injury is minimized and that it is independent of the reactions of an individual on encountering a source of ignition.

2.2. Source of Ignition

A review of available test procedures indicates that there exist several test methods for flame retardant fabrics. They all rate a fabric's ability to self-extinguish by measuring afterflame and/or char length. Afterflame refers to the time of flaming on the fabric after the burner has been removed, while char length refers to the extent of the damage that has occurred on the fabric, as measured by a tear test.

Since all existing tests (table 3) employ a Bunsen or Tirrell type of burner as the heat source with a variety of gases for the fuel, one could easily select a similar heat source without providing any rational motivation. However, this would violate the requirement that the test relate to real life performance. Therefore, it becomes necessary to investigate accident data in order to justify the use of an open flame.

Table 3. Partial List of Requirements of Vertical Flammability Tests

Test Method	Sample Size	Conditioning	Ignition Time
ASTM D 626-55T	2" x 12-1/2"	16 hrs @ 70°F 65% RH	12 sec
AATCC 34-1966	2-3/4" x 10"	8 hrs @ 70°F 65% RH	12 sec
Fed. Spec. CCC-T-191B Method 5903	2-3/4" x 12"	4 hrs @ 70°F 65% RH	12 sec
NFPA 701 Small Scale	2-3/4" x 10"	1 to 1-1/2 hrs. @ 140-145°F	12 sec
Underwriters Laboratory 214-1969	2-3/4" x 10"	1 to 1-1/2 hrs. @ 140-145°F	12 sec

For example, table 4, which is extracted from FFACTS [4], is a listing of the major sources of ignition that children 6-12 years old have encountered while wearing sleepwear. Almost 50 percent of the incidents reported involved electric or gas kitchen ranges. This is followed by matches and heaters, with approximately 17 percent and 16 percent, respectively. Tabulation of the heat sources - open flame, glowing surface, etc. - is shown in table 5. The mode of heat transfer most frequently experienced in real life situations should be simulated in some manner in a test method. Since approximately 65 percent of the reported cases were the result of an exposure to an open flame, the selection of a Bunsen type of burner is justifiable. This is in contrast to the case of mattresses [8] where the typical mode of heat transfer is a smoldering ignition (e.g. a cigarette). The selection of a cigarette as the ignition source for the children's sleepwear standards is as inappropriate as the selection of an open flame ignition is for mattresses.

Table 4. Sources of Ignition For First-to-Ignite Uncontaminated Sleepwear Worn By Children Ages 6-12[a]

Ignition Source	Pajamas		Nightgowns		Robes		All Sleepwear
	Male	Female	Male	Female	Male	Female	
Kitchen Range	5	22	-	9	1	1	38
Match/Lighter	4	1	-	6	-	2	13
Heater/Furnace	2	1	-	9	-	-	12
Open Fire	1	1	1	5	1	-	9
Candle/Lantern	1	2	-	1	-	1	5
Total	13	27	1	30	2	4	77

[a]Source: FFACTS.

Table 5. Mode of Heat Transfer For First-to-Ignite Uncontaminated Sleepwear Worn By Children Ages 6-12[a]

Heat Transfer Mechanism	Pajamas		Nightgowns		Robes		All Sleepwear
	Male	Female	Male	Female	Male	Female	
Open Flame	6	16	1	20	2	4	49
Glowing Surface	4	10	-	5	-	-	19
Spark	1	1	-	1	-	-	3
Radiant Heat	1	-	-	1	-	-	2
Unknown	1	-	-	3	-	-	4
Total	13	27	1	30	2	4	77

[a]Source: FFACTS.

In both DOC FF-3-71 and the Proposed Flammability Standard for Children's Sleepwear 7-14, methane was selected as the standard fuel for the test burner on the basis that it is the gas closest to that presently used in homes.

The ignition source is not completely defined until the duration of flame application has been specified. As can be seen in table 3, the traditional duration of flame impingement is 12 seconds. During a preliminary investigation of the effects of flame impingement time on char length, it was found that longer impingement time did not necessarily produce correspondingly longer char lengths. McCarter [9] has shown that for some marginally treated cottons longer char lengths were produced at relatively short exposure times as compared to tests conducted at longer exposure times. Figure 1 shows the effect of flame impingement over a range of exposure times on a marginally treated cotton fabric and a well treated cotton fabric. The well treated fabric ex-

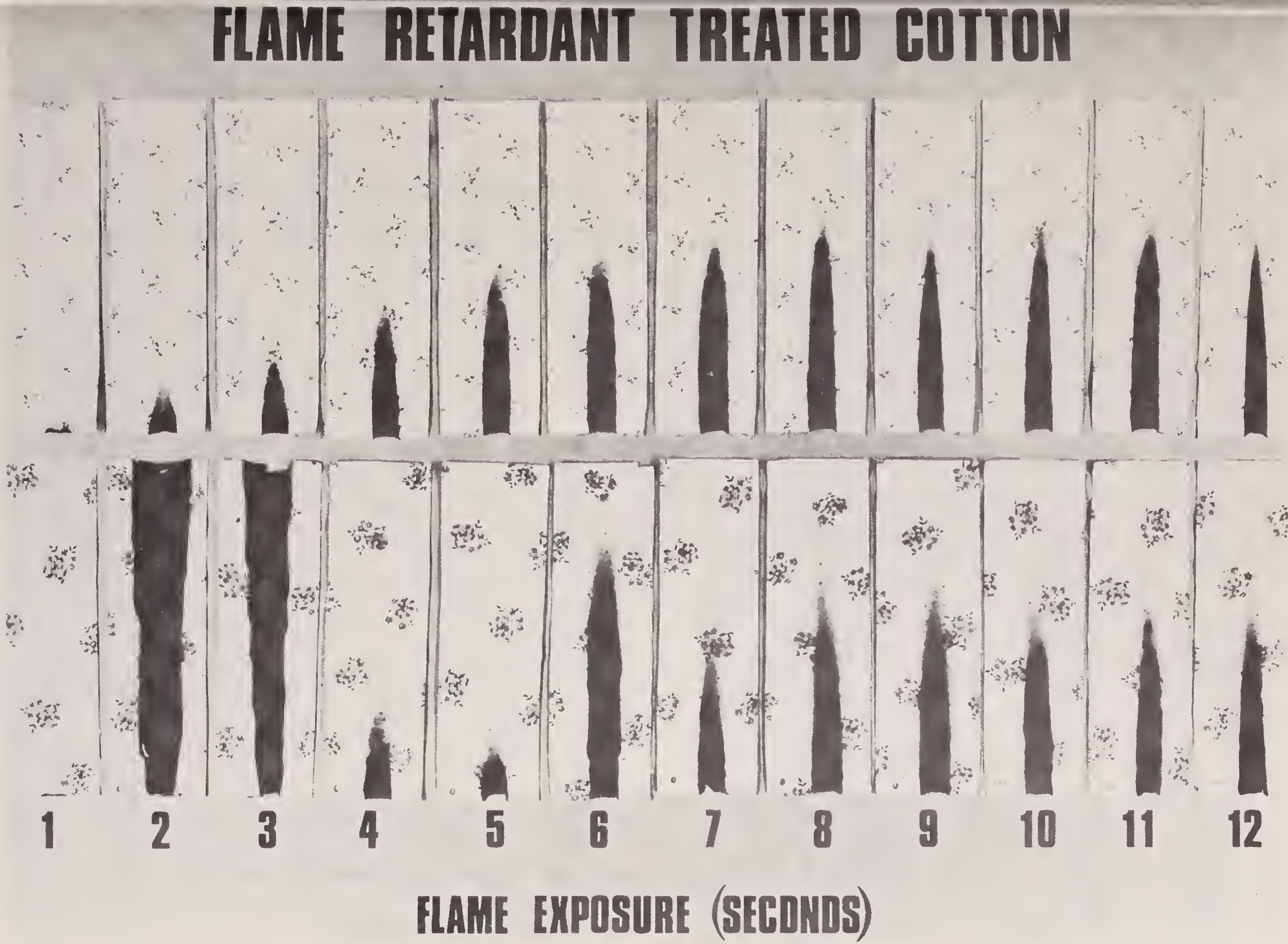

Figure 1. The effect of impingement time on char length for a well treated (top) and marginally treated (bottom) cotton.

hibits char lengths that become progressively longer with increasing flame impingement time until an upper limit is reached. However, the char length of the marginal fabric is shorter for 12 than for 3 second exposures. This behavior is accounted for by postulating the occurrence of oxygen partitioning between the fabric and the burner flame. That is to say, the flame from the test burner decreases the concentration of oxygen in the fabric's combustion zone. If the concentration of oxygen falls below a minimum value required for self-sustained burning, the fabric self-extinguishes.

Consequently, the use of a double exposure time was prescribed in the Proposed Standard For the Flammability of Children's Sleepwear 0-6X [10] - a 3 second application of the burner flame followed by a 12 second impingement of the burner flame. However, subsequent testing revealed that of all fabrics tested only thermoplastic fabrics would pass a 3 second impingement and fail a 12 second impingement of the burner flame. It was observed that the failure of the thermoplastic fabric at 12 seconds was not accompanied by any flaming. It was also noted that the resultant char length for a thermoplastic fabric was a function of fabric weight and flame exposure time. Figure 2 shows the test results of a series of nylon fabrics exposed to a 3 second flame and a 3 plus 12 second flame, as described in the proposed standard. The effect of the increased time was to simply shift the line upwards. Based to a large extent on a subjective appraisal of the relatively low hazard associated with a melting but not flaming thermoplastic, the 12 second exposure was deleted from the final standard for children's sleepwear sizes 0-6X.

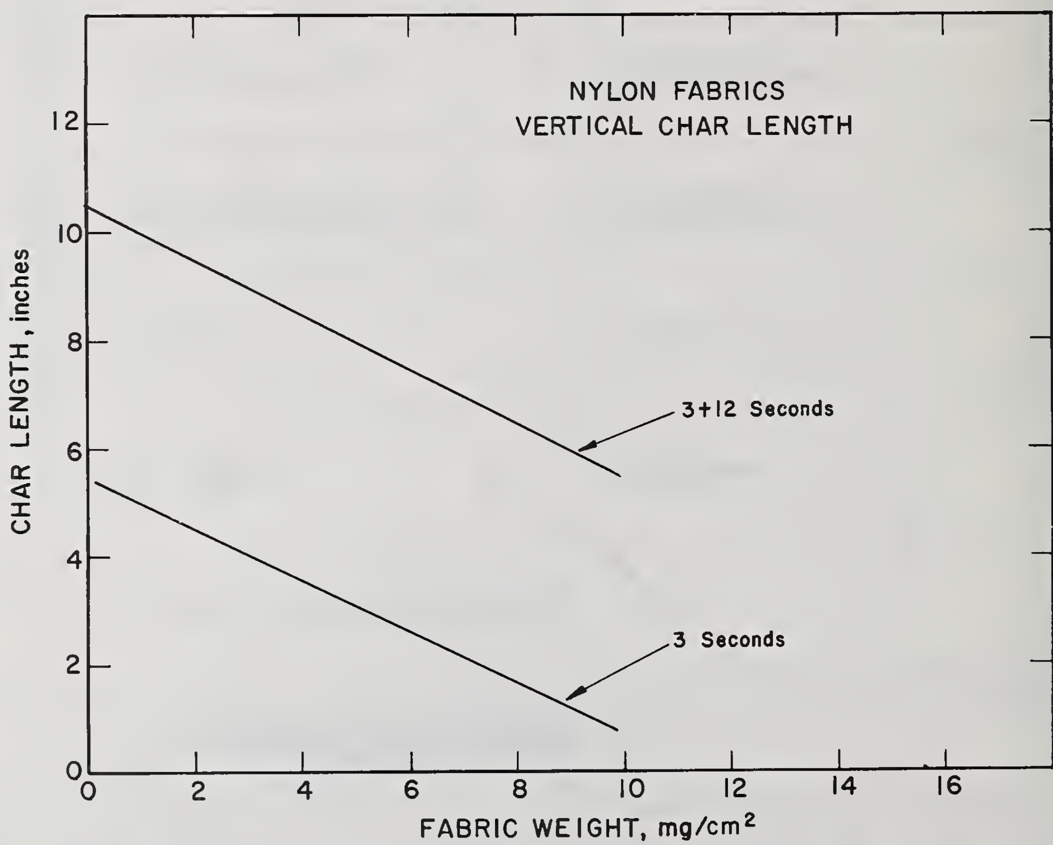

Figure 2. The effect of impingement time on vertical char length for nylon fabrics.

2.3. Specimen Configuration

Flammability tests have been developed that measure some property that can be related to a material's "inherent" hazard. These tests are conducted with the specimen held at various angles and with specimens of various sizes, depending upon the test specification.

The angle has been varied from the horizontal (0°), as in the Department of Transportation test (MVSS No. 302), to the vertical (90°) with other often used angles of 30°, 45° and 60°. Test specimen size has also been varied from a small two-inch circle used in some ignition tests to a 6 inch x 16 inch specimen used in a new vertical test under consideration by ASTM (semi-restraint test).

Because of a desire to provide maximum protection to children of ages 0-5, the most vulnerable age group, the decision was made to use a vertical orientation with ignition at the lower edge of the specimen.

The effect of specimen width on average char length was studied for a 2 inch and a 4 inch specimen width. Figure 3 shows a least squares fit of the data from tests conducted in the equipment described in DOC FF-3-71. If specimen width did not affect char length results (an ideal situation where experimental and material variability were zero), the fitted line would have a slope of 1. The actual regression line shown has a slope of 1.051. Introducing test and material error, one can see that specimen width does not affect char length (at a 95% level of significance). The specimen length was also investigated in the same manner and also indicated no significant effect on test results. Based on these results the exposed specimen size was established to be 2 inches by 10 inches.

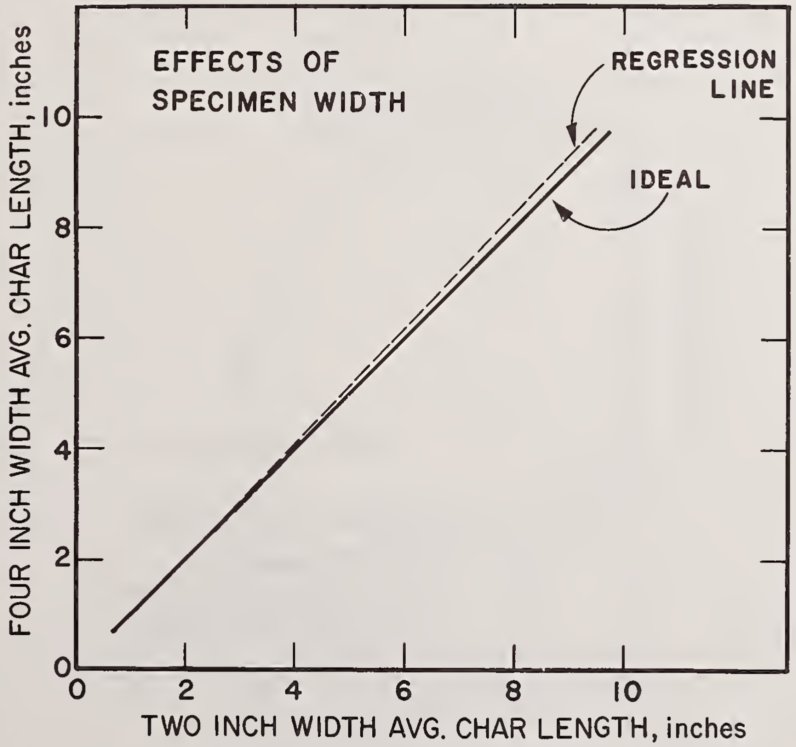

Figure 3. A comparison of char lengths obtained at two specimen widths.

2.4. Specimen Preparation

As can be seen in table 3 the conditioning specifications for vertical test methods have generally required that the specimen be placed in an atmosphere set at 65% RH and 70°F, the standard textile testing conditions. This, however, does not correspond to realistic end use conditions. It is, of course, impossible as well as unnecessary to duplicate the test under all possible conditions. If one is attempting to provide the maximum attainable protection, which is the case with children's sleepwear, then one need only determine the most hazardous conditions and measure the flammability of fabrics that are exposed to a heat source under these conditions.

A second factor not previously considered, but forced upon us by the above results, concerns test reproducibility (i.e. agreement between laboratories). Figure 4 [11] shows that, if testing were done in different laboratories under different humidity conditions, the agreement between laboratories would be poor for some fabrics. This phenomenon could present both technical problems, in the form of disagreement between seller and purchaser, and possible legal problems, in the form of enforceability.

The latter requirement, reproducibility, precludes the use of a range of conditions within which testing can be done. It forces the selection of a given humidity condition under which the test shall be performed. The former requirement, maximum protection, imposes the need for the selection of the most hazardous conditions. This leads one to the selection of "bone dry" specimens (oven dried at 105°C and cooled in a desiccator) as a reasonable conditioning requirement.

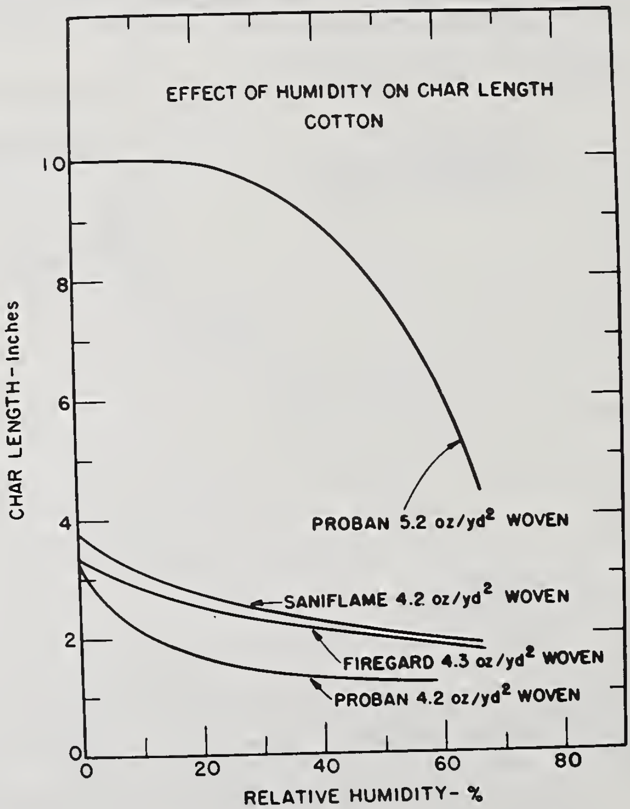

Figure 4. The effect of humidity on char length for several treated cotton fabrics.

3. ACCEPTANCE CRITERION

As mentioned earlier, the acceptance criterion sets the level of performance that is desired within the context of the test method. Irrespective of the measured variable, the level of performance chosen must meet the test of technological practicability. This means that industry must be capable of producing flame retardant goods and that these goods be acceptable to the consumer.

In the case of children's sleepwear, this requires knowledge of the performance in the vertical flammability test of available flame retardant treatments and/or in making flame retardant fabrics that are suitable for use in this segment of the textile industry. During the early stages of the development of DOC FF-3-71 the availability of materials with satisfactory vertical flammability performance was limited to specialty end uses, predominantly for the military. However, sufficient research and development had been completed to make possible the marketing of a small quantity of flame retardant cellulosic children's sleepwear. Based on the performance of these pre-market and market materials in the vertical test, a char length criterion was developed.

Figure 5 shows the results of tests performed on readily available fabrics that exhibited self-extinguishing properties. The histogram indicates that, of the materials tested, an average char length greater than 7 inches tended to result in complete specimen burns (specimen length is 10 inches), while the mean of all the average char lengths less than 7 inches was approximately 3.5 inches. Therefore, the selection of 7 inches as the char length criterion appears reasonable and technologically practicable.

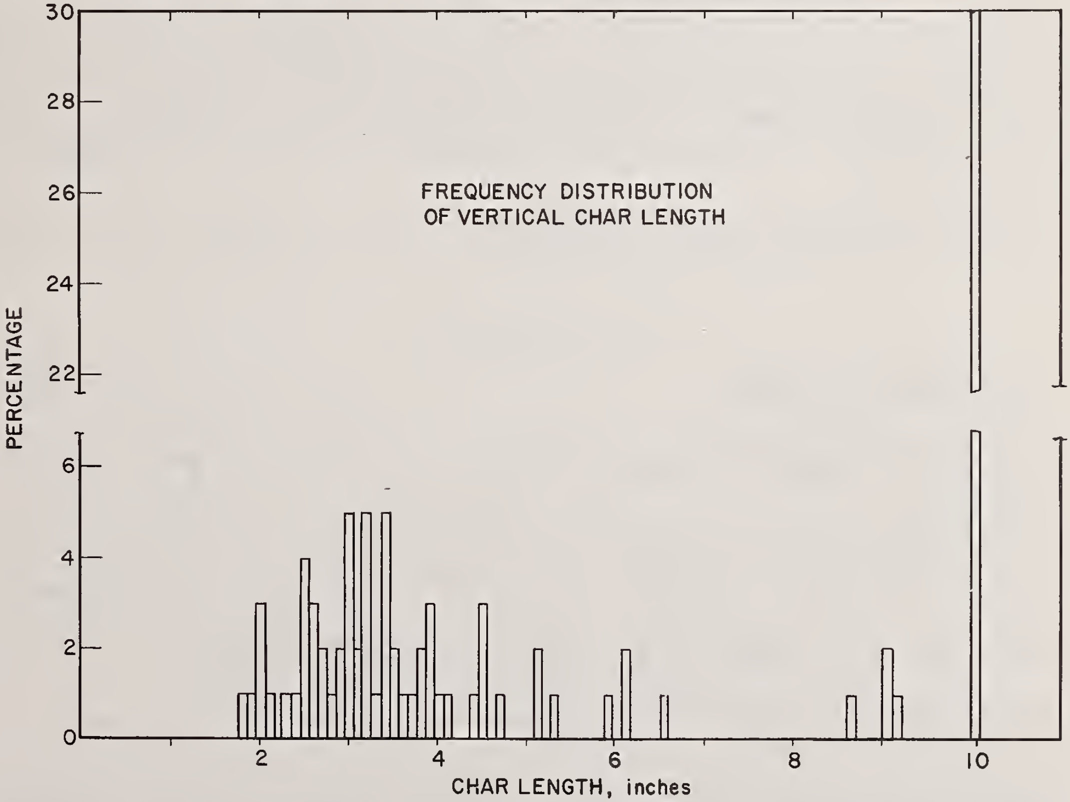

Figure 5. A histogram showing the distribution of average char length for a group of fabrics tested in the vertical test.

A criterion (referred to as "residual flame time") was developed for molten material that continued to burn on the floor of the test cabinet, limiting burn times of such material to 10 seconds. This was incorporated in the standard for children of ages 0-5 years (sizes 0-6X), because it was noted that flaming material falling from a garment represented two additional risk factors. The potential existed for the falling material to cause relatively deep localized burns and increased the likelihood of secondary ignition of other materials thereby increasing the extent of injury. However, there is a difference between hazard and an unreasonable risk. These flaming drips can be considered an unreasonable risk to children that are relatively immobile (i.e. sizes 0-6X covered by DOC FF-3-71), but are less of a risk to older more mobile children (i.e. sizes 7-14).

The proposed acceptance criteria for children's sleepwear sizes 7-14, therefore, differ from the criteria found in DOC FF-3-71. For children's sleepwear sizes 7-14 (PFF-5-73), the residual flame time criterion is deleted. In DOC FF-3-71, the most critical criterion is that the average char length shall not exceed 7 inches for a set of 5 replicate specimens. Secondary criteria are that no single specimen have a char length of 10 inches (specimen size: 3.5" X 10") and that no single specimen exceed the 10 second limit on residual flame time. The latter two criteria are secondary only in that a failure of average char length results in a unit rejection under the accompanying sampling plan. The same is not true of the single specimen criterion, which allows for sample retesting before unit rejection occurs.

4. CONCLUSIONS

A description of the methodology used in developing the children's sleepwear standards clearly establishes the need for a synthesis between accident data and laboratory experimentation. The basic approach taken has application in areas other than flammability. Any consumer oriented product safety standard must consider the best available end use and accident data and, at the same time, represent state-of-the-art technology with regard to repeatability and reproducibility.

The continued surveillance of accidents should, in several years, indicate the success or failure of this approach.

5. REFERENCES

[1] The Flammable Fabrics Act, 81 Stat. 568, 15 U.S.C. 1191, as amended and revised Dec. 14, 1967.

[2] Children's Sleepwear Sizes 7 Through 14, Notice of Proposed Flammability Standard, DOC PFF-5-73, Federal Register, 38, no. 47 (Mar. 12, 1973), 6700-6710.

[3] The Standard For the Flammability of Children's Sleepwear, DOC FF-3-71, Federal Register, 37, no. 141 (July 21, 1972), 14624-14632 (Revised).

[4] Slater, J. A., Fire Incidents Involving Sleepwear Worn By Children Ages 6-12, Nat. Bur. Stand. (U.S.), Tech. Note 810 (Dec. 1973).

[5] The Flammable Fabrics Program 1970, Nat. Bur. Stand. (U.S.), Tech. Note 596 (Sept. 1971), 28.

[6] U. S. Bureau of the Census, 1960 Census of Population, United States, General Population Characteristics, Advance Report, PC(V2)-1 (Feb. 1971).

[7] Heskestad, G., Kalelkar, A. S., and Kung, H. C., A Study of Pre-ignition Heat Transfer Through a Fabric-Skin System Subjected to a Heat Source - Annual Report, (Factory Mutual Research Corporation), Dec. 1971.

[8] Mattresses, Notice of Finding that a Flammability Standard May Be Needed, Federal Register, 35, no. 112 (June 10, 1970), 8944-8945.

[9] McCarter, R. J., The Cause of Anomalous Behavior in the Vertical Flammability Test, Textile Chemist and Colorist, 4, no. 4 (Apr. 1972).

[10] Proposed Standard For the Flammability of Children's Sleepwear, DOC PFF-3-70, Federal Register, 35, no. 223 (Nov. 17, 1970), 17670-17673.

[11] The Flammable Fabrics Program 1971, Nat. Bur. Stand. (U.S.), Tech. Note 749 (Dec. 1972), 62.

NATIONAL BUREAU OF STANDARDS SPECIAL PUBLICATION 411, Fire Safety Research, Proceedings of a Symposium Held at NBS, Gaithersburg, Md., August 22, 1973, (Issued November 1974)

SAMPLING PLANS IN MANDATORY STANDARDS

Paul Gottfried[1]
Consumer Product Safety Commission, Washington, D.C.

The Children's Sleepwear Standard for sizes 0-6X provides an example of the necessary interplay between sampling theory, industry capabilities and consumer safety assurance. The sampling plan imposes requirements for the fabric, for garment design and for garment production. These requirements address the differences between hazards due to design and those due to production errors. The requirements also interact to provide improved assurance of safety by limiting the potential for severe injury.

Key words: Flammable fabrics; product safety; sampling; standards.

1. THE NEED FOR SAMPLING

The Flammable Fabrics Act and other product safety legislation administered by the Consumer Product Safety Commission do not in themselves require product testing; they require only that products comply with applicable standards developed under such legislative authority.

In the past, standards have been enforced on the basis of compliance testing done by a regulatory agency. A failure discovered by the agency would result in an action against the manufacturer or his product, causing him to cease production of that particular product and withdraw that product from the market. Under such procedures, it is commonly found that failures are not detected until large quantities of the product are in the hands of retailers and and consuming public. Demands for "one hundred percent compliance" in this "post-mortem mode" can protect the consumer only after the fact and can cause severe hardship to manufactuers as well.

A more satisfactory way of protecting the consumer and limiting the risk to be accepted by the honest manufacturer is to require testing prior to marketing. When defective products are prevented from reaching the market, the consumer is protected more effectively and the risks and costs of product recall are decreased. At the same time, the amount of testing that can be done is increased because industry resources as well as Commission resources can be put to use.

When testing is destructive in nature, as it generally must be in the flammability context, it obviously is necessary to resort to sampling. Even in other situations, sampling may be the preferred approach because one hundred percent inspection can be prohibitively expensive. Furthermore, one hundred percent inspection is generally found to be much less than one hundred percent effective; effectiveness on the order of 70 to 80 percent is observed commonly. Finally, any regulatory agency is inherently limited to sampling; it could not obtain all of each product even if that were permitted by its resources.

2. EFFECTIVENESS OF SAMPLING

Few, if any, manufacturing processes are capable of turning out a consistently perfect product, just as few, if any, test procedures yield results of absolute accuracy and reproducibility. Sampling has similar limitations, and these arise from theory as well as from reality. Every sampling plan carries

[1]The author was a consultant to the Consumer Product Safety Commission at the time this paper was presented. The opinions expressed are those of the author and do not necessarily reflect the views of the Commission.

with it a finite probability of accepting a "bad" lot of products and of rejecting a "good" lot of products. Increasing the sample size can reduce these probabilities, but with diminishing returns at essentially linear increases in cost.

In quality control, the conventional buyer-seller relationship has led to the development of several concepts closely related to the problems of "error" in acceptance and rejection. Among these concepts are:

- Concentration on the "consumer risk" or "lot tolerance percent defective" -- the probability of erroneous acceptance and the corresponding fraction defective -- when isolated lots are sampled.

- The desirability of reduction of both risks, at the expense of increased sample size, for large lots in view of the disproportionately increased severity of the consequences of error.

- The notion of the "average outgoing quality limit" or AOQL arising from the effects of 100% inspection following lot rejection.

These conventional concepts have virtually no applicability in the context of product safety and destructive testing. The notion of AOQL is obviously inapplicable when one hundred percent inspection is impossible. From the consumer standpoint, lot size is irrelevant because no individual consumer acquires more than a very small fraction of any lot. Downgrading of lot tolerance percent defective concepts arises from less obvious considerations and hence commands more of our attention.

The costliness of destructive testing discourages the use of large samples and this in turn makes it difficult to limit comsumer risk in the usual ways. Fortunately, the physical phenomena that lead to destructive testing also lead to strong economic incentives on the manufacturer: in general, it is at best very difficult to rework a rejected lot and alternate markets are virtually nonexistent. The consequence is that the manufacturer must achieve a very high probability or frequency of lot acceptance in order to survive as a producer. We estimate -- we think conservatively -- that at least a 95% acceptance probability must be maintained routinely; that is, no manufacturer is expected to survive if more than one of every twenty lots is rejected. This means that ordinarily only the behavior of the sampling plan at low levels of "defectiveness" is of major concern; of course; we will still want to limit the chances that an occasional defective lot will slip through, but this is not as compelling a consideration as it is in conventional situations.

3. CHOOSING A TARGET

Having established that the manufacturer will need to control his process so as to achieve at least 95% acceptance probability leaves open the question of what level of quality -- what process average -- should correspond to this target value. Here, we enter an area demanding many tradeoffs -- which often must be made with incomplete information, largely because the response of an industry to the challenges posed by a mandatory standard is not entirely predictable.

There is a better than even chance that any standard, especially when flammability is involved, will drastically reduce available choices among materials and designs. This implies reduced consumer freedom-of-choice and increased costs that ultimately impact on the consumer.

When a product is a necessity, as is generally the case for basic wearing apparel, a further major consideration is the need to assure adequate availability of the product. (Nudism is a sure cure for garment flammability problems, but might introduce some health problems of its own.) Large cost increases or availability reductions for other textile-related products whose purchase is more discretionary, such as a replacement mattress, may have effects that are counterproductive from the standpoint of consumer safety. The delayed replacement of existing hazardous products in the interests of introducing a nearly perfect product rather than a merely superior one can mean avoidable casualties in the interim.

A prospective standard, including those aspects of stringency that arise from its sampling plan, therefore must be scrutinized carefully from the standpoint of its total impact on the public and the industry.

4. AN EXAMPLE: CHILDREN'S SLEEPWEAR STANDARD (SIZES 0-6X)

The standard for the flammability of children's sleepwear (sizes 0-6X), which went into full effect recently, provides illustrations of a number of the points in this discussion. It also provides an example of the way in which a multi-tiered approach can reduce the burden of consumer product safety improvement.

In many products, it is possible and appropriate to distinguish between hazards associated with the design characteristics of the product and those that can arise due to production errors. These distinctions lead to two sets of tests, each conducted on a different sampling basis. Design characteristics are evaluated appropriately by relatively stringent tests conducted on prototype (preproduction or early production) items; under some circumstances, it may be desirable to require that these tests be repeated at relatively long intervals. The presence of production errors, on the other hand, requires detection by the use of representative samples from production quantities. To the extent permitted by procurement practices, processes and industry structure, such samples should be drawn from internally homogeneous lots of production items. To reduce potential confusion with definitions of "lot" that may be traditional to an industry, standards now refer to these homogeneous production quantities as "production units", whose maximum size is limited by the standard.

Children's sleepwear is unusual in that a major component -- the fabric -- is itself amenable to control by a standard. This standard therefore involves a sequence of fabric production testing -- garment prototype testing -- garment production testing. (Fabric prototype testing was judged to have no special value or validity, as the dominant problems are of the production error type.)

In normal sampling, the production test employs ten fabric specimens. Each of two samples contains three specimens taken in one direction and two in the other, as the flammability characteristics may differ along warp and fill. The average char length over each five-specimen sample must not exceed seven inches; any violation of this requirement leads to rejection, so excessive average char length is treated as a "critical" defect. Any individual specimen fails if it chars its entire ten-inch length or if flaming of any fragments or molten material persists for more than ten seconds. If any single specimen fails, an additional sample of five specimens (all aligned in the direction experiencing the failure) must pass without further failure. If more than one specimen fails, the production unit is rejected.

It is worth noting that even a fabric production unit that is substandard -- i.e., has a specimen fraction defective above the target value -- and is passed as a result of statistical phenomena is certain to be vastly superior to fabrics in common use prior to issuance of the standard. Some of the latter fabrics consistently would burn entirely and, if tested, would certainly be rejected. Any "defective" fabric passed under the sampling plan could be defective only in the sense that it had locally variable characteristics such as might result from uneven application of flame retardants; such a fabric would not be subject to general and extensive burning. Sampling-plan rejects have flammability characteristics superior to 90 percent of the fabric in general use two years ago.

Fabrics that can pass more stringent sampling plans exist, but not in quantities adequate to meet sleepwear requirements. The target level here was set to admit the required variety of fabrics, with consideration being given to the capacity growth that could be anticipated in the period between the standard's promulgation and its date of full effectiveness.

It is known that the flammability characteristics of a fabric can be compromised by the thread material and construction used in garment seams and by the presence of trim materials. These problems can arise directly from flammability of the added materials or the mechanical or synergistic effects. The garment prototype test addresses these problems by requiring testing of specimens involving major seams and trim items of non-trivial dimensions. The number of specimens required is larger, but there also is an allowance for a larger number of failures (except in the case of the seven-inch average char length limit). It is unusual to allow these failures in a prototype test, but this approach is necessary here because the garments must be made from production fabric that may be imperfect and the garment cannot be required to be better than the fabric.

Finally, production garments are tested using three samples of five specimens each and the same specimen pass-fail criteria. The specimens are obtained from the seamed areas involving the longest seam in the garment. As many as three of the fifteen specimens are permitted to fail before rejection occurs; the absolute character of the average-char-length requirement remains intact. The failure allowance again reflects the accumulation of effects and the availability of materials. Note, however, that most of the garment consists of the plain fabric that was previously required to pass the most stringent of the tests. Protection against the most serious of the garment flammability hazards -- the large-area burn -- thus is still provided; in fact, it is enhanced to the extent that the seam tests constitute further validation of fabric characteristics.

The result of this three-tier sampling approach is a dramatic improvement in sleepwear flammability with a minor cost increment due to the testing burden *per se*. Increasing availability of suitable fabrics permits an impending extension of standards coverage to sleepwear in the 7-14 size range. Although details of approach will differ according to circumstances, the children's sleepwear standard can serve as a model for future mandatory standards in several areas of consumer product safety.

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HUMAN ACTIVITY PATTERNS AND INJURY SEVERITY IN FIRE INCIDENTS INVOLVING APPAREL

Laura Baker Buchbinder[1]
The Cotton Foundation, Memphis, Tennessee

Activities immediately preceding an apparel fire are identified, classified and related to the age/sex groups involved. The level of severity of burn injuries resulting from apparel fire accidents is discussed and is related to the type of activity causing the accident. The relationships defined in the study indicate the importance of the human behavioral aspects of a fire accident and aid in defining types of remedial action likely to be effective in reducing human loss due to fabric fires.

Key words: Accident patterns; apparel; apparel fires; burn injury; FFACTS; fire; flammable fabrics; flammable liquids; garment fires; garment parameters; injury severity; victim's activity; victim's reactions.

1. INTRODUCTION

It has already been noted that burn accidents result from the interaction of a number of environmental, human and physical factors. The activity of the victim, the ignition source, the involvement of flammable materials, including flammable liquids, and the reaction of the victim to an accidental fire are all variables which may determine whether the victim suffers little or no burn injury or severe burns over much of his body.

In order to gain a complete understanding of the total burn problem and to place the various factors leading to a burn injury in proper perspective, it is necessary to understand the interrelationships of all of the factors in a fire accident. Therefore, the purpose of this study is to identify patterns in these variables, activity, reaction, and garment parameters, and relate them to each other and to the severity of the injury incurred. This paper will deal primarily with two of the accident variables--activity of the victim and the level of injury severity.

2. STUDY DESCRIPTION

Eleven hundred twenty-six (1,126) cases from the National Bureau of Standards' FFACTS data base[2] met the criteria for this study which were:

1. Apparel was involved
2. Total area of body burned was given
3. Information on the activity or the reaction of the victim was given.

Because of the extremely detailed information required, it was necessary to go back to the original case histories, gather the appropriate information on activities, reactions and garment involvement, and classify and code the information. The major classifications are shown in table 1. They fall into 3 groups: those dealing with activities, those dealing with the reaction of the victim and those dealing with the garment involved.

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[1]The author is currently a research associate at the National Bureau of Standards, Washington, D.C. where the work reported here was performed.
[2]At the time of this study, the FFACTS data base contained 1,964 cases.

Table 1. Major Information Classifications For Activity of Victim

CLASSIFICATION	EXAMPLES
General Accident Type	Involvement of flammable liquids, flammable gases, high voltage electricity
General Activity Type	Using fire, playing with an ignition source, using flammable liquids
Additional Information on Activity	Body action, ignition source
Occupational Relationship and Location	Work, non-work, play
Contributing Circumstances	Physically disabled, intoxicated, senile

3. RESULTS

3.1. Accident Patterns

Accidents in the study were divided into four major categories which attempt to define the general type of accident by the physical mechanisms involved in it. Table 2 shows the number of accidents in each category. Fifty-seven percent of the cases in the study involved no flammable liquids, gases, or explosives; 35 percent did involve flammable liquids; and 7 percent involved gas or explosives. There were only 12 cases which involved high voltage electricity.

The first group is the one most affected by fabric flammability standards. The effectiveness of fabric flammability standards in preventing injury in the last three types of accidents is much less likely since flammable liquids will burn regardless of the fabric and the primary hazard from explosions is usually directed at exposed skin areas.

The secondary level of classification specifies the general type of activity the victim was engaged in before the accident. As can be seen in table 2, the most frequent activities for all types of accidents were:

1. Using fire
2. Starting a fire
3. Playing with an ignition source
4. Using flammable liquids.

The kinds of activities the victims were engaged in varied with the general accident type. For example, in accidents not involving flammable liquids or gases, "using fire" and "playing with an ignition source" were the two most frequent activities. When flammable liquids were involved, "using flammable liquids" was the largest group, accounting for one-third of the cases. Fifty-three percent of the accidents involving flammable gases or explosives happened as the victim was starting a fire--most of these as he lighted a match in a gas-filled room or attempted to light a malfunctioning furnace or gas water heater. Table 3 shows the number of accidents for males and females in six age groups. When compared with the distribution of these age groups in the general population, the 0-5, 6-10 and over 65 age groups are over-represented, and the other groups somewhat under-represented. There were an equal number of males and females in the 0-10 age group, but males outnumbered females in the groups from 11-65. Only in the over 65 group did women outnumber males.

Table 2. Number of Males and Females Involved By Accident Type and Activity Type

Activity Type	Accident Type										
	No Flammable Liquids Involved		Flammable Liquids Involved		Gas or Explosives Involved		High Voltage Electricity Involved		All Types		
	M	F	M	F	M	F	M	F	M	F	Total
Starting a fire . . .	31	39	27	16	29	15	-	-	87	70	157
Using fire or similar ignition source . . .	71	166	45	11	3	2	-	-	119	179	298
Using flammable or volatile liquids. . .	-	-	108	19	3	-	-	-	111	19	130
Using special ignition sources[a] . .	9	1	9	-	-	-	-	-	18	1	19
Extinguishing a fire.	7	5	15	12	-	-	-	-	22	17	39
Escaping a fire . . .	5	1	6	1	-	-	-	-	11	2	13
Standing, sitting or moving near an ignition source	27	53	16	5	-	-	7	-	50	58	108
Standing near an explosion	1	-	19	1	21	6	1	-	42	7	49
Playing or climbing near an ignition source.	17	37	1	-	1	-	2	-	21	37	58
Playing with an ignition source . . .	64	77	6	-	3	-	-	-	73	77	150
Playing with a flammable liquid.	-	-	9	2	-	-	-	-	9	2	11
Playing with ignition source and flammable liquid.	-	-	49	6	-	-	-	-	49	6	55
Miscellaneous	-	1	1	-	-	-	-	-	1	1	2
Unknown	14	15	3	2	1	-	2	-	20	17	37
Total	246	395	314	75	61	23	12	-	633	493	1,126

[a]Ignition sources such as welding torches, soldering irons, bunsen burners, etc.

Table 3. Age/Sex Distributions For FFACTS Apparel Cases and For the United States as a Whole

Age	Number of Cases			Percent of All Cases	Percent of U.S. Population[a]
	M	F	Total		
0-5 . . .	86	91	177	15.7	10.3
6-10. . .	76	75	151	13.4	10.0
11-15. . .	86	39	125	11.1	10.2
16-20. . .	57	13	70	6.2	9.1
21-65. . .	274	185	459	40.7	50.8
Over 65 . .	50	90	140	12.4	9.6
Unknown . .	4	0	5	0.4	
Total . .	633	493	1,126	99.9[b]	100.0

[a]Derived from 1970 U.S. Bureau of the Census population statistics.
[b]Total does not equal 100.0 due to rounding.

Fire accident patterns seem to be strongly related to the sex of the victim. While 55 percent of the victims in the cases studied were male, 81 percent of the accidents involving flammable liquids had male victims. Males were the victims in 73 percent of the accidents involving flammable gases, and all 12 of the victims were males in accidents involving high voltage electricity. Females, on the other hand, accounted for 62 percent of the accidents involving none of the above intermediary materials.

Results shown in table 4 indicate that diversification of hazardous activities between the sexes begins at an early age. In the 0-5 group, playing with matches was the major activity leading to clothing ignition for both males and females, but in subsequent age groups, accident patterns reflect the traditionally different activity patterns of the two sexes. Flammable liquid involvement was the dominant pattern in "pre-ignition" activities for males 6-65, with almost 70 percent of the accidents to males between the ages of 11 and 20 involving flammable liquids. Females, however, incurred more of a hazard from direct contact with an ignition source in activities involving ranges, space heaters and other open fires. Males over 65 seemed prone to accidents resulting from lighting or smoking cigarettes and elderly females were especially susceptible to garment ignition as they were using kitchen ranges.

3.2. Injury Severity

Having discussed patterns in activities preceding a burn accident, let's turn our attention to the injury resulting from these accidents. The severity of a burn injury is dependent upon several factors:

1. The area of the burn--that is, the percent of the total area of the body burned
2. The thickness of the burn--that is, whether it is superficial involving only the upper layers of skin or whether it is a full thickness or 3rd degree burn involving all layers of skin
3. The location of the burn, with such areas as the face, hands and neck posing more of a problem than other areas of the body.

Table 4. Major Activities Leading to Burn Injuries, By Age/Sex Group, Showing Flammable Liquid Involvement (Upper case denotes flammable liquid involvement)

Age Group (yrs)	Males		Females	
	Major Activities for Group	Percent of Group Involved	Major Activities for Group	Percent of Group Involved
0-5	Playing with ignition source	55	Playing with ignition source	52
	Playing or climbing near an ignition source	15	Playing or climbing near an ignition source	24
6-10	PLAYING WITH AN IGNITION SOURCE AND FLAMMABLE LIQUID	30	Using fire	32
	Playing with ignition source	17	Playing with ignition source	32
11-20[a]	USING FLAMMABLE VOLATILE LIQUIDS	22	Using fire	46
	PLAYING WITH IGNITION SOURCE AND FLAMMABLE LIQUID	13	Standing, sitting or moving near ignition source	18
	Using fire	9		
21-65[b]	USING FLAMMABLE VOLATILE LIQUIDS	23	Using fire	35
	USING FIRE	13	Starting a fire	13
	Using fire (no flammable liquid)	11	Standing, sitting or moving near an ignition source	11
Over 65	Starting a fire	20	Using fire	53
	Using fire	18	Starting a fire	16
	Standing, sitting or moving near an ignition source	12		

[a]A total of 69 percent of the accidents for males in the 11-20 age group involved flammable liquids.

[b]A total of 53 percent of the accidents for males in the 21-65 age group involved flammable liquids.

Development of a severity or morbidity index encompassing the above factors is in progress. However, until a better index is developed, percent of total area of body burned will be used to indicate the severity of the injury.

Figure 1 shows the distributions of total area of burn and area of full thickness burn for the 1,126 cases in the study. It can be seen that the two distributions have similar shapes. Thirty-nine percent of the cases suffered a total area of burn of 10 percent or less and 60 percent of the cases had a burn of 20 percent or less. Forty-three percent of the 868 cases in which the area of full thickness burn was given suffered no full thickness injury.

3.2.1. Accident Type and Severity of Burn

It would seem that the severity of the burn is related to the type of accident causing the injury. Figure 2 shows the area of the body burned for each of the three major types of apparel fires. The greatest difference seems to occur between the distribution of total area of burn for accidents involving no flammable liquids, gas, etc., and the distribution of total area of burn for accidents involving flammable liquids. This difference in the distributions is statistically significant.[3] The difference in injury severity between accidents involving flammable liquids and those not involving flammable liquids becomes highly significant when the effect of age--that is, the very young and the very old--is removed by considering only the adult (21-65) age group. It can be seen in figure 3 that accidents involving flammable liquids have a lower percentage of minor injuries, more moderately serious injuries and a smaller percentage of very serious injuries.

Presence of a flammable liquid presumably affects the course of the fire during the first seconds after ignition. Unlike most apparel fires not involving flammable liquids, ignition may occur at several points simultaneously--wherever the flaming liquid comes in contact with the garment. In addition to this, a flammable liquid fire gives off a great amount of heat and is very difficult to extinguish until the flammable liquid has burned off. Any of these factors would tend to make injury in the critical first few seconds of the fire more serious than if a flammable liquid were not involved.

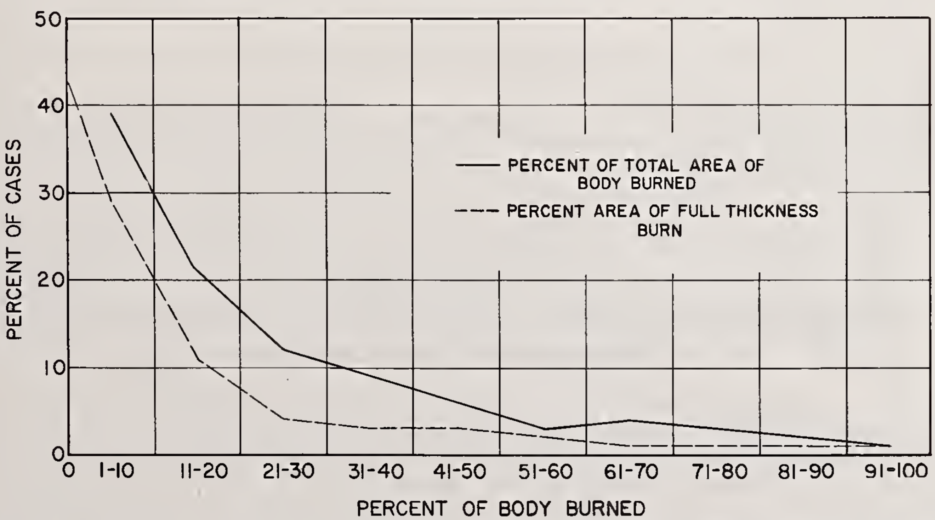

Figure 1. Frequency distribution of the percent of total area of body burned and of the area of full thickness burn.

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[3]All references to statistical significance refer to chi-square contingency tests.

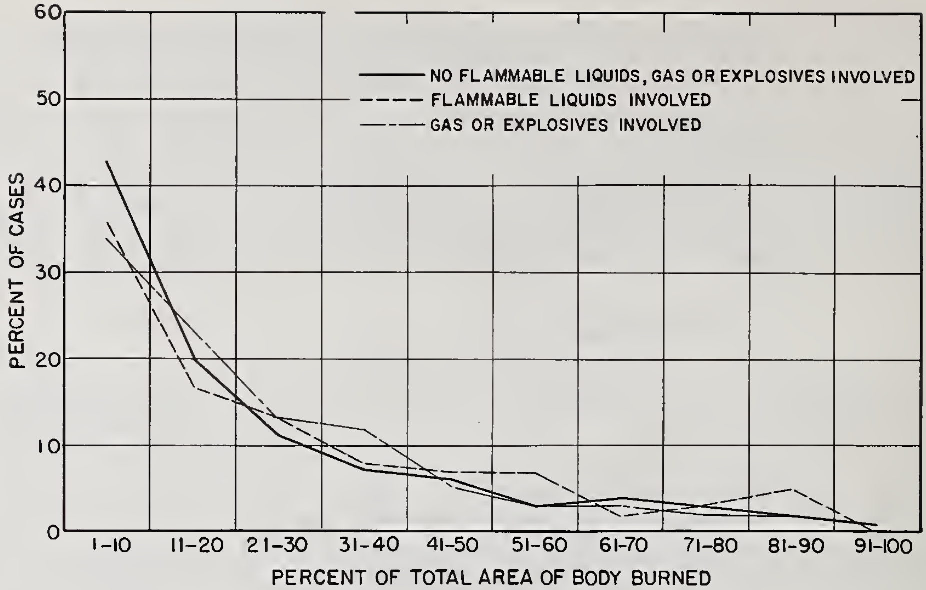

Figure 2. Frequency distribution of the percent of total area of body burned for three types of burn accidents.

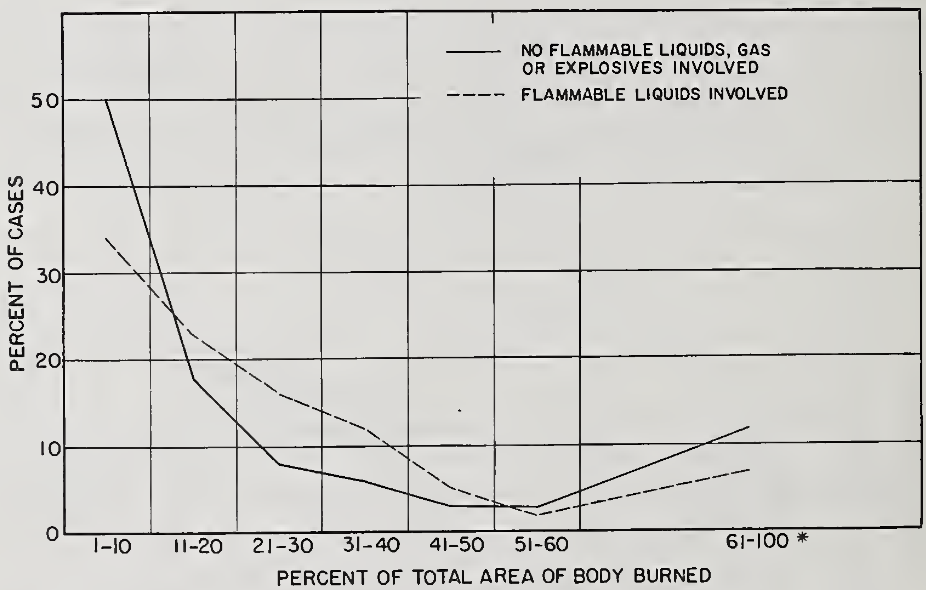

Figure 3. Percent total area of body burned in accidents with and without flammable liquids for age group 21-65.

*The apparent rise in the right tails of the distributions is due to combination of the highest four deciles of the distributions. These four deciles are combined because there is little practical significance, in terms of probability of survival, between total area of burn values in the range 60%-100%.

3.2.2. Age and Injury Severity

The severity of burn seemed to be somewhat related to the age and sex group involved. Females had a higher percentage of burns covering over 50% of the body than males. However, the most striking difference in injury severity patterns is seen in figure 4 where the area of the body burned is considered in relation to various age groups. While the 0-10, 11-20 and 21-65 age groups have very similar injury curves, the over 65 group has a significantly lower percentage of relatively minor burns and a larger percentage of burns covering 50% or more of the body. The significance of the difference in injury severity patterns for the over 65 group versus all other age groups has been established at the 99% level. This predominance of more severe burns in the over 65 age group may be due in part to the decreased "defensive capability" of elderly people. Preliminary results of this study indicate that the ability of the victim to effectively react to garment ignition is very important in determining the severity of the resultant burn injury. The defensive capability of the victim was estimated based on the following criteria:

1. Was the victim immediately aware of ignition?
2. Did the victim have normal adult reaction capability or were his reactions impaired by age, illness, or physical or mental handicaps?
3. Did the victim have help immediately available to help extinguish the fire?

The total area of body burned for the 70 cases in the study in which the defensive capability was judged to be very good was compared with the total area of body burned in the 56 cases at the other extreme with poor defensive capability. The results, shown in figure 5, indicate that victims with bad defensive capability had fewer minor injuries and a much higher percentage of severe injuries than the other group, indicating that the level of burn severity is in part a function of the defensive capability of the victim. Elderly people often have limited defensive capability since they often live alone and are usually not as physically and mentally fit as other groups in the population. Therefore the relationship between defensive capability and injury severity may partially explain the increased severity of burns to people over 65.

4. CONCLUSIONS AND RECOMMENDATIONS

At this point in the study, patterns in activities leading to fire accidents are evident. As might be expected, these activity patterns are related to the age and sex of the victims involved. It has also been shown that the severity of injuries resulting from burn accidents varies greatly, with the majority of the accidents in this study resulting in less than 20% total area of the body burned. Injury severity also seems to be related to such variables as accident type and the age, sex and defensive capability of the victim. Therefore, it would seem advisable to consider not only numbers of accidents but also the relative severity of the accident and to look at all factors contributing to a burn accident before determining the most effective remedial action.

This study and others[4] have indicated some problem areas such as young children playing with ignition sources; males from 6-65 improperly using flammable liquids; females of all ages, but especially the elderly, igniting their clothing while working near kitchen ranges; and adults of both sexes, especially those over 65, igniting their clothing as they light or smoke cigarettes. There are a number of ways to accomplish a reduction in fire

[4]For example: Slater, J. A., Buchbinder, B. and Tovey, H., Matches and Lighters in Flammable Fabric Incidents: The Magnitude of the Problem, Nat. Bur. Stand. (U.S.), Tech. Note 750 (Dec. 1972).

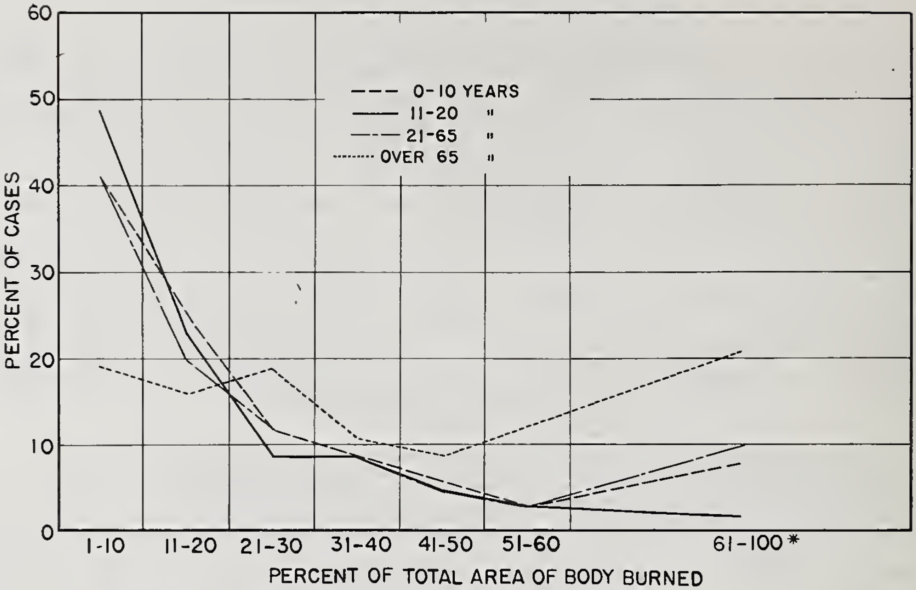

Figure 4. Frequency distributions of percent of total area of body burned for four age groups.

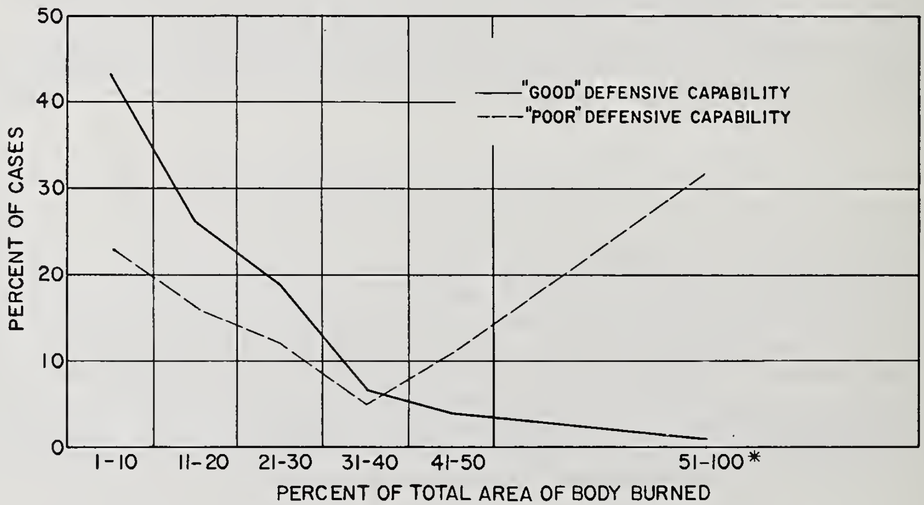

Figure 5. Comparison of the frequency distributions of percent of total area of body burned between cases with "good" and "poor" defensive capability.

*The apparent rise in the right tails of the distributions is due to combination of the highest four deciles of the distributions. These four deciles are combined because there is little practical significance, in terms of probability of survival, between total area of burn values in the range 60%-100%.

accidents in these groups, including fabric flammability standards, redesign of ignition sources and public education. However, it is important to remember that fabric flammability standards alone won't solve the problem. For example, the apparel fire accident problem for males of ages 6-65 is closely tied to the use and misuse of flammable liquids. Since this is largely a behavioral problem and is difficult to approach from a technological basis, it would seem that a broadly based educational program may be the most effective means of preventing this type of accident.

Further investigation is needed to effectively determine the hazard involved in various types of fire accidents and to consider the cost-benefit aspects of the various means of protecting people from fire injury. In addition, more detailed information is necessary for the development and implementation of effective educational programs. In relation to these needs, further analysis is in progress to define activity, reaction and garment parameter patterns in greater detail and to determine the relationship of these factors to each other and to the severity of the resultant burn injury.

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CHEMICAL ASPECTS OF FLAME INHIBITION[1]

John W. Hastie
National Bureau of Standards, Washington, D.C.

The role played by inorganic chemical additives in fire retardancy and flame inhibition is considered. Particular attention is given to the molecular level aspects of commercially important systems containing compounds of antimony and halogens.

Key words: Fire retardants; flames; inhibition.

For purposes of discussion, consider a fire where the fuel is supplied by pyrolysis of a polymeric substrate, such as a nylon or polyester carpet. The gases in the immediate vicinity of the carpet will usually consist of a fuel-rich mixture of pyrolysed and vaporized hydrocarbons together with entrained air. At a somewhat greater distance from the decomposing substrate, this fuel-air mixture may support combustion in the form of a flame.

Now, it is well known that one can extinguish such a fire, either by adding chemicals to the polymer substrate or externally throwing chemicals at the fire such as with an extinguisher containing halocarbons or alkali metal carbonates. The present discussion is concerned with the mode of inhibition that occurs when chemicals are added to the substrate. What we have to find out is how these chemicals are released from a pyrolysing substrate and then how the released molecular species interact with the flame reactions. The important reactions in flames are radical reactions and one can chemically affect the flame propagating radicals which are mainly hydrogen atoms, hydroxyl radicals and oxygen atoms. By reducing the steady state radical concentration, we can inhibit the flame and even extinguish it. So that is the problem that we are addressing ourselves to. I should mention that the main chemicals that are currently being used by industry are compounds of antimony, phosphorus and chlorides or bromides. We have been studying the mechanisms by which compounds containing these elements inhibit fires, but in this paper I am just going to discuss the antimony system.

There are two modes by which such chemicals can affect fires. They can alter the course of decomposition of the polymer such that a less flammable mixture is produced, or they can release chemicals to the vapor phase which actually poison the flame, and it is this latter mode of action which I am going to emphasize.

The antimony oxide halogen system is usually comprised of a mixture of antimony oxide solid and an organic halogen compound such as polyvinylchloride or some chlorinated paraffin. This mixture is added to the substrate that we want to fire retard. It has widespread use in industry; however, the mechanism by which it operates as a fire retardant is not very well understood. We have, therefore, chosen this as a model system for extensive study.

At the molecular level, without going into technical details, we are able to monitor the pyrolysis chemistry by using a mass spectrometer as a detector for the different vapor species. Our principal observations from this kind of research are that the hydrogen chloride which is released from the decomposing organic chloride additive interacts with the antimony oxide solid over a temperature interval of about 250-500°C, which is an interval characteristic for

[1] A more extensive discussion of the subject matter dealt with here may be found in the following reference: Hastie, J. W., Molecular Basis of Flame Inhibition, J. Res. Nat. Bur. Stand. (U.S.), 77A (Phys. and Chem.), No. 6, 733-754 (Nov.-Dec. 1973).

the pyrolysis of many commercial polymers. The main products of this interaction have been found to be gaseous antimony trichloride and water vapor. Also, during the course of this interaction we find that solid oxychlorides are formed. These oxychlorides really control the rate at which the antimony trichloride is released to the vapor phase. This is demonstrated in figure 1. The curves A, B and C give a measure of the rate of release of antimony trichloride to the gas phase at different temperatures. We have started out with an antimony oxychloride solid and gone through a heating sequence with a very small rate so that we could attempt to approach an equilibrium condition. The important thing about this observation, i.e., figure 1, is that the antimony trichloride is released in the form of three bursts, rather than being released all at once. If the trichloride was released just at one temperature, like 250°, we would rapidly lose all of the additive that had been introduced into the polymer, and the chances of the system being an effective fire retardant would be reduced because the extinguishant is only being released over a very narrow temperature interval which may not correspond with the temperature at which the polymer is decomposing. The rule of thumb here is that we want the vapor active ingredient to be released at about the same time as the polymer is producing flammable fuel, and in many cases that is up in the temperature interval of about 300 to 400°C.

To summarize the results of an extensive study on this system -- the release of antimony trichloride is controlled by the formation of solid oxychloride phases which are listed in table 1. This is fairly peculiar to the antimony oxide system. One would not expect to find a similar behavior in many other oxide-halogen fire retardant systems that one could conceive of.

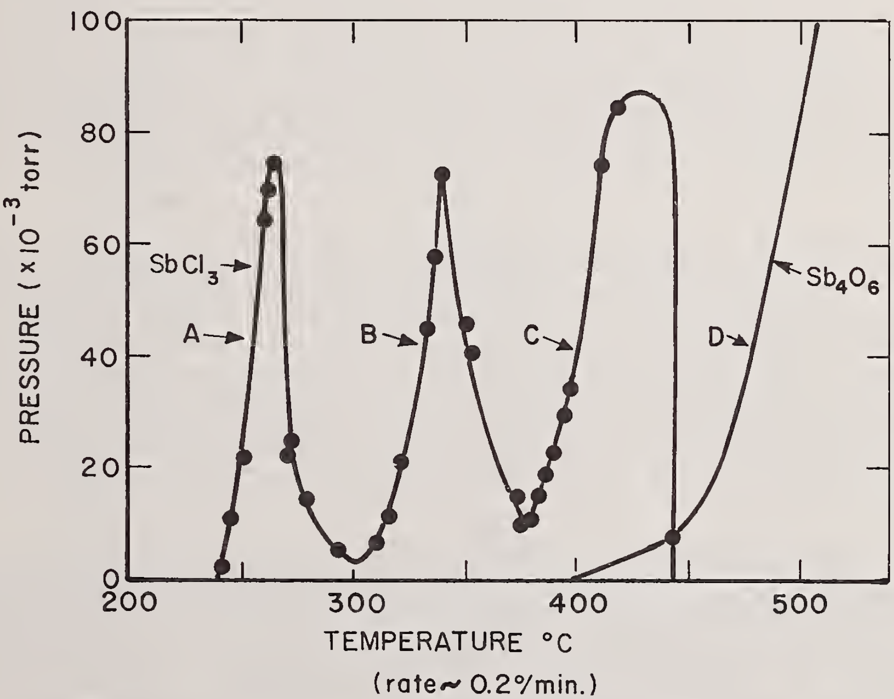


Figure 1. Pressure variation of the vapor species $SbCl_3$ (curves A, B and C) and Sb_4O_6 (curve D) as a function of temperature and time using solid SbOCl as a source and a heating rate of about 0.2°C min^{-1}.

Table 1. Antimony Oxide - Halogen Substrate Reactions For Typical Substrate of [R • HCl + Sb_2O_3 + Fabric][a]

	Reactants		Products	Temperature
	[R • HCl]	→	R + HCl	∼250°C
	HCl + [Sb_2O_3]	→	[SbOCl]	↓
A	5[SbOCl]	→	[2SbOCl • Sb_2O_3] + $SbCl_3$	Temperature Increasing
B	4[2SbOCl • Sb_2O_3]	→	5[SbOCl • Sb_2O_3][b] + $SbCl_3$	↓
C	3[SbOCl • Sb_2O_3]	→	4[Sb_2O_3] + $SbCl_3$	↓
D	2[Sb_2O_3]	→	Sb_4O_6	∼550°C

[a]Square brackets denote solids.
[b]Could also be [2SbOCl • 3Sb_2O_3].

Now, let me address the problem of how this antimony halide vapor actually affects the flame. In studying the chemistry of these additives in flames, there are two approaches that we can use, either a macroscopic level of observation -- which would involve measuring such things as flame speed, temperature, combustion limits and initial and final composition -- or we can look at the microscopic level which involves looking at all the molecular species present in the flame, and for this we would use optical and mass spectroscopic techniques. The important thing here is that if we can characterize the microscopic character of these flames and also the additives in the flames, then by use of kinetics and thermodynamics we can actually calculate these macroscopic properties. If this calculation agrees with the results of macroscopic measurements, then our model for inhibition which has been developed by the microscopic route is most likely a correct one. This is the approach that we are working towards.

Table 2 gives a rating of chemicals as flame inhibitors. The large numbers mean that only a small amount of inhibitor is required to reduce the velocity of a particular laboratory flame. Note that antimony trichloride has a rating of about 26, relative to say, a value of only 0.8 for carbon dioxide. Thus, there are many chemicals that are much more effective than chemicals which are currently being used as extinguishants and, in particular, some of the heavy metal systems are extremely effective. It is conceivable that such systems may be used in future retardant formulations. By looking at the molecular level processes of these chemicals in flames, one can eventually understand why an individual chemical has the particular effectiveness that it does on flame speed.

Now, in order to get at the molecular basis, we need to develop a system for analyzing flames at one atmosphere and to be able to extract very active species, such as radicals, from these flames. An apparatus developed for this purpose is shown schematically in figure 2; basically, it is a molecular beam mass spectrometer. The sampling of flames is carried out through a small pin hole in the tip of a conical probe into a vacuum system. The gas then freezes into a molecular beam-form and passes into the mass spectrometer where it is mass analyzed.

The position of the burner, and hence the flame, can be varied relative to the sampling probe. The mass spectrometer then tells us what the distribution of molecular species is in a laboratory flame. Typical results are given in figure 3. The zero is the burner tip and the luminous reaction zone for this flame is at the 9 mm distance position. From this, we see that one can monitor the decomposition of the fuel, the depletion of oxygen and the appearance of combustion products. More importantly, using molecular beam sampling, we can look at the distribution of radical species which are controlling the speed of these flames as shown in figure 4. The most important species in fuel-rich hydrocarbon flames are the hydrogen atom, hydroxyl radical and the methyl radical. Note that the hydrogen atom appears well upstream of the flame. It is diffusing back upstream and most of the pre-flame chemistry is probably the chemistry of this hydrogen atom.

Table 2. Relative Effectiveness, ϕ_v, of Selected Flame Inhibitors

Inhibitor	Flame Type	
	n - hexane/air ϕ_v	H_2 - air ϕ_v
CO_2	0.86	
Cl_2	1.8	-0.26
$Si(CH_3)_4$	3.9	
CCl_4	4.2	
Br_2	8.4	
$SiCl_4$	10.5	3.5
$(CH_3)_3PO_4$	23.0	
$SbCl_3$	26.0	
$TiCl_4$	30.0	10.0
$SnCl_4$	31.0	12.9
$POCl_3$	31.0	7.2
PCl_3	39.0	4.5
PBr_3	39.0	
CrO_2Cl_2	$\gtrsim$244.0	
$Fe(CO)_5$	356.0	19.0
$Pb(C_2H_5)_4$	390.0	

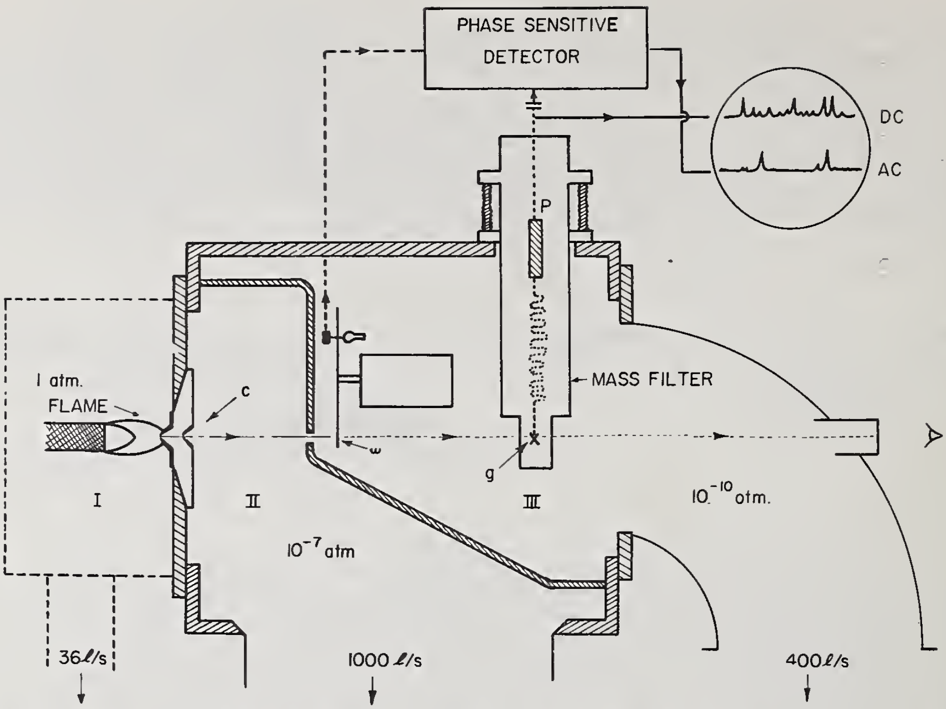
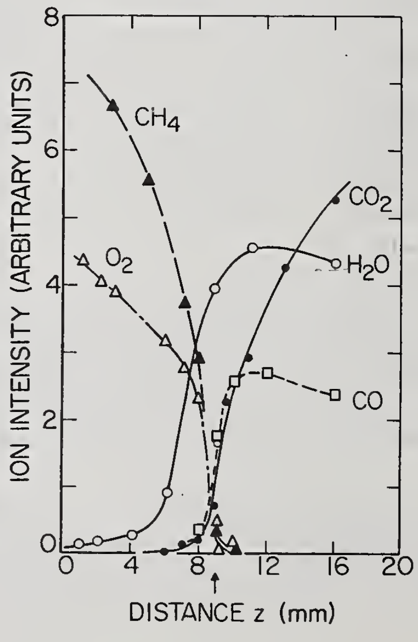


Figure 2. Schematic of mass spectrometric system for sampling 1 Atm flames. A representative gas sample passes through a cone system (c) into an evacuated chamber (region II); the beam then passes through an adjustable orifice into region III, which contains a wheel (w) for mechanical modulation of the beam, an ion source (g) for partial conversion of the molecular species into positive ions, and a mass filter and ion detection system (p).

Figure 3. Concentration profiles for major reactants and products in a 1 Atm fuel-rich CH_4 - O_2 flame.



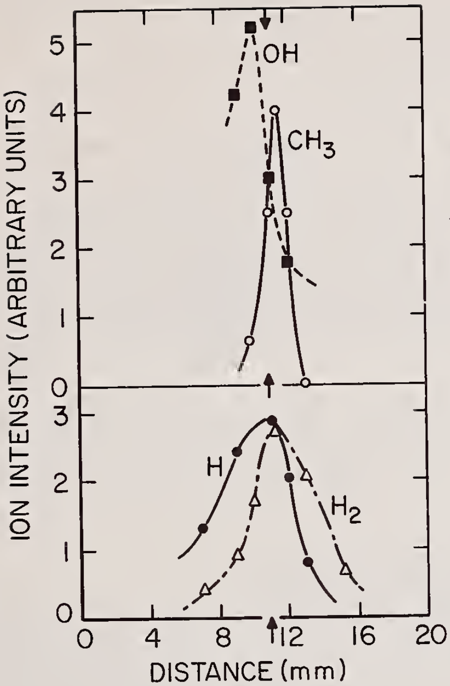


Figure 4. Concentration profiles for the main radical species in a fuel-rich $CH_4 - O_2$ flame.

We find that addition of antimony tribromide to such a flame gives composition profiles of the type indicated by figure 5. The hydrogen bromide and methyl bromide intermediates are only stable in the pre-flame region. The temperatures in this region and the rate constants for reactions of these bromides with hydrogen atoms are known, and it is generally agreed that at least some inhibition occurs in this pre-flame region. However, we also believe that there is a strong inhibition effect at the reaction zone where the radicals all have their maximum concentration. In this antimony case, we believe that it is the antimony monoxide species which is affecting the radicals by interacting with hydrogen atoms and catalyzing a recombination of hydrogen atoms to molecular hydrogen. This lowers the flame speed and causes inhibition.

Let me sum up this discussion by indicating a reasonable approach to this problem of chemically controlling flames as summarized by table 3. The primary problem that we have been dealing with up to now is to identify the flame species. Once these are established, then we have to worry about the kinetics of the reactions of these species in flames. Unfortunately, very little of this data is available and we will need to obtain some of it using the mass spectrometric flame sampling system. Once the flame kinetics are known, one can apply well developed flame theory and test a molecular model. When the model has been established, one can then look at basic data to see what other kinds of species would be good flame inhibitors. For instance, we think that species such as antimony oxide, phosphorus monoxide and tin monoxide are good flame inhibitors at the present time. Once we know what the various optimum flame retarding species should be -- such as antimony trihalide, the molecular precursor to antimony monoxide. We then have to be concerned with the solid state chemistry such as the interaction of antimony oxide and the organic halogens to generate these molecular precursors. Finally, there is the problem of how to incorporate these additives into real polymers. Clearly, there are many chemical problems to be solved before a definitive understanding of chemical fire retardance can result.

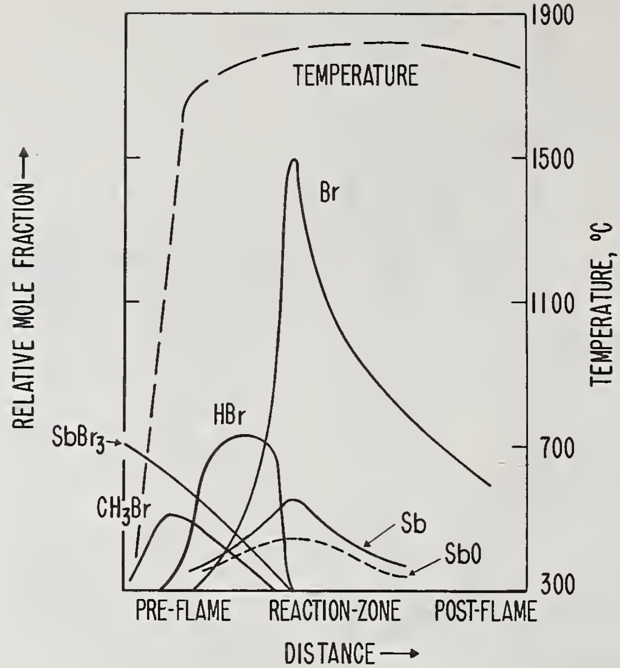


Figure 5. Concentration profiles for species resulting from $SbBr_3$ addition to a 1 Atm fuel-rich CH_4 - O_2 flame.

Table 3. Flame Inhibition And Extinction - Systems Approach

Programs	Classification
(a) identify flame species	spectroscopy
(b) determine flame kinetics	basic data
(c) test kinetic models	theory - flame equations
(d) determine optimum flame species for inhibition	basic data
(e) design stable molecular precursors to inhibitor species	thermodynamics kinetics basic data
(f) determine solid sources of such molecular precursors	thermochemistry basic data
(g) define chemistry of incorporation of additives to polymer substrates	thermochemistry solid state - structural studies

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MECHANISM OF FLAME RETARDANT ACTION IN TEXTILES

Robert H. Barker
Clemson University, Clemson, South Carolina

Flame retardants may exert their effect on textile materials by either modifying the pyrolysis reactions of the polymer substrates so that smaller quantities of flammable gases are produced or by interfering with the oxidation reactions in the flame. The modes of action for several common types of retardants on cellulose, nylon, and polyester have been determined by use of thermal analysis, pyrolysis-gas chromatography, oxygen index, and calorimetric techniques.

Key words: Calorimetry; cellulose; flames; flammable gases; nylon; oxidation reactions; oxygen index; phosphorus; polyester; polymer substrates; pyrolysis-gas chromatography; textiles; thermal analysis.

1. INTRODUCTION

For combustible textile materials the most serious hazard is usually that associated with their propensity toward flaming combustion. It is therefore the flaming reaction which is most commonly the focus of inhibitory action. This flaming process is basically cyclic in nature. In the initial stages of the process heat is supplied to the non-volatile polymer substrate to initiate an endothermic degradation reaction which for most polymer systems is thought to be predominantly pyrolytic in nature. There seems to be little evidence of significant oxidative processes occurring in the condensed phase except in the case of afterglow. The products of this polymer pyrolysis migrate to the surface of the fabric and are released into the atmosphere immediately above the fabric. As they diffuse away from the surface of the fabric, they begin to mix with the oxygen of the air so that combustion can take place. The combustion is, of course, an exothermic process, and the heat thus liberated can be returned in part to the fabric surface. This heat causes further pyrolysis of the polymer, assuring a continuous supply of fuel for further flame propagation.

Because of the cyclic nature of this process, it is usually amenable to attack at any of several points. Effective flame retardants may, therefore, act either in the condensed phase, or in the vapor phase above the decomposing polymer. Retardants which act in the gas phase exert their effect by functioning as either inert diluents or as free radical inhibitors which slow the oxidation processes and decrease the heat returned to the fabric surface. Those retardants which act in the condensed phase may operate by several mechanisms. They may inhibit the polymer pyrolysis so that it does not break down to produce the small volatile molecules necessary for flame propagation. More commonly, however, they act to alter rather than inhibit this pyrolysis reaction. The alteration is such that the mode of pyrolysis is changed and lesser quantities of flammable gas are produced. Finally, they may also exert their effect in a physical rather than a chemical manner. In this case they act as a shield to prevent the transfer of heat from the flame back to the fabric surface. This reduces the rate of polymer pyrolysis and fuel production is decreased.

In order to evaluate a particular flame retardant system, it becomes necessary to determine the mechanism of action of the various flame retardants on the fabric. This usually requires a knowledge of whether the flame retardant is gas phase or condensed phase active. Once this is known an investigation may be begun to determine the actual chemical mechanism involved in the retardation process.

2. DETERMINATION OF THE SITE OF FLAME RETARDANT ACTIVITY

A wide variety of phosphorus-containing flame retardants are known to be effective on cellulosic substrates. Of these, phosphoric acid is one of the simplest and most effective. For many years, it has been postulated that this material acts completely in the condensed phase to alter the fuel producing reaction. That this is actually the case has been shown in a recent study. [1] Thermal analysis of cotton fabrics treated with various amounts of phosphoric acid are shown in figure 1. The DTA curves show that the endothermic pyrolysis

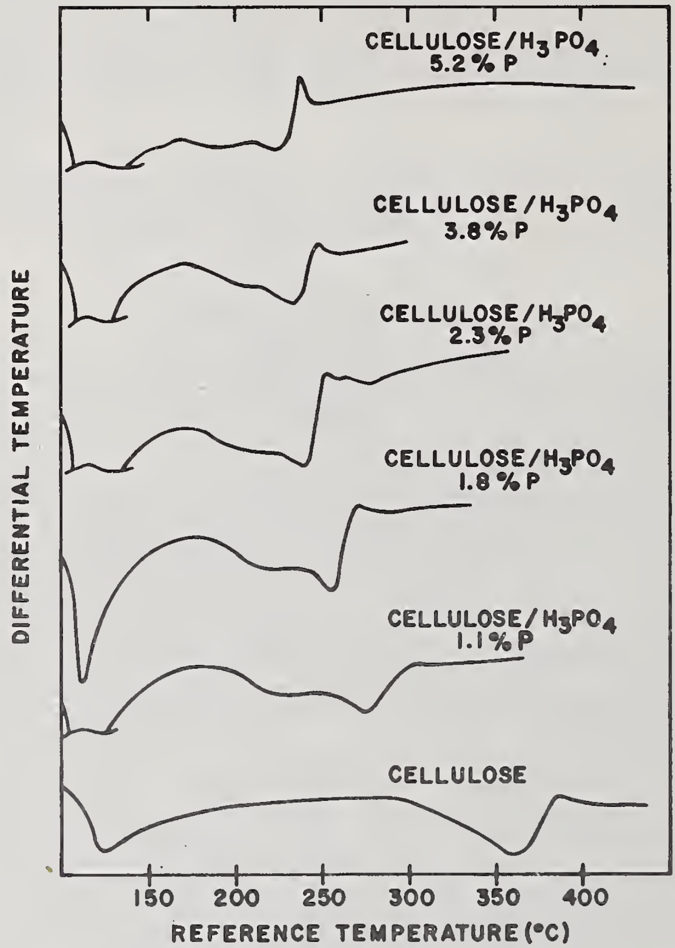


Figure 1. Thermal analysis of cotton fabrics treated with various amounts of phosphoric acid.

reaction of the cellulose occurs at progressively lower temperatures as increasing amounts of phosphoric acid are present. In fact, the endothermic decomposition reaction becomes two endotherms in the presence of phosphoric acid. These endotherms correspond to catalyzed decomposition and catalyzed phosphorylation of the cellulose. This is possible in the case of cellulose because of its ability to undergo decomposition by at least two competing pathways, as shown in figure 2. The decomposition to carbon dioxide water proceeds only very slowly in the absence of catalysts. In the presence of a catalyst such as phosphoric acid, however, this reaction becomes the predominant one at the expense of the fuel producing reaction.

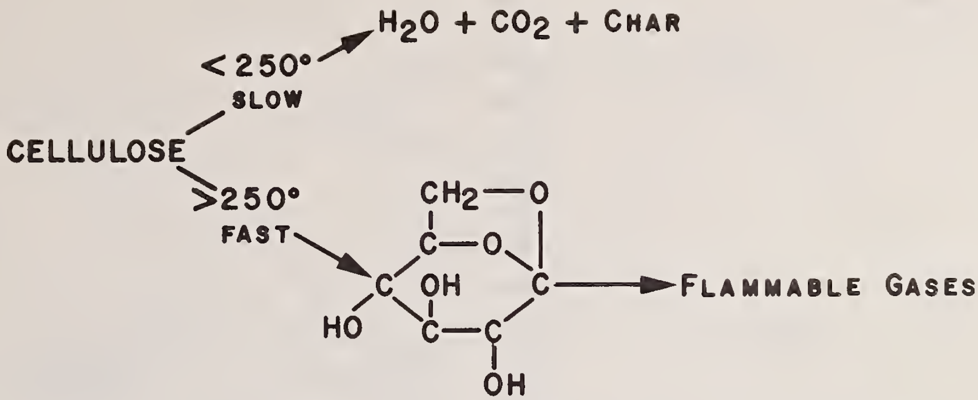


Figure 2. Decomposition of cellulose by two competing pathways.

This reduction in fuel supply is reflected in the behavior of these samples in the oxygen index tester. Fenimore and Martin have suggested that the oxygen index tester constitutes a good probe into flame retardant mechanisms when more than one oxidation medium is used. [2] If a flame retardant exhibits similar efficiencies in two or more oxidizing agents, it is generally considered that the flame retardant does not interact with the oxidant itself, but acts only to alter the amount of fuel supplied to the flame. That this is the case with phosphoric acid treated cellulose can be easily seen from figure 3. Measurements using oxygen and nitrous oxide as oxidants exhibit very similar dependency upon the concentration of retardants present as shown by the parallel lines. These results together with the DTA results show quite conclusively that essentially all of the phosphoric acid activity is confined to the condensed phase. However, it is necessary to use both techniques in order to reach this conclusion.

This approach has been used quite successfully in several cases. For example, a number of transition metal salts are known to be good flame retardants for cellulosic fabrics, but their mechanism of action is almost completely unknown at present. [3] The oxygen index data shown in figures 4 and 5 show that the molybdates and vanadates are particularly efficient even when compared with phosphoric acid. [4] This is surprising since most sodium salts of phosphorus acids are quite ineffective as flame retardants.

Differential thermal analyses shown in figure 6 and thermogravimetric analyses, figures 7 and 8, indicate considerable condensed phase activity with both the sodium and ammonium salts. [4] Both series seem to be capable of catalyzing the cellulose decomposition and increasing the amount of residue remaining at the end of pyrolysis. In the case of sodium salts such as sodium molybdate, this seems to be the most important activity of the retardants. Their effect is almost completely in the condensed phase as indicated by the oxygen index results shown in figure 9. The ammonium molybdate, however, seems capable of additional reactivity in the vapor phase (fig 10); however, the relative importance of these two modes of action cannot be determined. It should also be pointed out that there is no particular reason to assume that the condensed phase activity of the ammonium molybdate is the same as that of the sodium molybdate.

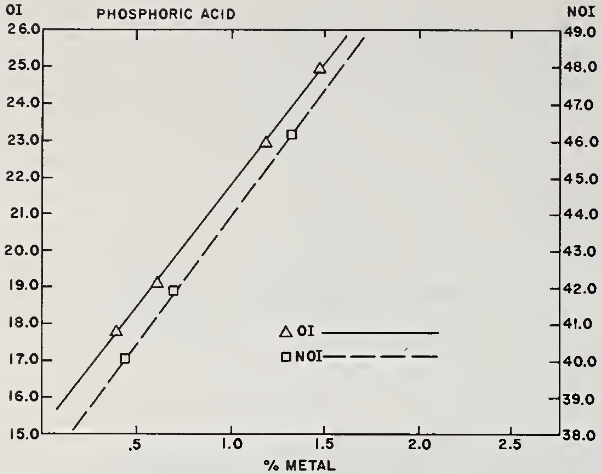


Figure 3. Phosphoric acid treated cotton.

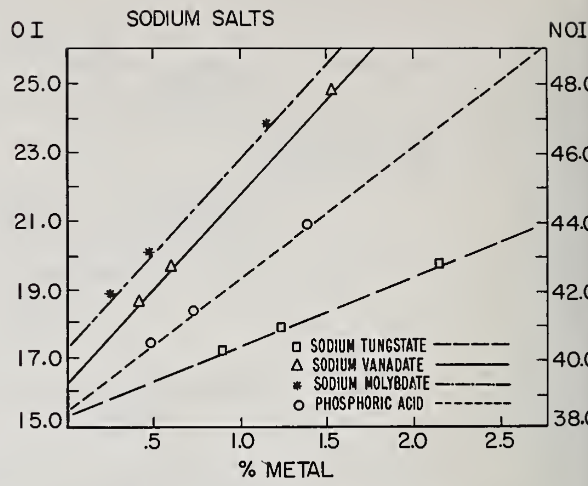


Figure 5. Cotton fabrics treated with sodium salts.

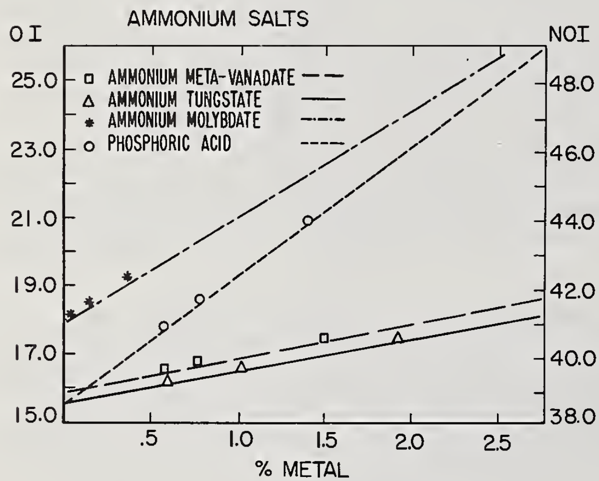


Figure 4. Cotton fabrics treated with ammonium salts.

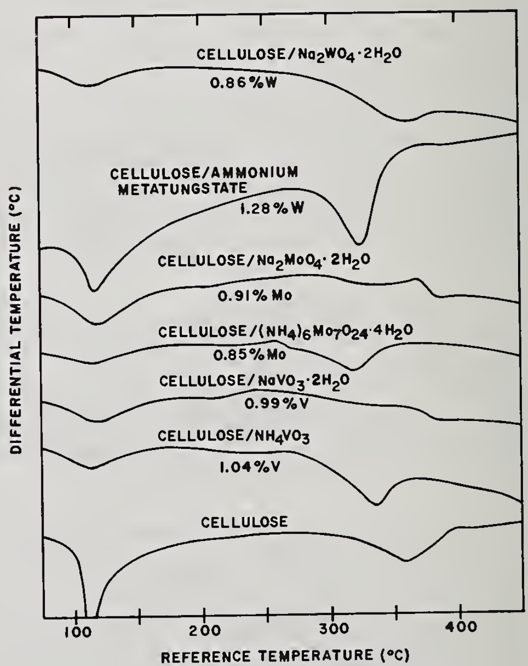


Figure 6. Differential thermal analysis thermograms for cotton cellulose treated with sodium and ammonium salts.

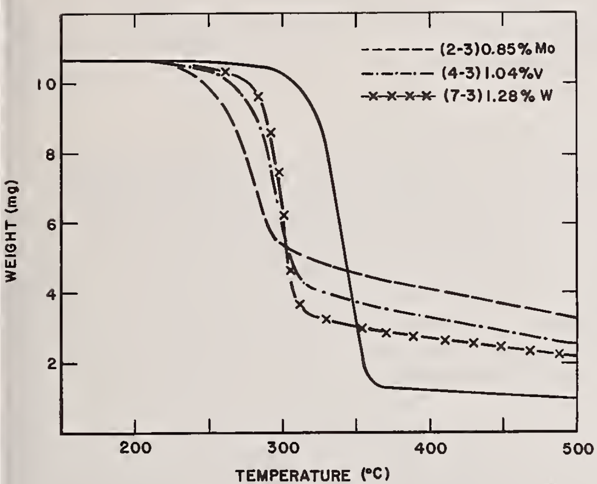


Figure 7. Thermogravimetric analysis thermograms for cotton cellulose treated with ammonium salts.

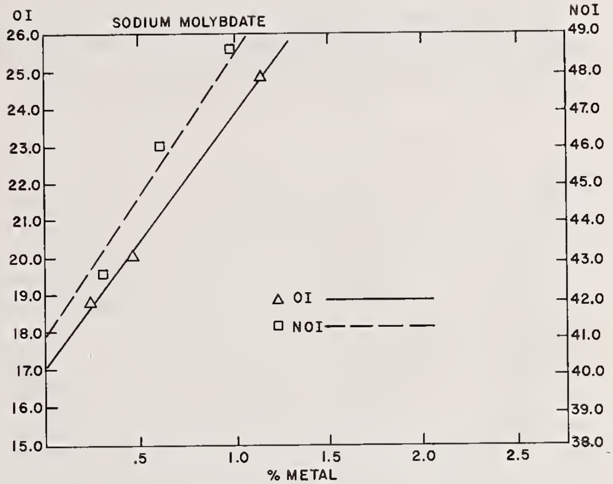


Figure 9. Cotton fabric treated with sodium molybdate.

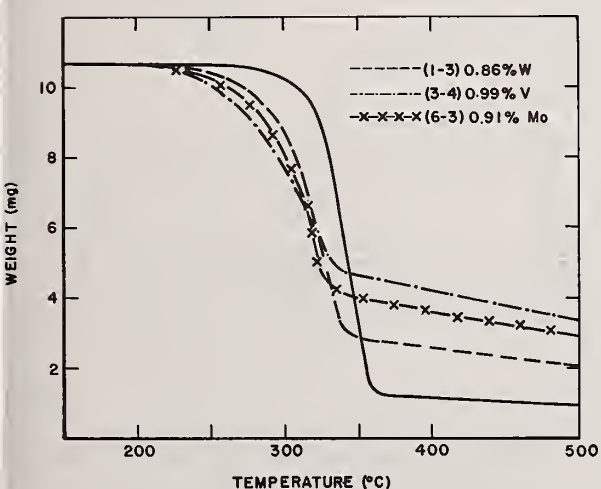


Figure 8. Thermogravimetric analysis thermograms for cotton cellulose treated with sodium salts.

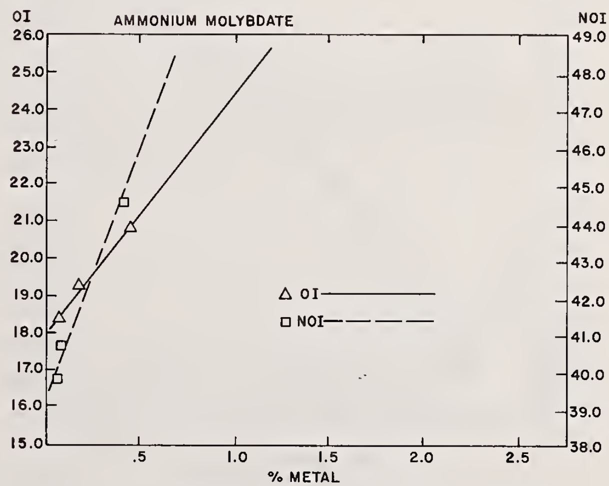


Figure 10. Cotton fabric treated with ammonium molybdate.

This technique has been extremely useful in studying many types of flame retardants on cellulosic substrates. It is, however, not limited to such substrates. Triphenylphosphine oxide has been studied as a flame retardant for polyester. [5] The results, as shown in figure 11, indicate that there is considerable vapor phase activity in this system. Differential thermal analysi and thermogravimetric analysis show no differences in the decomposition of the polymer when the phosphine oxide is present (fig. 12). It is therefore reasonable to assume that there is no condensed phase activity exerted by triphenylphosphine oxide on polyester.

Triphenylphosphine oxide has also been investigated as a flame retardant for nylon-6. [6] The oxygen index results shown in figure 13 indicate that the triphenylphosphine oxide acts in the vapor phase in this system also. Similar studies of samples containing varying amounts of triphenylphosphine, triphenylphosphite and triphenylphosphate are shown in figures 14-16. In all cases the dependence of the flame retardant efficiency on the chemical nature of the oxidant indicates considerable vapor phase activity. As with the polyesters, thermal analysis of the treated nylons shows no significant alteration in the decomposition pattern when the flame retardants are present. On this basis it can be concluded that these types of thermally stable phosphorus compounds act almost completely in the vapor phase. This is, of course, of considerable importance in these systems since it indicates that they will produce no alteration in the melt-drip characteristics of the thermoplastics. It also has significance in terms of smoke and carbon monoxide evolution since all of these vapor phase flame retardants act to inhibit oxidation and should, therefo increase the amount of incomplete combustion products present in the off-gases from the burning fabrics.

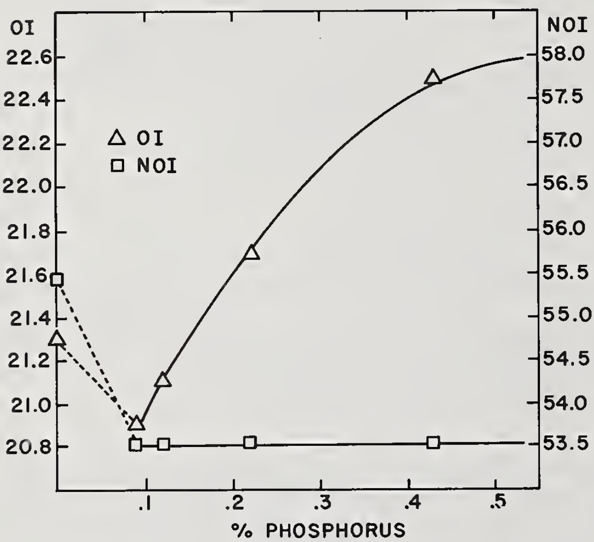


Figure 11. Plot of oxygen index and nitrous oxide index versus phosphorus content in the PET/ TPPO System.

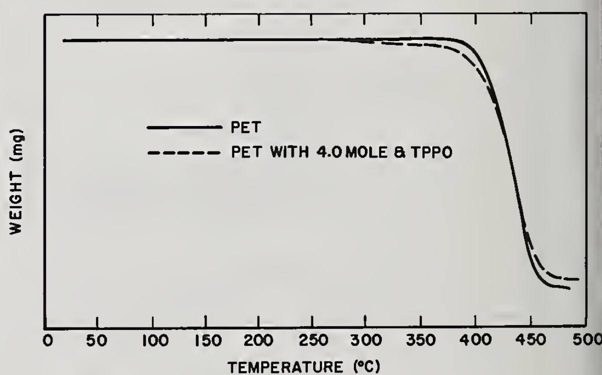


Figure 12. TGA thermograms of PET and PET with 4.0 mole percent TPPO.

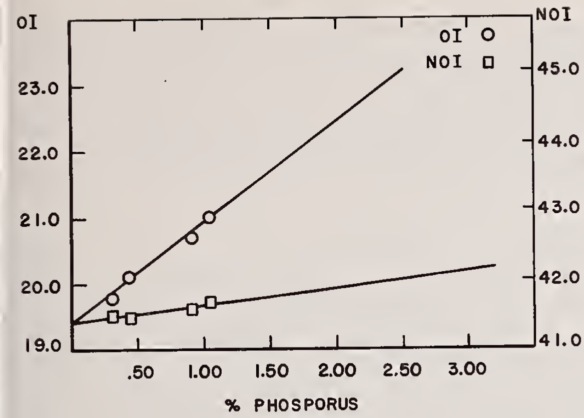
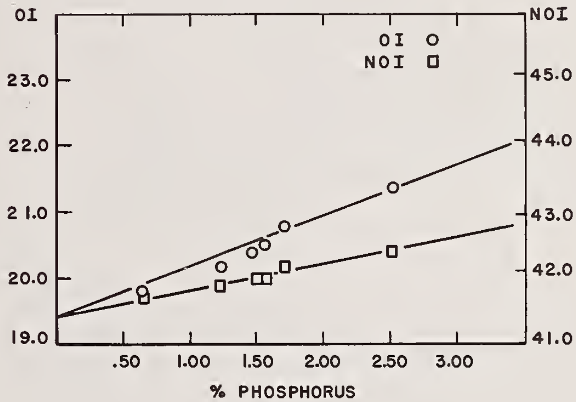


Figure 13. Plot of Oxygen Index (OI) and Nitrous Oxide Index (NOI) versus percent phosphorus for triphenylphosphine oxide.

Figure 14. Plot of Oxygen Index (OI) and Nitrous Oxide Index (NOI) versus percent phosphorus for triphenylphosphine.



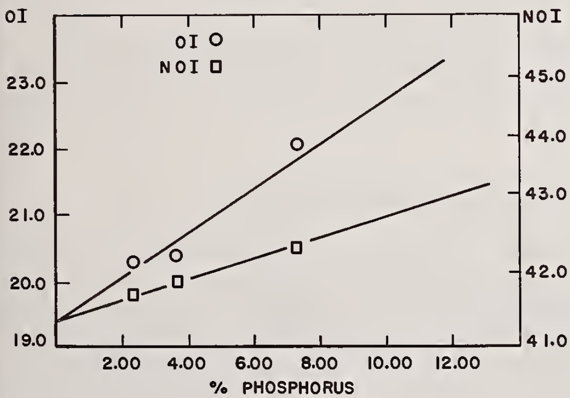
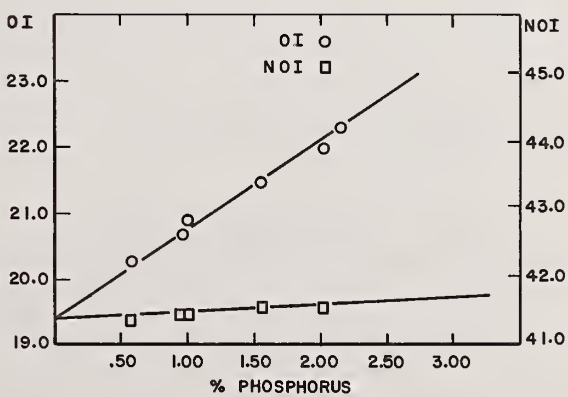


Figure 15. Plot of Oxygen Index (OI) and Nitrous Oxide Index (NOI) versus percent phosphorus for triphenylphosphite.

Figure 16. Plot of Oxygen Index (OI) and Nitrous Oxide Index (NOI) versus percent phosphorus for triphenylphosphate.



Similarly, and perhaps more surprisingly, a commercial chlorine containing organic flame retardant in combination with antimony oxide in a polypropylene matrix shows little indication of vapor phase activity in the oxygen index tester (fig. 17). Although it is usually assumed that halogen compounds act primarily as vapor phase inhibitors, this is not the first case in which only condensed phase activity has been observed for organochlorine compounds. Fenimore and Martin observed such behavior in the case of chlorinated polyethylenes. [2]

Even in the case of organobromine compounds where activity is almost always found in the vapor phase the possibilities for condensed phase activity cannot be ignored. This is particularly important since such condensed phase activity is not always desirable. A good example of this phenomenon can be found in nylon-6 samples treated with organobromine compounds. [7] Differential thermal analysis (fig. 18) and thermogravimetric analysis (fig. 19) of a nylon-6 sample containing hexabromobiphenyl shows that the bromine-containing flame retardant induces marked changes in the pyrolysis reaction of the nylon. Using only these data, and the results of the oxygen index tester, it is possible to conclude that both condensed phase and vapor phase activity are important in the flame retardation process. It is not possible, however, to determine the relative importance of the two processes. This is particularly significant in this system since further investigation shows that the vapor phase process is the only one responsible for inhibition of the flaming reaction. [7] That activity which occurs in the condensed phase turns out to have a deleterious effect on the combustibility properties of the nylon. This can be seen quite clearly by gas chromatographic analysis of the pyrolysis products when the reaction is carried out in the presence of the hexabromobiphenyl (fig. 20). Under these conditions the only observed pyrolysis products are the ε-caprolactam and the cyclic dimers and trimers normally found in the pyrolyzate from untreated nylon. The only other peak in the chromatagram is the carbon tetrachloride used as a solvent for the pyrolyzate mixture. On this basis it is possible to conclude that the hexabromobiphenyl acts in the condensed phase to catalyze the decomposition without altering the nature of the reaction. Thus the effect of the hexabromobiphenyl is to increase the amount of gaseous fuel produced by the pyrolyzing nylon. This, of course, makes the flame more difficult to inhibit and results in a much lower efficiency than would be expected for these types of compounds.

3. DETERMINATION OF HEAT EVOLUTION DURING BURNING

Although oxygen index testing and thermal analysis are frequently sufficient to gain considerable insight into fire retardance mechanisms, there are many cases similar to that of the hexabromobiphenyl in nylon-6 where additional techniques must be used to provide enough information to allow even tentative elucidation of the fire retardant mechanism. In many such cases calorimetry provides the most useful mechanistic probe available since the net effect of a flame retardant is almost always reflected in a reduction in the heat produced by the burning fabric. For this reason, considerable effort has been expended both at Clemson University and at the National Bureau of Standards to develop calorimetric techniques for the measurement of such heat evolution. One of the simplest of these is based on static oxygen bomb calorimetry and involves only one major limitation. [8]

When a fabric burns in open air, the evolved heat can usually not be measured directly without the aid of a specially designed isoperibol calorimeter [9]; but under certain circumstances it can be calculated from more easily measurable quantities such as the standard specific heat of combustion of the polymer and the standard specific heat of combustion of the char resulting from burning the polymer in the open air. [8] This calculated value, designated as Δ, corresponds quite closely to the actual heat liberation in the case of light-weight cellulosic fabrics where essentially all of the flammable gases

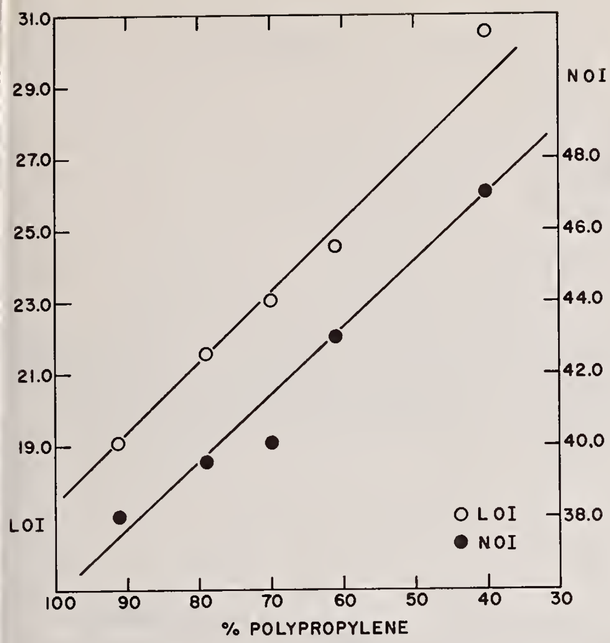


Figure 17. Polypropylene containing animony oxide and organo chlorine flame retardant.

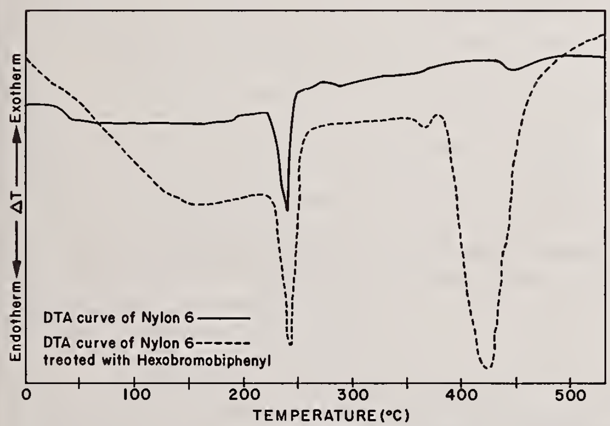


Figure 18. Plot of the differential thermal analysis (DTA) curve of Nylon 6 compared to the DTA curve of Nylon 6 treated with Hexabromo-biphenyl.

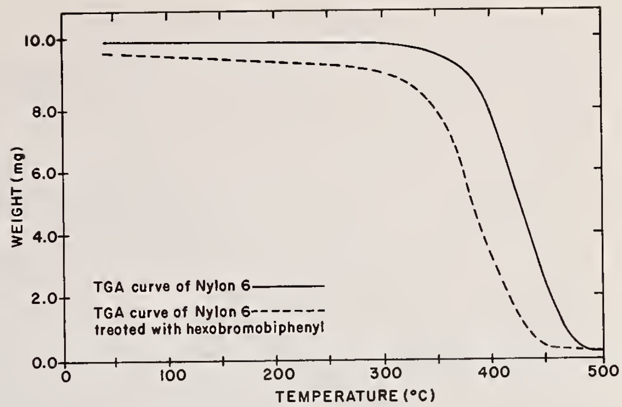


Figure 19. Plot of the thermo-gravimetric analysis (TGA) curve of Nylon 6 compared to the TGA curve of Nylon 6 treated with Hexabromobiphenyl. Samples were decomposed at a heating rate of 6°C per minute.

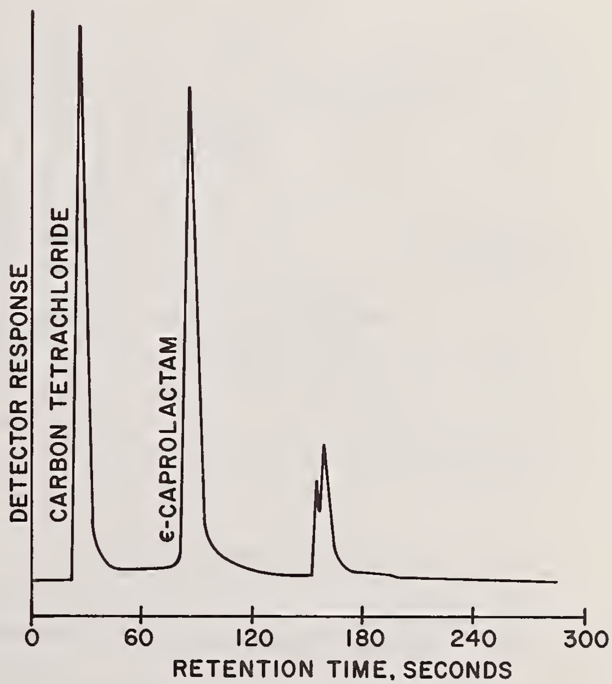
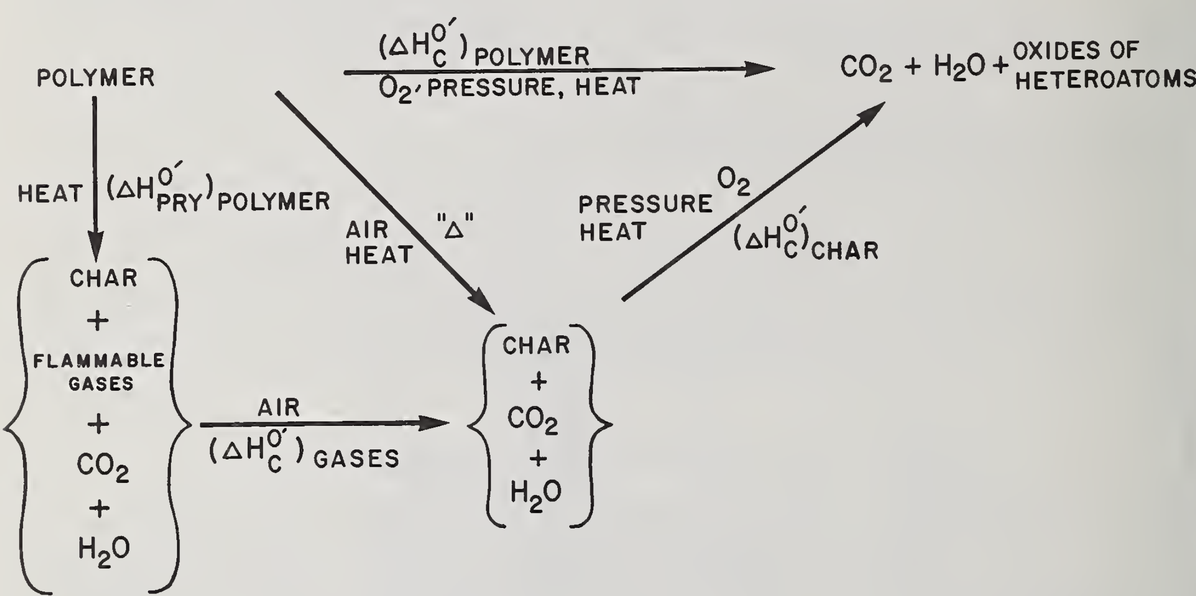


Figure 20. Gas chromatograph of Nylon 6 treated with hexabromo-biphenyl programmed at 15°/ minute from 90°C to 250°C.

are burned to produce carbon dioxide and water. This is shown diagramatically in figure 21. This value is closely related to the total flammability of the system and is, therefore, of considerable importance. Its significance, however, lies primarily in the fact that it can be further interpreted to produce information relating to the exact molar efficiency of a particular flame retardant system. The heat value, Δ, can be related to the amount of cellulose undergoing decomposition to produce flammable gases by the relationship shown in figure 22. As indicated, Δ equals the sum of Y, the weight fraction of cellulose converted to flammable gases, multiplied by the heat of combustion of the cellulose, and X the weight fraction of reagent on the sample, multiplied by the heat of combustion of the reagent. The fraction of cellulose converted to flammable gases can then be easily calculated as Y/(1-X). The dependence of Y/(1-X) as a function of the concentration of the flame retardant on the fabric provides a measure of the efficiency of the flame retardant system. Using this methodology it has been possible to study the relationship between the structure of the phosphorus-containing group and its efficiency in imparting flame retardant characteristics to cotton fabric. These results were the subject of several recent reports. [10,11]

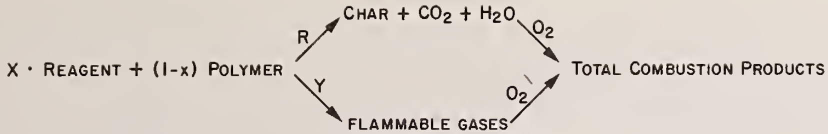


$$(\Delta H_C^{O'})_{POLYMER} = \Delta + R(\Delta H_C^{O'})_{CHAR}$$

$$\Delta = (\Delta H_{PRY}^{O'})_{POLYMER} - (\text{AMT. OF FLAMMABLE GAS})(\Delta H_C^{O'})_{GASES}$$

$$= (\Delta H_C^{O'})_{POLYMER} - R(\Delta H_C^{O'})_{CHAR}$$

Figure 21. Thermochemistry of polymer combustion.



X = WEIGHT FRACTION OF TREATING REAGENT

R = WEIGHT FRACTION OF POLYMER CONVERTED TO CHAR

Y = WEIGHT FRACTION OF POLYMER CONVERTED TO FLAMMABLE GASES

Figure 22. Thermo-decomposition pathways.

In the investigation of simple phosphorus flame retardants for cellulose the results shown in figure 23 were obtained. [8] Compounds such as phosphoric acid, diammonium phosphate, and the THPOH-ammonia polymer were all found to have essentially the same efficiency characteristics. This indicates that the limiting factor in determining the efficiency of these types of flame retardants is not their chemical structure but rather is their ability to break down to form phosphorus oxides. These phosphorus oxides are the common intermediate in the reaction of the retardants with the cellulose substrate. The ultimate efficiency of such non-thermally stable systems is, therefore, given by the effectiveness of the interaction between cellulose and the phosphorus oxides. The only possibility for their efficiency to be enhanced would be for them to be converted into some degradation product other than phosphorus oxides by a preceding reaction with an additional reagent applied to the cellulose. This has been found to constitute the basis for the phosphorus-nitrogen synergistic effects observed by many workers. [11]

The situation becomes considerably more complex when the flame retardants are thermally stable up to the point of polymer degradation. In such systems the nature of the phosphorus-containing functional group is important in determining the flame retardant efficiency of the system. Figures 24 and 25 show that for the phenyl derivatives, the efficiency of the flame retardant system increases as the number of oxygen bonded to the phosphorus increases. [10] An exception to this behavior is observed with triphenylphosphate which probably represents a special case because of its volatility. This would indicate that for thermally stable flame retardant additives the efficiency of the system can be limited by the chemical nature of the phosphorus compound. These results, when viewed in the context of other experiments involving product analysis and model compound studies [12,13] allow the elucidation of the complete chemical mechanism for the interaction of phosphorus flame retardants with cellulose. The efficiency of such reagents appears to be related to the electron density at the phosphorus atom. As the electron deficiency increases, the molecule becomes more electrophilic and more acidic. This leads to enhanced interaction in phosphorylation reactions and increases its efficiency in catalyzing the degradation of the cellulose. Both of these reactions inhibit the formation of flammable volatiles from the cellulose and promote formation of char and incombustible volatiles.

Although such correlations are fairly straightforward in most cases, the calorimetric technique is also capable of discerning unusual and unexpected effects. For example, it has recently been found that for structures of Type I the flame retardant efficiency of the phosphorus compound depends strongly upon the chemical nature of the moiety attached to the other end of the carbon chain. [11] (fig. 26)

$$(CH_3O)_2-\overset{O}{\overset{\|}{P}}-CH_2-CH_2R$$

I

R - CN
$C(O)OCH_3$
$C(O)NH_2$
$C(O)NHCH_2OH$

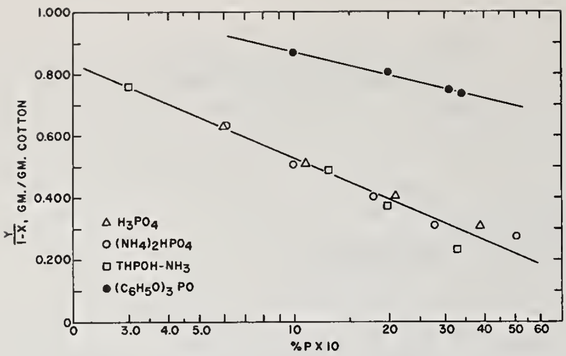


Figure 23. Estimated tar formation for treated cotton.

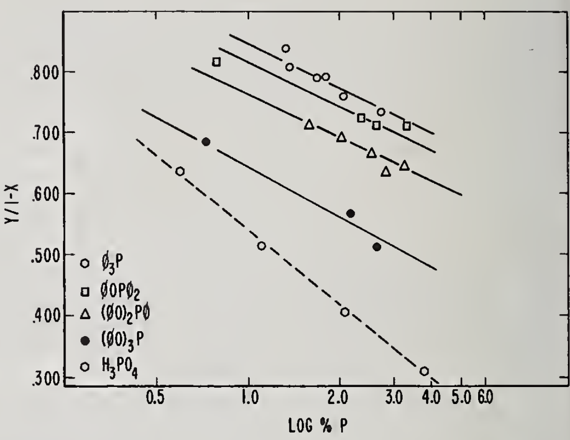
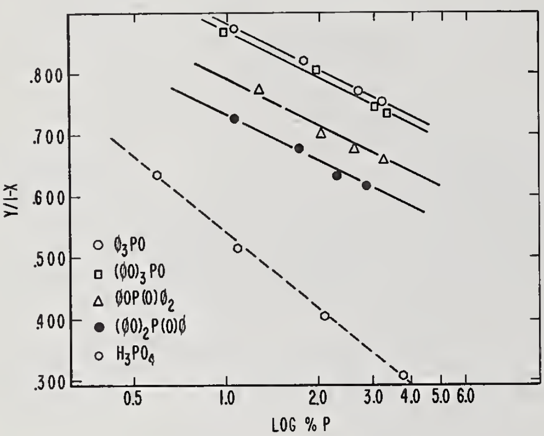


Figure 24. Flammable gas production from cotton treated with trivalent phosphorus compounds.



'igure 25. Flammable gas production from cotton treated with pentavalent compounds.

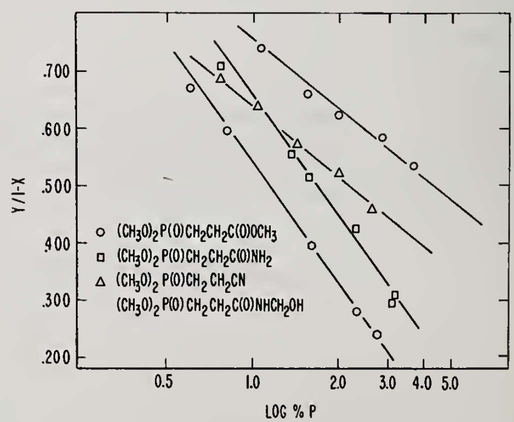


Figure 26. Flammable gas production from cotton treated with aliphatic phosphonates.

The reasons for these unusual structural effects are not obvious from the calorimetric data alone; but these results have been interpreted in terms of an interaction between the phosphorus and nitrogen-containing groups within the same molecule. This happens prior to interaction with the cellulose so that the species which reacts with the cellulose is most probably a phosphoramide rather than a phosphonate.

4. CONCLUSIONS

It has been shown that considerable insight into the mechanism of flame retardant action on textiles can be obtained by a combination of oxygen index testing using two or more oxidants, thermal analysis, and static oxygen bomb calorimetry. The first two methods, when used together, allow a determination of the site of activity of the flame retardants. The calorimetry gives a more detailed picture of the type of interaction involved and allows, in many cases, a quantitative estimation of the efficiency of this interaction.

5. REFERENCES

[1] Hendrix, J. E., Bostic, J. E., Jr., Olson, E. S. and Barker, R. H., J. Appl. Poly. Sci., Vol. 14, 1701 (1970).

[2] Fenimore, C. P. and Martin, F. J., Proceedings of the 4th Materials Research Symposium, National Bureau of Standards, 1970.

[3] Wu, H. S., M.S. Thesis, Clemson University, 1970.

[4] Archie, W. A., Gill, J. T. and Barker, R. H., Abstracts of Papers Presented, 163rd National Am. Chem. Soc. Meeting, Boston, Mass., April, 1972, CARB-22.

[5] Bostic, J. E., Jr., Ph.D. Dissertation, Clemson University, 1972.

[6] Barker, R. H., Bostic, J. E., Jr., Reardon, T. J. and Strong, R. A., Abstracts of Papers Presented, 164th National Am. Chem. Soc. Meeting, New York, N.Y., August, 1972, CELL-67.

[7] Reardon, T. J., M.S. Thesis, Clemson University, 1972.

[8] Yeh, K. and Barker, R. H., Text. Res. J., Vol. 41, 932 (1971).

[9] Birky, M. and Yeh, K., J. Appl. Poly. Sci., Vol. 17, 239 (1973).

[10] Batavia, B. A. and Barker, R. H., Abstracts of Papers Presented, 162nd National Am. Chem. Soc. Meeting, Washington, D.C., Sept., 1971, CELL-47.

[11] Drews, M. J., Yeh, K. and Barker, R. H., Textilveredlung, Vol. 8, 180 (1973).

[12] Hendrix, J. E., Drake, G., Jr. and Barker, R. H., J. Appl. Poly. Sci., Vol. 16, 41 (1972).

[13] Hendrix, J. E., Drake, G. L., Jr. and Barker, R. H., J. Appl. Poly. Sci., Vol. 16, 257 (1972).

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ADDITIONAL STUDIES OF THE TRANSFER OF FLAME RETARDANT EFFECTS WITH CELLULOSIC FABRICS

Bernard Miller
Textile Research Institute, Princeton, New Jersey

Burning rate measurements on double layers of the same fabric when one layer has been treated with a flame retardant have indicated that certain effects of the retardant can be transferred to the untreated layer. To learn more about the mode and chemistry of this phenomenon, a study of non-flaming combustion of cellulosics has been carried out on mixed systems using thermogravimetric analysis. By arranging to have untreated cotton physically separated from the flame retardant material during heating it was possible to determine that the transfer depends on a chemical process and is most likely the effect of a volatile product generated during heating. Data are presented also showing that rayon containing an alkoxy-phosphazene flame retardant does not transfer its flammability properties to untreated rayon.

Key words: Cellulosics; cotton; DAP; fabric flammability; flame retardants; flammability; rayon; thermogravimetric analysis.

1. INTRODUCTION AND BACKGROUND

The customs of usage of textile materials make it highly probable that many fabrics will be used, either deliberately or inadvertently, as components of multilayer assemblies. When such structures have layers made up of different materials, it is necessary for us to know whether or not the flammability behavior of the combinations would be predictable from knowledge of the behavior of the individual fabrics involved. A large amount of experimental data is needed to answer this question; much of it is still to be obtained. We have been studying one aspect of the problem: the behavior of double layers of a single material when one of the layers has been treated with a flame retardant. In a previous publication [1] it was shown that the effect of a flame retardant, in terms of altering the burning rate, could be transferred to an adjacent untreated fabric. This was found to be the case for cotton treated with diammonium phosphate (DAP), for nylon treated with thiourea, and for polyester treated with tris (2,3-dibromopropyl) phosphate (T23P). With cotton plus DAP, transfer was most evident when the treated layer was placed underneath the untreated cotton (during horizontal burning). This has led to the conjecture that the transfer effect is the result of the crossover of a volatile product formed during the heating of the treated fabric (that is, physical contact between the layers may not be a necessary condition for this phenomenon).

It was thought that useful information relevant to this and other points might be obtained if potential transfer situations could be studied without the occurrence of flaming combustion. Consequently, an experimental program was devised to study the pyrolysis behavior of such systems with controlled degrees of contact between components.

2. PYROLYSIS WEIGHT LOSS STUDIES

Weight loss studies on heating in air were carried out with the aid of a thermogravimetric analyzer (TGA) which used a platinum cup as a macro sample holder (fig. 1). This holder, considerably larger and deeper than the sample holders of most commercial TGA units, allowed the stacking of materials one above the other. One material could be placed in the bottom of the cup below a removable metal mesh screen which served to support a piece of fabric as the upper component. It was thus possible to obtain weight loss data under programmed heating for a variety of stacked combinations.

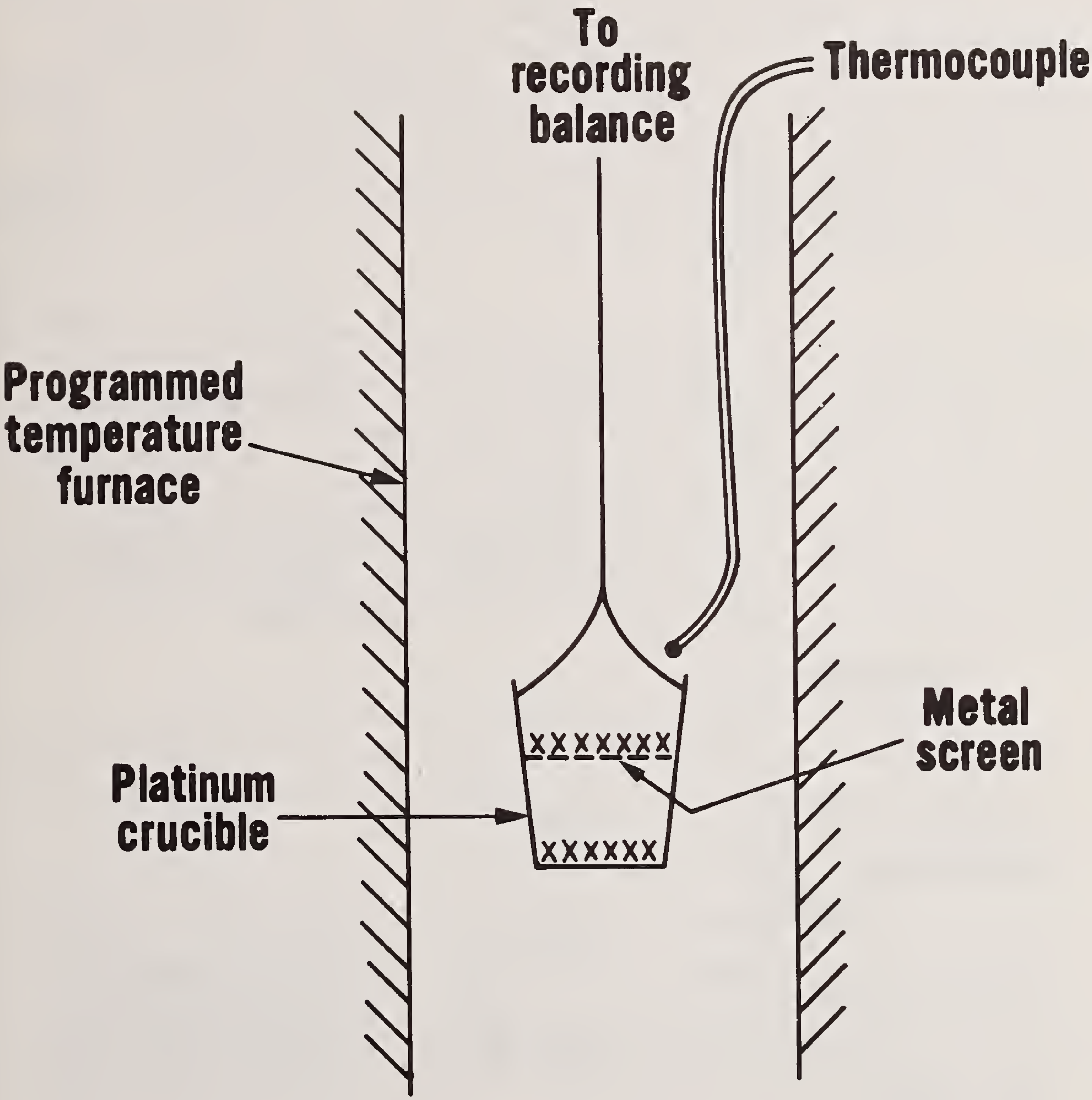

Figure 1. TGA assembly for stacked sample systems.

2.1. TGA of Cotton and DAP-Cotton Fabric Systems

Figure 2 compares TGA thermograms for an untreated cotton fabric and the same fabric treated with flame retardant. A considerable change in the pattern of weight loss with increasing temperature is introduced by the addition of 7.8% DAP; both the temperature at which the maximum rate of weight loss occurs and the amount of weight loss are reduced. Figure 3 shows thermograms for two systems containing equal weights of the untreated and the treated cotton, in one case intimately mixed, and in the other separated, with the treated fabric underneath. Two weight loss peaks occur close together in the case of the intimate mixture, the first one at a temperature slightly higher than the maximum rate of loss temperature for the treated fabric. For the separated system, the two peaks are discrete. In both instances, the second drop in weight occurs at a temperature lower than the peak rate of loss temperature for plain cotton. This is an indication that the effect of DAP on the peak rate of loss temperature of cotton is in some measure transferred from treated to untreated layer even when the two are not in contact.

In table 1 are listed the amounts of residual char at 500°C (taken from the thermograms) for the four systems studied, and the directly measured final weights of residue in the two-layer experiment after heating to 560°C. It is seen that DAP, like most flame retardants for cellulose, increases char production. The results for the mixed systems substantiate that cotton is modified in the presence of DAP-treated fabric even without contact. If there were no interaction, the total char weight at 500°C for each of the mixed systems should be no more than (17.5 + 1)/2 = 9.3%, whereas the percentages are 13.8% and 17.2%. Further, since plain cotton leaves virtually no char after heating to 560°C, the weight of residue in the cotton layer after the two-layer experiment, if there were no transfer, should be insignificant rather than the measured 5.0%. A control experiment in which two separated layers of untreated cotton were heated produced a 1% residue, with no significant difference between the amounts of solid remaining in each layer.

Table 1. Residual Char Weights After Heating In Air

System	At 500°C	After 560°C[a]
Cotton	<1%	Ash
7.8% DAP-Cotton.	17.5%	
Cotton + 7.8% DAP-Cotton (1/1) .	13.8%	
Cotton / 7.8% DAP-Cotton 2 Layers (1/1) .	17.2%	5.0% (of original cotton) / 12.6% (of original treated cotton)

[a]Final weights of each layer after heating to 560°C and cooling to room temperature.

2.2. TGA of Cotton Fabric Pyrolyzed Over Solid DAP

A series of two-layer TGA experiments were run involving varying proportions of plain cotton fabric and solid DAP, with the latter in the bottom of the crucible. By itself DAP salt begins to lose weight slowly at 150°C; at 500°C under these heating conditions it has lost 29% of its original weight, a few percent more than the theoretical value if the only loss were two molecules of ammonia. Allowing for this, the weight of cotton residue can be calculated from the total weight loss of the system.

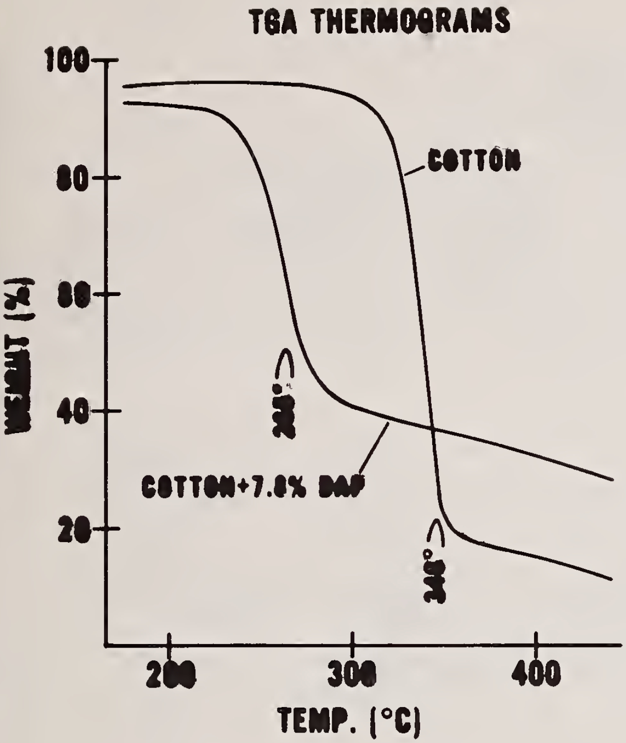

Figure 2. Weight losses on heating in air at 15°/min.: untreated cotton and cotton treated with 7.8% diammonium phosphate.

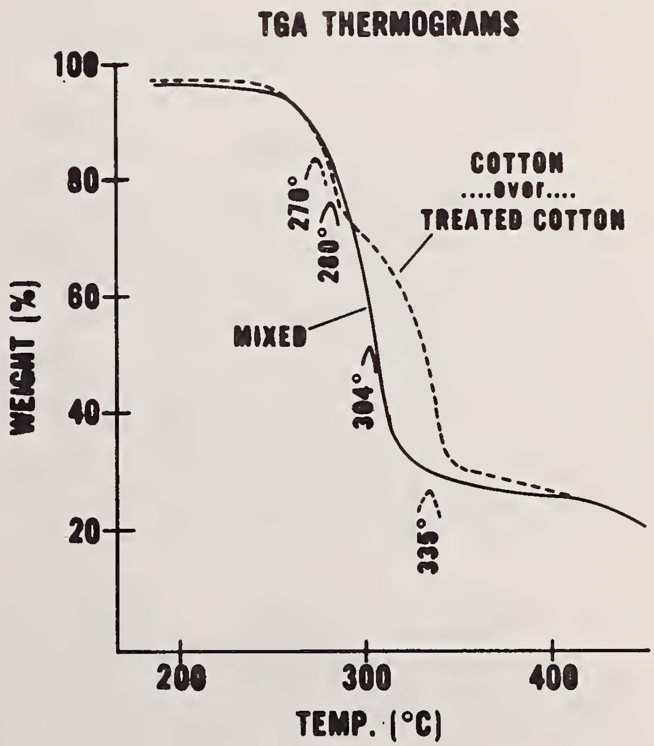

Figure 3. Weight losses on heating in air at 15°/min.: untreated cotton and cotton treated with 7.8% diammonium phosphate, in one case intimately mixed and in the other, separated, with the treated fabric underneath.

The thermograms of figures 4 and 5 and the weights of cotton residue at 500°C listed in table 2 appear to confirm that properties conferred by DAP are transferred from the solid to the fabric though the two are not in contact. The peak rate of weight loss for 75 mg of cotton over 25 mg of DAP (fig. 4) occurs at a temperature lower than that for cotton alone, and there is more residue (4%) at 500°C than expected if there were no interaction. For 50 mg each of cotton and DAP in the same arrangement, the peak rate of weight loss occurs at an even lower temperature and again there is appreciable cotton residue (5%). Surprisingly, the trend toward lower peak decomposition temperature is reversed when 25 mg of cotton is pyrolyzed over 75 mg of DAP, the maximum rate of weight loss coming at a higher temperature than for plain cotton (fig. 5). The amount of cotton char is increased to 26%, however, which presumably indicates a high degree of imposed flame retardancy. This last effect is essentially duplicated when the same proportions of cotton and DAP are intimately mixed and pyrolyzed (fig. 5): the weight loss curve falls more gradually than for the separated components, but the greatest loss is still at a higher temperature than for cotton; again, the amount of cotton char is high -- 35% of the original sample.

Table 2. Weight Losses of Cotton Heated to 500°C in Air Over DAP

Cotton Over DAP (mg/mg)	Total Weight Loss (mg)	Cotton Weight Loss[a] (mg)	Cotton Residue (%)
75/25	79.2	72.0	4.0
50/50	62.0	47.5	5.0
25/75	40.3	18.5	26.0
25 + 75 (mixed)	38.0	16.5	35.0

[a]Calculated by adjusting for a 29% loss in weight of DAP.

2.3. TGA of Cotton and Pyrovatex-CP-Cotton Fabric Systems

Although DAP is a convenient prototype of a phosphate flame retardant for cellulose, it is not chemically bound to cotton before heating. It was of interest to determine if transfer effects occur in a system involving a "permanent" retardant, chemically combined with the cotton. Pyrovatex-CP was considered such a permanent retardant in view of its fastness to washing, and a sample of cotton treated with this phosphorus-containing additive to an unknown but effective add-on level was run in the TGA apparatus. Its weight loss behavior, shown in figure 6, is very similar to that of DAP-cotton (fig. 2). Here the maximum weight loss occurs near 300°C and 24.7% of the sample remains at 500°C. In a two-layer experiment with 50 mg of cotton fabric above an equal weight of this treated fabric (fig. 6), just as in the parallel experiment with DAP-cotton (fig. 3), the weight loss peak for the untreated material drops to a lower temperature than for cotton alone, and there remains an appreciable cotton char residue at 500°C (8.8%).

2.4. Direct Test For Transfer of Phosphorus

A series of experiments was performed to determine whether phosphorus could be detected as having transferred to untreated cotton under appropriate conditions. Cotton sheeting was stretched over the top of a dish (2-1/2" deep) containing either DAP or cotton treated with DAP. The dish was placed on a hot plate and heated for at least one hour at temperatures between 150 - 200°C.

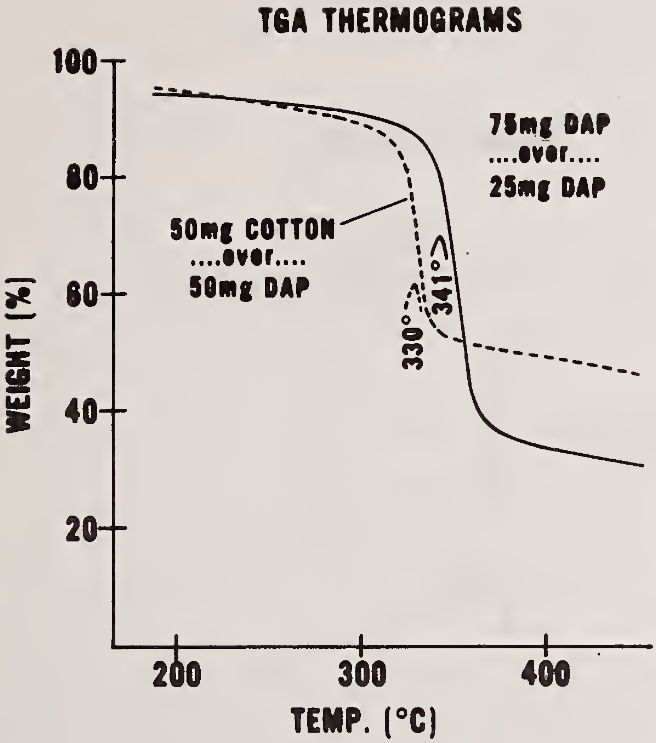

Figure 4. Weight losses on heating in air at 15°/min: Cotton/DAP two-layer systems.

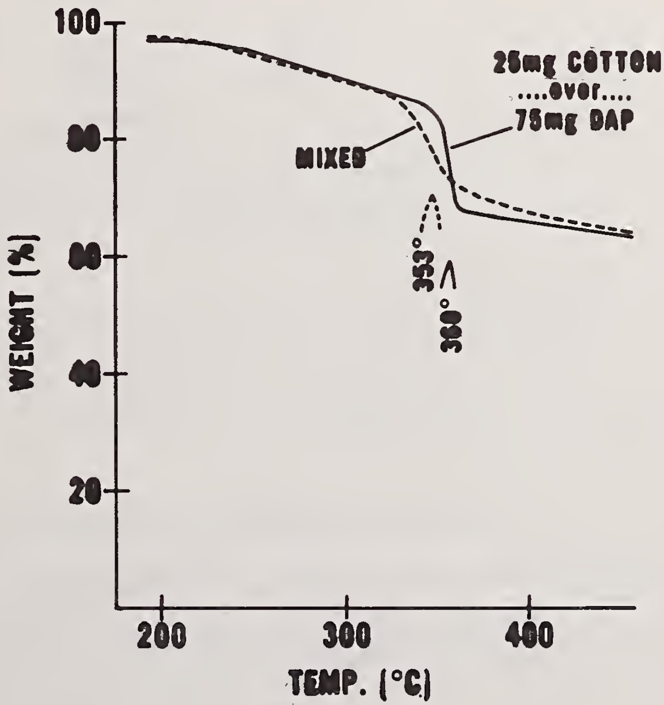

Figure 5. Weight losses on heating in air at 15°/min: Cotton/DAP (1/3).

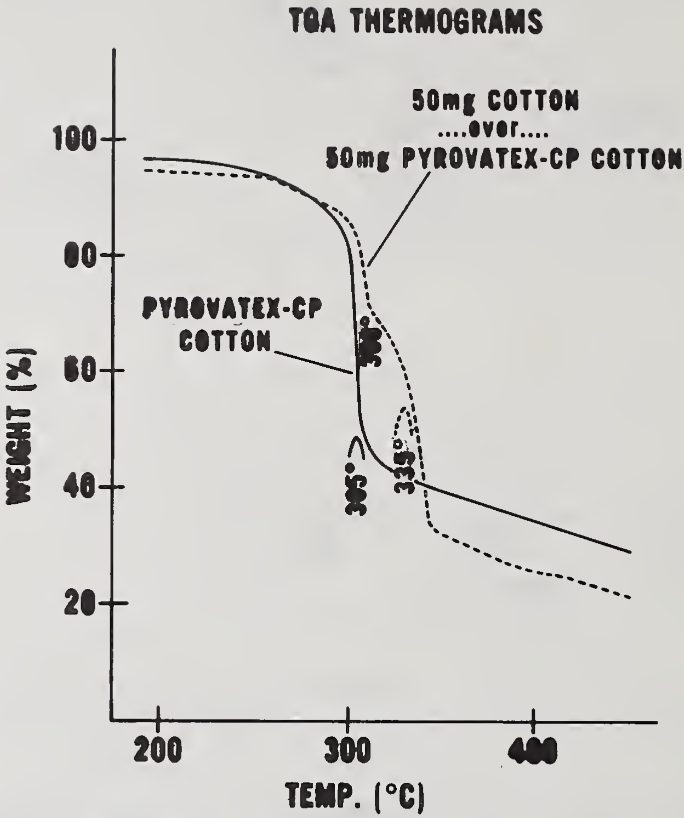

Figure 6. Weight losses on heating in air at 15°/min: Pyrovatex-CP treated cotton and untreated cotton.

Part of the cotton sheeting was masked from below with aluminum foil and asbestos to supply a control for each transfer experiment. After heating, a qualitative test for phosphate was performed by digesting the fabrics with nitric acid and ammonium molybdate. The formation of a yellow precipitate indicated the presence of phosphate. [2] In all cases, a significant positive test for phosphorus transfer was obtained.

3. BURNING RATE STUDIES WITH FLAME RETARDANT RAYON

In extending our studies on flame retardant transfer effects, one system has been found to be anomalous in that burning rates for mixed double layers do not reflect the presence of the flame retardant. This occurs with PFR rayon, a commercial fiber produced by adding an alkoxy-phosphazene to viscose spinning dope to accomplish the deposition of this additive in the regenerated rayon filaments. [3] Burning rates for various double layer combinations are shown in table 3. It can be seen that, whereas a double layer of 13% PFR rayon

Table 3. Burning Rates For Rayon Double Layers

System Configuration	Top Layer / Bottom Layer	Propagation Rate (in/min)	Mass Burning Rate (oz/min-in)
Horizontal at 29.5% O_2	Rayon / Rayon	4.15	0.026
	PFR (13%) / PFR (13%)	6.28	0.034
	Rayon / PFR (25%)	4.51	0.026
45° Upward at 21.7% O_2	Rayon / Rayon	13.7	0.085
	PFR (13%) / PFR (13%)	23.3	0.126
	Rayon / PFR (25%)	14.5	0.084
	Rayon / PFR (13%)	14.0	0.081

burns faster than a comparable sample of untreated rayon[1], a mixed system of untreated rayon over 25% PFR rayon has the same burning rate as the untreated material. Indeed, it seems that the burning rate of each mixed system is determined by the untreated rayon and not influenced by the amount of additive in the treated layer. This is in sharp contrast to the results found with other flame retardant cellulose materials. [1]

4. CONCLUSIONS

The pyrolysis data obtained in this investigation reinforce the earlier observation that the effect of a flame retardant can be transferred to an adjacent untreated layer of material. Also, it seems possible for this to occur without actual physical contact between the solid phases. Since certain effects of flame retardants are not desirable (e.g., enhancement of the burning rate of treated cellulosics), it is necessary that we increase our knowledge about how such mixed systems will behave. The absence of any transfer effect with flame retardant rayon reiterates the oft-repeated warning that no generalization can be made as yet as to the influence of chemical factors on flammability behavior.

[1]The reader might be surprised to note that flame retardant treated rayon burns faster than untreated rayon; however, this is not an unexpected result. Every flame retardant for cellulose tested so far actually increases the flame propagation rate across the material. An example of this is given in the earlier paper on the transfer effect [1] and a more extensive report on this phenomenon is being prepared. The reputation of so-called flame retardants for cellulose is based on their ability to enhance the self-extinguishability of the material, as determined by char length or oxygen index tests (see table 4).

Table 4. Oxygen Index Values For Rayon Double Layers

Top Layer / Bottom Layer	Oxygen Index
Rayon / Rayon	0.189
Rayon / PFR (13%)	0.223
Rayon / PFR (25%)	0.226
PFR (13%) / PFR (13%)	0.259
PFR (25%) / PFR (25%)	0.263

5. REFERENCES

[1] Miller, B. and Turner, R., Textile Res. J., Vol. 42, 629 (1972).

[2] Feigl, F., Laboratory Manual of Spot Tests, 176-177, Academic Press (1943).

[3] Godfrey, L. E. A. and Schappel, J. W., Ind. & Eng. Chem., Products Research and Development, Vol. 9, 426 (1970).

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AN EVALUATION OF FLAME SPREAD TEST METHODS FOR FLOOR COVERING MATERIALS

James Quintiere and Clayton Huggett
National Bureau of Standards, Washington, D.C.

Flammability properties of materials have traditionally been measured by small scale laboratory tests. The relationships between test results and performance in real fires have been largely inferred by intuition or subjective judgement. Flame spread test methods for floor covering materials are examined. Through full-scale fire experiments and laboratory studies the nature of the potential flame spread hazard of flooring materials is presented. The factors promoting flame spread in each test method are identified. Test method results are compared with relevant full-scale fire experiments involving floor covering materials in a corridor. An effort is made to relate test results, where possible, to the potential flame spread hazard of floor covering materials in building corridors and exitways.

Key words: Corridor fires; fire test methods; flame spread; flammability tests; floor covering flammability; floor coverings.

1. FIRE SPREAD OVER FLOOR COVERINGS IN BUILDINGS

In the last decade, concern has been expressed about the flammability hazard of floor covering materials. This concern has probably been induced by the widespread use of carpeting and by several fire incidents which have suggested that the floor covering was a significant factor in fire spread. Yuill [1] described the state of this issue in 1970. Previous to this, except for fire safety regulations for hospitals financed under the Hill-Burton Act (1965), fire officials had not considered floor coverings to be a significant fire hazard, although, several fires had indicated that carpeting could be significant in the early spread of a fire. Using a 5 lb wood crib as an ignition source, Yuill demonstrated that two high-cut pile (shag) carpets would propagate a flame over a 5 ft wide x 15 ft long corridor. (One carpet had a flame spread rating of 55 by ASTM E-84 [14], the other had a rating of 1100!) With the introduction of DOC FF-1-70 [2], a mandatory nationwide flammability standard for carpets incorporating the "Pill Test", one may assume that no carpets easily ignited by "small" ignition sources entered commerce after April 15, 1971. However, the flammability hazard associated with carpets which pass the Pill Test and with other floor covering materials not subject to regulation remains to be defined and dealt with.

1.1. Fire Incidents

In recent years several fires in nursing or retirement homes and hotels, apparently aggravated by floor covering flame spread, have resulted in deaths and extensive loss in property. Thus, one of the objectives of the evaluation reported here has been an analysis of the reports of these and other fires with the purpose of gaining some appreciation of the role played by the floor covering material in the spread of fire.

Robertson [3] has reviewed the available statistics. The following is taken from this report, where tables 1 and 2 of this paper are condensed versions of tables developed by Robertson. He states

"...the data available are not voluminous. They comprise reports published in the NFPA Fire Journal and fire injury reports in the NBS

FFACTS[1] file which specifically mention floor covering materials as influencing fire spread. A total of seven Fire Journal reports were studied while the 135 reports of carpet related fire accidents in the NBS records were carefully reviewed. In most of the latter reports it became clear that either the carpeting involved was excessively flammable on the basis of DOC FF-1-70 (the Pill Test) or data were lacking to clearly identify the carpeting as a significant contributor to the fire. From study of these reports only seven cases have been identified in which the floor covering material appears to have actively participated in spread of the fire. These are summarized in table 1. Table 2 summarizes information on some of the fires in which fire spread was attributed to the influence of the floor covering. It seems likely though that in most of these instances the floor covering involved would have failed the ignition and spread test currently applicable to carpeting under DOC FF-1-70. In both tables the order of listing is in apparent decreasing relevance to the problem in question."

Hence, only seven fire incidents, which indicate a major contribution to fire spread by carpets that pass the Pill Test, have been identified from a data base of fabrics fires. In all cases a large ignition source was necessary before the carpeting apparently became involved in fire spread. The first two fire incidents in table 1 clearly illustrate the potential hazards of floor covering fires in corridors. This type of fire blocks paths of escape, can increase the spread of fire and smoke to adjoining compartments, and make suppression and rescue operations difficult. Other incidents listed in table 1 demonstrate other factors relevant to the potential hazard of flooring fires. The Palm Beach case clearly shows that the relative hazard of combustible wall lining is far greater than that associated with combustible flooring. Indeed, in this case, given an ignition exposure of a room fire, the fire chose to spread along the upper wall carpeting, and no significant spread developed on the floor carpeting. Also, draft conditions determined by wind and building stack effects direct the flow of fire products within the building and thus affect the spread of fire on combustible flooring. From case 3269 (table 1), it is reasoned that the fire did not spread along the flooring into the north corridor because the products of combustion were channeled into the elevator shafts and the east corridor first. With insufficient heating of the north corridor, the fire did not continue to propagate on the floor.

In addition to these cases, the data bank on fire incidents in the United Kingdom provides a source of information on flooring fires. A study of building fires by Chandler [4] in which the floor covering material was first ignited yields table 3. Also, these data reveal that in 1962, 75 percent of floor covering fires were due to space heaters, 86 percent did not spread beyond the room of origin and that an increase in the number of non-wool carpets resulted in an increase in the number of carpet fires.

More recent data from the United Kingdom by Fry [5] are displayed in table 4. It is significant here that floors, stairs, and skirting board fires are listed in addition to floor covering fires. Fry reports that although building fires have increased in frequency since 1962, there has been a decrease in fires started by open fires. It is apparent that floors and stairs, presumably of wood construction, are involved in the initial spread of fires as frequently as floor coverings, such as carpets and tile.

[1]This acronym, FFACTS, stands for "Flammable Fabrics Accident Case and Testing System." The case numbers in this system involve uniform five digit numbers. The zero prefix digits have not been included in this report.

Table 1. Cases in Which Carpet Ignited By an Exposure Fire Was the Major Factor in Subsequent Fire Spread and Growth (It is presumed that all of these carpets would pass the Pill Test.)

Case	Flooring Fire Exposure	Flooring Material	Location of Flooring	Other Combustibles Assoc. With Flooring	Extent of Flame Spread on Flooring	Comments
No. 3269 Atlanta, Georgia	Room Fire	Polypropylene carpet with integral foam backing on concrete	Corridors of three wings, each approx. 90 ft long	None	Complete south corridor, parts of east and north corridors.	Nine fatalities, four found in corridor. Wind and elevator shaft affected fire spread. Carpet passed Pill Test.
No. 488 Marietta, Ohio	Room Fire	Nylon carpet with rubber back on concrete	Corridor	None	180 ft along corridor	Twenty-one fatalities. Carpet passed Pill Test*.
No. 2241 Salt Lake City, Utah	Room Fire	Nylon carpet on hair pad	Corridor and Stairway	Chipboard Wainscotting	Some portion of stairs	Wainscotting burned. Draft conditions directed fire toward stairs. Carpet passed Pill Test*.
No. 2167 Tucson, Arizona	Room Fire	Acrylic carpet on two pads	Corridor and Stairway	8 in wainscotting rail, carpet on lower 22 in of walls.	Entire corridors and stairway from 4th to 11th floors	Draft from open stair ways directed fire spread. Carpet passed Pill Test*.
Palm Beach, Florida	Arson Fires in Corridor	Polypropylene carpet	Corridors	Carpet on walls	Not significant	Fire spread total of 160 ft along upper portion of wall carpeting.
No. 1481 San Francisco, California	Room Fire	Nylon carpet foam pad	Room	Living room contents	100 ft^2 around chair	Carpet passed Pill Test*.
No. 1730 Buechel, Kentucky	Furnishings	Modacrylic carpet	Library, Dining room, Chapel	Wood paneling, furnishings	Entire floor	Complete burn out of first floor. Carpet passed Pill Test*.

*Eight samples were not available for a complete test.

Table 2. Cases in Which Carpets Ignited By an Exposure Fire Significantly Aggravated Conditions But Was Not the Major Factor in Subsequent Fire Spread and Growth

(In some of the following the carpet would probably have failed the Pill Test.)

Case	Flooring Fire Exposure	Flooring Material	Location of Flooring	Role of Flooring in Spread	Extent of Fire Spread	Comments
No. 333 Colorado Home	Couch Fire	Nylon Carpet	Entire Home	Believed fire spread from couch to carpet	Living room and stairs	
No. 942 Home	Couch Fire	Nylon carpet on foam pad	Entire Home	Believed fire spread from couch to carpet	Entire contents of home	2 fatalities
No. 1137 4-Story Apt.	Candle on Floor	1. Nylon carpet 2. Rayon poly-propylene carpet 3. Urethane foam pad	1. Room 2. Corridor	Candle ignited room carpet and spread to corridor	Room carpet not burned completely. Corridor carpet completely burned on floor of fire origin.	1 fatality
Nashville, Tenesee	Closet Fire	Polypropylene carpet on foam pad	Corridor and Room	Spread fire 84 ft along corridor	Carpet completely burned along 84 ft	Carpet easily ignited by match

Table 3. Fires in Buildings in Which Carpets and Floor Coverings Were Ignited, 1955-62, United Kingdom [4]

Year	Fire in Which Carpets and Rugs Were Ignited	Fires in Which Floor Coverings Were Ignited	Percentage of Floor Covering Incidents Involving Carpets	Total Fires in Buildings
1955	692	904	76.5	50,492
1956	624	844	73.9	51,464
1957	603	816	73.9	50,694
1958	648	860	75.3	51,992
1959	708	908	78.0	61,328
1960	800	1,228	65.1	62,460
1961	950	1,344	70.7	69,588
1962	1,046	1,452	72.0	73,406

Table 4. Fires Involving Floors and Floor Coverings From the United Kingdom [5]

Year	Floor Coverings	Floors, Skirting-Boards Stairs
1961	1,344	1,828
1962[a]	1,452	1,880
1963[a]	1,454	1,878
1964	1,216	1,428
1965	1,225	1,621
1966	1,049	1,171
1967	1,034	1,141
1968	1,160	1,176
1969	1,282	1,172
1970	1,181	1,174

[a]The years 1962 and 1963 had severe winters with an unusually high frequency of fires associated with the use of heating equipment.

1.2. Full-Scale Fire Experiments

To identify more precisely the hazard of floor covering materials, attention has been focused on full-scale fire experiments in which floor covering materials (i.e., an assembly placed over a subfloor) have been examined in a room -- corridor environment. In particular, these experiments involve a large fire in a room connected to the corridor by an open doorway. The corridor is lined with negligibly combustible materials along the walls and ceiling but with a combustible flooring assembly. This simulates the least combustible class of assemblies in which corridor fire spreads. Corridors lined with combustible wall and ceiling materials as well as floor covering represent a more severe fire hazard. Several organizations have conducted room/corridor fire experiments to investigate the hazard of combustible lining material in corridors. They include the National Research Council of Canada (NRC), Illinois Institute of Technology Research Institute (IITRI), and the National Bureau of Standards (NBS). Although the room/corridor arrangement has been similar in these experiments, a variety of ignition sources have been used, ventilation conditions have varied, and overall construction materials have been different. Moreover, recorded measurements have ranged from visual observations to extensive data from automatic record instrumentation. At a minimum, these experimental results serve to establish a spectrum of corridor building fires and serve to provide a definition of the hazards.

1.2.1. NBS Corridor Fires

The NBS corridor system is depicted in figure 1. A total of 18 experiments involving floor covering materials have been made. In 14 experiments the principal corridor combustible lining has been the flooring assembly, of which, 11 involved sustained rapid flame propagation to the exhaust window ("flameover"); and the remaining 3 experiments resulted in partial or no sustained flame spread. A summary of results from these experiments is shown in table 5. Recent publications have described this program [6,7,8].

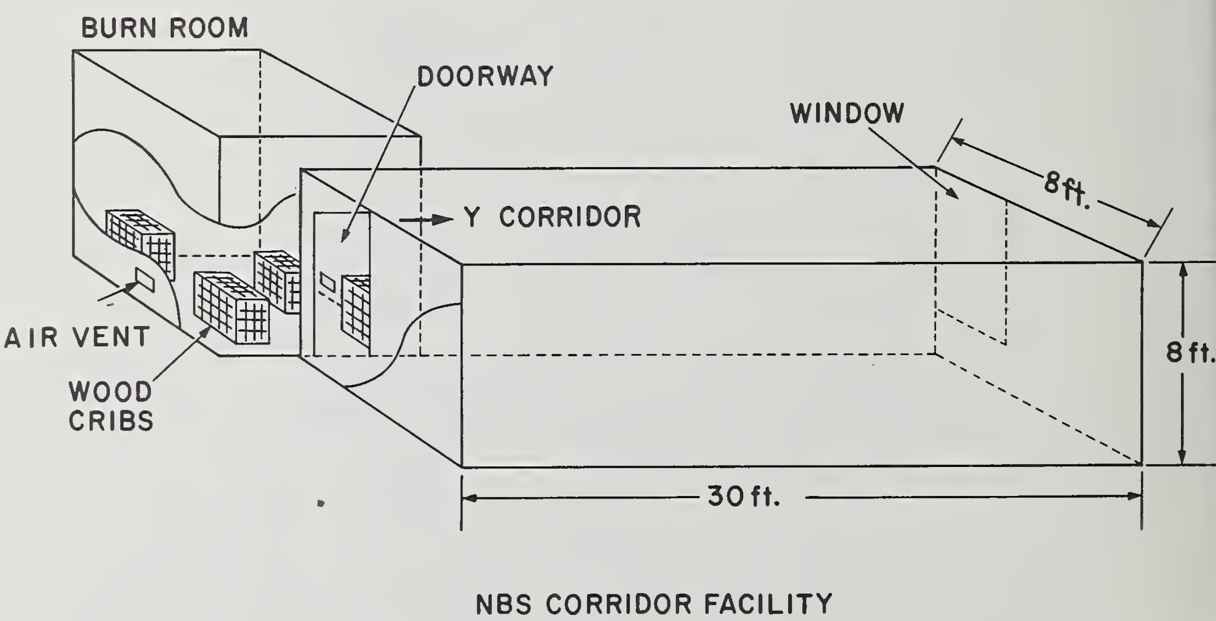


Figure 1. NBS corridor facility.

Table 5A. Summary of Corridor Fire Experiments

Test No.	Floor Assembly			Ceiling Lining	Wall Lining	Corridor Initial Conditions			Wood Cribs		
	Floor Lining	Underlay	Subfloor			Forced Air Flow (ft/min)	Air Temp. (°F)	Rel. Humidity (%)	Number	Total Weight (lb)	Moisture Content (%)
330	A-1	U-1	1/4" Cement Asbestos Board on Brick	Particle Board	Gypsum Board	None	74	25	4	172	---
332	A-1 pcs.	U-1 pcs.	"	"	"	"	--	--	4	---	---
333	A-1	U-1	"	Gypsum Board	"	"	75	51	4	172	---
334	A-1	U-1	"	Particle Board	"	88-176	84.	52	4	175	9.9
335	RO-v	---	"	Gypsum Board	"	None	82	49	4	172	7.5
336	VT-g	Oak	"	"	"	"	81	55	4	160	10.5
337	A-1	None	"	"	"	"	72	50	4	162	12.0
338	A-1	None	"	Particle Board	"	"	76	40	4	164	11.0
339	None	None	"	Gypsum Board	"	"	80	55	4	167	10.5
340	A-2	U-1	"	Min. Base Board	Min. Base Board	"	75	37	4	172	10.5
341	W-1	U-1	"	Gypsum Board	Gypsum Board	"	62	48	4	169	9.0
342	N-1/F	None	"	"	"	"	60	40	4	177	8.0
343	W-1	None	"	"	"	"	57	69	4	172	8.5
344	NO	None	"	"	"	"	55	28	4	178	7.0
345	W-1	None	"	"	"	"	77	42	4	172	8.5
346	R-4g	None	"	"	"	"	70	72	4	170	11.5
347	O-1-g	None	"	"	"	"	79	72	4	171	11.0
348	N-3	U-1	"	"	"	"	72	53	4	171	7.0
349	RO	Plywood	"	"	"	"	75	40-45	4	168	6.5

Table 5A. Summary of Corridor Fire Experiments (cont'd.)

Test No.	Single Crib Weight Loss		Inception Times				
	Time at 5% Loss $t_{5\%}$ (sec)	Avg. Burn Rate (lb/sec)	Ignition Burn Room Floor (sec)	Ignition Corridor Floor (sec)	Ignition Corridor Other (sec)	Start of Rapid spread (sec)	Flames at Window (sec)
330	---	---	---	155	150	---	175
332	---	---	---	615	470	---	560
333	---	---	340	455	---	555	700
334	---	---	---	---	---	---	560
335	216	0.041	---	300	---	444	530
336	294	0.048 0.039	--- ---	390-475	---	520 1,020	None
337	234	0.032	---	410	---	420	None
338	---	---	---	300	---	---	420
339	222	0.0430	---	---	---	---	---
340	204	0.035	---	300-330	---	342	421
341	330	0.046	302	315	---	460	570
342	234	0.038	---	300	---	300	381
343	186	0.045	270	300	---	312	355
344	210	0.054	180	480	---	740	840
345	---	---	---	---	---	420	470
346	190	0.044	330	400	---	None	None
347	210	0.041	330	380	---	840-860	1,000
348	100	0.040	180	316	---	440	540
349	200	0.048	250	310	---	630	710

Table 5B. Material Identification Code

Code	Material
A-1	Acrylic carpet, woven level loop, 55 oz/yd^2
A-2	Acrylic carpet, random shear, 69 oz/yd^2
N-1/F	Nylon carpet with integral foam back, 89 oz/yd^2
N-3	Nylon carpet, level loop, 69 oz/yd^2
NO	Aromatic polyamide carpet
O-1-g	Olefin carpet, level loop, bonded, 55 oz/yd^2
R-4g	Vinyl sheet, bonded, inorganic backing
RO	Red oak flooring
RO-v	Red oak flooring with spar varnish
U-1	Rubberized hair-jute underlayment
VT-g	Vinyl asbestos tile, bonded
W-1	Wool carpet, woven level loop, 76 oz/yd^2

A typical corridor fire test resulting in flameover is composed of 7 distinct stages of fire development. (1) The test commences with the ignition of four 40 pound wood cribs in the burn room. In several minutes the crib fire reaches a state of fairly steady burning. It appears that approximately half of the air required to support crib combustion flows into the burn room through the two floor level vents, while the remaining air supply enters from the corridor. (2) Products of combustion flow from the room along the corridor heating its walls and ceiling. Inlet air flows over the corridor floor which is heated by radiative transfer from upper hot walls and ceiling and by hot smoke products. (3) Once the crib fire builds-up, ignition occurs on a 2 1/2 ft wide floor covering runner which extends from the corridor into the burn room. This ignition results from a high radiant heating exposure over this runner and from flaming crib embers falling to the floor. Once ignition occurs at a location on the runner rapid flame spread follows over the entire runner in the burn room. (4) This flooring fire then begins to emerge and spreads slowly into the corridor. The flame fans out from the doorway advancing upwind against the incoming air flow and is driven by radiant heating of the floor. (5) As this fire advances it depletes the oxygen of the incoming air and preheats this air. This results in a buoyant force which diverts some air flow from entering the burn room. (6) It appears that the occurrence of flameover is preceded by a reduction in air supply from the corridor to the burn room such that the crib fire becomes fuel rich. The crib fires continue to produce pyrolysis products at the same rate but complete combustion is not possible within the burn room. Thus, a cloud of combustion products, probably including aerosols and soot, enter the corridor flowing out over the floor fire which extends not more than about 5 ft down the corridor. This is followed by the onset of flameover or rapid flame spread within the corridor. (7) Flameover occurs as a wave of flames and hot combustion products advance down the corridor producing a large increase in corridor temperatures and heat flux. In the order of 1 minute the flames emerge from the window completing the flameover process. More detailed data will be presented to further illustrate these processes.

During steady burning rate of the wood cribs a maximum energy release rate of 80,000 Btu/min occurs. Some of this energy is lost to the burn room and the rest enters the corridor. The convective energy flow values were calculated by Fung, *et al* [8], based on two to three velocity and temperature measurements in the doorway. These are plotted against the initiation time of flameover, t_{FO}, shown as open symbols in figure 2. (These flameover times do not agree with values given by Fung, *et al* [8] since they termed flameover the first indication of observed flooring fire in the corridor.) A straight line drawn through these points indicates a nominal convective energy flow rate to the corridor of 60,000 Btu/min and an average induction time of 220 seconds before this rate of energy was released. The time preceding steady crib burning generally occurs after 5% weight loss results ($t_{5\%}$). If the flameover time is adjusted for each test by subtracting $t_{5\%}$ from t_{FO}, then the solid symbols in figure 2 yield the same burning rate with the intercept through zero. These results indicate the degree of reproducibility for the crib fire source, and the extent to which energy input rate may be regarded as a step function of time.

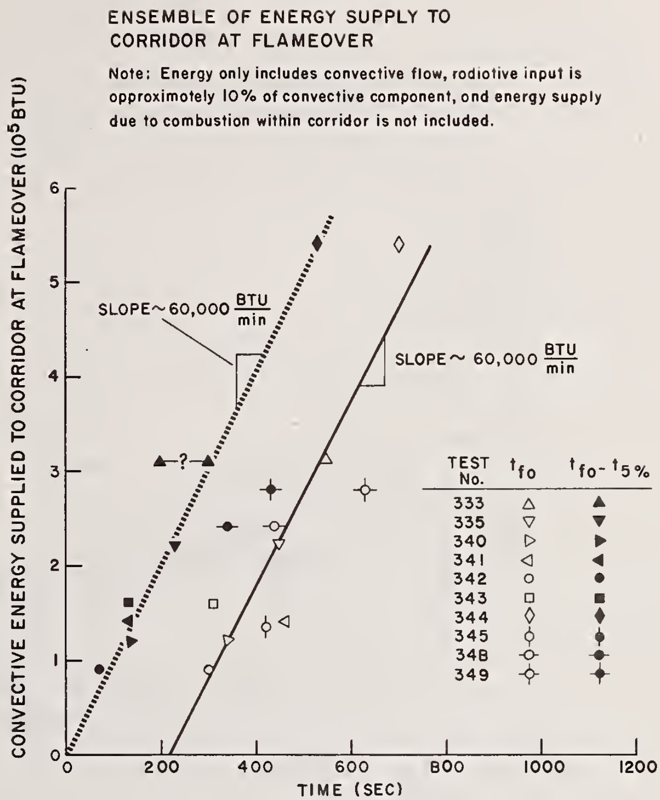
When the floor covering runner ignites in the burn room it releases an amount of energy which can become significant with respect to the crib fire. This sudden release of energy is indicated by an increase in the gas temperature near the corridor ceiling. Figure 3 shows this effect for a nylon carpet (N-3/U) which had a large energy release rate as compared to a vinyl sheet flooring (R-4) in which there was negligible energy release rate. This pair of tests (348 and 346) tends to bracket the range of conditions which result from exposure to the crib fire source in the burn room. They will be used to illustrate other phenomena which result during the fire development in order to contrast the range of resulting conditions.

During the relatively slow advancement of flooring flame along the corridor, radiant heat transfer to the floor tends to promote continued flame spread. The radiation levels developed depend strongly on the primary crib fire source but are also influenced by the rate of energy release of the flooring material. The exiting hot gases and ceiling temperatures along the corridor determine the extent of radiant heat transfer. Figures 4 and 5 illustrate typical radiation flux distributions along the corridor floor before flameover is initiated. In test 346 the flux was essentially due to the crib energy release; while, in test 348 the radiant flux (at 300 sec) includes the effect of energy release (and most likely smoke) from the sudden ignition of the nylon runner in the burn room.

Before flameover the corridor temperature distribution between the floor and ceiling was greatly stratified with hot products of combustion at the top and cool air flow at the bottom. At the inception of flameover, temperatures at all heights increased rapidly and significantly throughout the corridor space. This is illustrated in figure 6.

As pointed out earlier, air flow between the corridor and burn room appeared to become affected by the advancing floor fire. Eventually, this reduction of air supply to the burn room affected the crib burning rate. In fact, after flameover the crib burning rate always dropped. However, before flameover significant changes occurred in air supply to affect the nature of combustion in the burn room. Figure 7 illustrates this phenomenon by examining the measured crib weight loss rate and the maximum (estimated) burning rate which could occur within the burn room. This potential maximum rate was estimated from velocity and temperature measurements of the exhaust products at the burn room doorway (an assumed air to fuel ratio of 4 was used). No flameover occurred in test 346 and no drop in air supply is seen in figure 7. In test 348 the flooring fire had spread into the corridor by 320 seconds, and near 440 seconds (the onset of flameover), the figure suggests that most of the fuel generated in the burn room probably burned within the corridor space. Thus, the release of fuel-rich combustion products from the burn room to the corridor can be a contributing factor in causing flameover in addition to radiant heating of the floor covering.

Figure 2. NBS corridor flameover time compared to total energy input.



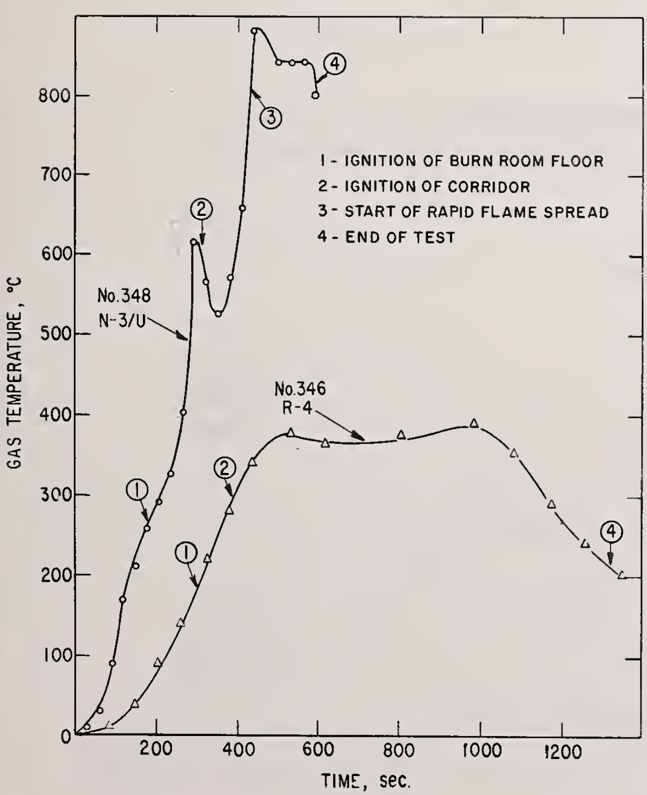


Figure 3. Comparison of corridor temperatures developed by two floor-coverings in the NBS experiments.

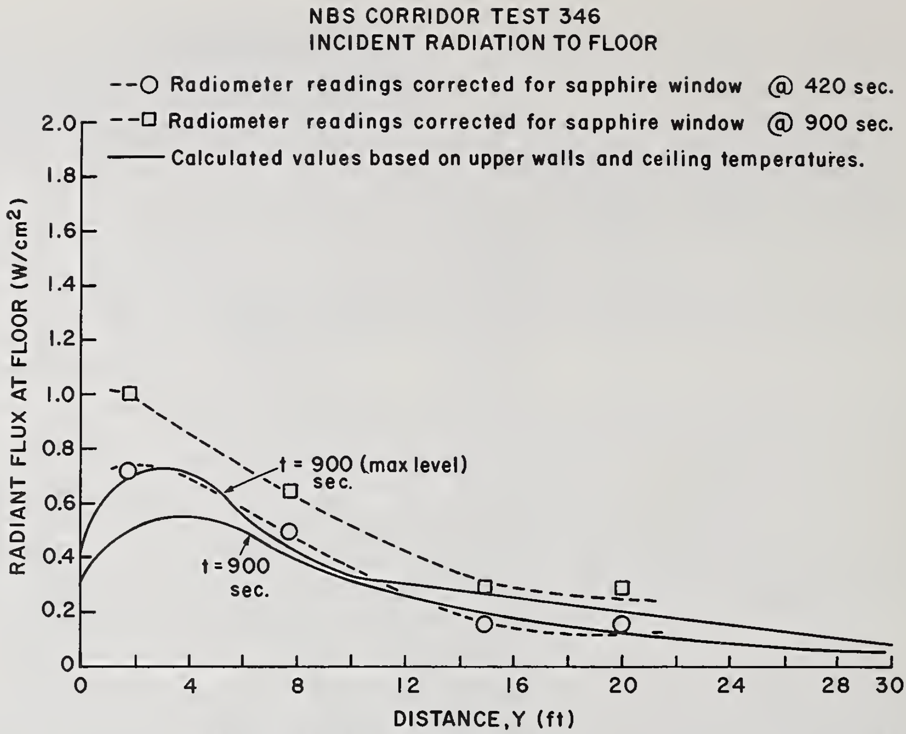


Figure 4. Incident radiant flux to floor in NBS Corridor Test 346.

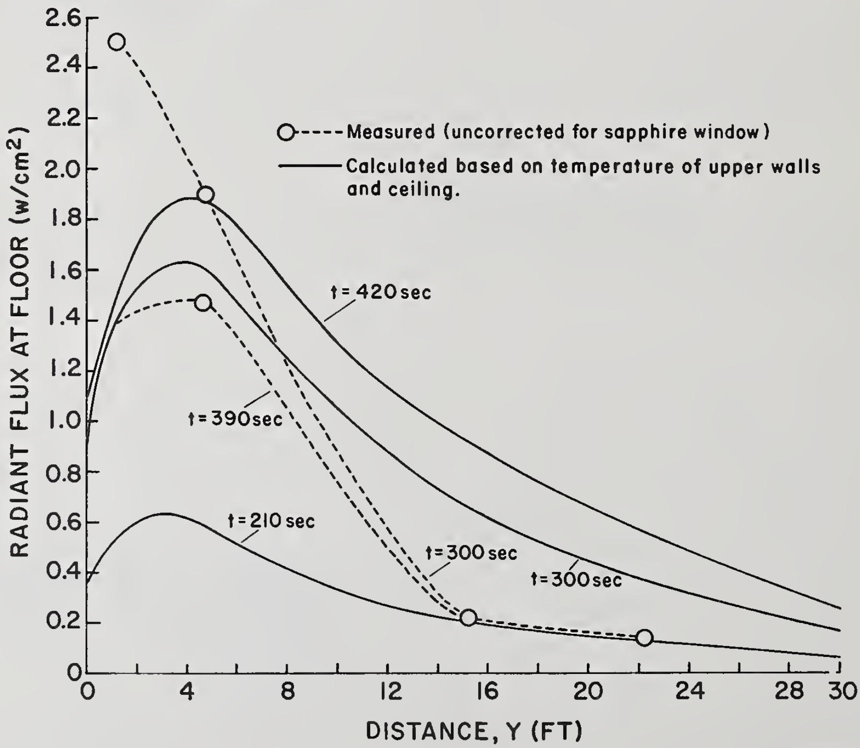


Figure 5. Incident radiant flux to floor in NBS Corridor Test 348.

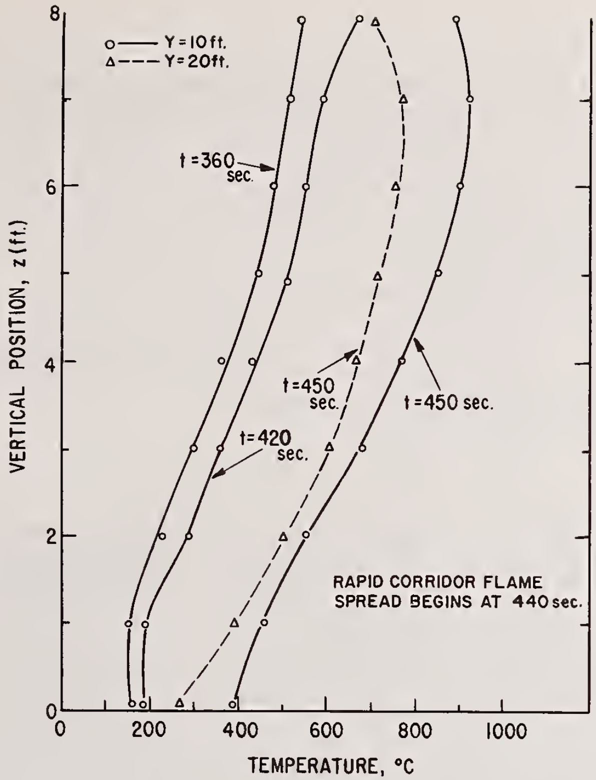


Figure 6. Corridor temperature distributions in NBS Corridor Test 348.

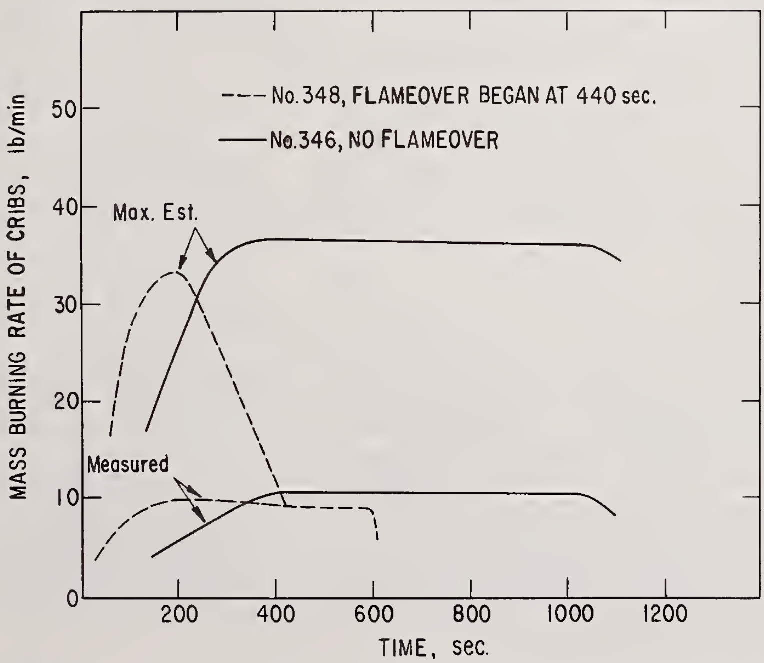


Figure 7. A comparison of fuel burning rate with available burning rate based on air flow.

In summary, flame spread in these experiments, and in similar systems, depends on radiant heat transfer and the gas flow patterns as well as on the flooring material properties. These factors can be related to independent initial parameters of the system. Thus, flameover is a function of:

1. energy release rate of the ignition fire, (i.e., room occupancy type);

2. corridor geometry, principally height and width;

3. ventilation openings between compartments;

4. flooring flame spread response under external radiation; and

5. material thermal properties in general.

1.2.2. IITRI Corridor Fires

The IITRI room/corridor experimental fire facility has been described by Christian and Waterman [9]. Information regarding the use of this facility to examine the flammability hazard of carpets in corridors has been furnished by T. E. Waterman [10] and by W. M. Segall [11]. A new interpretation of their results has been made from the available information. An overall comparison between the IITRI corridor system and the NBS corridor system is shown in figure 8. The values listed on the figure are based on the effects of the ignition fire only and do not include the effect on the flooring fire. It appears that radiant heating near the doorway was greater in the IITRI corridor than the NBS corridor. Also the air supply to the IITRI corridor system was greater than that in the NBS system, and the higher oxygen concentration in the IITRI exhaust flow implies more excess air than in the NBS system. The doorway and window openings in the IITRI system are larger than the NBS system. Thus, it appears that the heating conditions were greater in the IITRI corridor, and ventilation effects -- more availability of air flow -- were greater in the IITRI corridor than NBS. The differences in ventilation factors may be the reason for the differences in fire spread behavior of carpets between the IITRI and NBS systems. In only one experiment did IITRI observe a flameover behavior (for a carpet which had failed the Pill Test). It is believed that these differences are due to overall dynamics of the room/corridor systems and not due to the nature of the flooring material tested. The questions raised by these results reflect the range of real-life building fire conditions and represent our ignorance in understanding in a quantitative way all of the factors promoting flameover.

1.2.3. NRC Corridor Fires

J. H. McGuire [12] has described the NRC corridor fire experiments which included some work with floor lining materials. This system had a corridor 63 ft long, 8 ft high and 6 ft wide with an adjoining burn room and with a variety of small and large inlet and exhaust vents. In one experiment a large room fire sustained flame spread over a cellulose triacetate carpet to a distance of 40 ft from the burn room. The other corridor lining materials were noncombustible and the carpet had a rating (I_s) of 435 by ASTM E-162 [16]. McGuire reached the conclusion from this study that flooring with an ASTM E-162 index of 220 and less made little contribution to the propagation of fire along the large scale NRC corridor (compared with a rating of 130 or less for ceiling linings, and 35 or less for wall linings).

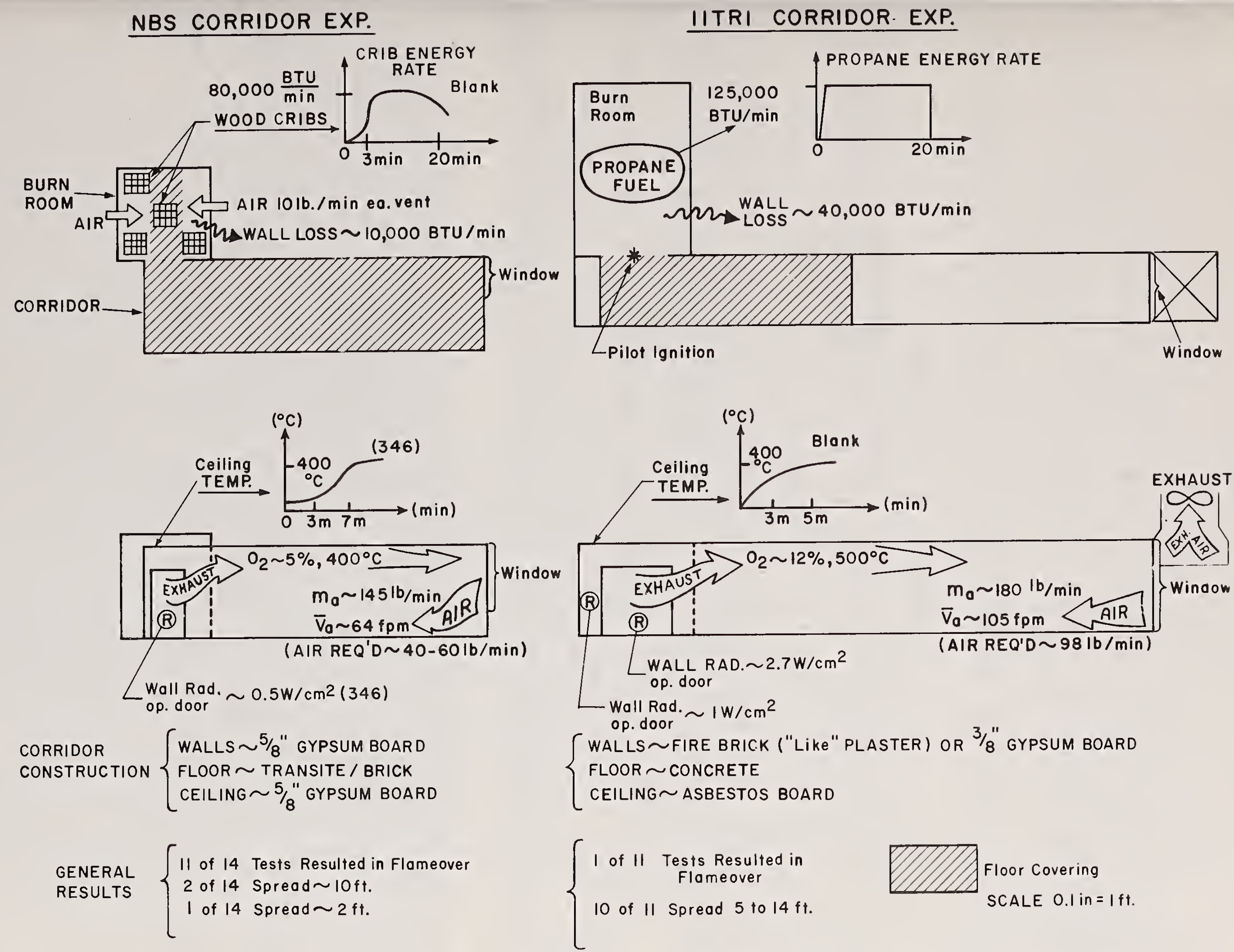


Figure 8. A comparison of the NBS and IITRI corridor experiments.

1.3. Summary of Statistics and Experiments

In reviewing the statistics and experiments, several factors emerge. First, floor covering materials are potentially less hazardous than comparable wall or ceiling materials with regard to fire spread. Second, based on the U.K. data, carpets in general do not appear to be more hazardous than other flooring materials. Third, extensive and possibly rapid flame spread over flooring materials in corridors and exitways where little additional combustibles are present is the primary potential hazard to be dealt with. Fourth, most floor covering materials require radiant heating from a large ignition source before flame spread can develop. Fifth, the dynamics of radiative heating and fire development depend on the nature of the building's interior design.

Given these factors, the question of a relevant test method for flooring and its application to the establishment of standards can be addressed.

2. EVALUATION OF TEST METHODS

A variety of methods and varying performance criteria have been used by many regulative agencies to regulate the potential fire hazard properties of floor covering materials. Such non-uniformity of regulation of flooring materials produces confusion and hampers industrial development to meet acceptable performance criteria. For this reason an investigation has been made of the performance, characteristics, and applicability of test methods as they relate to the flame spread hazard of flooring materials under conditions which simulate real fires from a relatively large ignition source. The methods discussed in this study are ASTM E-84, ASTM E-162, UL-992 Chamber, "Model Corridor", and the Flooring Radiant Panel. Although this is not a thorough study, some of the more significant factors and indications can be reported.

Up to now most test methods have been used to determine the comparative flammability of materials by an empirical scale of measure. If fire safety is to become a science the factors determining potential fire hazard must be known, as well as the necessary parameters to be measured by flammability tests. Only then can the test results be related to the potential hazard in a meaningful manner. Ultimately, several flammability properties for a material would have to be combined with design parameters of the building in a relationship to express potential fire hazard.

The previous discussion given for flooring fires in buildings serves to present a definition of the potential hazard of flooring fires and the factors promoting such fires. If flameover is accepted as the hazard, then two mechanisms are apparent for its cause: gas-phase dynamics and radiant heating of the flooring appear to be the cause of rapid flame spread. The gas-phase mechanism depends on the aero-dynamics of the fuel produced from the developing fire and the available combustion air. This mechanism clearly depends on the size of the ignition fire and the building interior design. In extreme instances flame propagation in corridors may depend only weakly on the flooring material. On the other hand, burning of the flooring material does seem important to flameover stimulated by radiant heating which depends on the size of the ignition fire and geometry of the building. Thus, it should be within the scope of a test method to measure the flame spread behavior of a material under radiant heating. Other factors would have to be assessed by an analysis of the building geometry and potential fire load.

2.1. Description of Test Methods

2.1.1. ASTM E-84 Tunnel Test

The ASTM E-84 Tunnel Test was first described by Steiner [13], and is currently described in ASTM E-84-70 [14]. Basically the apparatus consists of a horizontal duct (12 in high by 17 in wide) 25 feet long with a test specimen mounted on the ceiling of the duct. Initially air is forced into the duct at 240 ft/min and an ignition fire of 5,000 Btu/min with about a 5 ft flame impingment is released. Upon ignition of the specimen the flame propagates downwind under the influence of forced convection. An observer records the flame tip position advancing over the specimen. A more recent study on the reproducibility and repeatibility of this method as applied to floor coverings has been published by Lee and Huggett [15]. Although this method also measures smoke production and energy release, only the flame spread performance measure will be considered here. The flame spread factor (FSC) is an empirical parameter which gives a relative measure of distance burned or average flame spread velocity compared to the burning of red oak. In this test, carpet specimens are bonded to asbestos board (or held in place with a wire screen if an underlayment is used).

2.1.2. ASTM E-162 Radiant Panel

The ASTM E-162 Radiant Panel test method [16] has been discussed elsewhere by Robertson, Gross, and Loftus [17], Gross and Loftus [18], and Lee, Loftus and Gross [19]. It measures downward flame spread travel and energy release rate under a varying radiant flux distribution of about 4 to 0.3 W/cm^2. Flame spread is against the induced air flow generated by buoyancy and the exhaust hood over the specimen. Its flammability index I_s combines a flame spread rate factor F_s and maximum energy release rate Q as

$$I_s = F_s \bullet Q \tag{1}$$

The index I_s tends to correlate with the FSC of the E-84 tunnel.

2.1.3. UL 992 Chamber Test

The development of the Underwriters Laboratory Chamber Test emerged from a growing concern over the flammability of carpets. It sought to determine a flooring flame spread behavior when tested in its normally installed orientation (in contrast with the inverted position of the E-84 tunnel). The test and some results have been described by Engermann [20]. An ignition burner flame (500 Btu/min) is applied to a sample mounted on the floor of a duct 8 ft long, 10 in high and 22 in wide. Air is drawn through the system at an initial inlet velocity of 100 ft/min. A flame spread index is determined by a formula which uses the distance burned or the time to burn the full length of the duct (8 ft). Flame propagation is downwind directed by forced convection.

2.1.4. Model Corridor Test Method

This method is based on the physical system of the UL chamber test but has used asbestos board for its construction rather than fire brick and forces cool air into the test section as opposed to exhausting hot products by a fan as in UL 992. Its design and operation has been described by W. Denyes and J. Raines [21]. Its characteristics and mode of performance measure has been discussed by W. Denyes and J. Quintiere [22]. The bimodal flame propagation displayed by UL 992 has been used to relate the measured test results to the flameover hazard of building corridor fires. The Model Corridor gives this measure of performance by determining, by trial and error, the maximum gas burner energy flow rate to a specimen such that flameover does not occur in the Model Corridor. Thus, critical energy rate is its performance measure.

2.1.5. Flooring Radiant Panel

The system is similar in concept to E-162 except that the sample under test is horizontally "floor" mounted, and the radiant panel and specimen are enclosed in a vented chamber. A recent report by G. Hartzel [23] (continuing the development of this concept as a NBS Research Associate from Armstrong Cork Company) describes this system's performance and characteristics. The radiant flux prescribed varies from about 1 to 0.1 W/cm^2 over the sample length. Air flow is induced into the chamber by the hot radiant panel and flame spread is generally against the wind. The performance measure is expressed as the total length of flame spread over the sample. This distance can be related to radiant flux from the panel at the point of extinguishment.

An alternative mode of operation for this apparatus has used a different radiant flux distribution which ranged from 2.7 to 0.3 W/cm^2 over the specimen. At these conditions, distance burned or time to burn the sample length relative to the burning of red oak is used to express a relative flame spread index.

2.2. Comparison of Results with NBS Corridor

No discussion of test method results would be complete without some comparison to full-scale fire experiments. Since most of the flooring materials examined in the NBS corridor experiments have been evaluated by the above test methods a direct comparison can be made. The measure of performance in the NBS corridor chosen for comparison is the time at the onset of flameover, t_{Fo}. This time will be used, although its interpretation could be refined by considering the nature of the flame spread results (fig. 9) and the nature of the

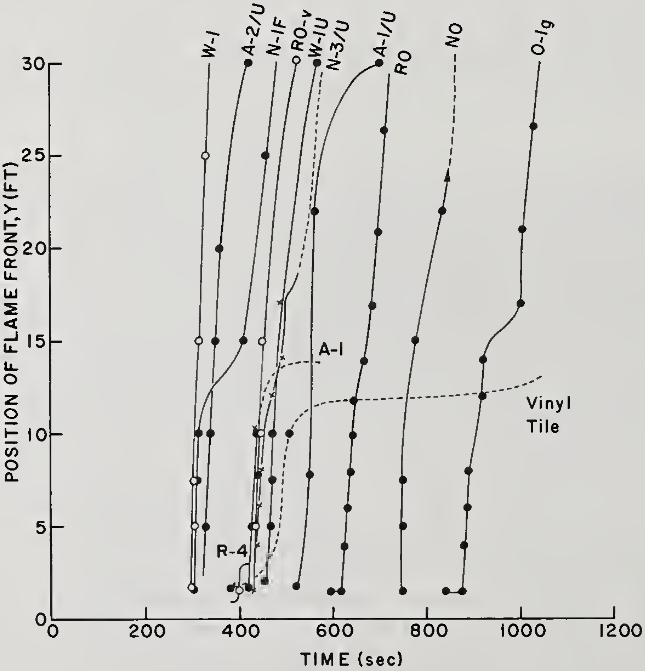


Figure 9. Flame spread results in the NBS corridor experiments.

corridor energy input rate. For example, an adjusted time could be used as a performance criterion. This could be defined as t_{FO} minus the crib build-up time, $t_{5\%}$ (table 3). If crib fire development and flooring ignition were similar for each experiment, the reciprocal of flameover time would represent an "average" flame spread rate during radiant heating of the floor. Hence, t_{FO} may tend to correlate with flame spread tests which measure flame spread velocity as the index of performance.

A comparison of test method results with flameover time is shown in table 6. The range of E-84 FSC values given for some materials represents variation between different laboratories [15]. The FSC index has the significance of flame spread velocity for values above 78. Correlation may be judged as fair for E-84. The I_s index for E-162 yields a similarly fair correlation, yet the flame spread factor F_s does not demonstrate any significant trend. The UL I factor yields poor results but it should be realized that these low numbers for I only represent a distance burned in the test method. Hence, they would not likely agree with t_{FO}. Moreover, the Model Corridor critical energy and Flooring Panel distance burned would not necessarily yield any agreement with t_{FO}. However, attempts at interpreting these two test methods in a manner more consistent with flameover time has been done. A weighted flameover time in the Model Corridor based on the product of gas burner energy supply rate and time was compared and yields a fair correlation. Also, an average velocity measured in the Flooring Radiant Panel was compared with t_{FO} and yields fair results. Since the driving forces and measure of performance generally differ between test method and full-scale corridor fires, successful correlation between the two need not be expected. However, the relevance of each test can be judged on its phenomenological similarity with full-scale fires.

2.3. Characteristics of Each Test Method

The parameter being measured by a test method must be understood, and its relationship to the controlling variables of the test must be known. Only then can the applicability and limitation of the test method be addressed.

2.3.1. Characterization of E-84

Recently an E-84 tunnel facility has been instrumented with thermocouples, pitot tubes, and a heat flux sensor in order to determine a quantitative measure of its character. Although these results have not been completely analyzed, some of the findings can be presented. Beyond the burner flame, vertical gas temperature distributions in the tunnel can vary from 400 to 150°C with no burning specimen. The energy release rate from the burner should be about 5,000 Btu/min, yet the steady-state enthalpy flow rates, $\dot{m}_a c_p (T-T_\infty)$, (based on a steady mass flow of air, $\dot{m}_a$ = 25.4 lb_m/min) at 15 and 24 ft from the burner are about 3,000 and 2,500 Btu/min respectively. This means that about 40 percent of the burner energy release is lost within the first 15 ft from the burner. Part of this loss can be radiation from the flame and perhaps incomplete combustion due to quenching of the flame on the ceiling. Thus, a specimen would receive a severe heating load near the burner in this test. Measurements on air inflow to the tunnel during a test have confirmed initial calculations which suggested the fall off of air flow as the temperature of gases within the tunnel increases. This is firstly a thermal effect as a result of maintaining constant pressure drop over the system during a test; and secondly,

Table 6. Comparison of Time to Flameover in NBS Corridor With Flammability Test Method Results

Floor Covering	NBS Corridor Flameover	ASTM E-84 FSC	ASTM E-162 I_s	ASTM E-162 F_s	UL-992 I	Model Corridor Critical Energy at FO.	Model Corridor Total Energy at FO.	Flooring Rating Panel Index (High Flux)	Flooring Rating Panel Distance (Low Flux)	Flooring Rating Panel Average Velocity
	sec	-	-	-	-	Btu/min	Btu	-	cm	cm/min
N-1F, Nylon Carpet	300	208-264	284	11.3	1.1	600	5,100	89	45	3.8
A-2/U, Acrylic Carpet	342	279	445	19.4	2.3	400	1,800	580	70	10.0
W-1, Wool Carpet	312,420	50	64	6.7	-	≥1,250	-	36	30	14.3
N-3/U, Nylon Carpet	440	169	185	9.0	-	750	6,200	52	35	2.2
Ro-v, Varnished Red Oak	444	-	-	-	-	≥1,250	-	-	44	2.8
W-1/U, Wool Carpet	460	197	64	6.7	-	750	5,000	46	32	12.5
A-1/U Acrylic Carpet	555	200-331	143	7.2	2.6	300	5,600	167	86	4.8
RO Red Oak	630	100	100	7.0	1.0	≥1,250	-	100	60	2.9
NO, Nomex Carpet	740	5	51	8.2	-	≥1,250	-	-	8	0.8
O-1g, Olefin Carpet (glued)	840	69	424	18.2	2.1[a]	300[a]	8,200	148[a]	54	2.4
A-1, Acrylic Carpet	No Sustained Spread	23-77	141	7.1	0.9	750	6,200	82	44	4.8
Vinyl Tile (glued)	" " "	-	122	9.8	-	-	-	-	-	-
R-4g, Sheet Vinyl (glued)	" " "	25-80	46	5.0	-	≥1,250	-	-	22	5.5

[a] Sample not bonded to substrate

it is due to the release of fuel gases from the specimen. It can be shown that the average inlet air velocity at the tunnel slit orifice follows the relationship.

$$\bar{V}_a = \sqrt{\frac{2\Delta P/\rho_i}{K_e + \left[1 + \left(\frac{T}{T_\infty}\right) K_f\right]\left(\frac{H_o}{H}\right)^2}} \tag{2}$$

where ρ_i is the inlet air density,

Δp is the pressure drop between tunnel inlet and the manometer station,

T_i is inlet air temperature,

T is average tunnel gas temperature,

K_e is the entrance loss coefficient,

and K_f is the duct loss coefficient which includes the skin friction effect.

If the internal flow losses dominate the losses in the system then the velocity at the inlet during a test is related to the initial inlet flow, $\bar{V}_{a,i}$, by approximately

$$\bar{V}_a \approx \bar{V}_{a,i}\sqrt{\frac{T_i}{T}} \tag{3}$$

Thus, an increase in average gas temperature by a factor of 2, can lead to a 30 percent decrease in inlet air flow to the tunnel. Figure 10 illustrates this behavior by changes in the mass flow rate of air at the tunnel inlet orifice.

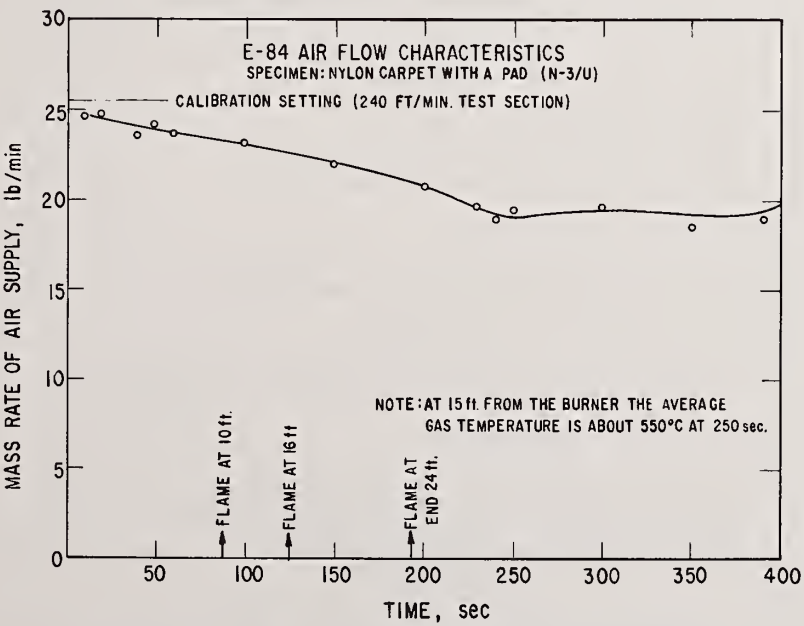


Figure 10. E-84 air flow characteristics.

Another aspect of air supply is its effect on the combustion process. It has been estimated that, irrespective of the subsequent drop in air supply rates the initial air supply may not be sufficient to completely burn a 24 ft length of some materials. Although this estimate has not been substantiated directly, low oxygen concentrations have been reported for the E-84 tunnel which would then support this indication of oxygen deficiency. If this is true then work done on the study of fuel-rich fire spread over the lining material of ducts [24,25,26] would apply to fully-developed flame spread in E-84. This question bears further examination.

The processes affecting flame spread in E-84 are complex and no theory exists to explain flame behavior generally for this system. Some results for flooring samples are shown in figure 11.

2.3.2. Characterization of E-162

This method can measure flame spread rate and energy release rate under a prescribed radiant flux distribution. Some typical flame spread results are shown in figure 12.

It would be helpful to have a theory which can predict this method's results for classes of materials. A first attempt at this which was considered by Rockett [27] examines

$$V_F = \frac{4\dot{q}_F''^2 \, \delta_F}{\pi (K\rho c) \left[(T_{Vap} - T_\infty) - \frac{\dot{q}_R''}{h}\left(1 - e^{\tau}\mathrm{erfc}\sqrt{\tau}\right)\right]^2} \quad (4)$$

where $$\tau = \alpha\left(\frac{h}{K}\right)^2 t$$

as an approximate empirical expression for flame spread velocity. The symbols are defined as

$\dot{q}_F''$ is the heat flux from the flame,

$\dot{q}_R''$ is the heat flux from the panel,

T_{Vap} is ignition temperature of the material,

T_∞ is the initial temperature,

h is a convective/radiative loss coefficient,

c is specific heat of the material,

δ_F is the flame downstream heat transfer zone length,

ρ is density of the material,

α is the thermal diffusivity of the material,

K is thermal conductivity of the material,

and t is time.

In the least, this equation illustrates the processes affecting flame spread in E-162.

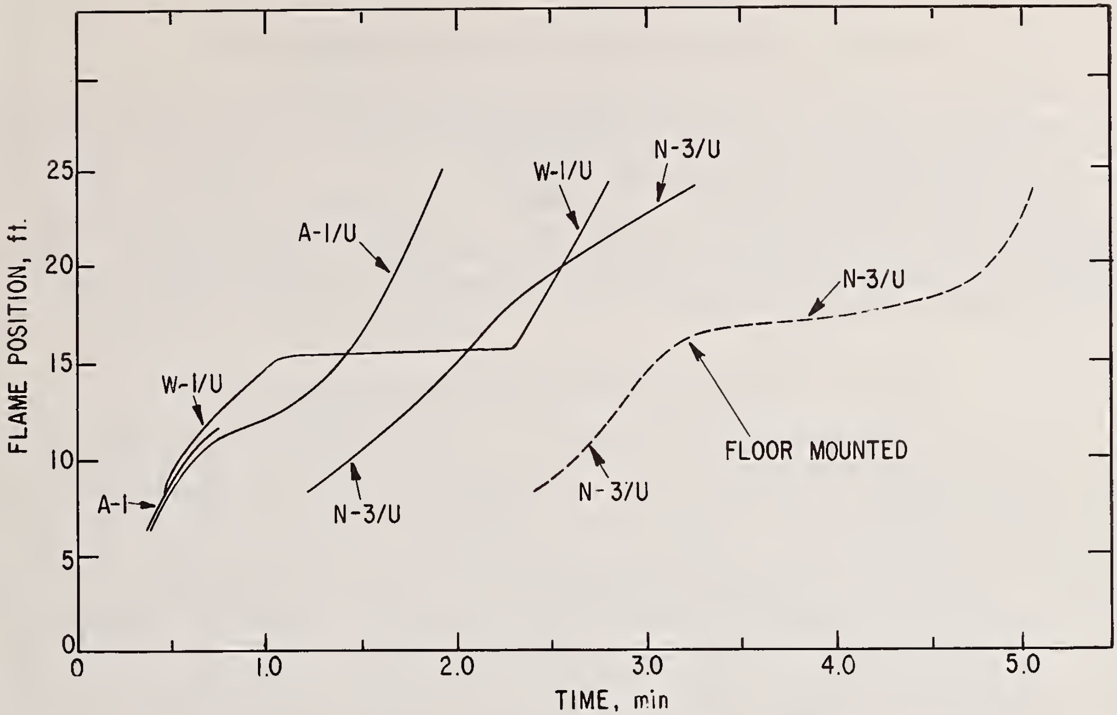


Figure 11. E-84 flame Spread results.

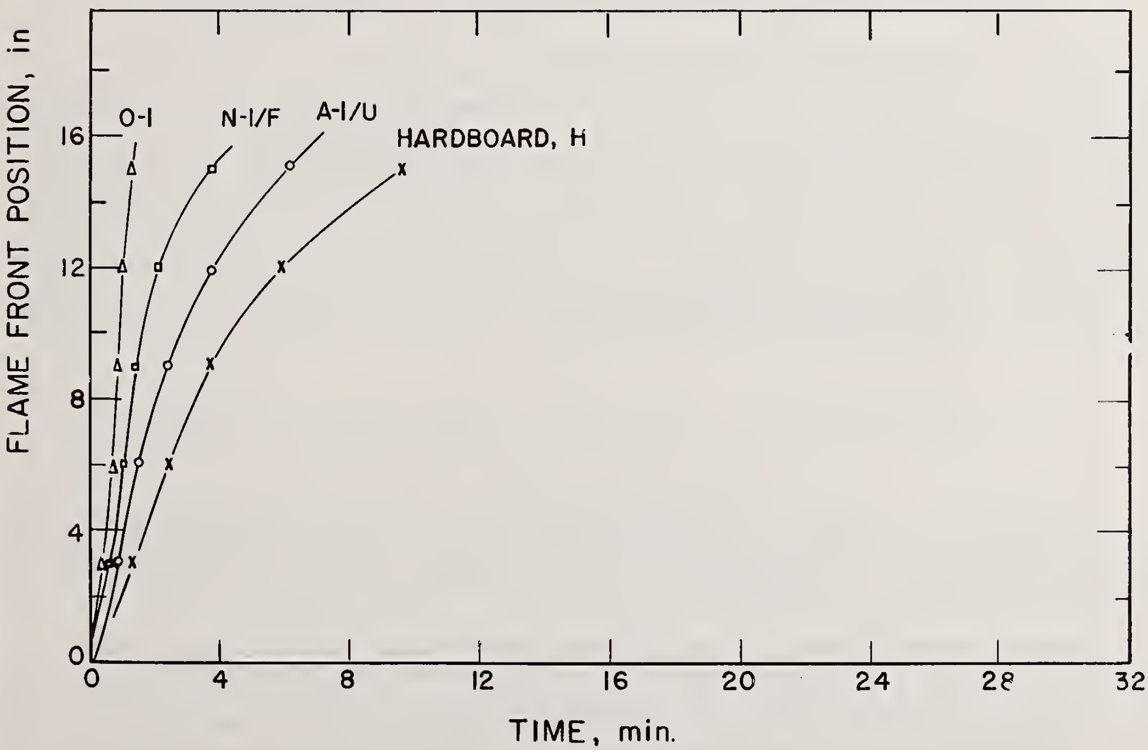


Figure 12. E-162 flame spread results.

2.3.3. Characteristics of the UL Chamber Test

One obvious fact from the results of Engermann [20] is that the system acts in such a manner that there is either complete flame spread propagation over the test section length or propagation of 1 to 2 ft beyond the ignition flame. This characteristic has been observed by others in similar experimental facilities [22,24,25,28]. In addition, Engermann [20] reports that initial inlet air velocities of less than or greater than 100 ft/min led to reduced flame spread potential for a given material. Yet, air flow is not maintained constant during a test, but allowed to vary according to the burning characteristics developed and the characteristics of the exhaust fan.

2.3.4. Characteristics of the Model Corridor

The driving force for flame spread in the Model Corridor is radiation heating of the flooring ahead of the flame front. This radiation results from the energy supply of the burner and the combustion of the flooring material which heats the ceiling and upper walls of the test section and which in turn reradiate to the floor. An empirical correlation [22] of a series of experiments for the same materials at various energy levels and ceiling heights displays clearly the critical propagation condition in dimensionless form in figure 13. This dimensionless correlation suggests a method of determining full-scale conditions by scaling the energy release rate of the ignition fire (E_B), the height of a corridor (H) and its width (W). The effect of air flow rate has also been examined and an optimum air velocity for propagation is apparent. Its effect is not completely understood at this time.

2.3.5. Characterization of the Flooring Radiant Panel

Typical flame spread results are shown in figure 14. This flame spread behavior is described roughly by eq (3). Since flame spread is very slow, the transient heating term in eq (4) would approach a constant value dependent on the radiative flux and surface heat transfer coefficient. Thus, the flame spread appears quasi-steady. If the flame heat flux plus the local radiant flux is insufficient to heat the specimen to its ignition temperature, eq (4) has no solution; physically, flame spread will cease at a critical flux value. A comparison of these results with those of Kashiwagi [29] shown in table 7 indicates support for this concept of critical irradiance for flame spread. Actual flux values in the flooring panel can be greater than those established initially since radiative interaction of the burning specimen with the panel and enclosure has not been accounted for.

2.4. Applicability of Test Method Results to Flooring Hazard

2.4.1. E-84 Tunnel Test

Because of the lack of understanding of the factors promoting flame spread in the tunnel, it is difficult to relate its results to the flameover hazard of floor coverings. It is apparent that both radiation and convection serve to preheat the specimen in the tunnel.

The National Building Code of Canada (1970) has recently been revised (July 1972) such that a floor-mounted-specimen version of E-84 is now prescribed for a measure of flame spread on floor surfaces. It requires a FSC of 25 in exit ways and 300 for corridors (previous prescriptions for the standard E-84 test method were 25 and 200 respectively). Tests have shown that general correlation exists for FSC values between floor and ceiling mounted materials except for some shag and acrylic carpets. Although the correlation indicates a 50 percent increase in FSC-ceiling compared with FSC-floor ratings, the Canadian

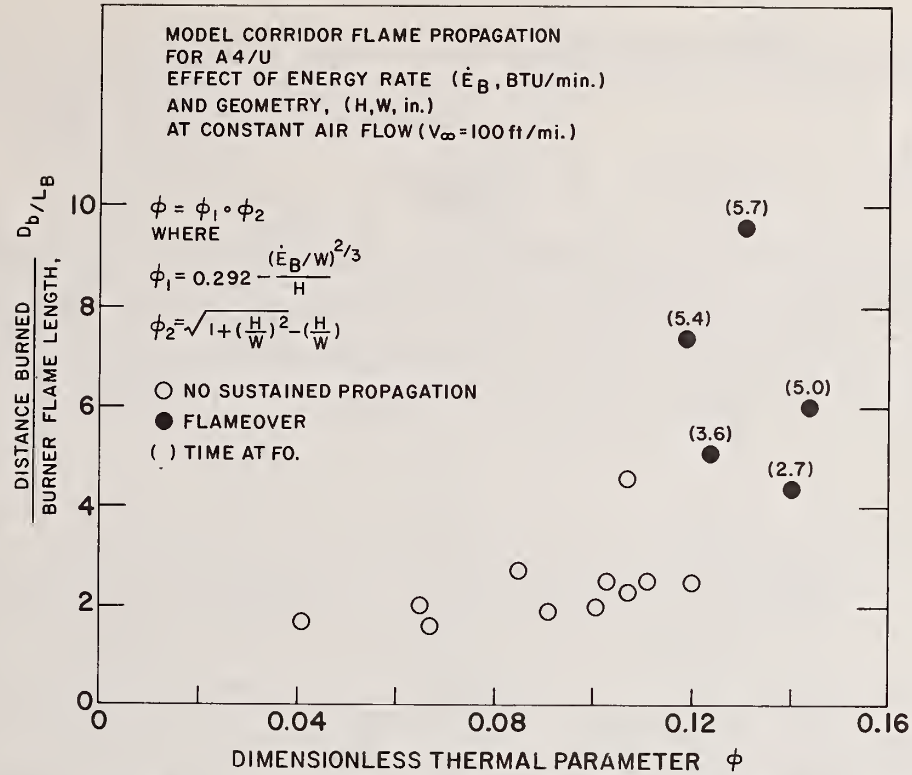


Figure 13. Correlation of flame spread results in the model corridor.

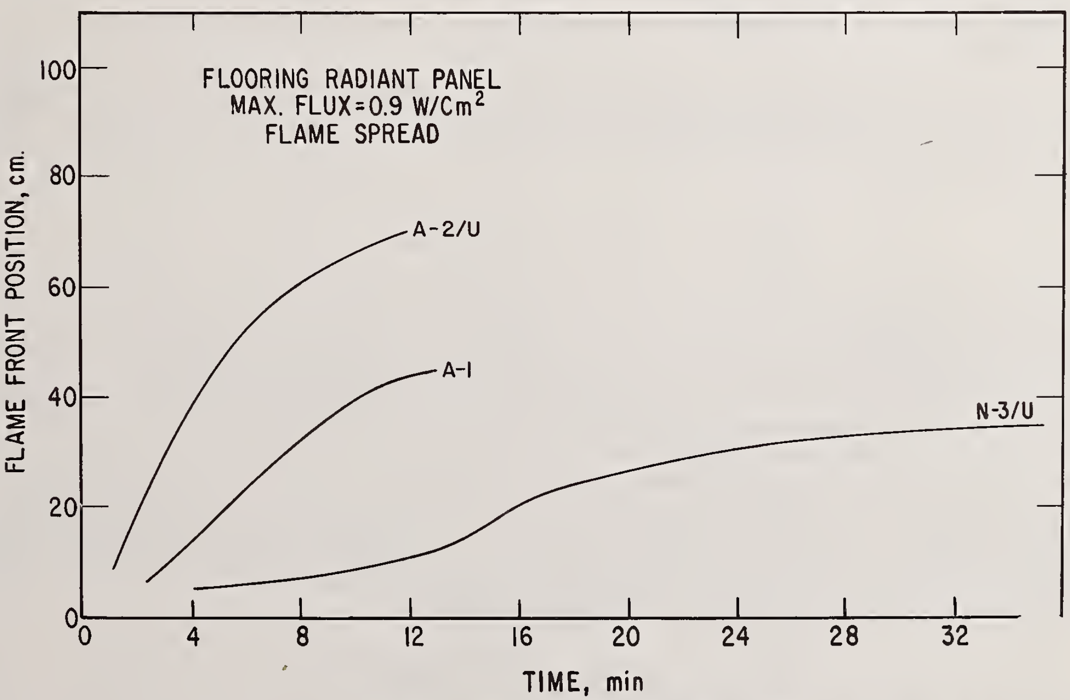


Figure 14. Flooring radiant panel flame spread results under a maximum radiant flux of 0.9 W/cm^2.

Table 7. Comparison of Minimum Radiant Flux to Support Flame Spread Under Several Flux Conditions

Sample Tested	Uniform Irradiation[a] [29]	Radiant Flux At Extinguishment			
		Electric Source [29]	Flooring Panel Temperature [23]		
		600°C W/cm²	670°C W/cm²	550°C W/cm²	490°C W/cm²
W-1	>1.2	-	1.35	0.61	0.60
N-4	~1.0	-	0.35	0.27	0.25
A-1	~1.0	-	-	0.46	0.50
RO	~0.8	-	-	-	0.25
A-4	~0.7	0.60	0.36	0.44	0.38
A-4/U	~0.5	0.48	-	-	0.25
A-2	<0.44	0.38	0.28	0.31	0.29
A-2/U	<0.44	0.35	-	0.20	0.16
A-5	<0.44	<0.24	0.26	0.24	0.25
A-5/U	<0.44	<0.24	-	0.20	0.16
A-1/U	<0.44	<0.24	-	<0.19	0.11

[a] Three minute sample preheat followed by a three minute pilot flame exposure.

building code has increased its FSC acceptance level for corridors in the floor mounted version of E-84 by 50 percent over its earlier code. Thus, they apparently have weakened their flammability requirement for flooring materials in building corridors.

2.4.2. E-162 Radiant Panel

Although the concept behind E-162 is potentially useful in achieving quantitatively meaningful and useful information for fire safety design, it is not used that way and is not directly suited for flooring evaluation. The sample orientation provides a well-defined flame front progressing upwind as occurs in the early spread of flooring fires, but since it spreads downward it is inappropriate for flooring materials. Such an orientation does not allow flooring assemblies to be mounted as they may be installed, and more importantly, the physical deterioration of the sample during burning will affect combustion significantly. The melt, drip, run effect of polymers which accelerates flame spread is a case in point. Moreover, the radiant flux level prescribed seems to be at least twice as high as those typical of corridor flooring fires with noncombustible walls and ceiling. These factors tend to preclude E-162 as a suitable method for measuring flooring flammability.

2.4.3. UL 992 Chamber Test

The sample mounting and the testing of the entire flooring assembly is a favorable attribute of UL 992 in relating to the real-life performance of flooring materials. The index used to measure the potential hazard can provide a relative measure of potential flame spread, yet it is not suitable for any quantitative interpretation. The bimodal flame spread behavior of this test leads to a non-continuous index classification scale for materials. These factors and others relating to reproducibility of results between facilities have been addressed by Huggett and Lee [30].

2.4.4. Model Corridor

The similarity of the flameover mode in the Model Corridor and the NBS corridor fires, as well as the guidance of partial scaling relationships are good features of this method in its bearing on the real-life hazard. However, the accuracy of such scaling relationships have still to be assessed. Moreover, the energy release contributed by the material tested is an important factor in determining flameover in the Model Corridor. Thus, this energy release property is also inherently measured by the system. Table 8 demonstrates the effect and magnitude of energy release from the tested material. The effect

Table 8. 2 ft x 1 ft Model Corridor - Estimation of energy release rate of floor coverings and effect of available floor covering on flameover energy requirement

Conditions: V_∞ = 100 fpm, H=11 in, W=24 in

CFT	Material	FO	Burner $\dot{E}_B$ (Btu/min)	Maximum Energy Release Rate Before Flame-out or Before Flameover	
				Based on Exit Gas Temp.	Based on Heat Balance
129	A-4/U	yes	500	1,200	-
194	A-4/U	yes	600	-	1,500
141	N-3	no	1,000	900	-
142	N-3	yes	1,250	1,150	-
171	W-1	no	1,250	350	-
261	RO	no	1,250	250	-
195	N-5	no	500	-	700
196	N-5/U	yes	500	-	1,500-2,000

CFT	Material	Minimum Burner Input Rate to Flameover (Btu/min)	Time at Flameover (min::sec)
173	A-3, 2 ft x 8 ft sample	750	4::50
441	A-3, 7 1/2 in x 8 ft sample	1,500	-
443	A-3, 7 1/2 in x 18 in initial section, 2 ft w x 75 in follows	1,000	4::51
444	A-3, 2 ft x 8 ft sample with 3 in deflector plate at burner	750	4::48

of air flow on flame propagation could also prove troublesome in such systems if good design is not achieved. These latter factors detract from this system's ability to produce a complete design parameter for the material, and could affect reproducibility between systems.

2.4.5. Flooring Radiant Panel

This test method offers the most promise of obtaining a meaningful design parameter which relates to the hazard and can be related to the building system with increasing predictive accuracy as more knowledge of building fires is developed. As our understanding has developed on the potential hazard of flame spread over flooring materials, it has become clear that radiation from an external source is a very important factor in this type of fire spread. In particular, the application intended from this program has been the limitation of fire spread through corridors and exitways. Hence, the determination of the minimum radiant flux level necessary to sustain flame spread on flooring materials is a parameter directly related to the hazard and potentially useful in a fire safety design analysis in buildings. Hopefully, a flooring radiant panel system can be designed and operated satisfactorily to measure, with a suitable degree of precision, this "property" referred to as the "critical irradiance to support flame spread." In addition, a theoretical development of flame spread under an external radiant source, as proposed by eq (3), would enhance the understanding of this test method, and support the "property" interpretation of "critical flame spread irradiance." Thus, some additional work needs to be done to support the design and interpretation of this method.

A final consideration is the application of the performance measured by such a flooring radiant panel test method. Initially, judgement might be applied in setting performance acceptance levels for building corridors and exitways in various building occupancies. Guidance from recent full-scale experimental fires could be used to set performance levels. In addition, an empirical design approach could be used to determine acceptable performance and guidance in extrapolation to full-scale data. For example, calculations can be made based on energy release from a fire within a corridor spreading products in two directions. The radiation flux levels to the floor $\dot{q}_R''$ can be estimated for different fire energy release rates ($\dot{E}$) and different corridor heights (H) and widths (W). Some results of this kind of analysis are shown in figure 15. In this calculation it was assumed that all of the radiation comes from the ceiling and upper walls which are heated to the temperature of the fire plume intersecting the ceiling. A simple line fire plume theory was used and based on an analysis by Alpert [31] the gas temperature of the ceiling jet does not greatly vary with corridor length. The corridor was assumed infinitely long and no accounting was made for direct flame radiation. The result for floor radiant flux is

$$\dot{q}_R'' = \frac{0.0348}{\sqrt{\left(\frac{H}{W}\right)^2 + 1}} \left[1 + 0.014 \frac{(\dot{E}/W)^{2/3}}{H}\right]^4, \quad \frac{\text{Btu}}{\text{ft}^2\,\text{sec}}$$

where $\dot{E}$ is fire energy release rate in Btu/min,

H is ceiling height in ft,

and W is corridor width in ft.

Thus, this equation could be used to calculate the potential radiative floor flux in a building corridor. The "critical irradiance" measured by the flooring radiant panel test could then be used as a means of evaluating the material for the building corridor considered.

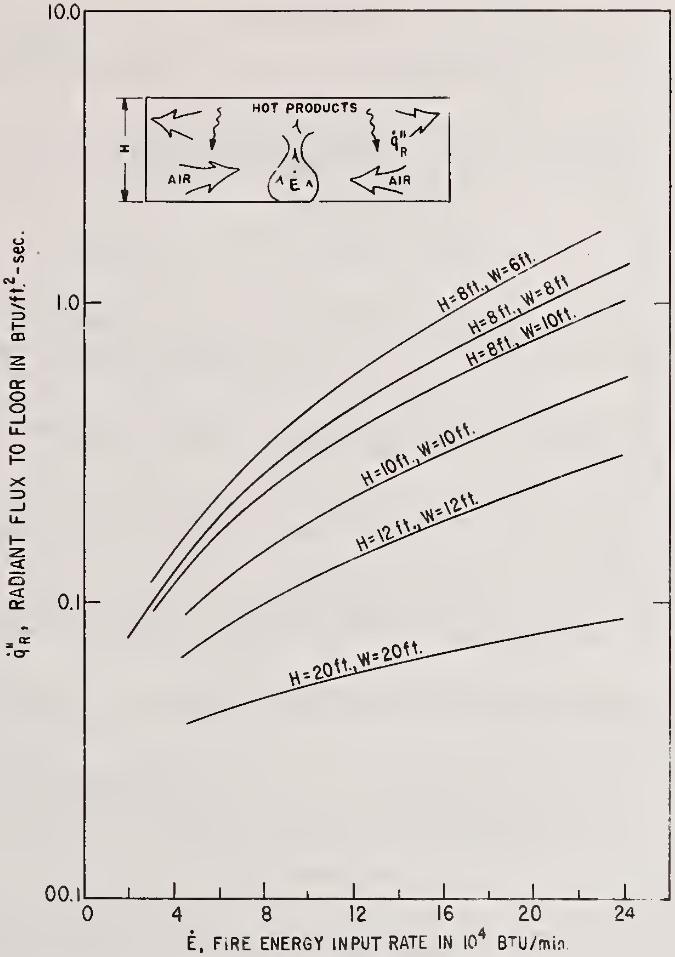


Figure 15. Estimated radiant flux to floors in building corridor fires.

3. CONCLUSIONS

The flammability of flooring materials has been examined through accident analysis and full-scale fire experiments. These results indicate that (except for carpets failing the Pill Test) a large ignition source is necessary to initiate flame spread on flooring material. Radiant heating of the flooring material due to a large ignition fire, along with building interior geometry, can lead to rapid flame spread over the flooring. This is recognized as the potential hazard of flooring materials in building corridors. Flame spread through corridors would block escape routes and transmit the fire to other areas of the building.

Available and proposed test methods for flame spread of flooring materials have been examined. Based on this study and on the dynamics of corridor fires a radiant panel test is recommended for flooring materials. Since this test can measure the flame spread behavior of flooring material under a controlled external radiant flux, it can yield data of quantitative value. Moreover, by estimating potential radiant flux levels in particular building occupancy type, a direct means of linking the test result to the application of the product can be achieved.

4. REFERENCES

[1] Yuill, C. H., The Flammability of Floor Coverings, J. Fire & Flammability, Vol. 1, 64 (Jan. 1964).

[2] Carpet and Rug (Pill Test) Standard for the Surface Flammability of Carpet and Rugs, DOC FF-1-70, Federal Register, 35, No. 74 (Apr. 16, 1970), 6211.

[3] Robertson, A. F., Private Communications, National Bureau of Standards, May 1973.

[4] Chandler, S. E., Fires Due to the Ignition of Carpets and Floor Coverings, 1955-62, Fire Res. Note No. 623, Fire Res. Station, Borehamwood, Herts, U.K.

[5] Fry, J. F., Private Communication -- Fires Involving Floors and Floor Coverings FRO/80/018, Fire Res. Station, Borehamwood, Herts, U.K., April 10, 1973.

[6] Fung, F. C. W., Suchomel, M. R. and Oglesby, P. L., The NBS Program on Corridor Fires, Fire Journal, 41 (May 1973).

[7] Huggett, C., Carpet Flammability and the NBS Corridor Fire Program, Standardization News, Vol. 1, No. 5 (May 1973).

[8] Fung, F. C. W., Suchomel, M. R. and Oglesby, P. L., NBS Corridor Fire Tests: Energy and Radiation Models, Nat. Bur. Stand. (U.S.), Tech. Note 794 (Oct. 1973).

[9] Christian, W. J. and Waterman, T. E., Fire Behavior of Interior Finish Materials, Fire Technology, 165 (Aug. 1970).

[10] Waterman, T. E., Private Communications, IIT Research Institute, February 1973.

[11] Segall, W. M., Private Communications, The Carpet and Rug Institute, January 8, 1973.

[12] McGuire, J. H., The Spread of Fires in Corridors, Fire Technology, Vol. 4, No. 2 (May 1968).

[13] Steiner, A. J., Method of Fire-Hazard Classification Building Materials, ASTM Bulletin, 19-22, (Mar. 1943).

[14] Standard Method of Test for Surface Burning Characteristics of Building Materials, ASTM E-84-70, American Society for Testing and Materials, Philadelphia, Pennsylvania (1970).

[15] Lee, T. G. and Huggett, C., Interlaboratory Evaluation of the Tunnel Test (ASTM E-84) Applied to Floor Covering, Nat. Bur. Stand. (U.S.), NBSIR 73-125 (Mar. 1973).

[16] Surface Flammability of Materials Using a Radiant Heat Source, ASTM E-162-77, American Society for Testing and Materials, Philadelphia, Pennsylvania (1968).

[17] Robertson, A. F., Gross, D. and Loftus, J., A Method for Measuring Surface Flammability of Materials Using a Radiant Energy Source, Proceedings, Am. Soc. Testing and Materials, Vol. 56, 1956, 1437-1453.

[18] Gross, D., and Loftus, J. J., Flame Spread Properties of Building Finish Materials, ASTM Bulletin, No. 230, 56-60 (May 1958).

[19] Lee, T. G., Loftus, J. J. and Gross, D., Effect of Moisture on Surface Flammability of Coated and Uncoated Cellulosic Materials, ASTM Special Tech. Publication, No. 385, 112-123 (1965).

[20] Engermann, H. S., Floor Covering System -- A Test for Flame Propagation Index, J. Fire and Flammability, Vol. 2, 11 (Jan. 1971).

[21] Denyes, W. and Raines, J., A Model Corridor for the Study of Flammability of Floor Coverings, Nat. Bur. Stand. (U.S.), NBSIR 73-200 (May 1973).

[22] Denyes, W. and Quintiere, J., Experimental and Analytical Studies of Floor Covering Flammability with a Model Corridor, Nat. Bur. Stand. (U.S.), NBSIR 73-799 (May 1973).

[23] Hartzel, L. G., Development of a Radiant Panel Test for Flooring Materials, Nat. Bur. Stand. (U.S.), NBSIR 74-495 (May 1974).

[24] Roberts, A. F. and Clough, G., The Propagation of Fires in Passages Lined with Flammable Materials, Combustion and Flame, Vol. 11 (1967).

[25] Roberts, A. F., Fires in the Timber Lining of Mine Roadways: A Comparison and Data from Reduced-Scale and Large Scale Experiments, Safety in Mines Research Establishment, Report 263, Sheffield, Eng. 1970.

[26] de Ris, Duct Fires, Combustion and Science Technology, Vol. 2, 239-258 (1970).

[27] Rockett, J., Mathematical Modeling of Radiant Panel Test Methods, Fire Safety Research, Proceedings of the NBS in Action Series-IV Fire, Nat. Bur. Stand. SP, Gaithersburg, Md., August 22, 1973 (to be published).

[28] Rhodes, A. C. and Smith, P. B., Experiments with Model Mine Fires, The Use of Models in Fire Research, National Academy of Science, Berl, W. G., Ed., Washington, D.C. (1961).

[29] Kashiwagi, T., Private Communications, National Bureau of Standards, 1973.

[30] Huggett, C. and Lee, T. G., Investigation of Carpet Flammability Test Methods, Nat. Bur. Stand., NBS Report 10585 (Sept. 24, 1971).

[31] Alpert, R. L., Fire Induced Turbulend Ceiling-Jet, Factory Mutual Research Corp., FMRC Ser. No. 19722-2 (May 1971).

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MATHEMATICAL MODELING OF RADIANT PANEL TEST METHODS

J. A. Rockett
National Bureau of Standards, Washington, D.C.

Standard flame spread tests characterize complex physical phenomena by a relatively simple experiment. Analytic modeling of the standard test identifies the sample geometry and material properties controlling the test outcome. Systematic variation of the model parameters verifies the analytic model for many broad classes of test samples provided parameter values appropriate to each test are determined by independent measurements. In most cases the standard test is not a satisfactory way to quantify the important sample parameters. The standard test is a suitable way to verify the applicability of a particular model or set of analytic models for a particular sample. If sample parameters are independently determined, the applicable models may then be used for hazard determination.

Key words: Fire modeling; fire test methods; flame spread; test method.

1. INTRODUCTION

There are several recognized fire test methods in which a sample is exposed to a radiant energy flux and, after either self or piloted ignition, burns [1,2]. The standard measurement of material performance is either the extent or rate of burning. Commonly, an index is computed from the measured quantities and is the only test result usually reported. An analytic model of a test method can provide information on the material properties and sample characteristics controlling the test outcome. This information, much more than the contrived test figure of merit, tells something about the burning characteristics to be expected from materials in actual fire situations. The modeling process yields material properties and sample characteristics important to the specific burning situations modeled and illuminates what the test does (and does not) measure. The model also allows some inferences on the extent to which test results fully characterize the material and sample variables needed to predict performance in fire situations.

2. FLAME SPREAD AGAINST THE WIND

A decade ago Gross and Loftus presented a simple model for radiant panel tests [3]. Their model suggested some similarity relations which were well verified by their experiments. Recently, J. Quintiere has developed a more detailed model for flame spread under a situation similar to that found in radiant panel tests. His model, derived for the case of propagation of flames against the ambient wind, appears to represent quite well the principal features of the test methods for sufficiently thin samples. This is appropriate because, although there is no forced convection with most radiant panel test methods, a certain amount of natural convection is always present, and in some test configurations quite a bit. Usually, the experimental configuration is arranged so that the flame propagates against such wind as is present.

Because of the importance of test modeling, Quintiere's model has been rederived in a somewhat more general way and extended to more general sample configurations. The present model is for thermally thick and laminated fuel beds. The model assumes there is a heat flux, Q, acting on the sample which is composed of two parts: the heat flux, Q_R, supplied to the sample from the radiant panel, which is normally a function of distance along the sample length, and the reflexive heat flux, Q_F, from the flame back to the sample surface.

Q_F is a rapidly decreasing function of the distance ahead of the flame. The Gross-Loftus model includes only Q_R and neglects loss of heat from the surface, but is otherwise similar to the present model.

In developing the present model it was assumed [4,5] that:

1. Negligible heat is transferred from the burning zone or flame to the unburned fuel ahead of the flame via the fuel bed.

2. For upwind flame propagation, heat transferred from the flame to the fuel ahead of the flame is localized to a very short region ahead of the flame.

3. The sample ignites when its surface temperature reaches a fixed, critical value. This is a surrogate for the more accurate but very much more complex and analytically intractable assumptions needed to describe the pyrolysis kinetics within the sample.

The new model which encompasses Quintiere's thin bed and Gross-Loftus's models as special cases is obtained by solving the one-dimensional transient heat conduction equation for a laminated fuel bed on a semi-infinite solid backing with a given applied surface flux, Q, and loss of heat proportional to surface temperature [6]. The one-dimensional solution may be used since heat flow in the fuel bed in the direction of flame spread is ignored.

The solution of the differential heat conduction equation is straight forward through the method of Laplace transformation. Transformed expressions can be readily written for single or multilayer fuel beds. The multilayer expressions are more complex and harder to invert. Unfortunately, test results are often sensitive to the backing behind the sample; consequently, such samples are not well modeled by the single layer expressions. For these, a multilayer model seems essential. The transformed expression evaluated at the sample surface for a two layer fuel bed (on an inert, insulating backing) consisting of an outer, exposed layer (1) of thickness d_1, a core layer (2) of thickness d_2 and an inert insulating backing is:

$$L(o,p) = Qg/p(Hg + k_1 q_1) \tag{1}$$

where

$L(o,p)$ = the transformed fuel surface temperature

p = the transformed time

$$g = \frac{k_1 q_1 \cosh(q_1 d_1)\cosh(q_2 d_2) + k_2 q_2 \sinh(q_1 d_1)\sinh(q_2 d_2)}{k_1 q_1 \sinh(q_1 d_1)\cosh(q_2 d_2) + k_2 q_2 \cosh(q_1 d_1)\sinh(q_2 d_2)} \tag{2}$$

H = surface heat transfer coefficient

k_1 = thermal conductivity of layer 1

k_2 = thermal conductivity of layer 2

$q_1 = \sqrt{\frac{p}{\alpha_1}}$ α_1 = thermal diffusivity of layer 1

$q_2 = \sqrt{\frac{p}{\alpha_2}}$ α_2 = thermal diffusivity of layer 2

At this writing a detailed study has only been undertaken for single layer fuel beds on an insulating backing, $k_2 = 0$. For this case inspection of the transform shows

$$L(o,p) = Q/p[H + k_1 q_1 \tanh(q_1 d_1)] \quad (3)$$

This in turn has two limiting forms which may be readily inverted. For large $q_1 d_1$, or time relatively short compared to that required for the temperature of the rear face to rise appreciably,

$$L_\infty(o,p) \simeq Q/p(H + k_1 q_1) \quad (4)$$

and, for small $q_1 d_1$, i.e. long times,

$$\begin{aligned} L_o(o,p) &\simeq Q/p[H + k_1 d_1 q_1^2] \\ &\simeq Q/p[H + (\rho c_p d_1)p]. \end{aligned} \quad (5)$$

Here, ρ is the fuel density and c_p is the fuel specific heat.

An exact inversion of the more general expression has not been found. Calculations reported here were carried out using the approximate function whose transform satisfied these two limiting conditions. This can be written as

$$I(t) = I_\infty(t)\exp(-\frac{Ht}{\rho c_p d}) + I_o(t)[1 - \exp(-\frac{Ht}{\rho c_p d})] \quad (6)$$

where $I(t)$ is the temperature response of the fuel to a unit step change in heat flux, I_∞ and I_o are the functions whose Laplace transforms are L_∞ and L_o, respectively, and d is the fuel thickness. The thin bed approximation, I_o, valid for short times, yields Quintiere's thin bed model. However, for small but finite time this approximation breaks down. The short time during which the flame heat, Q_F, is felt is the limiting factor in this. For practical purposes the thin bed model is valid only for films thinner than about 1/10 centimeter.

The model treats the two components of the incident heat flux slightly differently. The heat flux due to the radiant panel is treated using the heat transfer analysis stated above. The heat from the flame, however, is felt ahead of the flame for so short a period of time prior to arrival of the flame that only the limiting form for short times (large $q_1 d_1$) was used for computing the flame induced part of the fuel surface temperature rise. A thickness effect correction is included, however, since I, eq (6), does vary with thickness. For very thin samples a velocity formula based on the thin bed model should be used. The result of this and the further assumption that the flame velocity is constant over the time interval in which a particular element of the fuel surface feels the heat of the approaching flame, leads to the flame spread-velocity expression:

$$V = \frac{\delta_F}{\rho c_p k}\left\{\frac{Q_{F_o}}{2D}\left[1 + \sqrt{1 - 4D\left(\frac{H}{Q_{F_o}} - \frac{\rho c_p k Q_R}{Q_{F_o}^2} K(t) - H^2(1 + \frac{k^2}{H^2 d^2})\frac{D}{Q_{F_o}^2}\right)}\right]\right\}^2 \quad (7)$$

where

Q_F, Q_R, ρ, c_p, H and d are as previously defined

$D = T_c - (Q_R + \delta_F Q_R')I$

$$Q'_R = \frac{dQ_R(x)}{dx}$$

$K(t) = \frac{dI(t)}{dt}$, I(t) being the approximate heat flow solution, eq (6)

V = rate of flame spread

T_c = ignition temperature of the fuel

δ_F = distance ahead of the flame over which heat from the flame is felt by the fuel

Q_{F_o} = incident heat flux at the flame leading edge due to the flame

Experimental data from test samples have been used to evaluate the parameter groups in eq (7). The reciprocal of the velocity expression (7) was numerically integrated with respect to distance to give time, t, as a function of the flame location, x. The basic data recorded in the ASTM E-162 and some other radiant panel tests is the time at which the flame passes fixed positions; thus, the integral could be compared directly with experimental data. The result of the numerical integration for fixed values of the parameters in eq (7) was compared with experimental data and the parameters were adjusted to minimize the square error.

$$E = \sum_{i=1}^{N} [y_i - t(x_i)]^2$$

where y_i is the experimental time of flame passage measured at x_i, and $t(x_i)$ is the computed time from the integration.

Measured radiant flux distributions $Q_R(x)$ were used and these measured values were numerically differentiated with respect to distance to give Q'_R. Four of the parameters were adjusted: Q_{F_o}, HT_c, $H/\sqrt{\rho c_p k}$ and δ_F. Two other parameters enter but were not varied in individual data fits. They were varied for sets of data from a group of similar samples. One of these is the sample thickness parameter, k/Hd, which is important for relatively thin or slow burning samples. This parameter enters eq (7) in several terms: (1) it changes I, and, through the change in I, it changes D, and (2) it changes K which appears in one of the terms under the square root. Thickness dependence in these two terms has little effect on V for a range of thickness large enough to effectively change I from I_∞ to I_o. However, in eq (7), the last term on the right under the square root contains the thickness parameter and it does have an important effect. A discussion of the origin of this term is beyond the scope of this paper but it is associated with the heating of the sample by the flame. This term becomes increasingly important as the decrease in sample thickness allows the insulating effect of the backing to be felt such that less of the flame's heat is lost to the interior of the sample. The second "fixed" parameter, a constant of integration, is the time delay between sample insertion and ignition. This time is not usually recorded on the data sheet because the actual moment of ignition is hard to observe. The computed ignition is strongly influenced by the assumed heat flux from the pilot ignition flame. It was found that good data fits were obtained for E-162 tests with the pilot flame strength about 1.35 times the peak radiant panel flux, Q_{R_o}. For these tests, a variation of ±10% in the assumed pilot strength significantly changed the qualitative shape of the time-distance curve between the origin and second (6 inch) measuring point and changed the fit at the first measuring point (3 inch) slightly. There was little effect on the other parameters. Once a suitable pilot strength had been found it seemed to be satisfactory for all tests with the same test apparatus configuration. Of the four "variable" parameters, Q_{F_o} and HT_c changed the shape of the time-distance curve, and $H/\sqrt{\rho c_p k}$

and δ_F changed its scale with $H/\sqrt{\rho c_p k}$ having the greater influence. For this model the least squares fits are non-linear in the parameters. As expected in such cases, convergence did not always result in a good fit; there are several local minima for the error, E. The final fit was found by systematic variation of initial parameter guesses. Some results of this fitting are presented in table 1.

Table 1. Parameter Evaluation For Several Materials

Sample Designation	$H/\sqrt{\rho c_p k}$	HT_c	Q_{F_o}	δ_F	k/Hd
NBS Std. Hardboard 1/4"	0.101	2.37	14.22	0.127	0.5
NBS Std. Hardboard 1/4"(a)	0.098	2.35	14.14	0.129	0.5
Common Hardboard 1/8"	0.110	2.20	14.65	0.149	1.0
Common Hardboard 1/16"	0.153	2.04	13.75	0.119	2.0
Common Hardboard 1/32"	0.177	2.02	13.74	0.123	4.0
Fiberboard J #9 [3]	0.160	2.09	9.09	0.274	(b)
Exterior Plywood #30 [3]	0.107	2.13	9.19	0.252	(b)
Perforated Tile #17 [3]	0.127	1.73	7.70	0.541	(b)

[a]Repeat test, indicates degree of reproducibility.
[b]Fits insensitive to thickness parameter for range of values explored.

"Estimated" magnitudes of the quantities appearing in table 1 are given below and are of interest in assessing these data. Estimates are based on typical values for hard wood [6]. Convective component of the heat loss coefficient, H, was derived using McAdams, Chapter VIII [7].

$$H = \begin{cases} 2.77 \times 10^{-3}\ \text{W/cm}^2\cdot{}^\circ\text{C for a surface temperature of } 350^\circ\text{C} \\ 4.33 \times 10^{-3}\ \text{W/cm}^2\cdot{}^\circ\text{C for a surface temperature of } 490^\circ\text{C} \end{cases}$$

$$T_c = 350^\circ\text{C [8]}$$

$$HT_c = \begin{cases} 0.970\ \text{W/cm}^2 \text{ at } 350^\circ\text{C} \\ 2.122\ \text{W/cm}^2 \text{ at } 490^\circ\text{C} \end{cases}$$

$$\alpha = 1.3 \times 10^{-3}\ \text{cm}^2/\text{s}$$

$$k = 1.4 \times 10^{-3}\ \text{W/cm}\cdot{}^\circ\text{C}$$

$$\frac{H}{\sqrt{\rho c_p k}} = \begin{cases} 0.0713\ \text{s}^{-1/2} \text{ for } H = 2.77 \times 10^{-3}\ \text{W/cm}^2 \\ 0.1115\ \text{s}^{-1/2} \text{ for } H = 4.33 \times 10^{-3}\ \text{W/cm}^2 \end{cases}$$

$$\frac{k}{Hd} = 0.505 \text{ for } d = 1 \text{ cm}$$

$$Q_{F_o} = 4.0\ \text{W/cm}^2\ \text{[8]}$$

$$\delta_F = 0.1\ \text{cm [8]}$$

There are several implications of the data in table 1 which, if true, are somewhat surprising. Comparing the "fitted" values with estimates suggests that $H/\sqrt{\rho c_p k}$ and δ_F are reasonably close to what one might expect. The values of Q_{F_o}, however, are about twice those expected [8], although there is little published data to compare with these values. A recent paper by Hirano *et al* [9] suggests a value of 20 to 22 W/cm^2 for Q_{F_o} for cellulosic material. Also, the implied value of T_c for hardboard is close to 490°C, 100°C above the value experiments would suggest [8].

Gross and Loftus [3] found an experimental correlation over a range of two orders of magnitude in thermal inertia, $\rho c_p k$. This suggests that the theoretical dependence on thermal inertia of eq (7) is correct. However, it is not possible to evaluate the thermal inertia of a particular sample from examination of E-162 test data: one can only obtain values for parameter groups containing thermal inertia and other parameters.

3. FLAME SPREAD WITH THE WIND

Fire, starting low and spreading upward, burns into the unburned fuel preheated by the rising fire gases, and develops rapidly. On the other hand, fire starting high on an object and burning down moves against the natural convection and travels slowly. Aside from the obvious difference in direction of flame travel relative to the local natural draft, there are other basic differences in controlling physical processes. A hazard rating, based on a standard test of flame spread against the wind, might supply information needed to predict spread with the wind, but only if the test included supplemental measurements in addition to surface flame spread. The ASTM E-162 standard test method appears to recognize this by measurement of the total sample heat release rate in addition to flame spread.

There are several standard tests in which the surface flame spread measurements are made with the wind. Probably the most widely used test methods are the "Steiner Tunnel," ASTM Standard E-84, the "45° Fabric Test," CS 191-53, and the recently adopted vertical test, DOC FF3-71. If against-the-wind and with-the-wind tests each fully evaluated a sample material, it would be possible, through mathematical modeling of both tests, to cross predict the fire performance of the material. If this could be accomplished, a considerable step would have been made in predicting real fire growth in a building from standard test data. At present, this is not possible. On the other hand, if it could be shown that the result of one standard test did not allow prediction of that of the other, we would know why the test failed to fully characterize the hazard of the tested sample. Thus, it is worthwhile looking into the mathematical model of flame propagation with the wind and comparing this with the upwind propagation model.

A model for with-the-wind spread of a turbulent flame has been developed recently. This model is a generalization of a model proposed by de Ris [10]. The de Ris model is a quasi-steady analysis of a thin fuel bed and the generalized model is a transient analysis of thicker fuel beds. de Ris assumes that a turbulent flame produces a layer of gas, at the (constant) flame temperature, and that the heat transfer rate from this flame to the fuel is constant over the entire length of the flame projected along the sample surface. The generalized de Ris analysis has been used with some success to model E-162 stack heat data. However, the variability of measured stack heat for repeat tests of nominally identical samples suggests further work on this aspect of the radiant panel tests is needed.

4. CONCLUSIONS

The general theory presented here seems to satisfactorily represent the flame spread behavior of samples tested in the E-162 apparatus. Numerical constants found from actual data fits are generally of the expected magnitude. The effect of sample pyrolysis which does not appear in the present model is found to be significant. This important burning characteristic does influence the stack temperature measurement which is a part of the E-162 protocol but not of some other proposed radiant panel tests. To the extent that these other tests are essentially against-the-wind flame propagation tests and would presumably be well modeled by this same analysis, they will characterize the same groups of parameters found important here; and they will not include the effect of sample pyrolysis rate. Some additional feature, such as stack heat, or other heat release rate measurement should be included to quantify this important burning characteristic of materials.

5. REFERENCES

[1] Robertson, A. F., Gross, D. and Loftus, J., A Method For Measuring Surface Flammability of Materials Using a Radiant Energy Source, Proceedings of the American Society for Testing and Materials, Vol. 56, American Society for Testing and Materials, Philadelphia, Pa., 1956, 1437-1453.

[2] Anon., Fire Tests of Building Materials and Structures - Spread of Flame Test for Materials, British Standards Institution, BS 476: Part 7 (1971).

[3] Gross, D. and Loftus, J., Surface Flame Propagation in Cellulosic Materials Exposed to Thermal Radiation, Journal of Research, Nat. Bur. Stand. (U.S.), 67C (Eng. and Instr.), No. 3, 251-258 (July-Sept. 1963).

[4] Simms, D. L., Ignition of Materials Exposed to Thermal Radiation, Combustion and Flame, Vol. 4, No. 3, 293-300 (Dec. 1960).

[5] de Ris, J. N., Spread of a Laminar Diffusion Flame, Twelfth Symposium (International) on Combustion, University of Poitiers, Poitiers, France, July 14-20, 1968, 241-252 (The Combustion Institute, Pittsburgh, Pa., 1969).

[6] Carlslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids, 2nd Ed. (Clarendon Press, Oxford, 1959).

[7] McAdams, W. H., Heat Transmission (McGraw-Hill, New York, 1942).

[8] Parker, W., Flame Spread Model For Cellulosic Materials, Journal of Fire and Flammability, Vol. 3, 254-269 (July 1972).

[9] Hirano, T., Noreikis, S. and Waterman, T. E., Measured Velocity and Temperature Profiles of Flames Spreading Over A Thin Combustible Solid, Interim Technical Report No. 2, House Sponsored Project J1139, IIT Research Institute, Chicago, Ill. (May 7, 1973).

[10] de Ris, J. N., Technical Proposal, Dynamics of Textile Fire: A Study of its Mechanisms - Theory and Experiment, Factory Mutual Research Corporation, Ser. No. 205883, el-e5 (May 1971).

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FLAME SPREAD OVER A POROUS SURFACE UNDER AN EXTERNAL RADIATION FIELD

Takashi Kashiwagi
National Bureau of Standards, Washington, D.C.

Flame spread over carpet surfaces was studied under various constant external radiant fluxes from 0.4 to 1.2 W/cm^2. Characteristics of ignition and flame spread including speed of spread and net heat release rate were measured. The results indicate that these values increase rapidly with increasing external radiant flux. It was also observed that there exists a minimum radiant flux necessary to sustain steady flame spread for each carpet. The underlayment of a carpet has a significant effect on ignition and flame spread speed for nylon carpets due to melting of fibers before flameover. However, this effect is negligible for low pile density acrylic carpets.

Key words: Carpet flammability; flame spread; ignition.

1. INTRODUCTION

It has been observed in full scale experiments that radiation from ceiling, walls and hot smoke and gas heats a carpet before flameover in a corridor and this radiant preheating plays an essential role in flame spread over the carpet surface [1]. Under this condition, it is sometimes reported that flame will spread very rapidly over a carpet which passes the present carpet test standard, the so-called "pill-test". The objective of this study was to observe the characteristics of flame spread over various types of carpets under various radiant fluxes which simulate those measured in the full scale experiments. It was expected that we would learn about the behavior of flame spread over a carpet surface and that we could use this information to design a better test method for measuring carpet flammability.

2. EXPERIMENTAL APPARATUS

A schematic illustration of the apparatus is shown in figure 1. The radiant panel consists of twelve nichrome ribbons on a ceramic support. Its dimensions are 15 in x 33 in. This panel is electrically heated and its ribbon temperature can be controlled at about 600°C. A test specimen (6 in x 21 in) is held by a support and located on the cement asbestos board table. The distance between the panel and the test specimen surface can be varied by lowering or raising the table. Distances of 16 inches, 20 inches, 24 inches, 28 inches, and 32 inches were used in this study. Radiant flux distribution over a specimen surface is fairly uniform (within 10%) except at the 16 inch distance (15%). A shutter is used to allow a test specimen to be exposed suddenly to a constant radiant flux after the panel reaches the equilibrium condition. One end of the specimen is ignited by a pilot burner which is designed to produce a linear diffusion flame. Preheating time of the specimen is controlled by the time at which the pilot burner is turned on after the opening of the shutter. The pilot burner is turned off after the specimen is ignited and sustains a flame. This ignition time is significantly different for different specimens. After the pilot burner is turned off, the flame spreads over the specimen surface. The steady flame spread speed is attained within a few inches of the pilot burner. Flame spread speed is observed by eye with a stop watch used to time the passage of the flame front by scribed distance markers. A fine mesh screen surrounds the test apparatus to prevent air motion in the room from affecting flame spread.

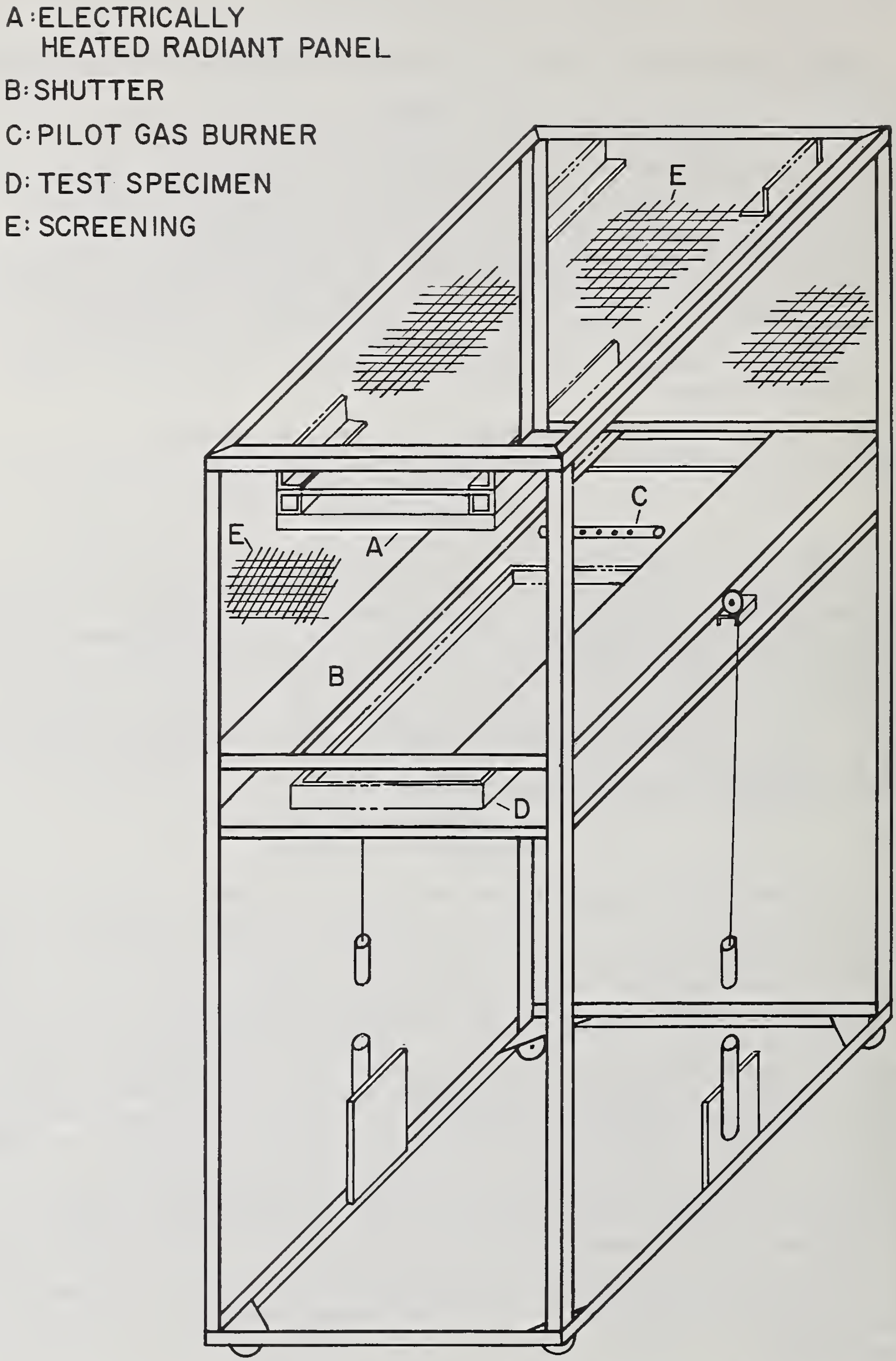

Figure 1. Schematic illustration of experimental apparatus.

A description of the carpets used in this study is given in table 1. The carpet specimens and underlayment were conditioned at 50% humidity and 23±2°C temperature for at least 48 hours prior to use.

Table 1. Carpet Designation

Code	Fiber	Type	Backing	Density (g/cm^3) Pile	Density (g/cm^3) Backing	Pile Height (cm)
A-1	100% Acrylic	Woven Level Loop	Jute/Cotton	0.18	0.51	0.64
A-2	100% Acrylic	Random Shear	Polypropylene/Jute	0.087	0.46	0.16 - 0.80
A-4	100% Acrylic	Random Shear	Jute/Jute	0.16	0.51	0.32 - 0.96
A-5	100% Acrylic	Plush	Polypropylene/Jute	0.074	0.52	0.91
N-4	Nylon (6 & 66)	Shag	Jute/Jute	0.086	0.51	0.99
N-5	BCF Nylon (66)	Multi-level loop	Jute/Jute	0.061	0.51	0.59
Pad	Rubberized Hair Jute			0.18		1.18

3. RESULTS AND DISCUSSION

Ignition is the initiation process of fire and it is one of the important parameters used to characterize the flammability of a material. In this study, ignitability was measured by observing the minimum duration time of the pilot flame necessary for a carpet to sustain flame after the pilot burner is turned off. The results are shown in figure 2. The data show that the minimum ignition time varies significantly from one material to another. The acrylic carpets A-2 and A-5 of low pile density require very short duration times. The effect of a pad on the ignition time is negligible for these carpets. On the other hand, nylon carpets N-4 and N-5 require much longer ignition times and the effect of a pad is significant. Acrylic carpets A-1 and A-4 of heavy pile density are intermediate in their behavior. It is observed that the fibers in nylon carpets melt before they ignite. This melting process requires a longer minimum pilot flame duration at high radiant fluxes compared with non-melting carpets.

The relation between speed of flame spread and incident radiant flux is shown in figure 3. It is observed that there exists a minimum radiant flux for a carpet to support flame spread without extinguishment, although this study did not conduct experiments at a radiant flux low enough to extinguish carpets A-5, N-4, and N-5. Since these carpets pass the pill test, they will not support a flame in the absence of an external energy flux. The trends described in the above discussion, such as the significant effects of pile density and composition on ignition, are not observed in the value of minimum radiant flux. The effect of a pad on the minimum radiant flux is negligible for the low pile density carpets A-2, and A-5, but significant for others. This is similar to the trend observed in the ignition study discussed above. The value of the minimum radiant flux necessary to support flame spread is one of the important characteristics by which to judge the fire safety of a carpet.

Another important characteristic shown in figure 3 is that speed of flame spread increases rapidly with increasing incident radiant flux for all carpets tested. Speed of flame spread increases in the order of nylon carpets N-4 and N-5, heavy pile density acrylic carpets A-1 and A-4, and low pile density acrylic carpets A-2 and A-5. This is the same order as observed for minimum ignition time. Therefore, in this range of radiant flux level and preheating time, the flame spread mechanism is considered to be a successive ignition process. From these results it is found that the type of pile of a nylon carpet has little effect on flame spread and ignition because the melting process ahead of the flame destroys the pile structure. However, the pile structure

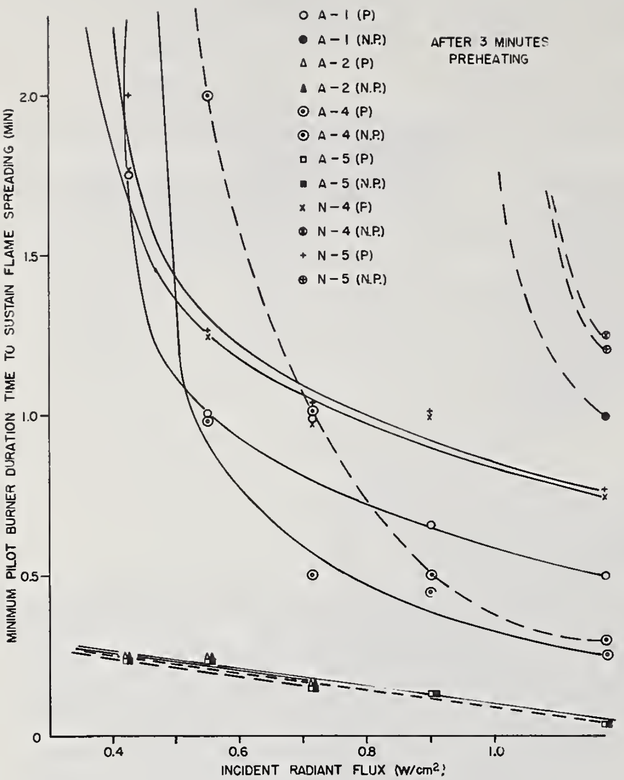

Figure 2. Relation between the minimum pilot burner duration time and incident radiant flux, N-Nylon, A-Acrylic, N.P.-No Pad, P-Pad.

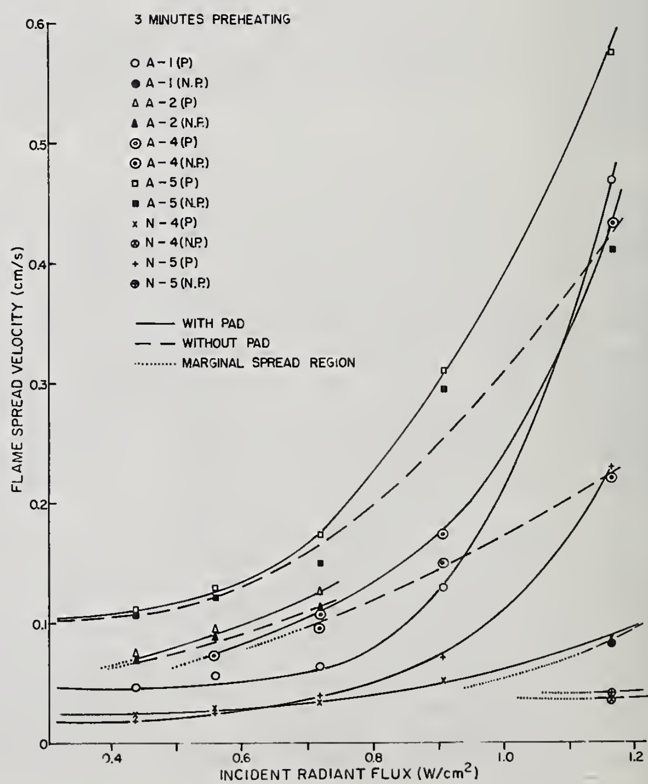

Figure 3. Relation between flame spread velocity and incident radiant flux.

of acrylic carpets has a significant effect on ignition and flame spread. The other experimental parameter is the duration of preheating. Except at the highest radiant flux used in this study, 1.15 W/cm^2, a preheating time longer than three minutes does not increase speed of flame spread significantly. At a radiant flux of 1.15 W/cm^2, the longer preheating time produces smoking and partial charring of the sample surface before it is ignited by the pilot burner. After pilot ignition and a transient stage, very rapid flame spread is observed. It spreads so fast that accurate measurement of its speed by eye is very difficult. The order of speed is a few centimeters per second. With a still higher radiant flux, this speed would eventually reach the flame propagation speed for the mixture of decomposed fuel vapor and surrounding air, which is about an order of magnitude larger. This rapid flame spread phenomenon is also observed in the full scale experiments [1].

This phenomenon can spread fire and smoke throughout a building, causing loss of life and extensive property damage. Therefore, the relation between radiant flux and preheating time leading to this rapid flame spread is an important factor by which to judge the fire safety of a carpet. There are three important parameters: ignitability, minimum energy flux to sustain constant flame spread, and the domain of rapid flame spread controlled by radiant flux and preheating time. The general trends of these parameters with incident radiant flux and pilot burner duration time are shown in figure 4. It is considered here that the minimum radiant flux is an asymptotic value of external

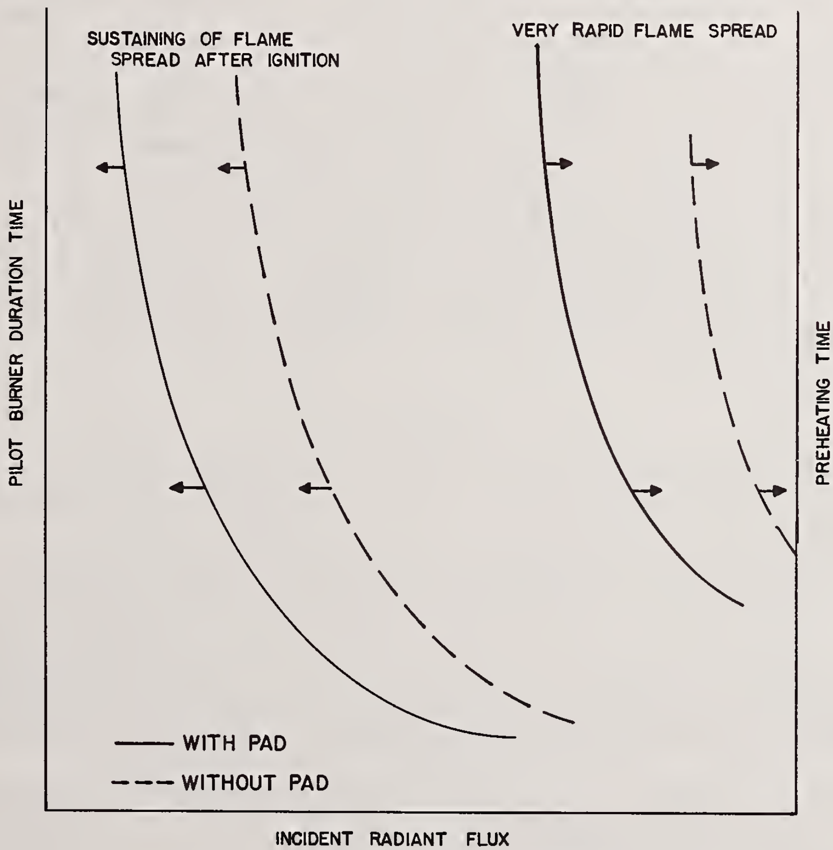

Figure 4. Qualitative relations between ignition and incident radiant flux and between flame spread velocity and incident radiant flux under variable preheating time.

radiant flux for sustained flame propagation. The plotted curves are relative ones and each carpet has its own characteristic curves. From the test standard point of view, ignitability and the domain of rapid flame spread should be measured by a pilot ignition study (because the preheating times and the external radiant fluxes necessary to cause rapid flame spread are well correlated with the pilot ignition delay time) and minimum radiant flux to sustain flame spread should be measured by a flame spread test under a radiation flux field which decreases in intensity along the sample surface.

Thus, we have discussed flame spread and ignition under an external energy flux. However, in an actual fire, there is another important energy source which is heat release from the burning carpet. This energy will also contribute to the rate of flame spread. For this reason, the heat release rate from a carpet over which the flame spreads with constant speed was measured. First, the total heat release from the unburned carpet is measured by the oxygen-bomb [2] method. Then, heat release from the char remaining after the flame spread test is also measured with the same technique. The difference between these values, adjusted to represent equal areas, is the net heat release which is measured per unit surface area. The product of this net heat release and the constant flame spread speed is the net heat release rate per unit width. The results are shown in figure 5 for various radiant fluxes. The data indicate that the net heat release rate increases rapidly with increasing incident radiant flux. It is interesting to note that net heat release rates of low pile density carpets A-2 and A-5 are smaller than those of other carpets at low radiant fluxes although flame spread speeds of A-2 and A-5 are faster than those of other carpets. This means that flame spread over A-2 and A-5 involves only a shallow zone near the surface. However, the other carpets burn more deeply. This is confirmed by the measurement of weight loss of carpets after flame spread tests. Net heat release rate decreases considerably when the carpets are burned without a pad even for low pile density carpets A-2 and A-5. This behavior is quite different from the negligible effect of a pad on ignition and flame spread speed for A-2 and A-5. This is illustrated in figure 6, which compares the flame shape with a pad and without a pad under the same radiant flux. Without a pad, there is only a main flame. This means that the carpet burns longer and over a larger area with these smaller flames. This behavior is observed only at high radiant fluxes. At low radiant flux, the width of flame increases slightly.

4. SUMMARY

1. For carpets which pass the pill test there exists a minimum radiant flux necessary to sustain flame spread over the carpet surface without extinguishment.

2. Speed of flame spread increases rapidly with increasing radiant flux and approaches values of flame propagation speed characteristics of the gas phase.

3. The construction of the pile layer of acrylic carpets significantly affects ignition, flame spread speed and net heat release rate. With nylon carpets the effect is smaller due to melting of the pile ahead of the flame front.

4. The effect of a pad on ignition and flame spread speed is significant for carpets of heavy pile density, but small for acrylic carpets of light pile density. However, the effect on heat release rate is significant for all carpets tested.

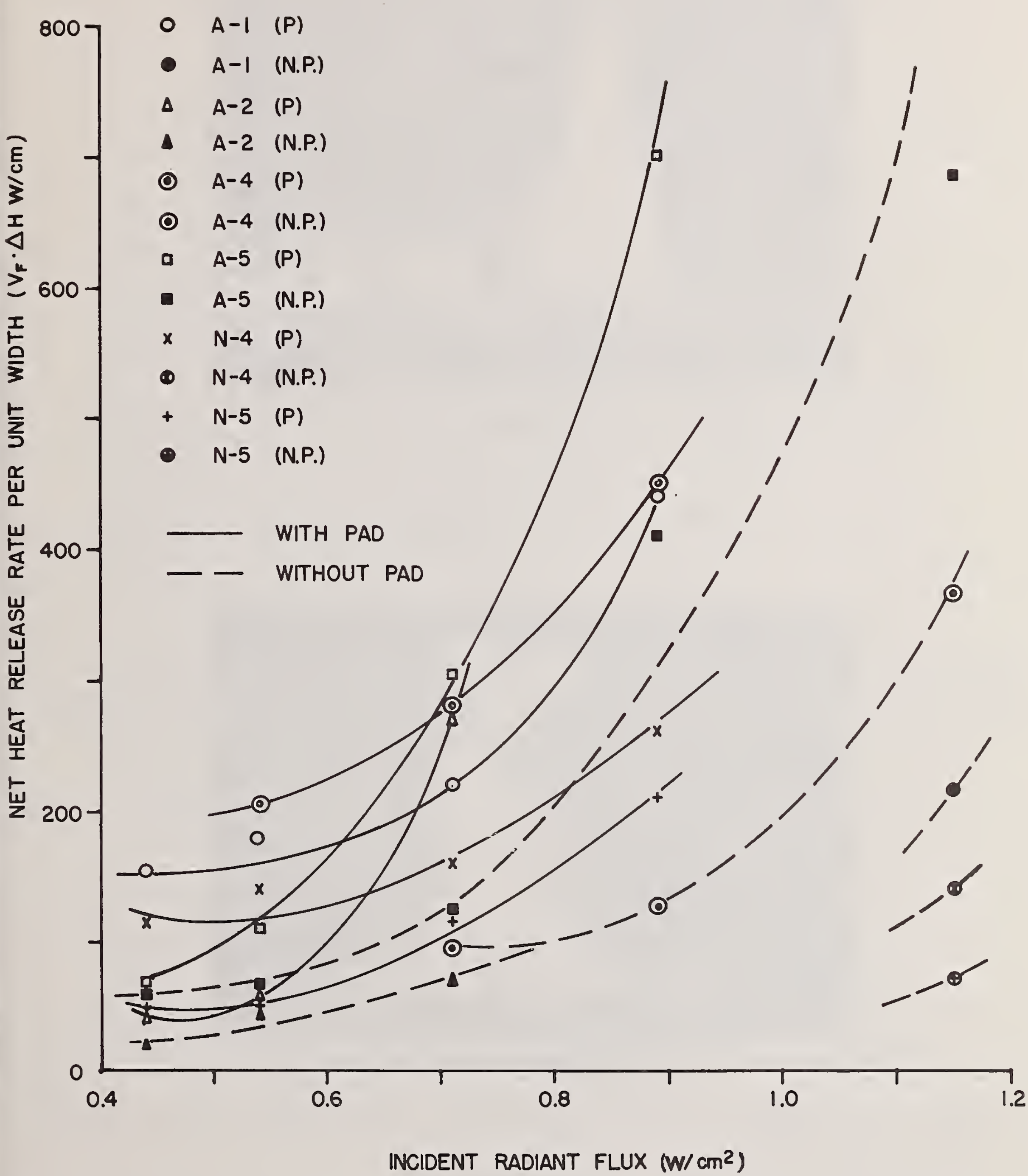

Figure 5. Relation between net heat release rate and incident radiant flux.

WITH PAD

WITHOUT PAD

Figure 6. The effect of pad on flame shape. Flame travels from right to left (0.86 W/cm^2).

5. REFERENCES

[1] Fung, F. C. W., Suchomel, M. R. and Oglesby, P. L., Fire Journal, Vol. 67, 41 (1973).

[2] Ambrosius, E. E. and Fellows, R. D., Mechanical Engineering Laboratory Practice, 245-247 (Ronald Press, N.Y., 1957).

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PHYSIOLOGICAL AND TOXICOLOGICAL EFFECTS OF THE PRODUCTS OF THERMAL DECOMPOSITION FROM POLYMERIC MATERIALS

M. M. Birky[1]
National Bureau of Standards, Washington, D.C.

I. N. Einhorn, M. L. Grunnett, S. C. Packham, J. H. Petajan, J. D. Seader
University of Utah, Salt Lake City, Utah

A program that combines the capabilities of the College of Medicine and the College of Engineering of The University of Utah has been instituted to evaluate the physiological and toxicological effects of the products of thermal degradation and combustion of cellulose, a polyvinyl chloride, a flexible polyurethane, and wood (Douglas fir). The products produced from these materials are being identified and quantified with a gas chromatograph-mass spectrometer-computer system. In addition, a National Bureau of Standards smoke chamber has been modified with a weight loss transducer to correlate, on a continuous basis, the quantities of smoke produced with sample weight loss. Extensive studies on the effects of these degradation products on rats is in progress. The results of exposure of the rats to carbon monoxide are reported. All of the laboratory results are being correlated with full-scale fire studies at the National Bureau of Standards.

Key words: Combustion; polymer; pyrolysis; smoke; specific optical density; toxic gases; toxicity.

1. INTRODUCTION

The flammability research program at The University of Utah is sponsored by the National Science Foundation's Research Applied to National Needs (RANN) Program. The program is directed to the physiological and toxicological aspects of humans during fire exposure and is divided into the following thirteen tasks:

Task	Activity
1	Materials Selection and Characterization
2	Development of a Chamber for Smoke Studies
3	Animal Exposure Chamber
4	Measurement of Smoke
5	Analysis of Smoke
6	Effects of Fire Retardants on Smoke
7	Gross Physiological Effects of Smoke
8	The Influence of Volatile Degradation Products of Combustion on the Survival Responses of the Rat
9	Toxicological Studies
10	Visual Aspects Dependent on Smoke Exposure
11	Neuropathological Studies Related to Fire Exposure
12	Large-Scale Fire Tests (NBS)
13	Analysis of Fire Injury by Smoke

[1]This paper was written during the 1973-1974 academic year while Dr. Birky was a visiting Professor at The University of Utah.

The program has been in existence approximately one year. The National Bureau of Standards has been, and is presently, supporting the program in a regular consulting mode and through interchange of a senior scientific staff member. This paper is a review of the technical accomplishments of the various tasks of the program at this date.

2. TECHNICAL ACCOMPLISHMENTS OF THE VARIOUS TASKS OF THE PROGRAM

2.1. Task 1 - Materials Selection and Characterization

Task 1 was completed early with the selection of cellulose, a PVC, a flexible urethane and Douglas fir as the four materials of interest. Douglas fir was chosen because of its extensive use in the building industry and since many building codes state simply that the use of new materials in buildings should be no more hazardous than wood (from a fire hazard view point). Wood then becomes a reference in determining the relative hazard of the two plastic materials chosen in the program. The effects of fire retardants on smoke and toxic gas profile (Task 6) will not be covered at this time since it is to be studied at a later date.

2.2. Task 2 - Development of a Chamber for Smoke Studies and Task 4 - Measurement of Smoke

2.2.1. Physical Characteristics of Smoke

Smoke may be defined as the airborne products from smoldering or burning materials. Thus, besides gas, smoke may contain various types of solid and liquid particulate matter. The physical characteristics of smoke that are of major interest are light transmission, airborne mass loss, particulate mass, and particulate size, shape and phase state. A relatively large number of variables may influence these dependent characteristics, such as polymer type, exposed area, sample thickness, weight, density, orientation, fire retardant additives, surface coatings, oxygen availability, and heat flux.

Light transmission has been considered from a theoretical point of view. If the smoke is considered to consist only of small spherical particulate matter, the light to be monochromatic, and the scattering to be single and independent, then combining Rayleigh and Bouguer laws leads to the following expression for the widely used specific optical density parameter D_s:

$$D_s = \frac{V}{AL} \log_{10}\left(\frac{F_o}{F}\right) = \frac{32\Gamma\rho_s t^4}{2.303\rho_p}\left(\frac{r^3}{\lambda^4}\right)\left(\frac{n^2-1}{n^2+2}\right)^2 \qquad (1)$$

where A = exposed surface area of material
F = attenuated light intensity
F_o = source light intensity
L = optical path length
n = particulate index of refraction
r = radius of particulates
t = sample thickness
V = smoke chamber volume
Γ = fraction of mass loss that is particulates
λ = wave length of light beam
ρ_s = density of sample
ρ_p = density of particulates.

This relation predicts that the specific optical density is directly proportional to material density and thickness. Limited experimental data from the NBS [1] and Hilado [2] tend to confirm this prediction provided that the light transmission is not attenuated to values less than about one percent. Figures 1, 2, and 3 show that, as predicted by eq (1), the maximum specific optical density (maximum value of D_s) is linearly dependent on sample thickness and density.

The above relationship suggests that the sample weight loss is an important parameter to correlate with the quantity of smoke produced from any given material and may indeed be a means of predicting the potential smoke hazard of a material. A new smoke index, referred to here as the mass-optical density, may be obtained from a rearrangement of eq (1) to the relation

$$\frac{D_s A}{m} = \frac{32\Gamma\pi^4}{2.303\rho_p}\left(\frac{r^3}{\lambda^4}\right)\left(\frac{n^2-1}{n^2+2}\right)^2 \qquad (2)$$

where m is the sample mass loss.

As a result of this theoretical development, the NBS smoke chamber has been modified to include a sensitive weight loss transducer system so as to simultaneously record weight loss and light transmission on a continuous basis. Details of the modification have been reported by Chien, Seader, and Birky [3]. Data using the modified smoke box in the non-flaming mode at 2.5 watts/cm^2 for a flexible polyurethane are shown in figure 4. In this case, after discounting the time lag of the light transmission because of the finite time for the particulate to spread through the chamber, the initial airborne mass loss appears to contribute less to the smoke particulate than the later mass loss. Correlation of mass loss with optical density is clearly indicated. The two curves in figure 4 can be combined according to eq (2). This type of data treatment for the urethane and other materials is shown in figure 5 for comparative purposes. In all cases, the data is for non-flaming using a radiant flux of 2.5 watts/cm^2. Significant differences are noted among the materials with the cellulosics occupying a central position. Significant differences in rate of smoke production are also evident which need to be investigated.

Of particular importance in the use of the NBS chamber for the evaluation of materials is the maximum value of D_s, referred to as D_m. Values of D_m and mass loss for the materials shown in figure 5 are tabulated in table 1 along with the maximum specific optical density normalized to the mass lost. These values are shown in column 5 of this table. Mass normalization of the maximum specific optical density shows a dramatic difference in the smoke hazard as compared to the maximum specific optical density alone as shown by column 2 and if materials of grossly different properties such as thickness, density, surface porosity, etc. are to be intercompared, then mass loss must be taken into account.

The standard non-flaming test utilizes a heat flux of 2.5 watts/cm^2 which is sufficient to prevent ignition of α-cellulose, as well as most other materials. In order to study the effect of radiant heat flux on the specific optical density, a new heat source was designed for higher temperatures. Results, using the new heat source for 0.030-inch thick α-cellulose and 1/4-inch thick Douglas fir are shown in figures 6 and 7, respectively. Data are plotted for a heat flux range of approximately 1.2 to 7.5 watts/cm^2. In both cases, the maximum specific optical density appears to go through a maximum just prior to ignition. In the flaming region, D_m values are generally significantly reduced below those for most of the non-flaming region. The effect of heat flux is particularly important if 2.5 watts/cm^2 is on the part of the specific optical density curve that is changing rapidly for any given material. When this is the case it will be difficult to obtain reproducible results, especially during interlaboratory evaluation of the smoke test method using that material. Thus, the effect of heat flux appears to be sufficiently important to warrant more study.

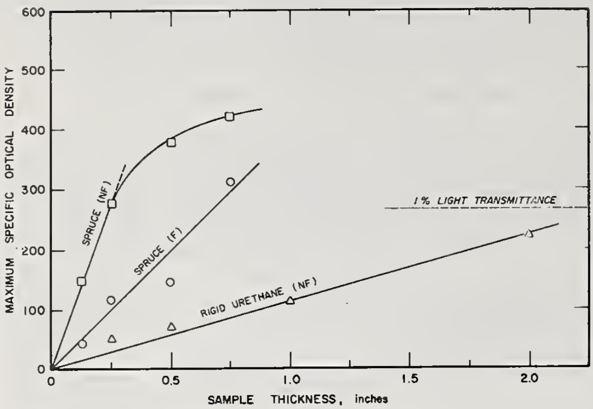


Figure 1. Effect of thickness on maximum specific optical density for relatively thick materials.

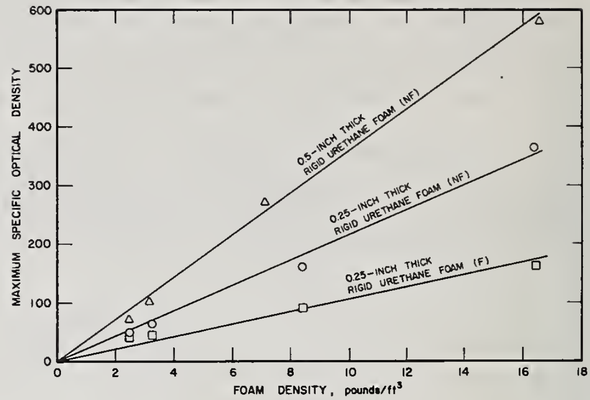


Figure 3. Effect of material density on maximum specific optical density.

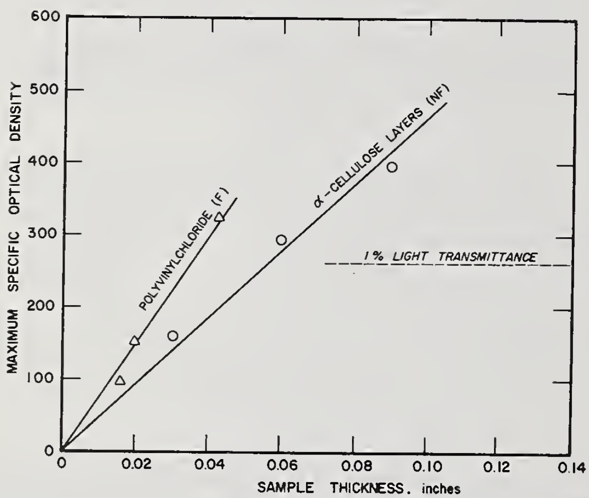


Figure 2. Effect of thickness on maximum specific optical density for relatively thin materials.

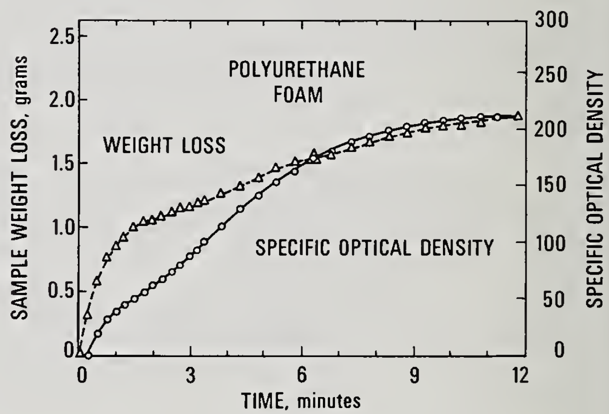


Figure 4. Specific optical density and sample weight loss curves for polyurethane foam (TDI-type).

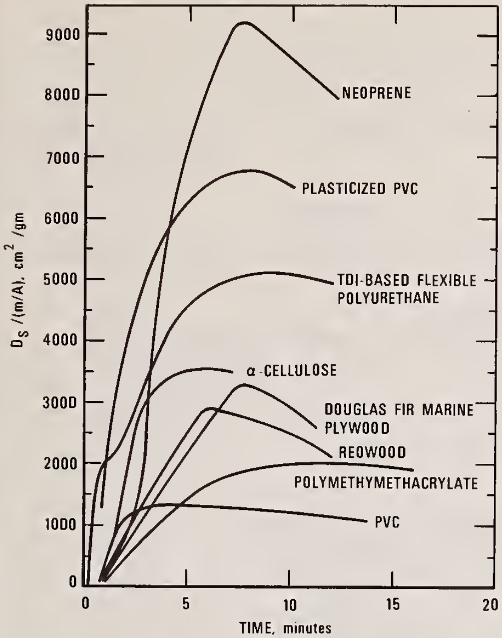


Figure 5. Mass-optical density for several materials.

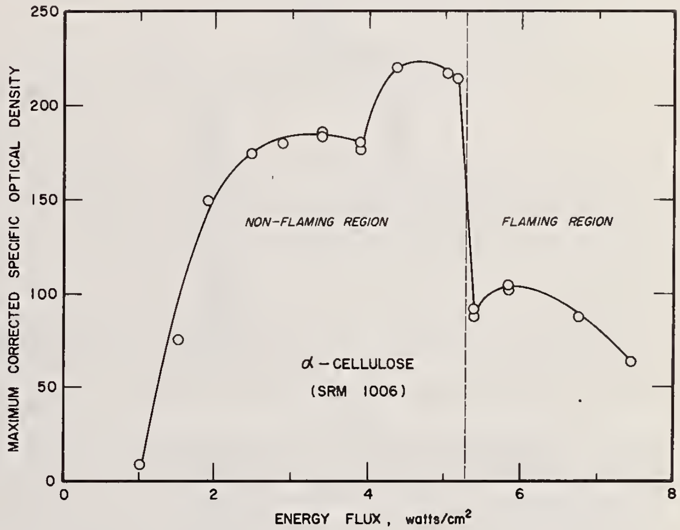


Figure 6. Effect of energy flux on maximum corrected specific optical density of α-cellulose (SRM 1006).

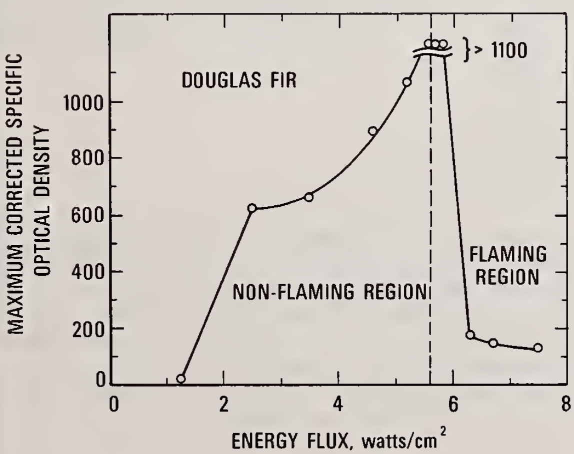


Figure 7. Effect of energy flux on maximum corrected specific optical density of Douglas fir.

Table 1. Maximum Specific Optical Density and Mass Loss For Several Materials

Material	D_m (corrected)	m (gm)	% mass loss	$\frac{D_m\text{(corrected)}}{m/A}$ (cm^2/gm)
Polyvinylchloride plasticized. . . .	350	2.30	63.7	6,430
Neoprene	877	6.75	14.1	5,490
TDI-based flexible polyurethane . . .	198	1.78	97.2	4,690
α-cellulose.	173	2.19	87.6	3,340
Douglas fir marine plywood . .	533	7.73	47.0	2,910
Douglas fir.	620	9.39	53.7	2,790
Redwood.	436	8.38	53.9	2,230
Polymethyl-methacrylate . . .	724	20.00	40.4	1,530
Polyvinylchloride. .	177	6.40	53.1	1,170

In the normal operation of the NBS smoke density chamber, ventilation is prohibited in order to measure the maximum smoke density. In a fire, however, some ventilation may be present, and for this reason Gaskill [4] has used a modified NBS-type chamber to determine the effect of ventilation on a wide variety of materials. His results show that most materials exhibit a significant monotonic decrease in D_m with ventilation rates in the non-flaming mode. For flaming combustion the effect of ventilation is not as clear cut. The availability of oxygen in the smoke box measurements was shown by Gross *et al* [1] to have a very significant effect on both the maximum specific optical density and on the time required to achieve D_m.

Results reported by Birky and Manka [5] from the full-scale corridor fires involving floor covering materials show rather extensive oxygen depletion related to limited ventilation rates. The effects of this oxygen depletion on the rate of smoke formation and maximum amounts of smoke produced, has not been studied in any detail. All of this work suggests that another area of fruitful research for the elucidation of the potential smoke hazard involves studying the effect of oxygen on the optical density in the smoke chamber.

2.3. Task 5 - Analysis of Smoke

2.3.1. Chemical Characterization of Smoke

The chemical analysis of smoke is a very complex problem due to the large number of possible products involved. Birky and Manka [5] collected the smoke from an acrylic carpet fire and followed the methodology used by Hueper *et al* [6] as shown in figure 8. The wet chemical separation was followed by gas chromatographic separation of the neutral fraction which contains the aliphatic, aromatic, and oxygenated fraction. The chromatographic separation and the temperature programming used to obtain the separation is shown in figure 9. The individual peaks in the chromatogram have not been identified.

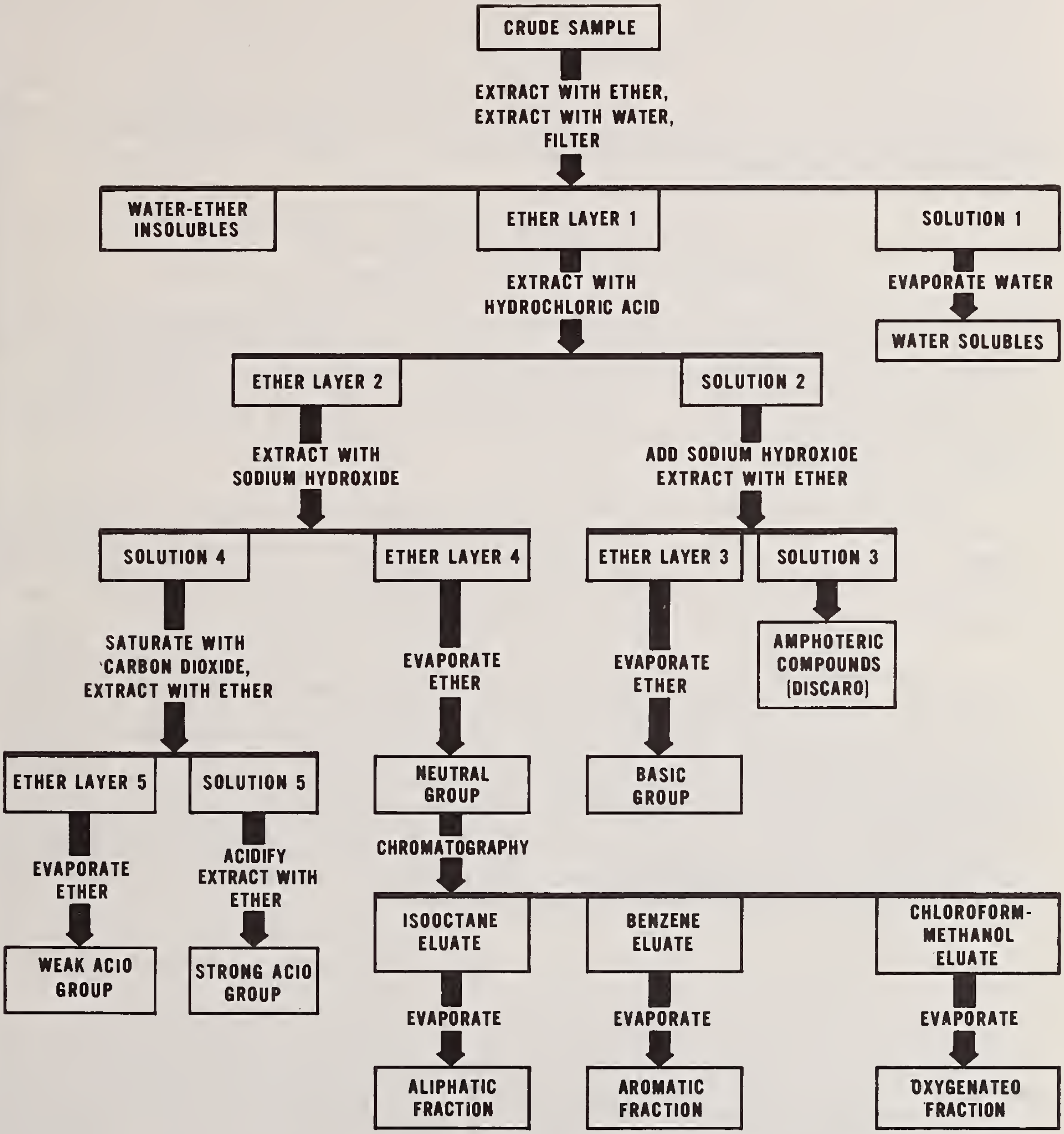


Figure 8. Schematic for separation of smoke into compound classes.

For the complex pyrolysis and combustion product analysis, a computer has been interfaced to a mass spectrometer-gas chromatograph for the qualitative and quantitative analysis. A computerized library of mass spectra is being developed for the combustion products of materials under study. The computer search format used a search routine based on the given number of mass spectral peaks and their relative abundance. Details of this system and preliminary results have been reported by Einhorn and Seader [7]. The results of the chromatographic separation of the products of combustion of a flexible urethane foam and the computer reconstruct are shown in figures 10 and 11. The computer identification of the eluted compounds from the chromatograph based on the fragmentation pattern of the mass spectrometer is still in progress.

2.4. Task 3 - Animal Exposure Chamber and Task 8 - The Influence of Volatile Degradation Products of Combustion on the Survival Responses of the Rat

The physiological and behavioral effects of carbon monoxide (CO) intoxication are being studied. Figures 12 and 13 illustrate a rat in the CO exposure chamber. Previous research has defined five levels of CO intoxication: (1) Ataxia; (2) Loss of Survival Response; (3) Loss of Postural Tonus; (4) State of Anoxic Shock - Complete motor collapse and failure to respond to direct electrical stimulation while respiratory rate is reduced from 1/2 - 1/3 normal; (5) Death.

Animals recovering from Level 4 have been found to exhibit damage to the Schwann cell, which produces and maintains the myelin sheath around the nerve fiber. Demyelination of the sheath is associated with decreased nerve conduction velocity. Conduction velocity of nerve impulses in the ventral caudal nerve is presently being investigated during and following CO intoxication. An example of pilot data of this work is shown in figure 14.

A behavioral conditioning chamber is shown in figure 15. The sling restrainer allows movement of the limbs and leg flexion conditioning. A flashing light, conditioned stimulus (CS), is presented and a leg flexion within a 2-5 second CS-US (unconditioned stimulus) interval opens the electric shock (US) circuit allowing the subject to avoid shock so long as a flexed position is maintained. The percent of trials on which the response is made during the CS-US interval provides one index of avoidance while the duration of the sustained flexed position is a measure of both avoidance and vigilance. Following conditioning training, the subjects are exposed to 1,100-1,500 ppm of CO (in air). Carboxyhemoglobin, avoidance, and response vigilance are monitored during the development of intoxication.

2.4.1. Effect of Carbon Monoxide on Skeletal Muscle

The toxicity of carbon monoxide has been considered to be primarily a function of its ability to combine with hemoglobin and displace oxygen. As a consequence of the decreased oxygen-carrying capacity of the blood, tissue hypoxia and dysfunction results. Further studies have indicated that carbon monoxide reacts with other heme compounds such as myoglobin and components of the cytochrome system. Under conditions existing during states of hypoxia and owing to the different shapes of the equilibrium curves, the affinity of carbon monoxide for certain tissue pigments such as myoglobin may actually exceed its affinity for hemoglobin. These findings suggest that a direct effect of carbon monoxide upon tissue function may be of theoretical as well as practical importance. In addition, the poorly understood late-onset sequelae of carbon monoxide intoxication manifested primarily as disordered nervous system function may result from more permanent carbon monoxide binding by intracellular components.

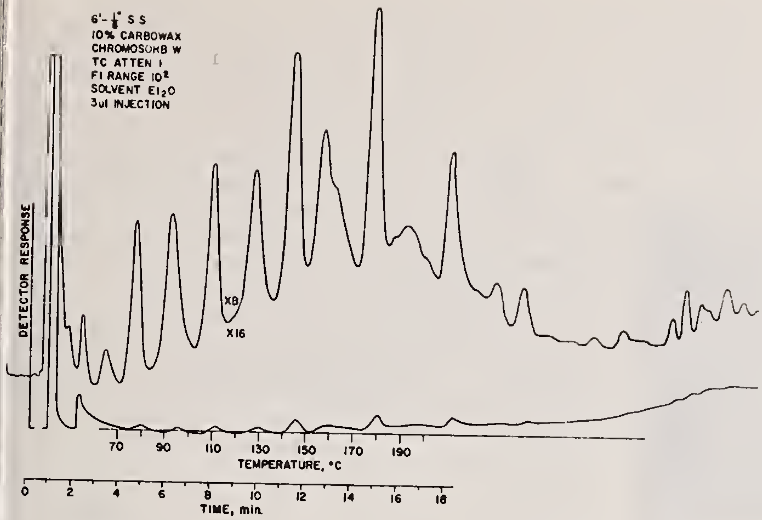


Figure 9. Gas chromatographic separation of smoke components.

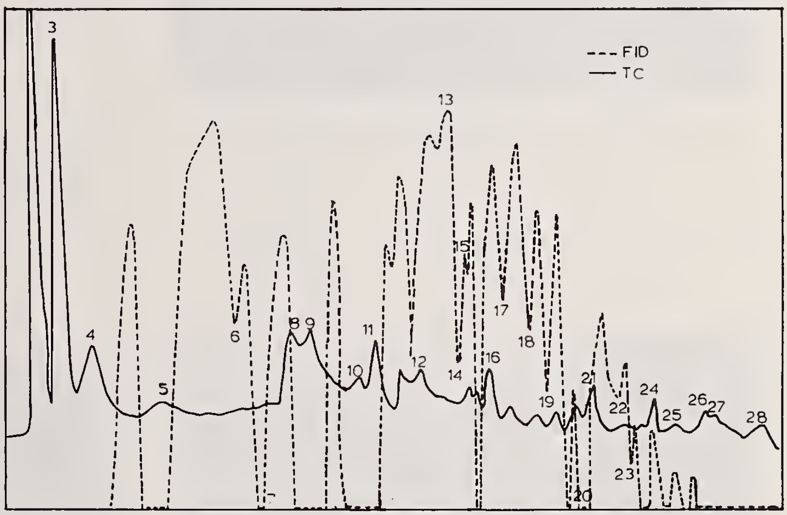


Figure 10. Dual detector chromatogram - combustion of flexible-urethane foam

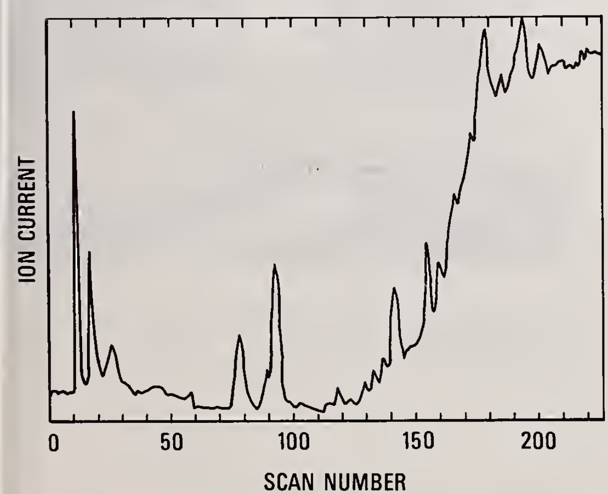


Figure 11. Computer reconstructed chromatograph combustion of flexible-urethane foam - 1180°C.

Figure 12. Animal exposure chamber.

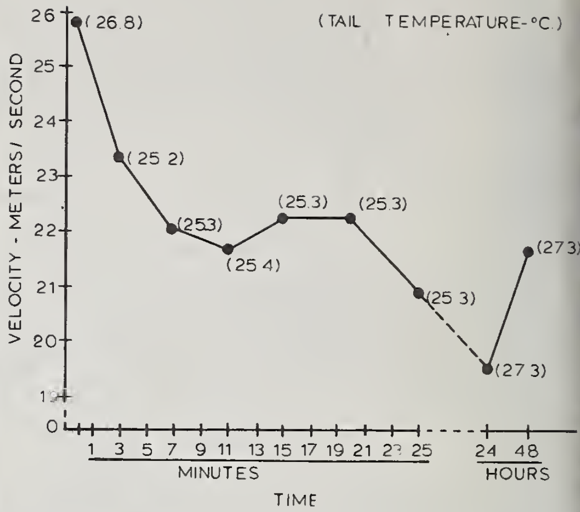


Figure 14. Nerve conduction velocity of ventral caudal nerve of rat after 60-minute exposure to 435 ppm carbon monoxide.

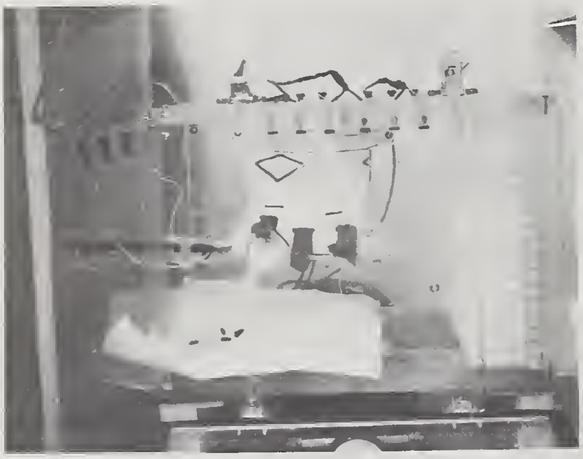


Figure 13. Animal exposure chamber (monitoring of vital functions).

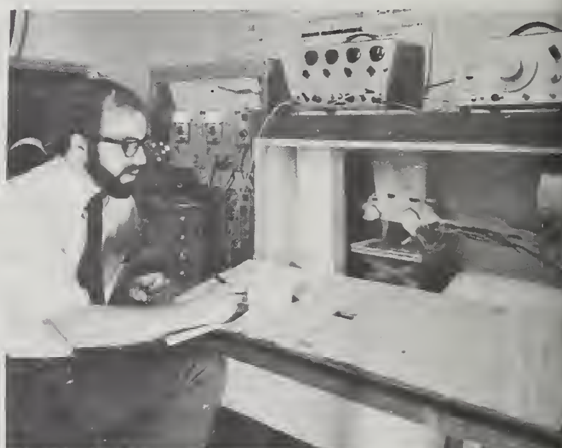


Figure 15. Behavioral conditioning chamber.

Based on these considerations, experiments have been conducted to determine muscle fatique *in vitro* during exposure to three conditions: (1) hypoxia; (2) carbon monoxide and hypoxia; (3) carbon monoxide and oxygen. Six gracilis anterior muscles were studied for each condition. The presence of carbon monoxide in the medium was found to enhance the development of fatique (fig. 16). At the end of the experimental period of hypoxia, tension had fallen to 24 percent of control level, while in the presence of hypoxia and carbon monoxide, tension fell to 7 percent of control level. During recovery, ten minutes after the experimental period, muscles exposed to hypoxia alone had recovered to 88 percent of control tension, while those exposed to hypoxia and carbon monoxide had recovered to only 39 percent of control tension (all differences significant at $p < .01$). In addition, tension did not ultimately recover to the level achieved by the muscles recovering from hypoxia alone. A decrement in tension and more profound delay in recovery also occurred when the muscle was exposed to the 80 percent oxygen - 20 percent carbon monoxide mixture (fig. 17). Tetanic stimulation resulted in complete loss of tension and prolongation of recovery time when the muscle was exposed to hypoxia and carbon monoxide.

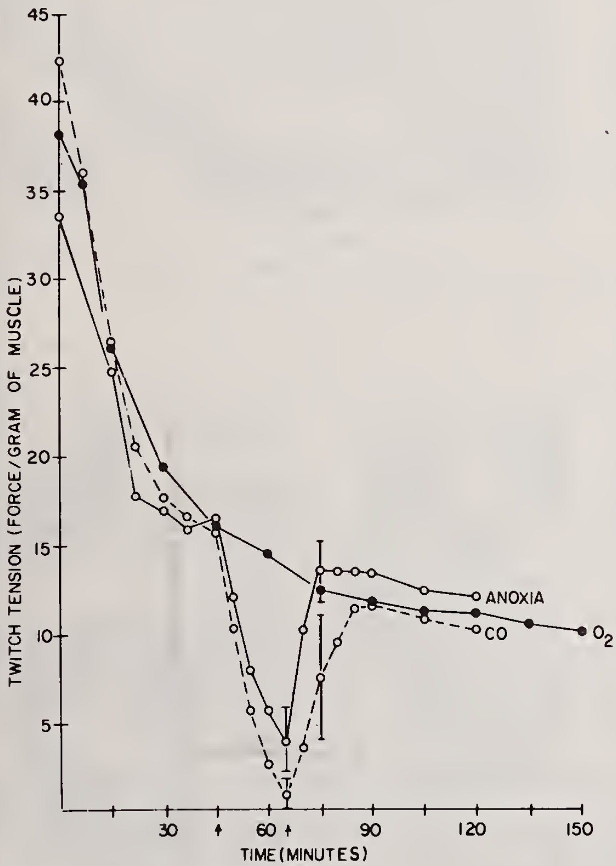


Figure 16. Enhancement of muscle fatigue by carbon monoxide.

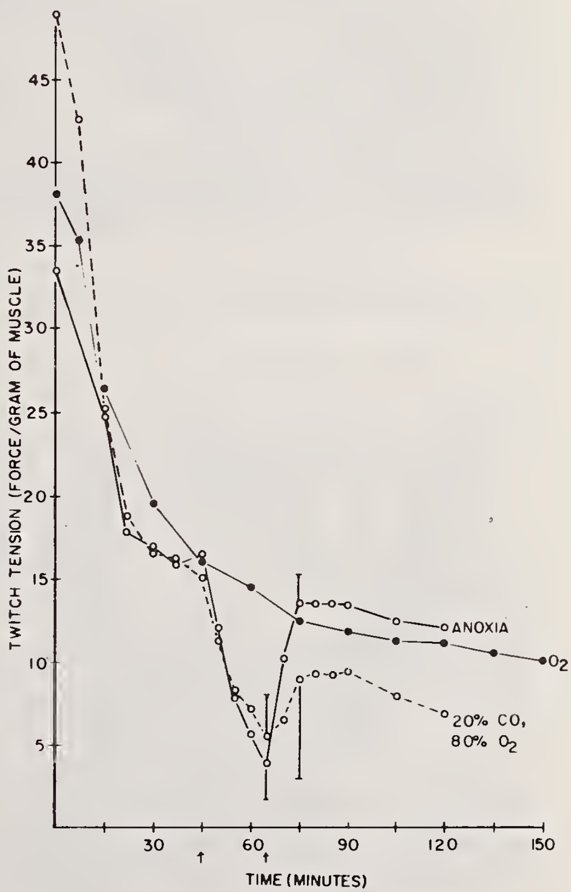


Figure 17. Enhancement of muscle fatigue by carbon monoxide-oxygen.

There is evidence for a direct effect of carbon monoxide upon twitch tension. This effect is most likely mediated by the influence of the gas upon intracellular oxygen transport, but other sites of action may also exist. The impaired recovery of tension in the presence of carbon monoxide suggests the displacement of oxygen from intracellular binding sites by carbon monoxide. The duration of carbon monoxide binding and the ability of oxygen to displace carbon monoxide apparently determines the persistence of long-term effects and perhaps even the appearance of the sequelae of intoxication. The greater impairment of recovery when the muscle is exposed to both carbon monoxide and oxygen suggests a greater binding of carbon monoxide when the muscle continues to metabolize in the presence of carbon monoxide. Exposure of binding sites during active oxygen transport may facilitate carbon monoxide binding. Factors influencing tissue binding of carbon monoxide are being investigated.

2.5. Task 11 - Neuropathological Studies Related to Fire Exposure

Studies on rats indicate that as a result of CO intoxication, behavior can become disorganized sufficiently to prevent an appropriate survival response even though the animal is physically capable of responding. At low levels of ambient CO this implies that survival may be impossible for a period of time before intoxication to levels which immobilize the animal exist.

Loss of motor response occurs before obvious impairment of respiratory or cardiac function from an impairment in peripheral nerve conduction. Thus, even though fully paralyzed, if rescued, survival is likely.

Long-term sequelae manifested as neurological deficits are most likely to occur following more profound intoxication, Level 4. At this level, CO binding by tissue would seem to be an important factor.

The results of neuropathological studies on CO-exposed rats suggest the concept of Schwann cell or neuronal injury with a dying back neuropathy rather than a segmental demyelinating neuropathy. Figures 18-21 are electron microscope photographs of nerves taken on autopsy from rats exposed to Level 4 during carbon monoxide exposure.

Figure 18 shows a longitudinal section through a myelinated axon of the peroneal nerve of a rat 30 days after exposure to CO to the anoxia shock level. It shows a normal myelin sheath but a marked increase in neurofilaments and the appearance of double walled structures.

A cross section through the ventral caudal nerve of a rat, 30 days after exposure to CO to the anoxic shock level, can be seen in figure 19. Myelinated axons show increased neurofilaments with one axon having a reduplicated myelin sheath. Unmyelinated fibers show increased microtubules and abnormal fiber shapes.

A cross section through a myelinated axon and Schwann cell cytoplasm of the ventral caudal nerve of a rat, 30 days after exposure to CO to the anoxic shock level, is shown in figure 20. The axon shows increased neurofilaments and a thickened myelin sheath. The most striking change is the marked dilation of the rough endoplasmic reticulum of the Schwann cell.

Figure 21 shows a longitudinal section through the ventral caudal nerve of a rat, 30 days after exposure to CO to the anoxic shock level. It shows a myelinated axon with an outpouching of axoplasm containing vesicular structure toward the basement membrane of the Schwann cell at the node of Ranvier.

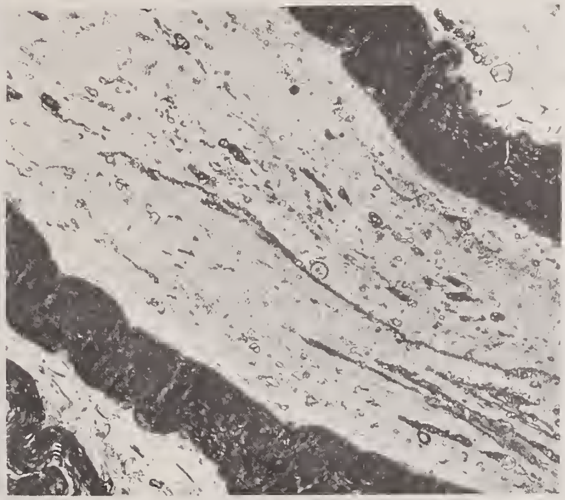


Figure 18. Myelinated axon with increased neurofilaments.

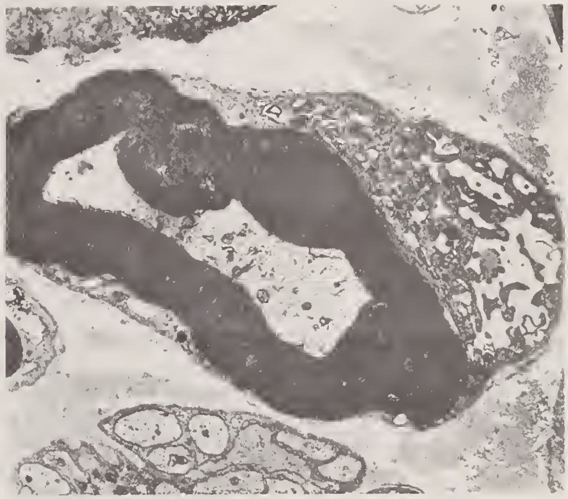


Figure 20. Schwann cell with dilated endoplasmic reticulum.

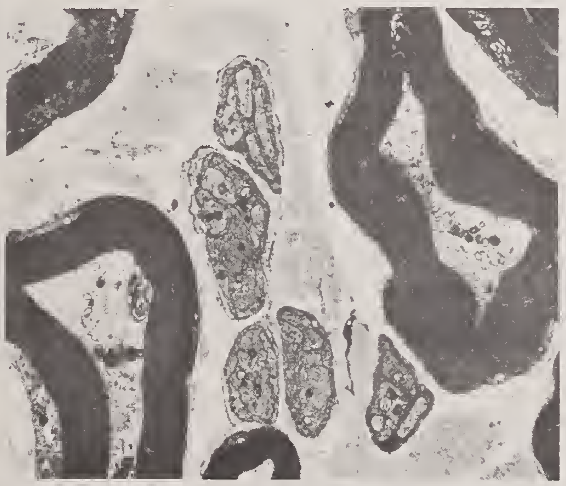


Figure 19. Unmyelinated axons showing abnormal structure.

Figure 21. Myelinated axon showing abnormal node of Ranvier.

2.6. Task 12 - Large-Scale Fire Tests

In order to obtain information on the behavior of floor coverings (mainly carpeting) under conditions simulating a real building fire, full-scale experiments are being carried out in a corridor-experimental facility at the National Bureau of Standards. The primary objective of the program is to determine the nature of the hazard associated with carpeting and under-layment in a fire situation, and the relationship or non-relationship of this hazard to current test methods and small-scale laboratory measurements. One of the ultimate goals is the development of a test method that takes into account the hazard associated with combustion gases and smoke. The results of this program are also being interfaced with the toxicological program at The University of Utah.

The experiments with fully developed fires are being conducted in the facility described previously [8]. The corridor is instrumented at numerous points for the measurement of temperature, heat flux, air flow, smoke density, and gas sampling.

Two gas sampling techniques were used to assess the corridor atmosphere during the tests: (1) continuous measurement of O_2, CO, and CO_2 concentrations and (2) grab samples collected in pre-evacuated 2-liter flasks for laboratory analyses. In addition, continuous measurements of HCl were made on a vinyl sheet flooring material. A technique is also under development for continuous measurements of hydrogen cyanide in fires involving polymeric materials that contain nitrogen (nylon, acrylic, wool, and urethane).

Figures 22 and 23 show the continuous carbon monoxide, carbon dioxide and oxygen data for a wool and a nylon floor covering material. These curves are quite typical of the rates of oxygen depletion and rates of increase of carbon dioxide and carbon monoxide that occurred in most of the corridor fires, indicating a ventilation-controlled fire. In most of the experiments a "gas phase flashover" occurred. In all of the experiments the carbon dioxide curves approximate mirror images of the oxygen concentration as one would expect and the carbon monoxide appeared during extensive oxygen depletion.

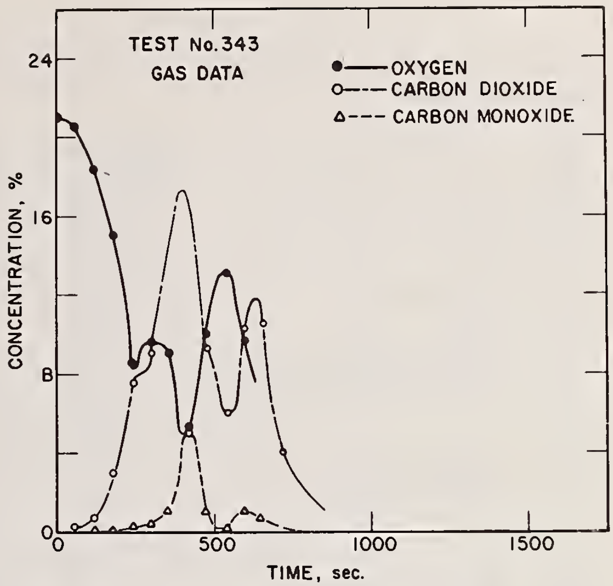
The results of the continuous hydrogen chloride measurements in experiment 346 are shown in figure 24. The areas burned and charred, as determined by temperature measurements and estimated by visual observations during the test, are overlaid on this graph. The correlation, although not exact, is fairly good.

The grab samples were used for more extensive analysis of the corridor atmosphere. Most of the analysis was performed with a dispersive infrared spectrophotometer using a 1-meter cell. A gas chromatograph was used in some of the later analysis. Analysis was made for CO, CO_2, CH_4, C_2H_4, and C_2H_2 which were, by far, the predominant gases. Hydrogen cyanide also appeared in some of the sample analysis, and in these cases, the amount of HCN was estimated. The results of these measurements are shown in table 2.

2.6.1. Discussion of Corridor Results

An effort to assess the hazard due to oxygen depletion, carbon monoxide, carbon dioxide, and high concentrations of smoke in the absence of special toxic gases such as HCN is shown in table 3. A word of caution is in order in interpretation of the table since large concentration gradients exist in the corridor at any given time, with the highest concentrations of CO and CO_2 and the lowest O_2 concentration being near the ceiling where the sampling tube was positioned. Consequently, the hazard of CO or O_2 depletion in terms of survival times may be the worst cases. However, the relative hazard of CO vs. O_2 depletion should be valid. The picture is further complicated by extremely high concentrations of

Figure 22. Results of continuous CO, CO_2, and O_2 measurement from wool carpet.



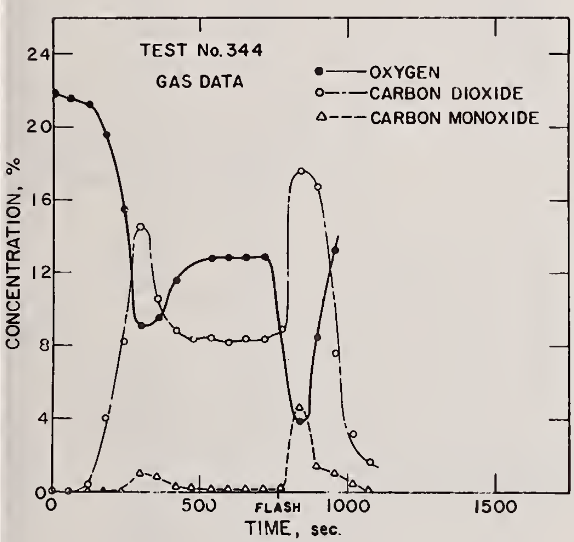


Figure 23. Results of continuous CO, CO_2 and O_2 measurement from nylon carpet.

Figure 24. Results of continuous HCl measurement.

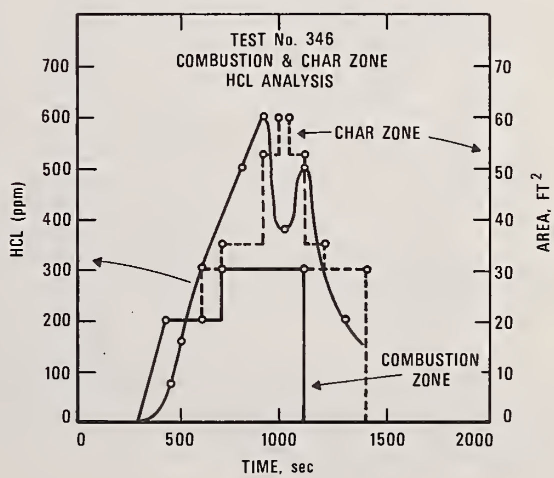


Table 2. Corridor Gas Sample Analysis

Exp. #	Material	Time(sec) Position*	% CO	% CO_2	% CH_4	% C_2H_4	% C_2H_2	Est. HCN (ppm)	Flash Time (sec)
334	Acrylic Pad (A-1)	395 b	3	5	0.6	0.2	0.2	0	
		420 a	3	6	0.7	0.2	0.3	0	
335	Oak Varnish	445 a	4	14	2	1	0.2	0	444
		485 b	2	18	0.1	+	+	0	
336	Vinyl Asbestos Tile	590 a	2	18	1	0.2	0.2	0	520
		600 b	2	10	0.1	+	+	0	
		780 c	0.5	6	<0.1	0	0	0	1,020
337	Acrylic (A-1)	360 a	4	12	0.8	0.2	0.1	+	420
		450 b	3	13	0.4	0.3	0.1	+	
		465 c	3	12	0.3	0.1	0.1	1,000	
338	Acrylic (A-1)	† a	7	18	2.0	0.7	0.5	50	
		† b	8	19	3.0	1.0	0.6	3,000	
		† c	8	17	2.8	0.6	0.3	2,000	
339	Blank	615 a	+	10	0	0	0	0	
		678 b	+	10	0	0	0	0	
		740 c	+	7.5	0	0	0	0	
340	Acrylic Pad (A-2)	327 a	1	10	0	0	0	0	
		360 a	3	12	1.0	0.5	0.4	1,000	
		390 b	3	14	0.4	0	0.3	1,000	
		345 c	4	15	0.3	0	0.1	500	
341	Wool Pad (W-1)	454 a	0.5	10	0	0	0	0	460
		530 a	6	15	2	0.8	0.5	400	
		551 b	4	17	0.6	0.3	0.3	300	
		568 c	3	15	0.3	0.3	0.1	200	
342	Nylon Pad	285 a	2	15	0.2	0.3	0.06	100	300
		308 a	3	16	0.3	0.7	0.05	200	
		322 b	3	18	0.4	0.2	0.1	100	
		338 c	5	16	1.4	0.6	0.5	600	
343	Wool (W-1)	237 a	2	14	0.1	0.3	0.05	+	
		297 a	2	15	0.1	0.2	0.07	0	N.D.
		307 b	3	14	0.8	0.6	0.4	0	
		327 c	4	16	0.9	0.6	0.6	300	
344	Nomex	360 a	1	12	0	0	0	0	740
		457 a	1	10	0	0	0	0	
		470 b	1	8	0	0	0	0	
		490 c	0.3	5	0	0	0	0	
345	Wool (W-1)	308 a	0.3	9	+	+	0	0	
		490 a	4	14	0.6	0.3	0.2	1,000	N.D.
		500 b	4	15	0.2	+	0.2	500	
		510 c	3	10	0.3	+	+	1,000	

*Position: a = 8 ft, b = 7 ft, c = 4 ft from floor.
+Indicates trace amount.
†Times are unknown.
N.D. - No Data

Table 2. Corridor Gas Sample Analysis (cont'd)

Exp. #	Material	Time(sec) Position*	% CO	% CO_2	% CH_4	% C_2H_4	% C_2H_2	Est. HCN (ppm)	Flash Time (sec)
346	Vinyl Asbestos Sheet	497 a	0.3	7	0	0	0	0	None
		765 b	0.3	8	0	0	0	0	
		805 c	0.2	5	0	0	0	0	
347	Polypropylene	390 a	2	13	0.1	+	+	50	840
		900 a	3	16	1.5	0.5	0.1	1,000	
		910 b	4	17	1.5	0.5	0.1	2,000	
		935 c	4	17	0.6	0.2	0.06	2,500	
348	Nylon Pad	450 a	5	15	1.5	0.6	0.6	+	440
		570 a	4	18	0.8	0.3	0.4	2,000	
		585 b	4	18	0.4	0.3	0.1	3,000	
		605 c	3	14	0.2	0.2	0.1	500	
349	Oak	635 a	8	18	2.8	0.9	0.7	0	630
		755 a	2	12	0.4	+	+	0	
		760 b	3	9	0.7	0.5	0.1	0	
		765 c	2	8	0.5	0.2	+	0	

*Position: a = 8 ft, b = 7 ft, c = 4 ft from floor.
+Indicates trace amount.
†Times are unknown.
N.D. - No Data

Table 3. Comparison of O_2-Depletion, CO and Smoke Hazard

Experiment No.	% O_2 (at time of 0.5% CO)	% CO_2 (at time of 0.5% CO)	O_2/CO_2 (at time of 0.5% CO)	Time(min) of Appearance of CO at .5% Level	Time(min) of 80% Attenuation From Smoke
330	10.5	5	2.1	2.5	2
333	17.5	6	2.9	6	3.6 - 4.1
334	13.7	5.5	2.5	6	3.4
335	10.5	10.5	1	5.4	3 - 6
336	11	9.5	1.2	6.2	4.0 - 5.0
337	N.D.*	5.5	N.D.	6	2.0 - 4.0
338	11	6.0	1.8	5.2	1.5 - 4.5
341	13	N.D.	N.D.	6.5	4
343	9	12.5	.72	5.3	3.0 - 3.2
344	9	11	.81	4.2	2.8
345	10.5	9.0	1.2	6.3	3
347	12.5	7.0	1.8	6.2	N.D.
348	18.5	7.0	2.6	4.0	N.D.
349	10.5+	7.6	1.4	5.0	N.D.
Average	12.1	7.8	1.7	5.2	2.9 - 4.2

*N.D. - No Data.
+Taken from exhaust window.

smoke. The time required to reach 80 percent optical attenuation as measured across the corridor was chosen as a level of untenable smoke from the point of view of escape and inhalation. Based on data from Jin [9] for smoke of various types, with 20 percent transmission one would be able to see an illuminated sign at a distance of about 15 feet. However, studies using human subjects indicate that the limitation on visibility is not due to light obscuration of exit signs, but due to lachrymal effects of irritating products on the eyes. This limitation frequently occurred prior to serious obscuration [10]. An additional consideration is inhalation toxicity that is not defined well enough to put into quantitative terms.

With these conditions in mind, table 3 was constructed. The second and third columns in this table give the percent of oxygen and carbon dioxide when the carbon monoxide level reached the 0.50 percent level. In column 6 of the table, the first number is the time (minutes) required after ignition for a 7-foot meter to reach 80 percent optical attenuation and the second number is the time for 80 percent attenuation for a 4-foot meter. The time required to give 80 percent visual attenuation is comparable to the time to produce a CO concentration of 0.50 percent. The time to collapse from (0.50 percent) CO can be calculated from the relationship of Minchin [11]:

$$t_{collapse(min)} = 4.5\% \div \%\ CO$$

For the 0.50 percent level one gets about nine minutes. In all the experiments except two, the O_2 level (column 2) at the time for 0.50 percent CO is low enough that muscular coordination for skilled movement (12-15 percent) is lost and faulty judgment occurs at the 10 to 14 percent oxygen level [12]. The high carbon dioxide levels further complicate the picture by increasing the respiratory rate. In addition, the hydrogen cyanide is also present in many of the fires. Based only on the carbon monoxide concentrations, one has something less than 10 minutes to leave the corridor, however, the smoke level by the 5-minute mark is quite severe and perhaps beyond the survival limit except very close to the floor. This data would suggest that the smoke hazard is as serious as the carbon monoxide and combining this with the very rapid oxygen depletion suggests a survival time less than either hazard alone would indicate.

The conclusions regarding oxygen depletion would tend to support the conclusions of Kingman *et al* [13]. The hazard that exists in another room connected to the corridor may not be oxygen depletion, but CO, which is the conclusion of Robinson *et al* [14] in rooms above the fire although the results from the corridor do not suggest that one hazard is predominant.

Another hazard that contributes to the observed rapid flame spread rate in the corridor experiments, that has not been considered, is the "gas phase flash-over" phenomena. As indicated in table 2 there were significant concentrations of methane, ethylene, and acetylene in the grab samples. The table further indicates that the total hydrocarbon content of these samples was high at the time when "flash-over" occurred.

The "flash-over" phenomena seen in the corridor experiments consists of the build-up of a combustible gas mixture, and is not the same phenomena that results when a material, such as furniture, bursts into flames when exposed to a large radiant energy source in another area of a room. While it is true that radiant energy contributed to the build-up of a combustible gas mixture, the rapid flame spread down the corridor appears to be a gas phase phenomenon.

A further verification of this was obtained in experiments 348 and 349 using a combustible gas detector located at the exit window of the corridor. In experiment 348 the detector showed a rapid rise at 450 seconds and in experiment 349 a rapid rise was recorded at 640 seconds, correlating well with observed "flash-over" times of 440 and 630 seconds, respectively.

Since the purpose of the full-scale floor covering fire experiments was to determine the nature of the hazard and the relevance of present test methods, the obvious question is: what insights and guidance can be obtained from these experiments for developing a laboratory scale or model for testing purposes that is realistic and assesses the hazard? If a laboratory measurement of the amount of smoke produced from a floor covering material such as in the NBS smoke box is to be realistic, then the dependence or independence of smoke quantities of oxygen availability must be determined in the light of the extensive oxygen depletion found in the corridor. Perhaps smoldering combustion and flaming combustion conditions will actually be the boundary extremes that represent the maximum and minimum smoke-producing conditions and it will not be necessary to control the atmosphere in the smoke box. However, this can only be determined by actual experimentation, as indicated earlier.

In relation to the toxicological hazard, it may also be necessary to determine the relative toxicity of the type of products produced in an oxygen limited atmosphere in addition to the increased CO production. One might raise the question, is the production of HCN, HCl and other toxic products enhanced in the limited oxygen atmosphere? And, is there a correlation between smoke production and carbon monoxide?

The hazard associated with the rapid "gas phase flash-over" must also be investigated. It may well be that the rapid flame spread reported in fires involving floor covering materials is actually a gas phase phenomenon resulting from the build-up of products related to the incomplete combustion process due to the limited availability of oxygen as seen in the corridor experiments and not just due to radiant energy.

3. ACKNOWLEDGEMENTS

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4. REFERENCES

[1] Gross, D., Loftus, J. J. and Robertson, A. F., Method for Measuring Smoke from Burning Material: A Symposium on Fire Test Methods -- Restraint and Smoke 1966, American Society for Testing and Materials, Philadelphia, Pa. (1967), 166-204.

[2] Hilado, C., Jr., The Effect of Chemical and Physical Factors on Smoke Evolution from Polymers, J. Fire and Flammability, Vol. 1, 217-238 (July 1970).

[3] Chien, W. P., Seader, J. D. and Birky, M. M., Monitoring Weight Loss in a NBS-Smoke Density Chamber, paper submitted for publication to Fire Technology.

[4] Gaskill, J. R., Smoke Development in Polymers During Pyrolysis or Combustion, J. Fire and Flammability, Vol. 1, 183-216 (July 1970).

[5] Birky, M. M. and Manka, M. J., The Use of Room and Corridor Tests in Predicting Fire Parameters, paper presented at the 1973 Polymer Conference Series, Fire Prevention and Control - A Major Societal Problem, June 4-9, 1973, The University of Utah, Salt Lake City, unpublished.

[6] Hueper, W. C., Kotin, P., Tabor, E. C., Payne, W. W., Falk, H. and Sawicki, E., Arch. Pathology, Vol. 74, 89 (1962).

[7] Einhorn, I. N. and Seader, J. D., Methods for the Identification of Products of Combustion of Polymeric Materials -- A Computerized Analytical System, paper presented at the 1973 Polymer Conference Series, Flammability Characteristics of Materials, June 11-15, 1973, The University of Utah, Salt Lake City, unpublished.

[8] Fung, F., Suchomel, M. and Oglesby, P., Fire Journal, Vol. 67, 41 (1973).

[9] Jin, T., Visibility Through Fire Smoke, Report of Fire Research Institute of Japan, Vol. 31, 33 (1971).

[10] Lopez, E. L., Study of Smoke Emission From Burning Cabin Materials and the Effect on Visibility in Wide-Bodied Jet Transports, Report No. DOC FA 72 NA-655 (May 1973).

[11] Minchin, L. T., Mild Carbon Monoxide Poisoning as an Industrial Hazard, Ind. Chemist, Vol. 30, 381 (1954).

[12] Bulletin of Research No. 53, Underwriters' Laboratories, Inc., 49.

[13] Kingman, F. E. T., Coleman, E. H. and Rasbash, D. J., J. of Applied Chemistry, Vol. 3, 463-468 (1953).

[14] Robinson, M. M., Wagner, P. E. and Fristrom, R. M., The Accumulation of Gases on an Upper Floor During Fire Buildup," APL/JHU (Apr. 1972).

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CONTRIBUTION OF INTERIOR FINISH MATERIALS TO FIRE GROWTH IN A ROOM[1]

J. B. Fang and D. Gross
National Bureau of Standards, Washington, D.C.

Characterization of the fire environment from the burning of the combustible contents of wastebaskets, upholstered furniture and interior finish materials is important for developing rational tests and establishing design criteria for reduction of fire hazard in buildings. Some experimental results on the burning characteristics of an upholstered chair, contents of waste receptacles and wood crib arrays in a well-ventilated room are presented. A procedure has been developed for evaluating the contribution to fire growth of wall and ceiling panels in a full-scale room corner with a standardized wood crib duplicating the conditions produced by an incidental fire. Results of full-scale and laboratory tests with selected interior finish materials on ease of ignition, surface flammability, flame penetration and smoke and heat generation measurements are presented and compared.

Key words: Buildings; fire intensity; flame spread; flames; furnishings; heat release; interior linings; material ignitability; room fires; smoke; upholstery; waste receptacle; wood crib.

1. INTRODUCTION

Interior finish materials on walls, ceilings and floors represent large exposed areas over which flame may spread, and rapid flame spread is one of the most frequent contributing factors to residential fire fatalities. An obvious method of reducing fire losses in buildings is to reduce the possibility of ignition and spread of a fire. This can be achieved by limitations on the use of materials with a high contribution to fire growth, confinement of the fire to the room of its origin with the aid of fire resistant constructions, and installation of fire detection and/or sprinkler systems for early warning and control of developing fires. In recent years, the rapidly increasing use of new interior finish materials in building construction introduces building fire safety problems since some of these newer materials can contribute to the rapid spread of fire in its early states. Urgently needed is the evaluation of the contributions made by these materials to the development of a compartment fire and to establish more meaningful performance criteria of building materials and constructions.

Small-scale laboratory tests can provide a comparative measure of surface flammability, flame penetration, heat release and smoke producing properties which are important from the standpoint of life hazard and property damage. However, there is little substantiation that the test conditions prevailing in most laboratory scale experiments simulate real fire environments.

The corner formed by the intersection of a ceiling and two adjacent walls constitutes a critical configuration for the evaluation of the fire performance of interior finish materials since fires within a corner represent a severe fire exposure through an increase of heat and confinement of combustion products. In order to compare flame spread characteristics of various building materials, corner wall fire tests have been developed to serve as an evaluation tool at the Forest Products Laboratory [1], Factory Mutual, Underwriters' Laboratories and other laboratories. Most recently, corner fire tests initiated by small incidental fire exposure were used to demonstrate residential fire hazards [2].

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This paper presents the results of full-scale corner fire tests conducted for evaluating the contribution to room fire growth of a variety of interior finish materials typical of those used in residential dwellings, and a comparison of these full-scale test results with those obtained by existing laboratory test methods. Experimental study of the characterization of the environment produced by typical incidental fires and the development of standardized wood cribs to simulate various levels of incidential fires are also described.

2. EXPERIMENTAL DETAILS

2.1. Test Compartment

The experiments were conducted in a 2.9 x 3.2 x 2.4 m (9.5 x 10.5 x 7.9 ft) high burn room with a door measuring 0.9 m (35 in) wide x 2 m (80 in) high in one of the smaller compartment walls. The door remained fully open during the course of the test. The test compartment was constructed of reinforced concrete and the interior surfaces were lined with 16 mm (5/8 in) thick gypsum wallboard finished with a vermiculite gypsum plaster. The whole test compartment was situated within a larger building to permit a wind and draft-free condition.

2.2. Instrumentation

The temperatures of the plume gas along the flame axis above the upholstered chair or wood crib, of the surfaces of interior finish materials, and of the product gas and air at selected locations inside the test compartment were measured by bare-beaded Chromel-Alumel thermocouples of 0.56 mm diameter wire Commercial radiometers and heat flux meters mounted on the walls, ceiling and floor were used to determine the rates of heat transfer from test fires to the enclosure walls. Stainless steel pitot tubes fastened horizontally at the doorway of the burn room in conjunction with variable reluctance pressure transducers were used to acquire information on horizontal air velocity profiles.

Continuous measurements of the weight loss rate of the burning furniture were made with a weighing device consisting of a platform mounted on four supporting beams which carried electrical resistance strain gauges. The burning rate of a standardized wood crib was measured directly by a 227 kg (500 lbs) capacity strain gauge load cell supporting a weighing platform.

The concentration of the smoke generated by the test specimen was determined by obscuration measurements using light beam and photocell set-ups. Smoke measurements were made at three locations -- one horizontal measurement at 1.5 m (5 ft) height within the compartment, and two vertical measurements, one at the center of the room, and the other at the doorway.

Continuous measurements of carbon monoxide, carbon dioxide and oxygen concentrations inside the room and at the upper edge of the doorway were conducted using infrared analyzers.

For each experiment, 110 channels of the output signals from thermocouples, radiometers, heat flux meters, load cell, pitot tubes, gas analyzers, and smoke meters were directly recorded on a magnetic tape at 10 second intervals using a high speed digital acquisition system.

2.3. Test Specimens

The chairs and sofas obtained from a local used furniture outlet were of different weights and constructions, and had undergone various degrees of use and wear. In addition to wooden frames, the upholstery fabrics utilized for the test furniture included cotton, nylon and rayon. The cushion pads were made of cotton batting, latex rubber and polyurethane foam.

The standardized wood cribs were developed to duplicate the fire environment produced by typical incidental fires. A large crib, measuring 560 x 560 x 550 mm (22 x 22 x 21-3/4 in) high and weighing approximately 33 kg (72 lbs), constructed of cross piles of 34 pieces of nominal 51 x 102 x 560 mm (2 x 4 x 22 in) long hemlock sticks was used to simulate a moderate intensity furniture fire. A smaller 360 x 360 x 300 mm (14 x 14 x 12 in) high crib weighing about 6.3 kg (14 lbs) constructed by stacking 28 pieces of nominal 51 x 51 x 360 mm (2 x 2 x 14 in) long sticks was used to represent an incidental fire of shorter duration and lower flame height. The large crib consisted of nine layers, except two sticks for the bottom layer, each containing four sticks with a 63.5 mm (2.5 in) stick spacing. The small sized crib had six four-stick and two two-stick layers, with successive layers laid cross-wise. The spacing between the sticks, except for the bottom two layers, was 51 mm (2 in). The moisture content of the wood cribs was found to be approximately 9 percent.

Seven types of interior lining materials and bare asbestos-cement board were selected to represent a wide range of flame spread and smoke levels. The surface treatments and nominal thickness of these interior finish materials are summarized in table 1.

Table 1. Results of Small-Scale Tests on Ease of Ignition, Surface Flame Spread, Heat Release and Smoke Generation

Material		Ease of Ignition	Flame Spread Index		Heat Release		Smoke D_m	
Name	Thickness (mm)	Ignition Time (sec)	ASTM E84 Tunnel	ASTM E162 Radiant Panel	Rate (W/cm^2)	Total (J/cm^2)	Flaming	Non-Flaming
Gypsum board finished with 2 coats of latex paint	12.7	∞	24	8	7.4	540	33	51
Vinyl covered gypsum board	12.7	∞	33	23	5.9	580	54	85
Particle board, unfinished	15.9	153	153	118	20.6	13400	398	570
Douglas fir plywood, prefinished	6.4	105	103	135	15.8	4580	146	445
Lauan plywood, unfinished	4.4	95	167	141	16.5	2720	50	310
Melamine finished tempered hardboard	4.0	151	226	117	52.4	6100	89	465
Acoustic Tile (fiber board base)	12.7	74	101	60	12.2	5840	113	261

3. TEST PROCEDURE

For each chair test, a methenamine "timed burning" tablet placed at the corner between the chair back and the seat cushion was used as the ignition source.

In the corner fire tests, three 1.2 x 2.4 m (4 x 8 ft) full sized interior finish test panels were used to cover a corner of the test compartment. Two test panels were separately mounted on steel studs at a spacing of 89 mm (3.5 in) from the two adjacent walls in the room corner, and one test panel was attached to the ceiling on wood joists to form an "L" shape along the walls. An air space of approximately 19 mm (3/4 in) was left between the panel and enclosure ceiling. A standardized small wood crib was erected in the corner at 254 mm (10 in) measured above the floor and 51 mm (2 in) away from the walls.

For the wood crib and corner test the fire was initiated by application of an open flame to ignite 80 ml of 95 percent ethyl alcohol in a steel pan placed beneath the crib. All recording instruments were turned on simultaneously at ignition of the alcohol. The height of visible crib flame, the ignition of the test materials and the progress of flames up the walls and onto the ceiling were noted and recorded. Data for corner fire tests were usually collected for an 8 minute period. For non-combustible materials slightly longer periods were observed.

4. TEST RESULTS

The time history of the temperatures of product gases at 25 mm (1 in) below the ceiling above the fires involving an upholstered chair, plasticized milk cartons in a waste receptacle and two standardized wood cribs is shown in figure 1. The ASTM E 119 standard temperature-time curve was also plotted in the same figure for comparison. As shown in the figure, the gas temperatures due to a waste receptacle fire, which was obtained by burning 2.8 kg (6.2 lbs) of plasticized paper milk cartons in a 0.12 m^3 (31 gallons) capacity steel trash container, increased faster than either chair or crib fires as the result of the high rate of heat release. The chair, waste receptacle and crib fires had a relatively short period of peak temperature whereas the standard ASTM E 119 curve increased continuously.

Figure 2 shows a comparison plot of the level of heat flux incident on a vertical surface measured at a height of 730 mm above the floor in the vicinity of test fires and a fully developed room fire. The latter curve has been calculated from the ASTM E 119 standard temperature-time curve with the assumption that the fire filling a 2.4 m (8 ft) high room can be considered as a blackbody emitter of infinite width compared with the dimension of a receiver located at a spacing of 610 mm (24 in) and 730 mm (29 in) above the floor level. The waste receptacle fire had a relatively rapid start and shorter duration in comparison to furniture and crib fires as indicated in the figure. The typical furniture and crib fires had a relatively short period of peak heat output whereas the heat flux level for a fully developed room fire increase rapidly and continuously.

A plot of heat flux measured incident on a vertical plane 730 mm above the floor at the peak fire condition against dimensionless separation distance on log-log coordinates is given in figure 3. The dimensionless separation distance is equal to the distance between the axis of the fire source and the receiver divided by the radius of the source. It can be seen that the rate of heat output from the burning chairs varied widely and was dependent upon the type of padding materials, design and construction of the furniture item involved. As shown in the figure, the data from many different tests plot as straight lines of equal slope, and the resultant heat flux levels created by the developed wood arrays lay within those produced by incidental (furniture) fires.

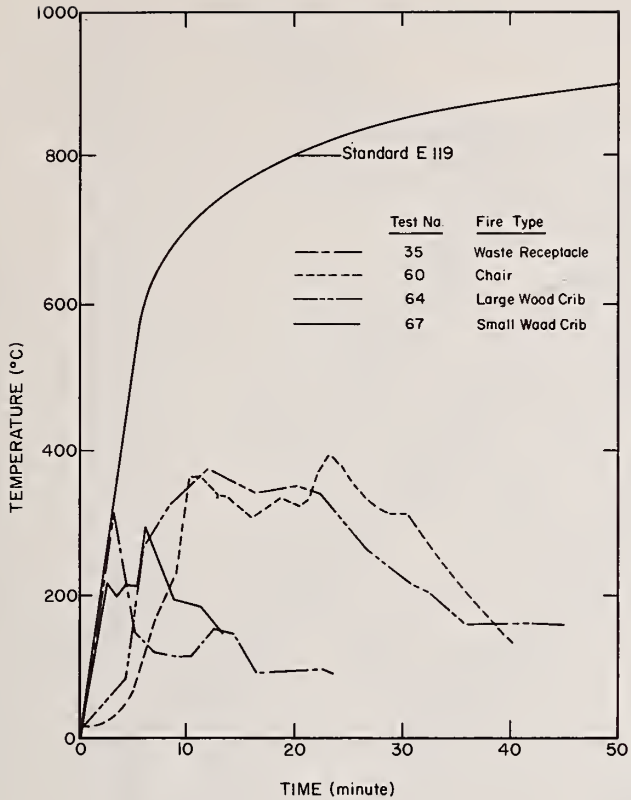


Figure 1. Comparison of air temperature 250 mm below the ceiling and directly above the upholstered chair, waste receptacle and wood crib fires.

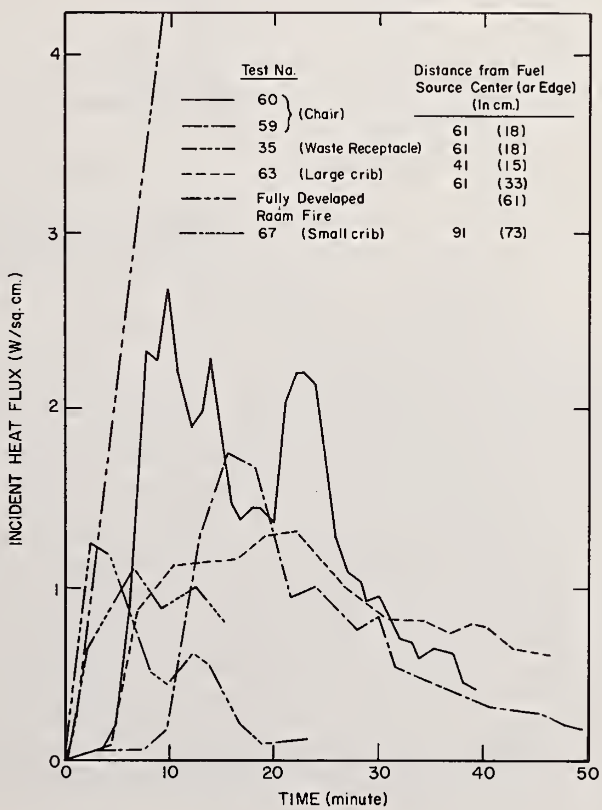


Figure 2. Heat flux incident on a vertical surface at specified distances and 730 mm above the floor from upholstered chair, waste receptacle and wood crib fires.

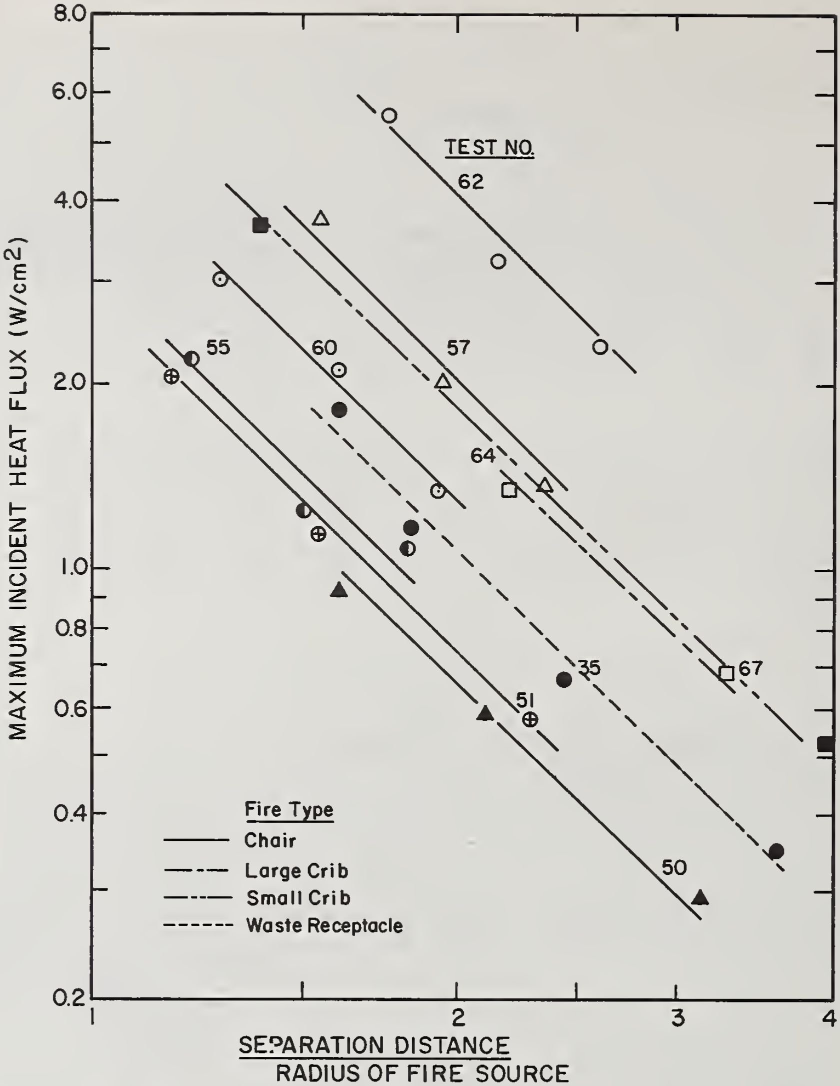


Figure 3. Relationship between incident heat flux at various locations and dimensionless separation distance.

Typical curves showing the calculated rate of heat release as a function of time for fires involving upholstered chairs, standardized wood cribs and plasticized milk cartons in a waste receptacle are presented in figure 4. The heat release rate was calculated from the rate of weight loss multiplied by the calorific value of the combustible involved divided by the projected area of the combustible item on the floor. When the total projected floor area of the item involved is accounted for, the maximum rate of heat output and the total heat energy released per unit area by different types of fires was estimated to be approximately 120 kW (6,830 Btu/min) and 2.7 x 10^4 J/cm^2 (2,370 Btu/ft^2), respectively, for the waste receptacle fire, 320 kW and 15 x 10^4 J/cm^2 for the fire with the large crib, 130 kW and 6.1 x 10^4 J/cm^2 for the furniture fire of moderate intensity. As shown in the figure, the wood arrays can be designed to duplicate fire buildup conditions for particular furniture items since the heat output pattern of standardized crib fires approximately match those of furniture fires. The levels of heat flux to the surroundings from both furniture and crib fires can be expected to be on the same order as the rate of heat transfer from a freely burning fire and was found to be directly proportional to the heat release rate [3].

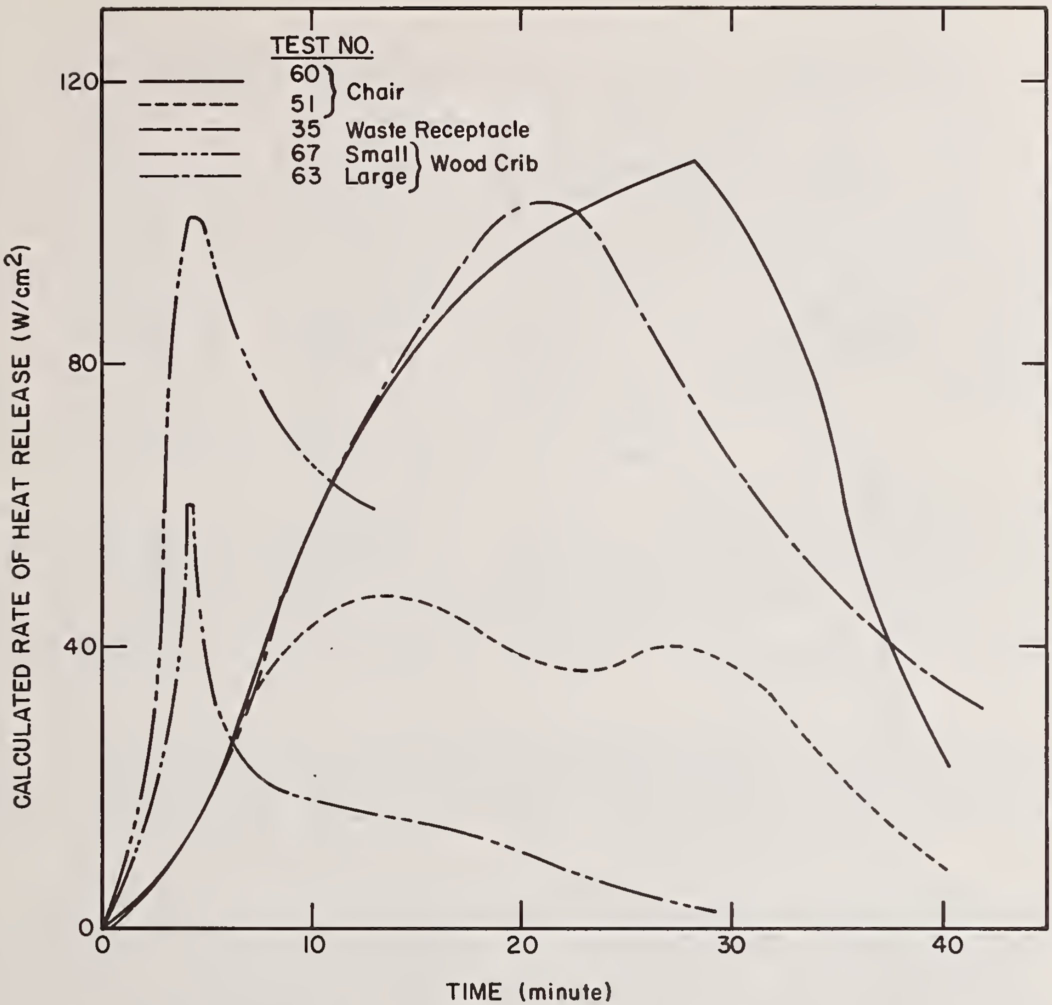


Figure 4. Comparison of calculated rate of heat release for furniture, wood crib and waste receptacle fires.

Summary data from full-scale corner tests on ease of ignition, surface flame spread, flame penetration, room flashover, smoke generation and emerging flames for various combinations of seven types of interior finishes as wall and ceiling covering materials are presented in table 2. It can be noted that the times taken for ignition of combustible wall materials varied from 2 minutes for acoustic tile to approximately 3.5 minutes for vinyl covered gypsum board.

Except for tests with painted gypsum wallboard and vinyl covered gypsum board, which burned only to a distance of 0.5 m (20 in) the elapsed times for flames travelling up the wall to reach the ceiling after ignition were found to range from 20 to 50 seconds. The data also show that the rate of flame spread along the ceiling was significantly lower than that across the wall surface and strongly dependent upon the nature of the materials and constructions utilized for the walls. As expected, these walls played a major role through generation and transport of heat energy required for the spread of ceiling flames.

Most finish materials tested, except particle board and gypsum board, were penetrated by flames at times varying from 5 to 10 minutes. It is obvious that the flame-through time is dependent on the fire properties and thickness of the material involved.

Table 2. Results of Full-Scale Corner Fire Tests for Various Interior Finish Materials

Materials		Time to Ignition (sec)		Surface Flame Spread				Time to "Flame-Through" (sec)		Time to "400°C" Room Temperature (sec)	Max. Smoke Conc. (O.D./m)	Time to "Flame Emerging from Doorway" (sec)
				On Wall		On Ceiling						
Walls	Ceiling	Wall	Ceiling	Max. Distance (m)	Duration Time (sec)	Max. Distance (m)	Duration Time (sec)	Wall	Ceiling			
Particle board	Particle board	193	227	1.83	26	2.21	48	∞	∞	319	0.94	323
Fir Plywood	Gypsum board	134	168	1.83	32	2.21	49	358	∞	502	0.75	∞
Lauan Plywood	Gypsum board	148	168	1.83	19	2.21	44	317	∞	∞	0.92	∞
Gypsum board	Particle board	192	∞	0.53	34	0	∞	∞	∞	∞	0.21	∞
Gypsum board	Gypsum board	170	∞	0.53	21	0	∞	∞	∞	∞	0.33	∞
Particle board	Gypsum board	155	179	1.83	21	2.21	54	∞	∞	387	0.93	342
Melamine/ Hardboard	Gypsum board	194	219	1.83	29	2.21	44	319	∞	343	0.97	315
Vinyl/ Gypsum board	Gypsum board	206	∞	0.61	40	0	∞	∞	∞	∞	0.39	∞
Gypsum board	Acoustic tile	207	∞	0.53	28	0	∞	∞	∞	∞	0.16	∞
Fir Plywood	Acoustic Tile	169	189	1.83	19	2.21	38	364	366	326	1.09	295
Lauan Plywood	Acoustic Tile	200	224	1.83	20	2.21	41	302	582	556	0.60	415
Melamine/ Hardboard	Acoustic Tile	211	250	1.83	38	2.21	36	311	504	352	0.94	334
Vinyl/ Gypsum board	Acoustic Tile	205	∞	0.61	31	0	∞	∞	∞	∞	0.23	∞
Particle board	Acoustic Tile	188	219	1.83	31	2.21	43	∞	534	451	0.78	335
Melamine/ Hardboard	Melamine/ Hardboard	191	222	1.83	39	2.21	36	298	309	304	1.06	265
Acoustic Tile	Acoustic Tile	128	175	1.83	46	2.21	40	587	488	462	0.33	366

In order to observe the time to full involvement of room contents in fires three indicator specimens including ordinary newsprint, 0.19 mm (0.0075 in) thick white cotton cloth and 6.4 mm (1/4 in) thick fir plywood commonly found in dwellings were placed within the test compartment. These indicators, each consisting of two 120 x 152 mm (4 x 6 in) sheets formed in a "L" shape, were placed at two locations; near one of the room corners and at the room center, respectively, at heights of 500 mm (20 in) and 100 mm (4 in) above the floor. Visual observation indicated that these indicators were ignited at different times depending on material type and location. In general the newsprint was the easiest and the plywood the hardest to ignite. It was found that the time to reach an average room temperature of 400°C (752°F) generally fell within the range of time for ignition of these indicators and was considered a critical point to the survival of occupants and property. As shown in table 2, the elapsed times to attain this critical temperature are widely varied from about 5 minutes to infinity. The possibility of complete involvement of combustible room contents was found to be significantly dependent upon the nature, amount and construction of the lining materials involved.

The average maximum concentrations of smoke produced by painted gypsum board, vinyl covered gypsum board and asbestos-cement board walls under fire, condition were on the order of 0.25, 0.31 and 0.11 Optical Density/m (O.D./m), respectively. For all tests with interior linings the walls covered with fir plywood panels generally produced the highest levels of smoke concentration and the gypsum wallboard finished with latex paint the least. The time taken to reach peak smoke levels was found to range from 4 to 8 minutes after initiation of the test.

Flames emerging from door and window openings are conducive to the spread of fires to the corridor or upper stories in the building. The elapsed time until the flames emerged from the doorway was obtained from visual observation and found to vary widely from approximately 5 minutes to infinity depending upon material type and construction.

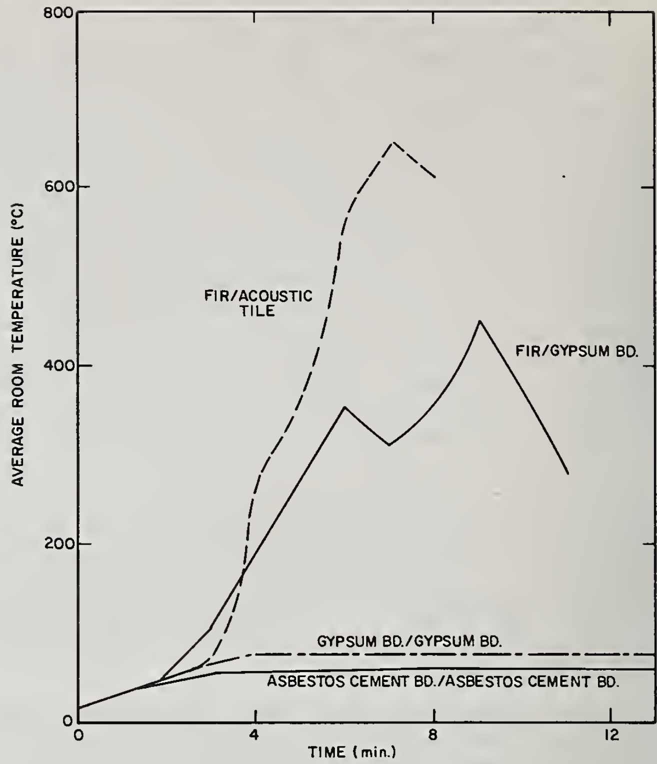
A comparison plot of average temperature versus time of air within the compartment for fires involving several different types of finish materials is shown in figure 5. Data on average room temperature from a blank test using 6.4 mm (1/4 in) thick asbestos-cement boards as wall and ceiling covering materials were also plotted in the same figure for comparison. As shown in the figure, the maximum temperature increased from 80°C to about 450°C for fir plywood walls, and 650°C for fir plywood walls and acoustic tile ceiling when combustible finish materials were substituted for gypsum boards. It was also found that the complete involvement of combustible contents frequently occurred immediately after rapid rise in the room air temperature.

Figure 6 shows the variation with time of the level of heat flux incident at a horizontal plane located 225 mm (9 in) above the floor directly beneath the center of the ceiling specimen. In these tests, portions of the two adjacent walls and the ceiling of a room corner were fitted with various types of building boards, and the combustible load consisted of the standardized small wood crib. The heat flux level increased more rapidly with a combustible ceiling than with a painted gypsum board ceiling and remained at a high level until most of the linings had burned away. Combustible finishes for walls and ceiling would result in a peak flux density of about 2 W/cm^2 at the floor within 7 minutes after start of the test. This downward heat transfer rate would cause ignition of typical combustible contents in dwellings.

5. COMPARISON WITH SMALL-SCALE TEST METHODS

In order to determine if useful correlation exists between laboratory and full-scale methods the results obtained by corner fire tests on seven types of interior finish materials were compared with those obtained by the existing standard test procedures.

Figure 5. Effect of material combination of wall and ceiling linings on average room air temperature. Legends on curves indicate wall/ceiling material.



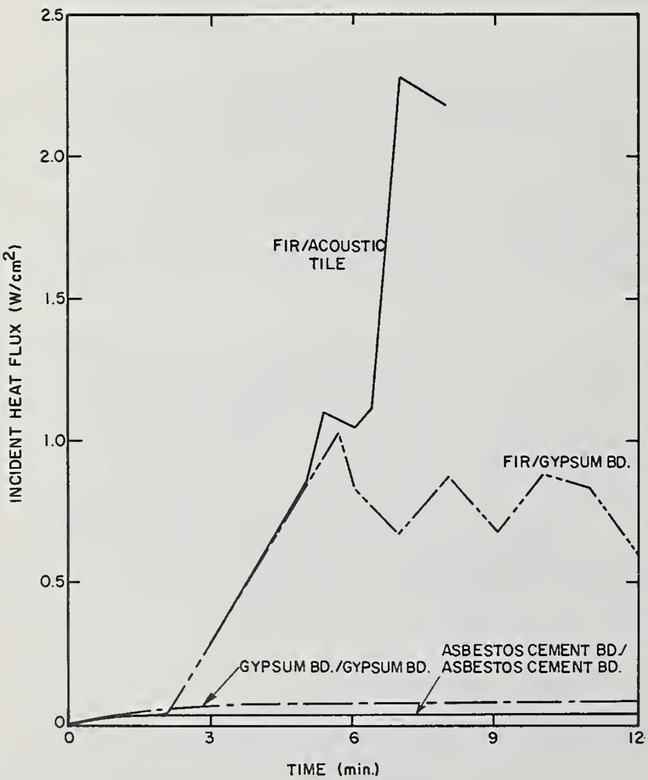


Figure 6. Effect of type of wall and ceiling materials on downward heat flux incident near the floor. Legends on curves indicate wall/ceiling material.

5.1. Ease of Ignition

A small-scale ease of ignition test by flame impingement, recently developed at NBS [4], was used to measure the ignition times of these lining materials in sustained burning. The results of small-scale laboratory tests on ease of ignition along with surface flame spread, heat release rate and smoke producing properties for each interior finish material are summarized in table 1. Figure 7 shows the laboratory test results compared to the ignition times obtained from the full-scale corner fire test. Excluding painted and vinyl covered gypsum boards, which did not have sustained ignition during laboratory tests, the correlation between the corner test and laboratory method for the lining materials examined was generally fair.

5.2. Flame Spread

The laboratory test methods used for evaluation of surface burning characteristics of these finish materials include the ASTM E84 tunnel and E162 radiant panel standard methods. These tests are separately described in the ASTM literature [5,6]. Typical curves showing the distance traveled by the flame, which is normalized with total distance available for flame spread, as a function of time for two materials evaluated for surface flammability by corner and laboratory fire tests are presented in figure 8. For corner fire tests the temperature records from thermocouples placed at the surfaces of test specimens were used for determining flame spread rate. Surface temperature in excess of a critical value at the test specimen face is considered to indicate the arrival of the flame front. The value for this critical flame propagation temperature was determined from both the observed ignition time and the surface temperature records and found to be approximately 370°C (698°F) for most lining materials examined. As expected, materials had different induction periods, varying linear rates of flame spread, and different distances traveled by the flames since the material properties, location and fire exposure level had a pronounced effect on material behavior. As shown in figure 8, the materials in the corner test generally had longer ignition times and higher rates of flame spread than determined by the tunnel and radiant panel tests. This is attributed to lower intensity of fire exposure to the materials in the early stage of the corner test and increasingly severe heating of the materials through the exposing flames and upward hot gas current in the development stage. A significant phenomenon can be seen from the curve showing the spread of flames over the wall surface in that the upper wall situated near the edge formed by the wall and the ceiling usually ignited before flaming covered the entire wall. The flame front would also progress down the surface for some distance. This is primarily due to enhancement of energy transfer to the upper wall by increased forced convection through cross-flow of hot gas impinging on the corner and flaring out radially beneath the ceiling.

5.3. Heat Release Rate

The heat release calorimeter being developed at NBS [7] was used to measure the rates of heat release of these lining materials. The peak one minute average heat release rate values obtained as the result of this laboratory test are plotted in figure 9 against the maximum average room temperatures from corner fire tests. As the intense heat produced by the fires within a room is considered a serious danger for safe evacuation, the average temperature of room air is a measure of both the magnitude and the duration of the heat released.

5.4. Smoke Generation

The smoke density chamber test method [8] was used to evaluate the smoke producing properties of these interior finish materials. Figure 10 shows the comparison between the maximum specific optical density obtained from smoke density chamber test measurements under both flaming and non-flaming conditions,

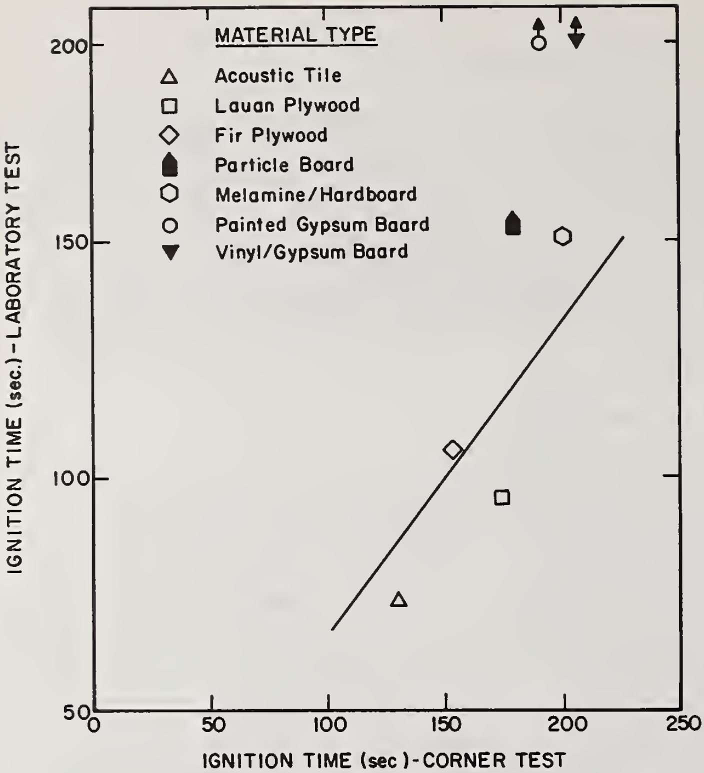


Figure 7. Comparison of the results of ease of ignition measurements by laboratory and corner fire tests. Arrow on top of the symbol indicates no sustained ignition in laboratory test.

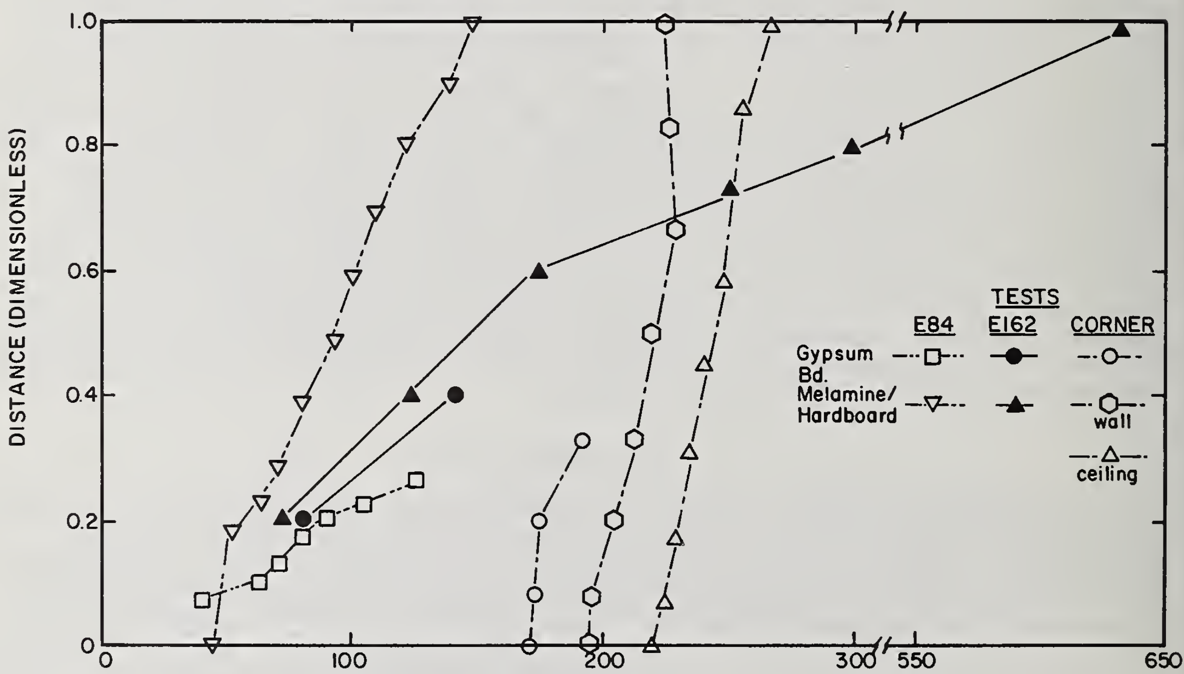


Figure 8. Flame spread data obtained by ASTM E-84 Tunnel, E-162 Radiant Panel and Corner Fire Tests.

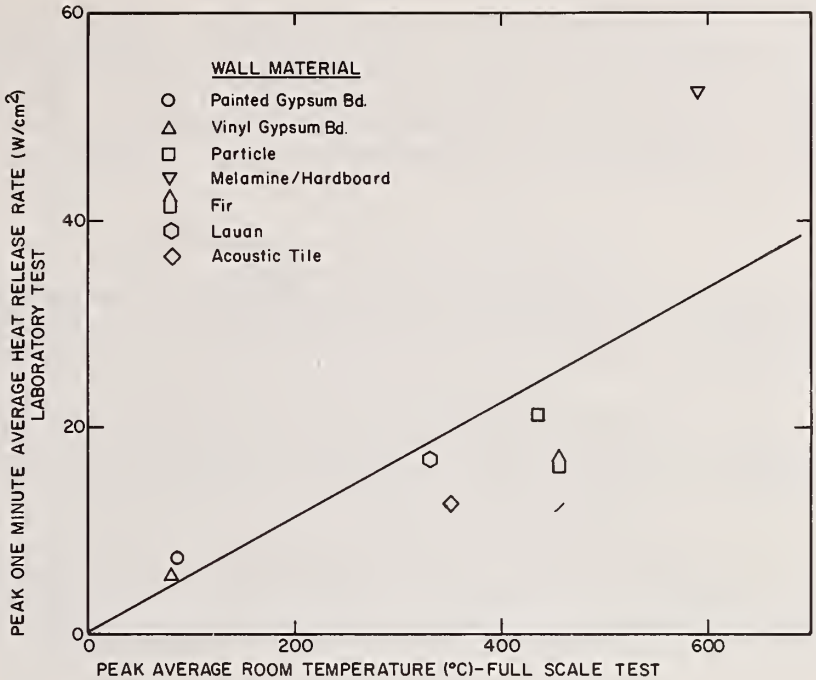


Figure 9. Comparison of data from small-scale and corner tests on heat release rate. Painted Gypsum board ceiling was used for all full-scale tests.

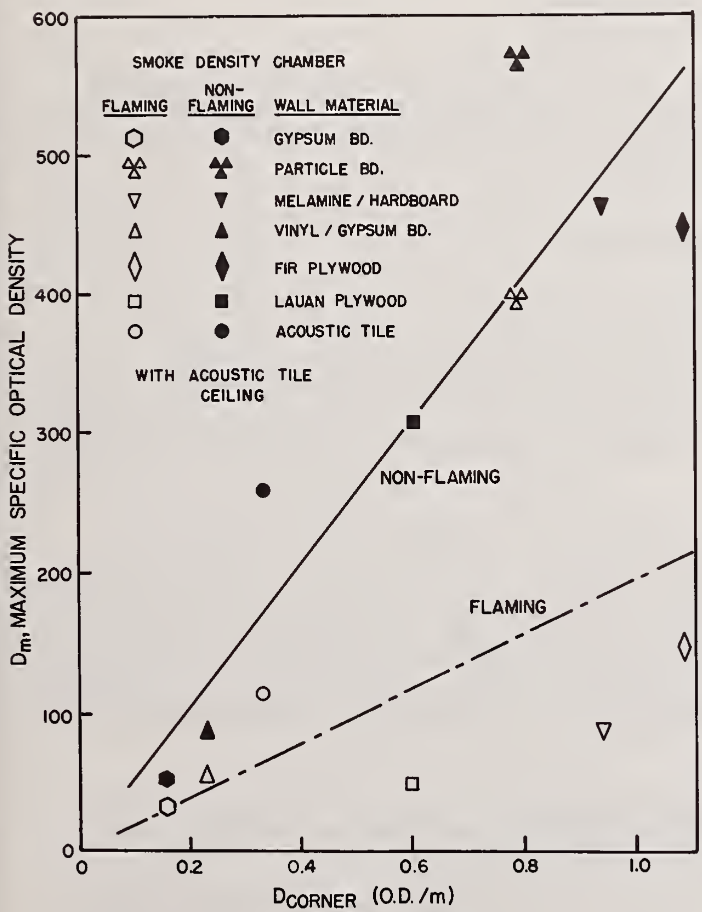


Figure 10. Comparison of the results of accumulated smoke measurement by smoke density chamber and maximum observed smoke level in the room during a corner fire test.

and vertical photometric smoke measurements during the full-scale corner fire tests. It should be noted that the chamber method measures the maximum accumulated smoke level under a closed system condition whereas the full-scale test is a measure of the smoke accumulation in a room with an open doorway through which a significant portion of the smoke leaves. The latter measurement obviously depends upon the degree of ventilation and the intensity of the room fire, and should not be considered unique. Despite this, correlation is fair as indicated in the figure.

6. CONCLUSIONS

A reproducible fire with a standardized wood crib was found to be capable of duplicating the essential features such as: temperature, heat flux and heat output levels, and the size and shape of the flame of typical well ventilated incidental fires.

The presence of combustible interior finish materials has a significant influence on fire growth in buildings by shortening the time to reach full involvement of combustible contents, enhancement of rapid spread of fire, and increased generation of heat and smoke.

The potential fire hazard of interior finish materials can be measured by use of a corner fire test in which the materials to be evaluated are installed as the walls and ceiling in a typical full-size room. This arrangement permits separate measurement of ease of ignition, flame spread rate, flame penetration, and smoke producing properties during a single test.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Surface Flammability as Determined by the FPL 8-Foot Tunnel Method, U.S.D.A. Forest Products Laboratory Report 2257 (1962).

[2] Williamson, R. B. and Baron, F. M., A Corner Fire Test to Simulate Residential Fires, J. Fire and Flammability, Vol. 5, 99-105 (1973).

[3] Fang, J. B., Measurement of the Behavior of Incidental Fires in a Compartment (to be published).

[4] Parker, W. J., The Development of a Test for Ease of Ignition by Flame Impingement (to be published).

[5] Standard Method of Test for Surface Burning Characteristics of Building Materials, ASTM E84-70, American Society for Testing and Materials, Philadelphia, Pennsylvania (1970).

[6] Surface Flammability of Materials Using a Radiant Heat Source, ASTM E162-67, American Society for Testing and Materials, Philadelphia, Pennsylvania (1968).

[7] Parker, W. J. and Long, M. E., Development of a Heat Release Rate Calorimeter at NBS, ASTM STP 502, American Society for Testing and Materials (1972).

[8] Lee, T. G., Interlaboratory Evaluation of the Smoke Density Chamber Test Method, Nat. Bur. Stand. (U.S.), Tech. Note 708, Appendix II (Dec. 1971).

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FIRE BUILD-UP IN REDUCED SIZE ENCLOSURES[1]

W. J. Parker and B. T. Lee
National Bureau of Standards, Washington, D.C.

A 30 x 30 x 32 inch enclosure was constructed to study the fire build-up process in a room. Conductive and radiative heat flux, temperature, air velocity, fuel supply rate, and oxygen concentration were measured. In order to relate the phenomena observed in the small enclosure to that in a full size room, the possibility of small-scale modeling with combustible walls was examined. This was done on a preliminary basis by comparing the results of some corner fire tests conducted both in the model and in a full size room. A preliminary examination was also made of the effect of the fuel flow rate and the location of the burner on the temperature and oxygen profiles in the enclosure. Since the ceiling temperature closely follows the upper air temperature the latter is a suitable measure of the degree of fire build-up in the room. Any analysis of the fire build-up process must account for this temperature.

Key words: Fire tests; flashover; heat release rate; scale models; thermal radiation.

1. INTRODUCTION

Proper selection of wall, ceiling, and room furnishing materials can prevent the build-up of a serious fire in a room. Unfortunately, the fire performance of any material is difficult to assess on the basis of a single test or even from a series of laboratory tests. The fire behavior of a material must be evaluated along with the room and its furnishings so that the combination will have a low probability of full involvement in the event of an accidental ignition. Prerequisite to this approach, it is necessary to develop an understanding of the growth and spread of fire in the room.

Instrumented compartment fires on both full and reduced scales can provide such information. However, smaller fires are more economical and manageable, and can be used to explore variables in a more expeditious and systematic manner. Reduced scale modeling methods for simulating the fire build-up in compartments have been developed at the Illinois Institute of Technology Research Institute (IITRI)[1] and at the Factory Mutual Research Corporation (FMRC)[2], however, their potential usefulness for predicting the performance of real room fires has not been thoroughly explored.

The IITRI technique requires a constant ratio of heat release rate to the volumetric rate of air inflow in order to maintain the same temperature distribution in the enclosure. The volumetric rate of air inflow, V, is proportional to $wh^{3/2}$ [1] where w is the width of the doorway and h is its height. If the ratios of the width of the doorway to the width of the room (W) and the height of the doorway to the height of the room (H) are kept invariant, then $V \sim WH^{3/2}$. The heat release rate, q, should be proportional to the floor area, W^2, where the width of the room is equal to its depth. Thus, if

$$\frac{V_1}{q_1} = \frac{V_2}{q_2} \text{ then } \frac{W_1 H_1{}^{3/2}}{W_1{}^2} = \frac{W_2 H_2{}^{3/2}}{W_2{}^2} \text{ or } \frac{H_2}{H_1} = \left(\frac{W_2}{W_1}\right)^{2/3} \qquad (1)$$

[1]Sponsored in part by U.S. Navy.

where (W_2/W_1) is taken to be the scale factor. Subscripts 1 and 2 refer to the full-scale and the model rooms, respectively. With the scaling of height by the 3/2 power, the area of the wall, WH, scales as $\left(\frac{W_2}{W_1}\right)^{5/3}$ whereas the area of the floor scales as $\left(\frac{W_2}{W_1}\right)^2$. If it is assumed that the mass burning rate of a combustible wall is proportional to its area, then its heat release rate is proportional to $W^{5/3}$ which violates the requirement that the heat release rate be proportional to W^2. To summarize: when the horizontal dimensions of the prototype compartment are reduced by a scale factor, the IITRI modeling criteria require that the vertical dimension should be proportional to the scale factor raised to the two-thirds power and the rate of heat release be proportional to the square of the scale factor. Using this technique for non-combustible walls, IITRI found that the radiation flux, CO_2 concentration, gas temperatures, and wall surface temperatures measured at several locations within the compartment were in fair agreement for both model and 10 x 10 x 8 foot room fires for model sizes as small as 1/8 scale. However, as seen above, the technique breaks down for combustible walls.

FMRC approached the scaling problem from dimensional analysis considerations. Their findings indicate that the temperatures and gas compositions in a room scale reasonably well for geometrically similar enclosures where the heat release rates are proportional to the 5/2 power of the scale factor. This method assures that the ceilings of the model and the prototype are at geometrically similar points of the convection column generated by the flames. If it is again assumed that the burning rate of a combustible wall is proportional to its area, then it is proportional to W^2 for geometric scaling, whereas, the burning rate required by the FMRC modeling is proportional to $W^{5/2}$. This scaling method also fails to account for the contribution of combustible walls.

The objectives of the present study are to determine the degree to which models can be used to scale the fire development in rooms with combustible linings, and to develop a procedure for predicting the potential for full fire involvement of a room based on measurements of the fire and thermal properties of the materials comprising the linings and the furnishings. This work is only in its initial stages.

This paper describes some tests conducted in accordance with the IITRI scaling rules in a small enclosure which approximates a quarter scale model of a 9.5 x 10.5 x 7.9 foot burnout room. It compares the results of some corner tests in the model with those obtained from tests conducted in the full-scale room. It includes a preliminary examination of the effect of the gas flow rate and the location of the burner on the oxygen and temperature profiles in the small enclosure.

2. EXPERIMENTAL

2.1. Procedure

The model has a 30 x 30 inch floor area, a ceiling height of 32 inches and a 6.8 x 27.4 inch doorway opening in the middle of one wall. The model enclosure consists of a steel shell with a non-combustible interior lining of one inch thick asbestos insulation board (36 lbs/ft^3) (AIB).

Several preliminary experiments with a gas burner at the center of the floor were conducted to assist in the selection, development and placement of adequate instrumentation to characterize the fire behavior in the model as well as to establish an overall energy balance. The latter not only contributes to an understanding of the fire behavior, but also checks on the accuracy of the measured data.

The effect of burner location and elevation on the air temperature, oxygen depletion, and thermal radiation was examined in the enclosure using AIB walls, ceiling, and floor.

The model was then used to approximately simulate three prototype corner fire tests [3] conducted in a 9.5 x 10.5 x 7.9 foot high room with a 35 x 80 inch doorway near one corner. The model was originally designed to be a quarter scale for a 10 x 10 x 7 foot compartment using the IITRI scaling rules. Thus, the height of the room and the doorway dimensions were not scaled exactly for these preliminary tests. All large-scale tests used a burning wood crib in one corner of the room. The corner was formed by two 4 x 8 foot panels of the sample wall material running from floor to ceiling where it joined the 4 x 8 foot ceiling panel that was to be tested. Three combinations of wall and ceiling materials of interest used in the full-scale tests were: (1) 1/2 inch thick gypsum board walls and ceiling, (2) 4.4 mm unfinished lauan plywood paneling and gypsum board ceiling and (3) 5/8 inch particle board walls and gypsum board ceiling. One test of the first combination using AIB as a substitute material for the gypsum board, two tests of the second and one of the particle board-gypsum board combination were done on the reduced scale. Panels 1 x 2.8 feet and 1 x 2 feet were used respectively for the walls and ceiling. The thickness of the linings was not scaled down as the modeling uses real time. In each of the model tests a gas burner was used with a rate of heat release equal to 1/16 of that of the wood crib in the full-scale tests. The natural gas was released through a 3 x 3 inch porous plate whose area was 1/16 that of the top surface of the wood crib. This provided essentially the same gas flow rate per unit area in the two cases and thus, eliminated the forced jet effect which results when the gas is delivered over a small area. The gas flow rate was adjusted during the test to correspond to the changing burning rate of the wood crib. The air for combustion of the gas was drawn in through the doorway by natural convection. A heat release of 7,200 Btu was assumed for each pound of wood consumed in the burning crib. This was based on oak with a moisture content of 13 percent.

2.2. Instrumentation

Measurements made to characterize the fire environment included heat flux into the walls and ceiling; radiation incident on the floor; air, ceiling and wall temperatures; air temperature and inflow velocity distributions in the doorway, and the concentration of oxygen at the top of the doorway.

Heat transfer to the ceiling and walls was determined using seven simple heat flux sensors consisting of 2 x 2 inch sections cut out from the ceiling or wall. Thermocouples were inserted inside each section -- one located near the exposed surface and another positioned a short distance behind. The temperature difference between the thermocouples was calibrated in terms of heat flux using commercial heat flux meters. The plugs were then put back into their original locations and the seams were caulked over. Since the sensor was made of the same material as the wall, the heat conducted through the sensor was the same as that through the wall. Conventional heat flux sensors would not give the same readings due to their different surface absorptivities and thermal properties. The thermal radiation incident on the lower portion of the room was monitored with a water cooled radiometer. Indicator panels of cotton fabric and plywood were placed at the center of the floor and at one back corner of the compartment; their ignition signaled the occurrence of flashover. The term, flashover, as used in this paper, means the condition in which the radiant flux levels are high enough to ignite essentially all of the combustibles in the room. It is synonomous with the phrase, "full room involvement". All temperatures and air inflow velocities were measured with AW6 No. 30 wire chromel-alumel unshielded thermocouples and a hot-wire anemometer, respectively. An oxygen cell was used to measure the oxygen concentration of the outflowing air by continuous sampling through a copper tube. No precautions were taken against reactions in the tube.

3. RESULTS AND DISCUSSION

3.1. Preliminary Tests

In the preliminary tests with the model enclosure the overall energy balance at 5 minutes, after introduction of a constant rate of heat input, showed the following:

1. Energy in, Btu/min

   a. gas burner - 800

2. Energy out, Btu/min

   a. conduction through the hot upper walls and ceiling - 190

   b. thermal radiation absorbed by the surface area below the hot and cold fluid interface, and the thermal radiation carried out through the doorway - 160

   c. heat absorbed by the air and carried out the doorway - 450

The hot and cold fluid interface is the horizontal plane where the temperature rise is half of its value in the upper part of the room. In this case it was located at about 1/2 of the distance from the floor to the top of the doorway. At five minutes, the temperature distribution across the ceiling surface varied from 215°C at the center to about 195°C near the edge. This finding, along with the data taken across the room at 4.5 inches below the ceiling, indicated a fairly uniform horizontal distribution of temperature. The temperatures gradually increased with elevation above the mid-height of the doorway up to 1 inch below the ceiling. The ceiling temperature was about 50°C lower than the highest air temperature. Below the mid-height of the doorway the temperatures fell off rapidly with decreasing elevation.

The energy balance indicated that by 5 minutes the heat radiated by the hot upper surfaces of the compartment was nearly as much as the heat conducted into them. It took approximately 30 minutes for the model compartment to reach its equilibrium temperature, at which time the heat radiated from the upper interior surfaces of the room was considerably more than the heat conducted through them.

3.2. Comparison With Full-Scale Corner Tests

Following these preliminary tests with a gas burner on the center of the floor, the model enclosure was used to simulate some full-scale corner fire tests [3]. Whereas the prototype fires had a burning crib in one corner of the room, the model used a gas burner in the same location. Although differences existed between the prototype and the model enclosure, which was designed to scale down a compartment, they were not major. The model doorway area was 30 percent too small and was not offset towards one corner as in the prototype for proper scaling. In the first full-scale test gypsum board was used while the model used AIB for its interior lining.

Figure 1 shows that the average temperature inside the model chamber was about the same as for the full-scale test. However, the inflow velocities in the model were about 30 percent higher than the scaled-down velocities in the prototype as shown in figure 2, so that the volumetric air flow was similar. The scale factor which was taken to be equal to the square root of the ratio of the doorway heights was 0.58. In figures 1 and 3 both temperature profiles at the doorway and within the chamber showed that the hot and cold fluid interface was lower for the model enclosure. This was also apparent from IITRI's data [1].

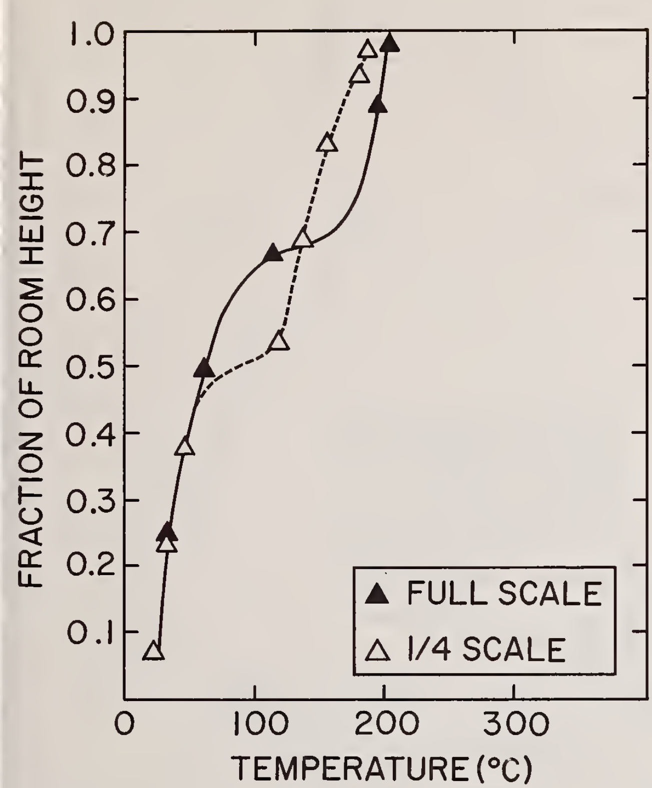
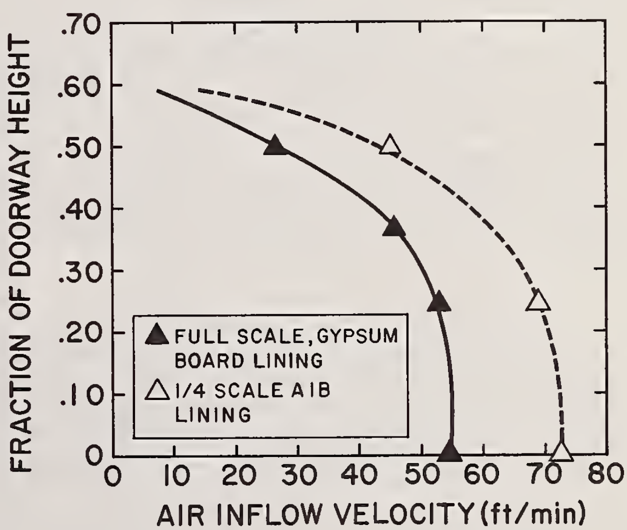


Figure 1. Air temperature profile in center of compartment for full and quarter scale enclosures at 10 minutes.

Figure 2. Velocity profile in doorway at 10 minutes for full and quarter scale enclosures. The velocity data for the full-scale test is scaled down by the square root of the ratio of the doorway heights.



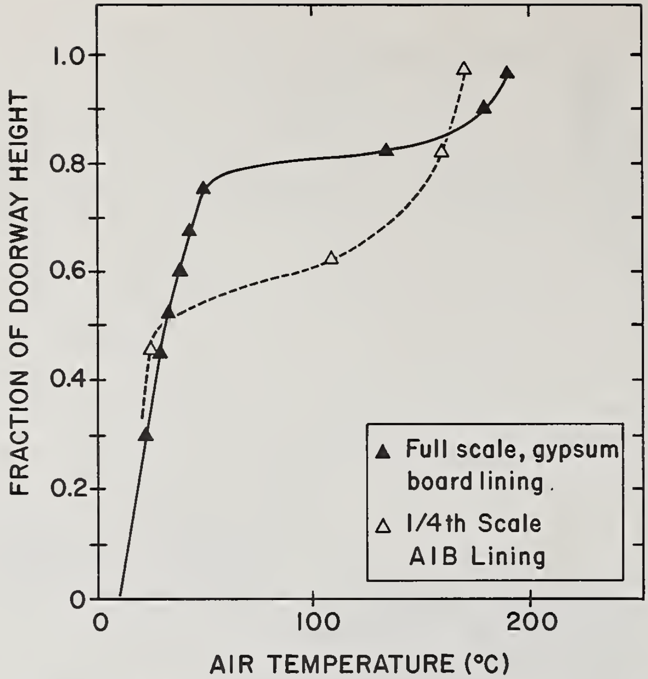


Figure 3. Temperature profile at doorway at 10 minutes for full and quarter scale enclosures.

Since the burning rate of a combustible wall is proportional to $(W_2/W_1)^{5/3}$, whereas proper scaling requires that it be proportional to $(W_2/W_1)^2$, the ratio of the fuel produced to the fuel needed is proportional to $(W_1/W_2)^{1/3}$. This amounts to a 59 percent excess fuel for a quarter scale model. This non-scaling of the wall lining is evident from figure 4, where the air temperature variation with distance down from the center of the ceiling is shown for enclosures having lauan walls and gypsum board ceilings. Except for a sudden upturn in temperature close to the ceiling on the model, the temperature profiles are in fair agreement at 3 minutes which is before active lauan burning. At 5 minutes the temperature increase attributed to the burning of the lauan was about 70 percent greater in the model than it was in the burnout room. After 10 minutes, when the active burning of the wood panels was completed, the temperature was again similar in the two tests.

The up-swings in temperature near the ceiling at 3 and 10 minutes, which were also present with particle board, may have been due to the relatively higher flames which flash partway across the ceiling in the case of the model. This type of behavior was absent in the full-scale fire except at locations close to the corner. Data taken from the full-scale test indicated that a sudden temperature rise near the ceiling occurred at a position two feet away from each of the adjacent walls where the crib was located.

The data in figure 4 indicates that the hot and cold fluid interface within the chamber is lower in the model. A comparison of the flow out of the doorway for enclosures having non-combustible and combustible linings (figs 3 and 5) shows that the height of this interface at the doorway is also lower for the model and is not strongly dependent on the heat release in the enclosure. These results are in agreement with the theoretical finding by Thomas and Heselden [4] that the vertical position of the interface is a weak function of heat input.

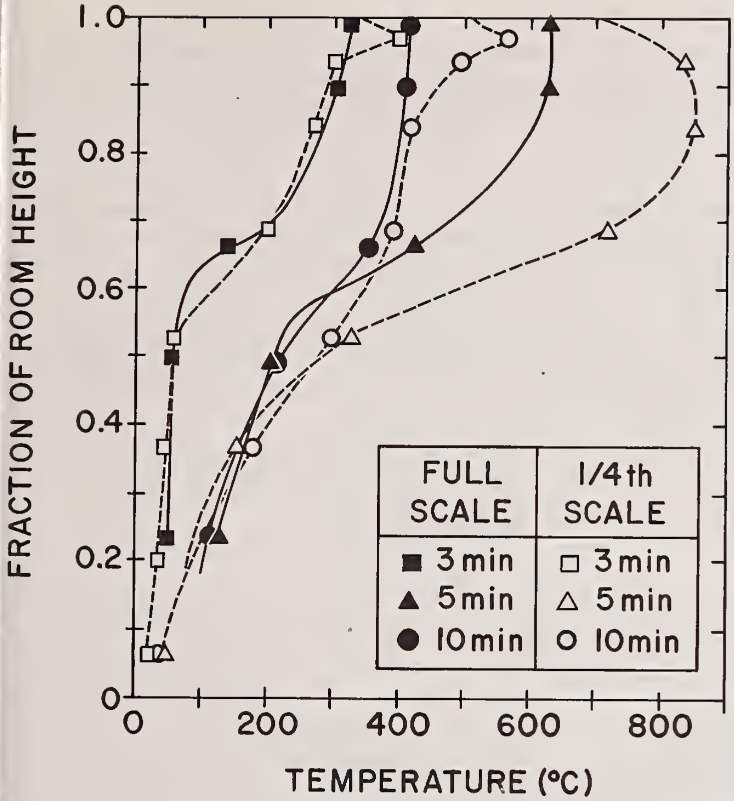


Figure 4. Air temperature profile in center of compartment for enclosure having lauan plywood walls and gypsum board ceiling. Wall panels start burning after 3 minutes.

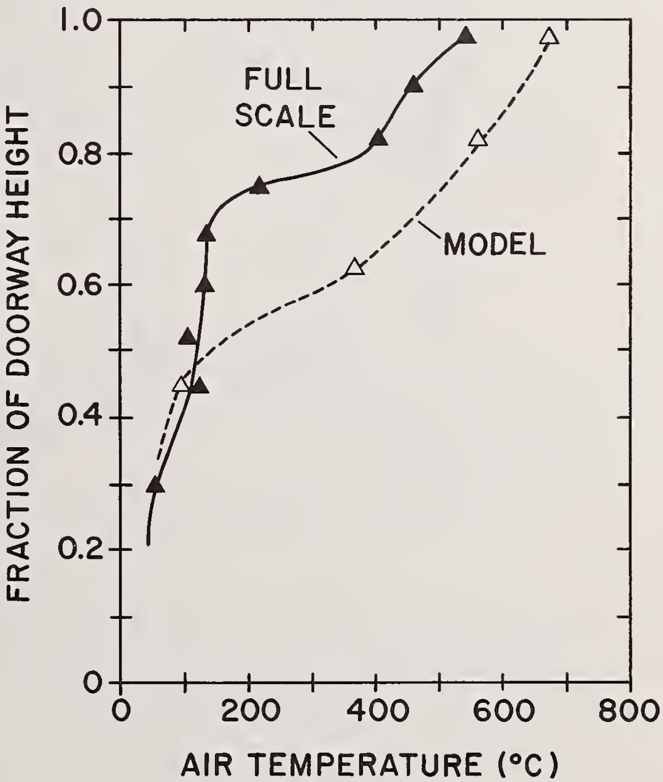


Figure 5. Temperature profile in doorway at 5 minutes for enclosures having lauan plywood walls and gypsum board ceiling.

Although data were not available for a direct comparison for the same wall material, the radiant heat flux incident on the floor was similar for the model with the lauan paneling and the full-scale room with the particle board walls as shown in figure 6. The level of this flux is the main criterion for flash-over or full room involvement.

Tables 1 and 2 summarize some of the visual observations on the model and prototype tests. The ignition times for the combustible linings are in good agreement for the model and the full-scale fires. The pairs of ignition times indicate the times at which the panel on each side of the corner ignited. Ignition times of the cloth indicator panels for flashover were between 5 and 9 minutes for the particle board walls. Flashover did not occur for the full-scale lauan test and for only one of the model lauan tests. There was flame out of the doorway for both full-scale and model for the particle board, but only for the model in the case of lauan.

The fire behavior for lauan and particle board walls were approximately similar up to 5 minutes, after which only the heat release of the particle board continued to increase due to its larger thickness.

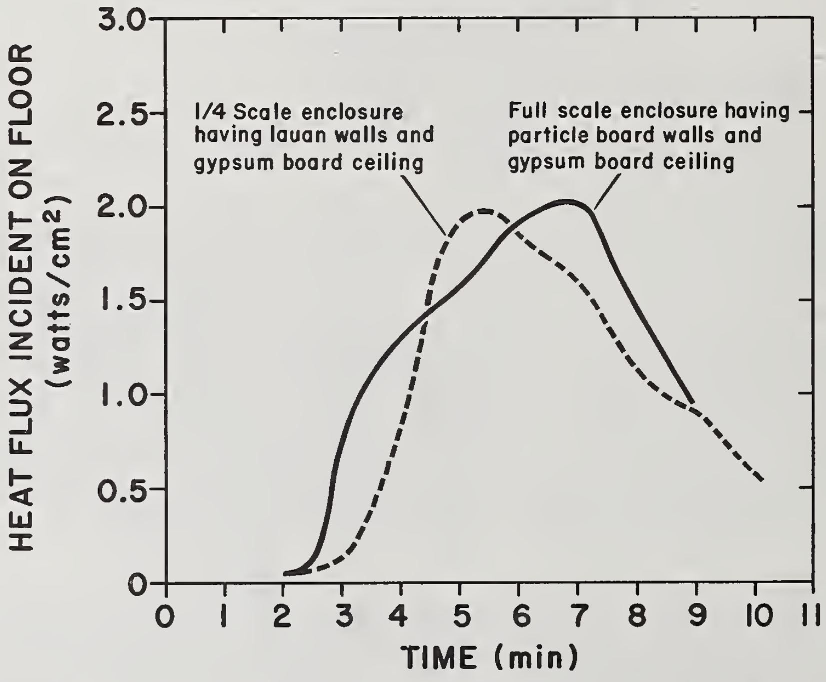


Figure 6. Radiant flux to floor for two enclosure fires.

Table 1. Visual Observations for Enclosures Having Lauan Plywood Walls

Test Size	Ignition Times for Adjacent Walls (sec)	Flashover Indicator Panels	Flame-Tip Height Above Floor (% Ceiling Height)	Flame Out Doorway (sec)	Other Observations
Full-Scale	150 150	All cloth and wood panels at floor center, scorched during the 660 sec test	30% at 30 sec. 100% at 180 sec.	none	Strong hot flow through top 1/3 of doorway at 300 sec.
Small-Scale	90 150	No ignitions. Cloth at corner turning brown at 360 sec. Wood panels at corner and at floor center smoking at 420 sec.	25% at 30 sec. 100% at 165 sec.	315	Strong hot flow through top 1/3 of doorway and weak flow out down to 1/2 of doorway at 360 sec.
Small-Scale	95	Cloth at corner ignited at 343 sec.	25% at 30 sec. 100% at 165 sec.	280	Same as previous small-scale test.

Table 2. Visual Observations for Enclosures Having Particle Board Walls

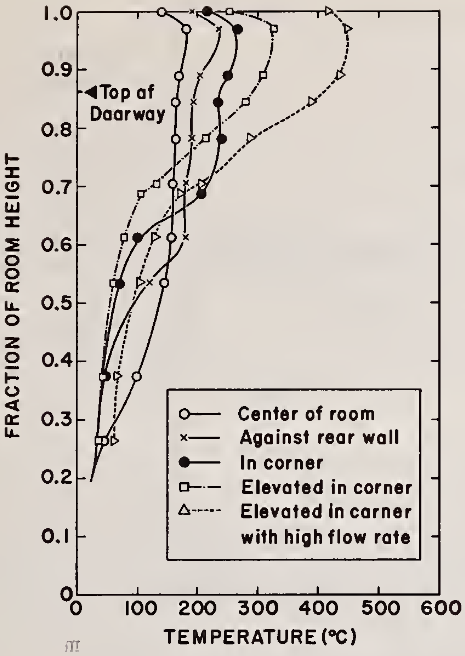
Test Size	Ignition Times for Adjacent Walls (sec)	Flashover Indicator Panels	Flame-Tip Height Above Floor (% Ceiling Height)	Flame Out Doorway (sec)	Other Observations
Full-Scale No. 407	140 140	Cloth at floor center ignited at 323 sec. Cloth and wood at room corner ignited at 455 sec. Wood at floor center ignited at 456 sec.	50 at 60 sec 75 at 120 sec	435	Strong hot flow through top 1/3 of doorway at 360 sec.
Full-Scale No. 411	155 160	Cloth and wood at corner ignited at 315 sec. Cloth at floor center ignited at 412 sec. Wood at center ignited at 415 sec.	60 at 60 sec 65 at 120 sec	342	Strong hot flow through top 1/4 of doorway at 420 sec and through top 1/3 at 450 sec.
Small-Scale	147 147	All panels smoking at 360 sec. Cloth at corner ignited at 480 sec. Cloth at floor ignited at 493 sec.	60 at 60 sec 100 at 120 sec	228	Strong hot flow through top 1/3 of doorway at 360 sec.

3.3. Effect of Flame Height and Location

The effects of burner location, height, and flow rate on the temperature and oxygen concentrations are shown in table 3 and demonstrated graphically in figures 7 and 8. Figure 9 shows the location of the burner in the enclosure. Table 3 indicates the flame height, the ceiling temperature, maximum air temperature, maximum oxygen depletion, air inflow rate, and lowest elevation at which a decrease in oxygen concentration is detectable. The air inflow rate is calculated from the oxygen depletion and the gas supply rate. Observations of the air flow using smoke tracers and suspended materials in the outgoing gas stream indicated a high velocity of the exhaust over the range of elevations at which the drop in oxygen concentration was significant. Smoke tracers also indicated that through the zone between the mid-height of the doorway and the oxygen depleted air there was a mild outflow of intermediate temperature air warmed by contact with the radiantly heated floor and lower walls. The pattern emerging from these observations is sketched in figure 10. In this case the burner is located at floor level adjacent to the center of the rear wall of the enclosure. Air enters the lower half of the doorway and is pulled downward toward the burner where it then moves upward through the flame or the region immediately adjacent to it. It ascends into zone C and thence moves horizontally out of the upper part of the doorway at high velocity. Reduced oxygen concentrations and high temperatures are restricted to this zone. Part of the air in the lower part of the enclosure is warmed by the radiantly heated surfaces, rises through the stagnant air region on either side of the doorway to zone B and then travels horizontally out of the doorway at low velocity. The dashed lines in figure 10 indicate 3 dimensional movement outside of the main flow field. Smoke tracers at the doorway within an inch of plane AB exhibit random changes in flow direction. The effect of increasing the flame height with the same gas flow rate is to raise the transition plane BC. This results in a decreased inflow velocity and thus, a higher upper air temperature. The flame height is increased by moving the fuel source close to the wall where burning can take place on only one side of the fuel stream. It can be increased still further by locating the source in a corner. Thus, even the proximity of a couch to a non-combustible wall could influence the fire build-up potential of the room. Increasing the gas flow rate without changing the flame height increases the air temperature without affecting the height of the transition plane or the air inflow significantly.

Table 3. Effects of Changing Burner Location and Gas Flow Rate

Test	Location	Elevation of Burner Surface (in)	Flow Rate (CFM)	O_2 Depletion Maximum (percent)	Air Inflow (CFM)	Lowest Elevation of O_2 Depletion (in)	Approx. Flame Height Above Floor (in)	Maximum Temperature: Upper Air (°C)	Maximum Temperature: Ceiling (°C)	Maximum Temperature: Δ (°C)
1	Center	3	0.37	5	74	17	11	180	140	40
2	Rear Wall	3	0.37	8	46	21	18	240	190	50
3	Corner	3	0.37	12	31	23	29	265	215	50
4	Corner	11	0.37	19	20	25	Flames impinge on ceiling	320	250	70
5	Corner	11	0.68	33	21	25	Flames impinge on ceiling	450	410	40



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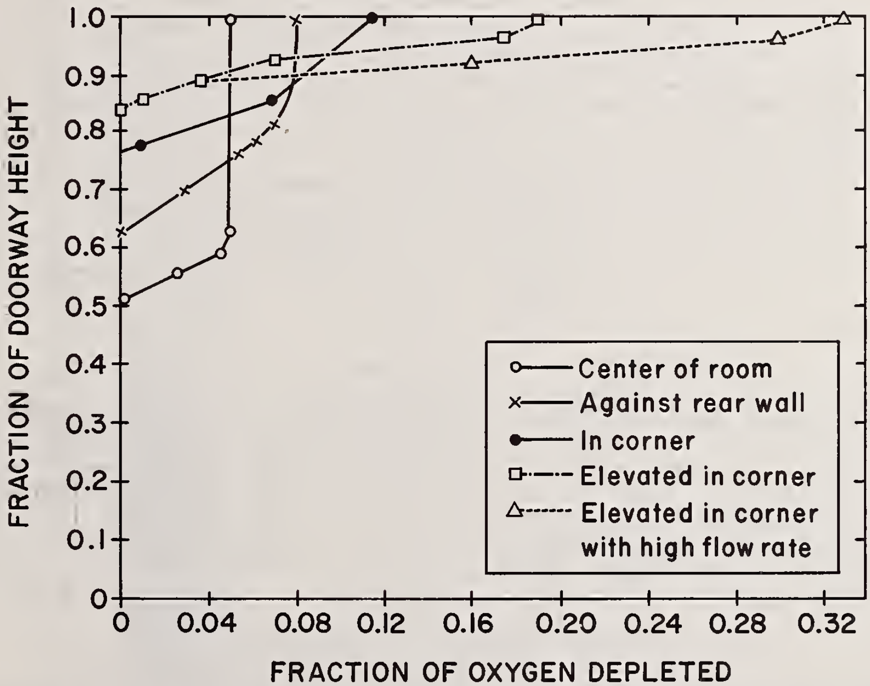

Figure 8. Vertical oxygen depletion profiles in the model for different burner locations and gas flow rates. See figure 9 for position of burner with respect to floor plan.

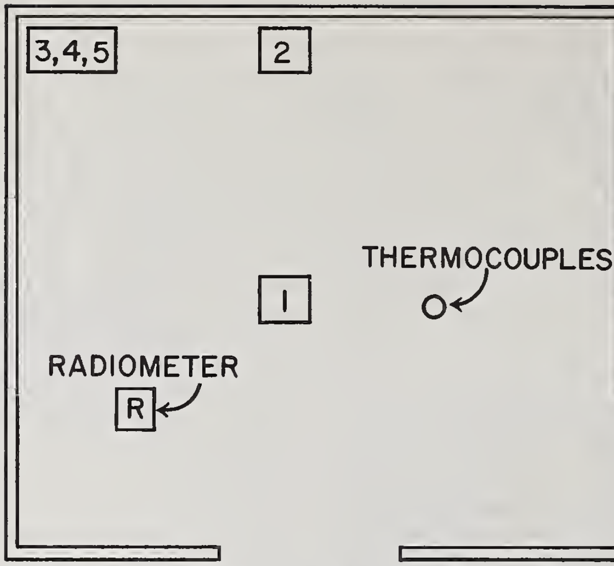

Figure 9. Burner locations in model for data in figures 7 and 8.

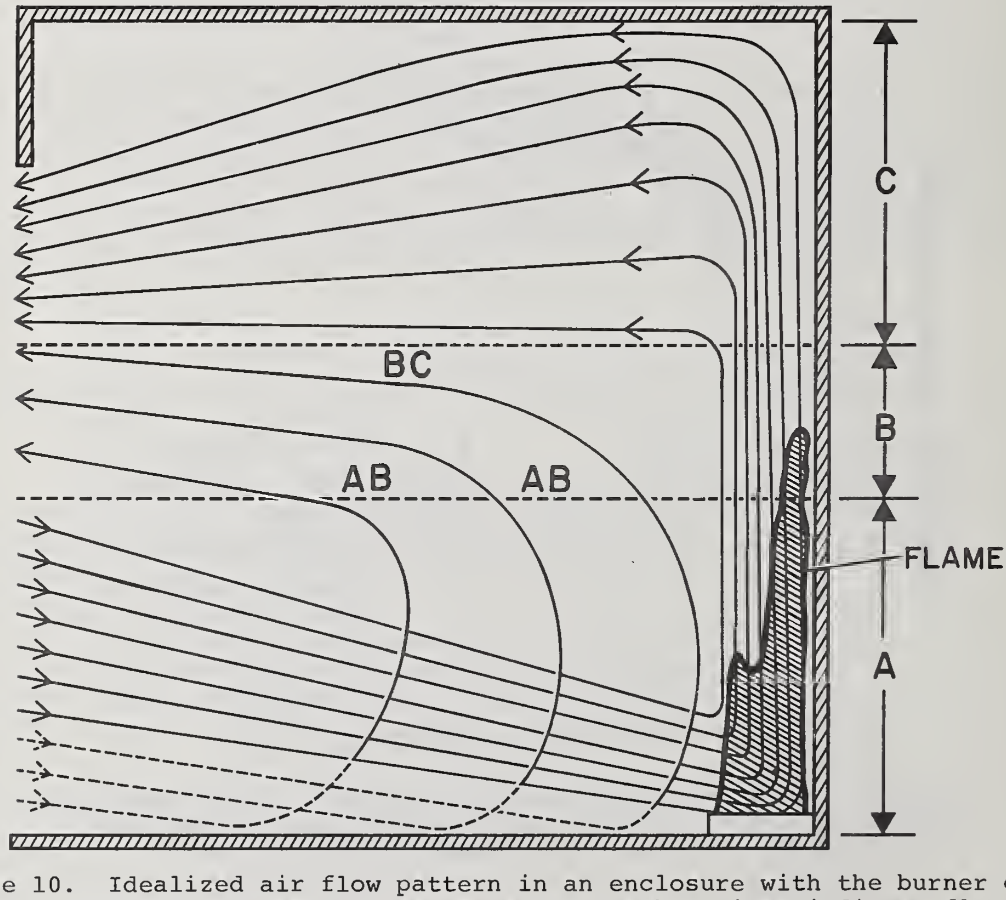

Figure 10. Idealized air flow pattern in an enclosure with the burner on the floor adjacent to center of rear surface. Dashed lines indicate flow in regions at either side of the main flow field.

3.4. Determination of Fire Build-up Potential

The critical factor in establishing whether flashover conditions occur is the achievement of a critical irradiance for spontaneous ignition of materials in the lower part of the room. This irradiance is about $2W/cm^2$ in the case of cellulosic materials. For large areas, such as carpets, it is only necessary to exceed the critical flux for piloted ignition since the concentration of pyrolysis products at that exposure level could be high enough some distance from the source to be ignited by flames already present in the room. Assuming a radiation shape factor of 1/2, the ceiling would have to radiate $4W/cm^2$ which corresponds to a temperature of 650°C for a black surface and 700°C for one with a total emissivity of 0.9 which is typical of non-metallic materials in this temperature range. Note in figure 7 that with the AIB ceiling the temperature drop between the upper air and the ceiling was about 50°C at equilibrium regardless of the flame height, location, and gas flow rate. This suggests a critical upper air temperature of about 730°C to induce flashover after fairly long times.

As seen in the last section, the locations, horizontal as well as vertical, along with the burning rates of the combustibles, control the height of the transition plane BC which to a large extent determines the rate of air inflow for fixed doorway dimensions. The rate of air inflow, the burning rates of the combustibles, and the heat losses determine the air temperature. All three must be capable of estimation in order to build a prediction model for fire build-up. The effect of the burning rate on the elevation of the transition plane is through its effect on the flame height. The burning rate itself depends on the material and its temperature and radiation environment.

In the case of the gas burner the heating time can be extended as long as necessary to attain the maximum air temperature and thus, the maximum radiant flux. In the case of combustible contents the initial fire may be burned out before the wall and ceiling lining materials reach a sufficient radiating temperature to induce flashover. The rate of temperature rise of the surfaces of the walls and ceiling depends on the products of their thermal conductivity, heat capacity, and density ($K\rho C$). If the $K\rho C$ is low the surface temperature rises rapidly and radiation feedback increases the heat release rate of the burning contents. This enhancement may be enough to induce flashover when it might not otherwise occur. Thus, the $K\rho C$ of the lining materials is very important in predicting the occurrence of flashover.

4. SUMMARY

4.1. Heat Balance

A satisfactory heat balance could be obtained during the fire build-up phase in the model where about 60 percent of the heat produced was carried out through the doorway with the exhaust gases and the remainder was distributed between heat conduction into the hot upper surfaces and heat radiation by these surfaces into the lower part of the room or out of the doorway. The portion radiated away increased with time up to about a half hour when steady temperatures were attained using a gas burner with a constant fuel flow rate.

4.2. Simulation of Corner Tests

1. The elevation of the interface between the high and low temperature air layers was lower in the model than it was in the prototype for both combustible and non-combustible walls. In both cases it was above the mid-height of the doorway. It should be noted that the doorway height was not scaled exactly.

2. The air velocities in the model were about 30 percent higher than the product of the square root of the ratio of the doorway heights and the measured velocities in the prototype. This may have resulted from improper scaling of the doorway. At any rate, the volumetric air flow rates were similar.

3. The upper air and ceiling temperatures in the model were similar to those in the prototype when non-combustible walls were used.

4. In the case of combustible walls, the temperatures in the model were higher than those in the prototype. This difference could be accounted for by the relatively larger combustible area.

5. Radiation fluxes on the floor were roughly similar for combustible walls. The higher ceiling temperatures in the model were partially compensated for by a decreased radiation shape factor.

4.3. Flame Height and Location

1. The high temperature air was confined to the region above a horizontal transition plane whose elevation was above the mid-height of the doorway. The air from this region flowed out of the doorway at high velocity. If a constant gas flow rate was maintained, the height of the plane increased with increasing flame height resulting from different burner locations within the enclosure. As the plane was raised the air inflow rate decreased and the temperature of the outgoing air increased.

2. The flame height increased as the constant fuel supply was moved against a wall or placed in a corner.

3. There was a region between the mid-plane of the doorway and the high temperature region in which warm air heated by contact with the radiantly heated lower surfaces of the enclosure rose and passed out of the doorway at low velocity.

4.4. Determination of Fire Build-up Potential

A prediction method for fire build-up potential must be capable of estimating the ceiling temperature which controls the radiant flux level in the lower part of the room. When this level exceeds some critical value, full involvement of the room occurs. This ceiling temperature is dependent on air temperature which in turn is determined from the heat release rates of the burning materials in the room, the heat losses, and the air inflow rate.

5. CONCLUSIONS AND RECOMMENDATIONS

This preliminary work, investigating the usefulness of the quarter scale model as a tool in the study of fire build-up in full sized rooms, is encouraging. However, the scaling rules used by IITRI, which work well for rooms with inert walls, are not adequate to scale rooms with combustible walls. It appears advisable to go to geometrical scaling (i.e., keep all dimensions proportional to the scale factor) in order to keep the heat release rate of the walls proportional to the area of the floor. At the same time it would be necessary to alter the doorway dimensions in order to maintain a constant ratio of air inflow to floor area. Because of the importance of the region above the doorway it would be desirable to keep the height of the doorway proportional to the scale factor and let the width of the doorway vary to provide the proper air flow. The ratio of heat release rate to volumetric air flow must be kept constant to maintain the same temperatures in the model and the prototype.

Geometrical scaling has the added advantage of keeping the radiation shape factor constant. If the shape factors and the temperatures are the same, then the radiation levels which are responsible for flashover can be duplicated in the model.

The upper air temperature which is close to the ceiling temperature is the most important indicator of the degree of fire build-up in the room. It was modeled satisfactorily for the corner fire tests using the IITRI scaling criteria up to the time of ignition of the walls. When the walls were burning the rate of heat release in the model was too high for proper scaling of this temperature. Although the times to flashover and the radiation levels on the floor were roughly similar for the model and the prototype and the increase in air temperature in the model could be estimated in terms of the relatively greater surface area involved, satisfactory scaling for combustible walls requires alterations in the scaling criteria.

It has been practical to keep the thickness of the room lining materials constant between full and quarter scale and thus, maintain real time in the model.

The upper air temperature was found to depend on the height of the flame above the floor and the proximity of the flame to the wall, even when both the walls and ceiling are non-combustible.

6. REFERENCES

[1] Waterman, T. E., Determination of Fire Conditions Supporting Room Flashover, Final Report IITRI Project M6131, DASA Contract No. DA-49-146-XZ-475 (Sept. 1966).

[2] Heskestad, G., Modeling of Enclosure Fires, Fourteenth Symposium (International) on Combustion, The Combustion Institute, 1021-1030 (1972).

[3] Gross, D. and Fang, J. B., Contribution of Interior Finish to the Growth of Fire in a Room, Fire Safety Research, Proceedings of a Symposium held at the National Bureau of Standards, Gaithersburg, Md., Aug. 22, 1973.

[4] Thomas, P. H., Helselden, A. J. M. and Law, M., Fully-Developed Compartment Fires - Two Kinds of Behavior, Fire Research Technical Paper No. 18, October 1967, Fire Research Station, United Kingdom.

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AN ANALYTIC MODEL FOR CALCULATING THE FIRE RESISTANCE OF SIMPLY SUPPORTED PRESTRESSED AND REINFORCED CONCRETE BEAMS

Lionel A. Issen
National Bureau of Standards, Washington, D.C.

At present the fire resistance of concrete beams is determined either by running a fire test or by interpolation from existing fire test data. The second method can only be used if the data are for beams that are closely similar to the object beam. Other ad hoc empirical methods are equally limited. To overcome these difficulties an analytic model was developed for the rational analysis of prestressed and reinforced concrete beams. This model will be checked against available test data. A computer program based on the analytic model is being tested and will be used for developing graphical tools (graphs, nomograms, tables) for estimating the fire endurance of simply supported prestressed and reinforced concrete beams.

Key words: Analytic methods; concrete; creep; elevated temperature; finite differences; finite elements; fire endurance; fire tests; isotherms; prestressed concrete; reinforced concrete; steel.

1. INTRODUCTION

1.1. Requirement For Fire Tests

Structural elements such as beams normally carry a load. During a fire the materials of which the beam is made degrade; that is, they lose strength, they soften and flow as the beam is heated. The fire performance rating of a beam is related to the results of a standard fire test [1] during which the beam is subjected to a prescribed time-temperature exposure representing a fully developed fire.

Major U.S. building codes have fire resistance rating requirements based on these tests for the structural elements of buildings. These ratings may depend on the proposed building size, occupancy classification and, in some cases, fire district classification.

These fire tests are relatively expensive ($5,000, plus construction of the specimen in the test furnace) and in the case of concrete elements there may be a waiting period of several months while the test unit dries.

To overcome the problems of cost and waiting time, alternative procedures to the fire test have always appeared attractive. The alternative methods that are usually considered are interpolation methods, small-scale models and analysis of mathematical models.

1.1.1. Interpolation Methods

In the interpolation method, as applied to estimating the fire resistance of beams, an effort is made to interpolate between the results of tests on similar beams to provide an estimate of the fire resistance of a particular beam. This method works best when the particular beam is similar to those beams comprising the test data. By similar is meant similar shape, material and load factor.

Experienced individuals can do this reasonably well. The process is not objective, being dependent on judgement, intuition and experience and therefore is not suitable for general use.

1.1.2. Small-Scale Models

Small-scale models have long been considered an attractive tool in engineering analysis. Their attractiveness lies in the fact that they are usually smaller, cheaper and easier to test than a prototype; the effects of a wide range of loading conditions can be studied and a check can be provided for a quick analysis. Small-scale models for fire tests are not feasible at the present state of furnace and material technology, because the thermal scaling relationships [2] require that the rate of temperature rise in the furnace be inversely proportional to the scale of the model. For instance for a 1/2 scale model the furnace temperature must rise at twice the rate for a test with a full size prototype.

The scaling relationships are difficult to satisfy exactly since the thermal and mechanical properties of materials, including concrete and steel, are not linear functions of temperature, and heat transfer by radiation, convection and conduction may not be in similitude.

1.1.3. Mathematical Models

Analysis of mathematical models is a popular method for estimating or predicting the performance of structures. The use of this method is limited in the case of thermo-structural analysis of structural elements because both the thermal and structural properties of concrete and steel (the main structural materials of interest) are non-linear with temperature and stress level. For these reasons closed form solutions to either the thermal or the structural parts of the problem have not been found and, therefore, it is necessary to use numerical methods.

The two methods of numerical analysis that are of interest here are the finite difference [3] and the finite element [4] methods.

The finite difference method is as old as the calculus; there is thus a long history of use and experience. In the method, the differential or integral equation is replaced by a series of algebraic equations which are solved using algebraic methods. Briefly described, the method divides the region of interest into a grid (1-, 2- or 3-dimensional), where the intersections of the grid lines are called nodes or node points. The values of the process (in this case temperature, stress and strain) are calculated at the nodes by the finite-difference equations which are comparatively easy to set up and solve. Difficulties arise if the grid is not regular, if the boundary of the region is other than simple, or if the material properties change with temperature or time.

The finite element method is quite recent, having been developed as a practical method in the late 1950's in the aerospace industry. As with finite differences the differential or integral equation is replaced by a set of algebraic equations. In the method, the physical body is divided mathematically into a number of elements, hence the name finite element, and the conditions along the boundaries of adjacent elements are matched up to give the values at the nodes, or vertices, of the elements (usual shapes are triangles or quadrilaterals for two-dimensional problems). The finite elements do not have to be of uniform shape so that irregular boundaries can be closely matched by the elements and varying temperature and time dependent properties can be easily incorporated into the equations. For these reasons the finite element method was selected for the thermal analysis.

1.2. Previous Work on Analytic Methods

NBS pioneered in rational analysis of structural fire resistance design. In the middle 1950's Robertson and Genensky analyzed transient heat flow in fire-exposed reinforced concrete beams using a computer analysis[1]. At the time the only thermal properties of concrete that were available were for temperatures below 150°F. Since this work was never published except as an internal NBS report, it never received the attention it deserved.

Other work[2] has been done at the Portland Cement Association (PCA) [5,6,7], the Technical University in Braunschweig [8], the National Research Council of Canada [9,10,11], and at other centers. Gustaferro [12] who was formerly with PCA has summarized, in a set of graphs, existing test data on the fire resistance of beams and slabs. Gustaferro showed great ingenuity in arranging the available data into a readily useable form. He also included suggestions for extending the data to beams of different shapes. The graphs are probably best suited for beam and slab configurations that are similar to the test specimens and less effective for configurations that are dissimilar to the test specimens.

2. CURRENT WORK AT NBS

2.1. Thermal Analysis

In the fall of 1968 a copy of the TRUMP [13] thermal analyzer program was acquired from the Lawrence Radiation Laboratory. This program is a large, general purpose thermal analyzer[3] which includes radiation and mass transfer effects.

There are several associated programs that may be used with TRUMP in order to facilitate its use. In particular the user is referred to FED [14] and TRUMP/XB2. [15]

The program can be run for 1-, 2- or 3-dimensional problems, though the output format appears to be designed for 1-dimensional analysis. By judicious numbering of the nodes, the output can be put into a form that will facilitate interpreting the results of 2- and 3-dimensional analyses. Because of its general purpose nature, the program may be used for corroborating other programs. TRUMP was found to be a good general thermal analyzer and the calculated results compare favorably with those from other similar programs.

The user is advised to obtain the latest version of the program and also a copy of the current defect list. As with any large computer program, the defects are uncovered by widespread use of the program. The Lawrence Radiation Laboratory periodically issues a correction list and these are automatically incorporated into subsequent issues of the program. There are, of course, other general purpose thermal analyzers available and the user should examine them in order to select the one most suited to his needs.

In 1971 the Building Fires and Safety Section of NBS acquired a modified version of AMG065 [16], a finite element thermal analyzer. This program was originally developed by Brisbane of the Rohm and Haas Corporation for the Army Redstone Arsenal. For a detailed description of the program see reference 16.

[1]Unpublished report, 1956.

[2]This listing represents only a part of the work done in this field.

[3]A thermal analyzer computes the thermal distribution in a solid body. A thermo-structural analyzer uses the output of the thermal analyzer to compute the structural response to these temperatures.

The acquired version allowed the input of temperature-dependent thermal properties. The program was further modified at NBS for fire test problems by including in the analysis heat transfer via Stefan-Boltzmann radiation, a power exponent in the convection equation, and view factors.

The radiation equation for this analysis is given by:

$$q_r = BEAV(\overline{T}_a^{\,4} - \alpha \overline{T}_s^{\,4}) \quad (1)$$

where q_r = rate of heat transfer by radiation

B = Stefan-Boltzmann constant

E = emissivity of surface

A = surface area through which heat flows

V = view factor of surface

$\overline{T}_a$ = temperature (absolute) of furnace atmosphere

$\overline{T}_s$ = temperature (absolute) of surface

α = ratio of emissivity of furnace atmosphere to black body radiator.

The inclusion of the V term is necessary as experience has shown that the amount of heat going into the side of a beam shape is less than that entering through the bottom surface. Since the difference seems to be related to furnace shape, this term includes the effect of furnace geometry. In this analysis V was determined by estimating the view factor for points at the middle of the bottom face of the beam and at the middle of the side surface of the beam. This simple procedure has been found to give the correct relationship for the differing amounts of heat entering through the bottom and sides of the beam.

The convection equation for this analysis is written:

$$q_c = \overline{h}A(T_a - T_s)^n \quad (2)$$

where q_c = rate of heat transfer by convection

$\overline{h}$ = heat transfer coefficient (different for vertical and horizontal surfaces)

A = surface area through which heat flows

T_a = temperature of atmosphere

T_s = temperature of surface

n = exponent where $1 \leq n \leq 2$ (usual values are 1, 1.25, 1.33).

The above parameters may be in any consistent set of units. The values of n are based on the Nusselt number at the specimen surface. The greater the Nusselt number the higher the exponent (see for example [17]). For the rate of heat transfer that occurs on the fire exposed faces of the beams the value of n is of the order of 1.25 or 1.33. For the rate of heat transfer at the unexposed face (top face) of the beam where the rate is much lower than on the fire side, n is of the order of 1.0 or 1.25.

In the present NBS version of AMG065 eqs (1) and (2) are combined into a single quasi-convection equation, and with $\alpha = 1$ for simplicity

$$q_T = q_r + q_c$$

$$= BEAV(\bar{T}_a^{\,4} - \bar{T}_s^{\,4}) + \bar{h}A(T_a - T_s)^n$$

$$= A(T_a - T_s)[BEV(\bar{T}_a^{\,2} + \bar{T}_s^{\,2})(\bar{T}_a + \bar{T}_s) + \bar{h}(T_a - T_s)^{n-1}]$$

or

$$q_T = A(T_a - T_s)[R + S] \qquad (3)$$

where q_T = total heat transfer

$R = BEV(\bar{T}_a^{\,2} + \bar{T}_s^{\,2})(\bar{T}_a + \bar{T}_s)$

$S = \bar{h}(T_a - T_s)^{n-1}$ (positive real root only)

Eq (3) is the form used in the thermal analyzer.

The detailed theory for a finite element thermal analyzer program is adequately discussed elsewhere. [16] The fundamentals of heat transfer can be found in Myers' book [18] which also discusses the finite element method in heat transfer.

The capability of the program was extended to include a plotting program which takes the output of the thermal analyzer and uses it to produce either printer plots[4] or line drawings (via a line plotter) of the isotherm contours at selected time intervals. An example of these contours is shown in figure 1.

2.2. Structural Analysis

In 1971 the Building Fires and Safety Section initiated the preparation of a thermostructural analysis computer program for simply supported prestressed and reinforced concrete beams under fire test exposure.

Originally, it was thought that a normal temperature structural analysis program could be modified without too much difficulty for this analysis. With this in mind the listing of BEAMBUSTER [19] was acquired. This computer program computes the ultimate capacity in bending of simply supported reinforced and prestressed concrete beams at normal temperatures. The program is quite compact.

Though this program had to be discarded after several trials and a new structural analyzer prepared, several ideas on the sequence of the calculations and the table search method were retained. The main difficulties encountered were the inclusion of time dependent and temperature dependent material properties, the proper sequencing of the different parts of the calculations, incorporating thermal stresses and modifying differences in program logic that had to be compatible.

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[4]The printer plotter subprogram came with the acquired version of the program.

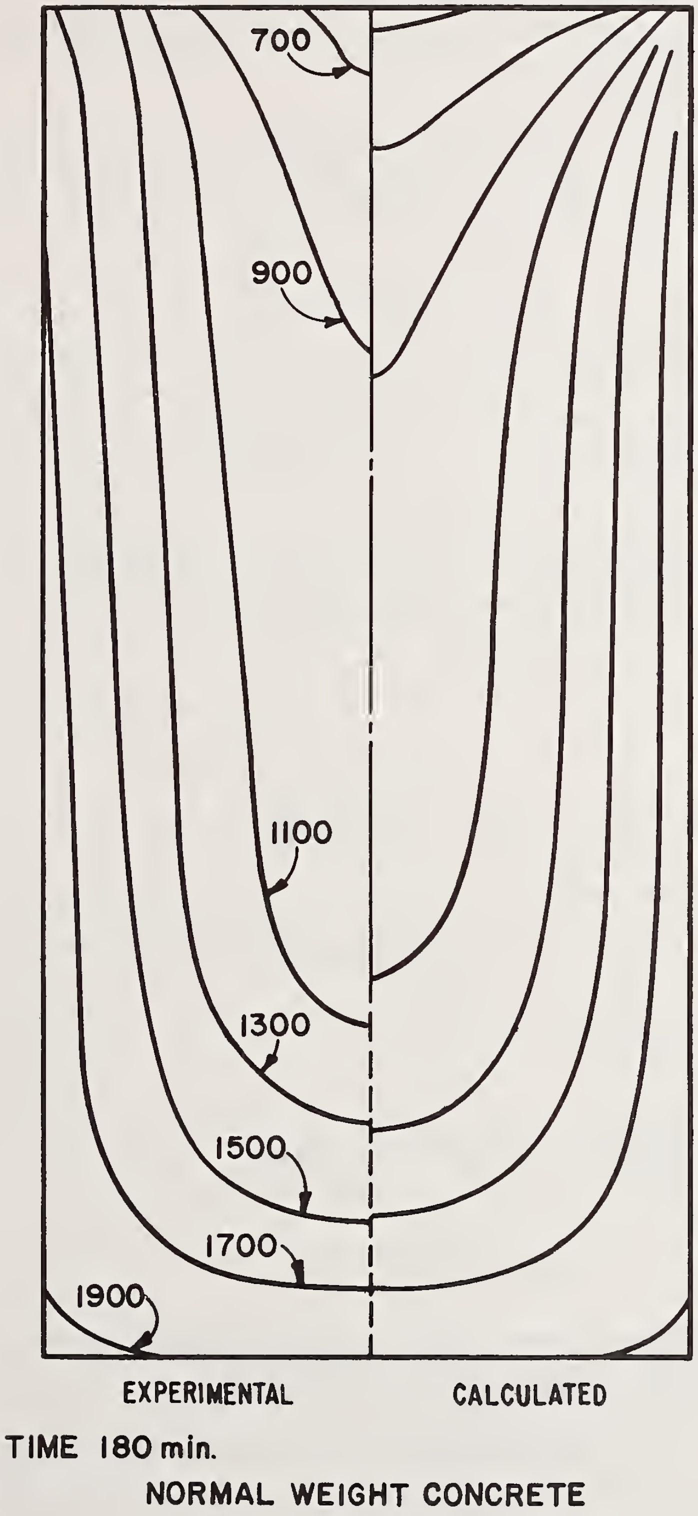
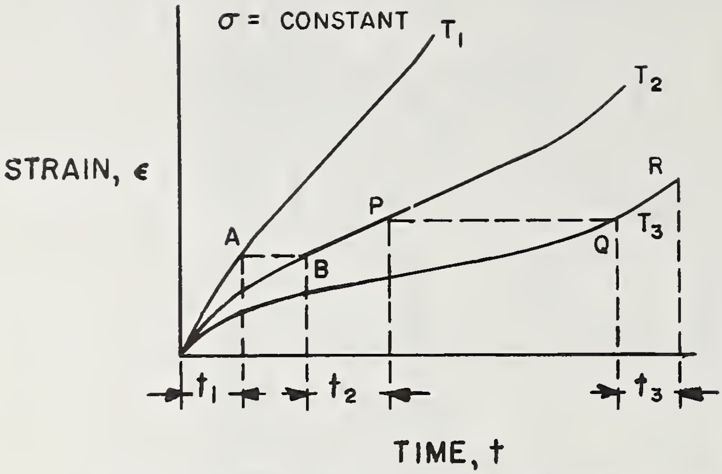
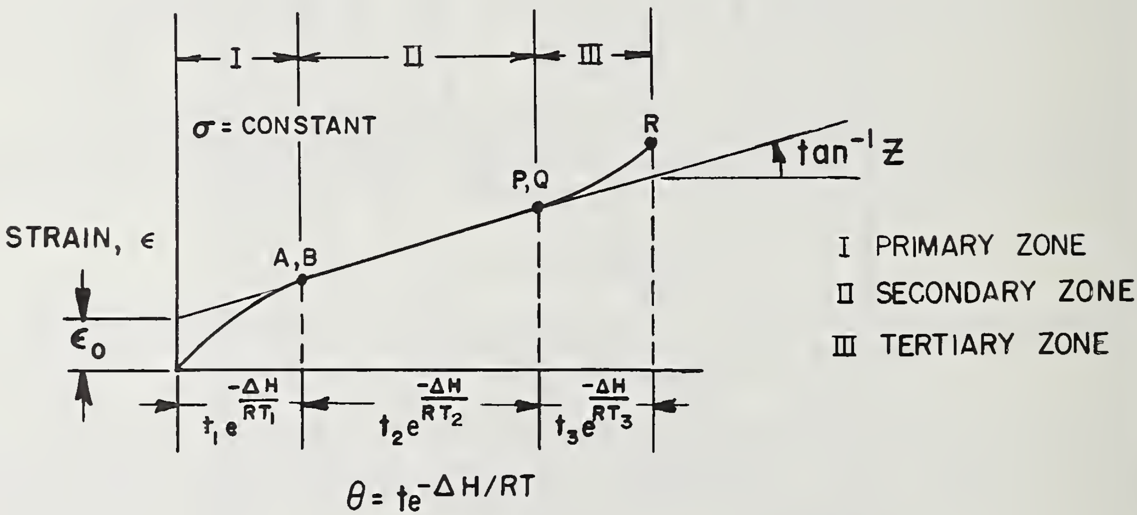


Figure 1. Comparison of calculated with measured temperatures.



CREEP PATH FOR A TEST AT CONSTANT STRESS WITH SEVERAL TEMPERATURE CHANGES.



REDUCTION OF CREEP CURVES AT SEVERAL TEMPERATURES TO A SINGLE CURVE BY θ PARAMETER.

Figure 2. Diagrammatic representation of Harmathy-Dorn theory.

The structural analysis program that is being developed includes a capability of either computing the material property tables from room temperature values or reading in a full set of material property tables for the full range of temperatures.

The creep analysis in this program is based on the Harmathy-Dorn [10,11] theory and on a modification of the time hardening rule[5]. [20] The thermal properties of concrete and steel are based mainly on the comprehensive summary in Bizri's thesis [21] and on Harmathy's recommendations. [9,11]

2.2.1. Outline of Creep Theory

The Dorn [22] theory states that if the creep curves for metals at the same stress but at different temperatures are plotted against the temperature compensated time, which is defined below, all the curves will be coincident. This immediately leads to a great simplification in analysis, as now only a single curve (and its associated equation) is needed to calculate creep strains at constant stress. This is shown in figure 2. Harmathy [10] extended the temperature range of the Dorn theory and added a term to account for the stress level. The term turns out to be the Zener-Hollomon parameter. [9,11,23] The Zener-Hollomon parameter is the slope of the secondary portion of the creep curve when it is plotted against the temperature compensated time. This is shown in figure 2. Thus, this parameter may be considered as a temperature compensated creep rate and it is a function of stress only.

Harmathy [10] proposed the following equations for calculating the creep in reinforcing and prestressing steels:

$$\frac{1}{Z}\, d\varepsilon/d\theta = \coth^2(\varepsilon/\varepsilon_o) \tag{4}$$

which when integrated and rearranged gives

$$Z\theta/\varepsilon_o = \varepsilon/\varepsilon_o - \tanh(\varepsilon/\varepsilon_o) \tag{5}$$

where Z = Zener-Hollomon parameter (function of material and stress; (fig. 2)

θ = temperature compensated time (function of temperature and material)

$= e^{-\Delta H/RT} t$

and ΔH = activatior energy of creep [10]

R = gas constant

T = absolute temperature

t = time

ε = creep strain

ε_o = intercept of the secondary portion of creep curve plotted against the temperature compensated time (function of material and stress; see figure 2).

The restriction on eqs (4) and (5) is that either the stress is constant or at most the stress is slowly changing with time. Under the conditions of a fire test, this restriction is satisfied.

[5]This is in conformity with Harmathy's theory which is discussed below.

In order to solve for creep using eq (5), an iterative procedure must be used.

Thus, Harmathy's recommendations greatly simplify the computation problems for estimating the creep in the steel, since varying temperature level and moderately varying stress level are included in a single equation. It is assumed that since the creep of the concrete in the compressive zone of the beam is much smaller than the creep in the steel, it may be neglected in the analysis of simply supported beams. The assumption is based on the fact that in most fire tests the average temperature of the concrete compressive zone is generally within the range of elastic or elasto-plastic behavior.

2.3. Outline of Structural Analysis Program

In the structural analysis program, the calculations are controlled by two program elements. These are designated MAIN and BEAMB. MAIN controls the reading in of the problem data, the preparation of tables of material properties, the initializing of the problem, controlling the time sequencing of the problem and reading in the temperature data that had previously been prepared by AMG065. BEAMB controls the structural calculations within each time cycle and calculates either the ultimate normal temperature capacity of the beam section, the stresses and strains in the concrete and steel under working loads (required for initializing the creep calculations), or the capacity of the beam section during the process of a fire test exposure. These two program elements also call other subprograms which perform specific calculations during a run, such as setting the temperature of each element, calculating or reading in the temperatures of each bar, creep calculations and so forth.

2.4. Verifications of Structural Analysis

The structural analysis computer program will be verified by comparing the analytic results with available test data. In this, some discrimination is necessary as it has been found that test results from different laboratories vary.

3. FUTURE DIRECTION

The computer programs will be used to generate fire performance information for a variety of beam shapes. These data will be used to develop design aids such as graphs, tables, and nomographs for use by designers, architects, building code officials and other interested users.

Based on experience with its use, the computer program will be modified. Possible modifications are: inclusion of creep in concrete, calculation of available strength at selected fire exposure times and testing of alternative creep algorithms.

4. ACKNOWLEDGEMENT

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5. REFERENCES

[1] Standard Methods of Fire Tests of Building Construction and Materials, American Society for Testing and Materials Designation E119, American Society for Testing and Materials, Philadelphia, Pa. (1973).

[2] Issen, L. A., Scaled Models in Fire Research, Journal of the PCA Research and Development Laboratories, Vol. 8, No. 3 (Sept. 1966).

[3] Hamming, R. W., Numerical Methods for Scientists and Engineers (McGraw-Hill Book Co., New York, 1962).

[4] Zienkiewicz, O. C., The Finite Element Method in Engineering Science (McGraw-Hill Book Co., New York, 1971).

[5] Issen, L. A., Gustaferro, A. H. and Carlson, C. C., Fire Tests of Concrete Members: An Improved Method for Estimating Thermal Restraint Forces, Fire Test Performance ASTM STP 464, American Society for Testing and Materials, Philadelphia, Pa. (1970).

[6] Abrams, M. S., Gustaferro, A. H. and Salse, E. A. B., Fire Tests of Concrete Joist Floors and Roof, Research and Development Bulletin RD006.01B, Portland Cement Association, Skokie, Ill. (1971).

[7] Gustaferro, A. H., Abrams, M. S. and Salse, E. A. B., Fire Resistance of Prestressed Concrete Beams Study C: Structural Behavior During Fire Tests, Research and Development Bulletin RD009.01B, Portland Cement Association, Skokie, Ill. (1971).

[8] Ehm, Herbert, A Contribution to the Design of Fire Endurance of Reinforced Concrete Beams and Similar Structural Elements, Doctoral Thesis, Faculty of Structural Engineering of the Carolo-Wilhelmina Technical University in Braunschweig (West Germany), 1967, translated by K. F. Zaluda, Portland Cement Association Foreign Literature Study. 545.

[9] Harmathy, T. Z., Thermal Performance of Concrete Masonry Walls in Fire, Fires Test Performance ASTM STP 464, American Society for Testing and Materials, Philadelphia, Pa (1970).

[10] Harmathy, T. Z., A Comprehensive Creep Model, Transactions A.S.M.E. Journal of Basic Engineering, Vol. 89, American Society of Mechanical Engineers, New York, N.Y. (1967).

[11] Harmathy, T. Z. and Stanzak, W. W., Elevated-Temperature Tensile and Creep Properties of Some Structural and Prestressure of Steels, Fire Test Performance ASTM 464, American Society for Testing and Materials, Philadelphia, Pa. (1970).

[12] Gustaferro, A. H., Fire Endurance of Concrete Slabs and Beams, unpublished proposals to the American Concrete Institute Committee, No. 216 (1973).

[13] Edwards, A. L., TRUMP: A Computer Program for Transient and Steady-State Temperature Distribution on Multi-dimensional Systems (available from the NTIS, Springfield, Va., Report No. UCRL-14754, Rev. II).

[14] Schauer, D. F., FED: A Computer Program to Generate Geometric Input for the Heat-Transfer Code TRUMP (available from the NTIS, Springfield, Va., Report No. UCRL-50816).

[15] Edwards, A. L., TRUMP/XB2: A Computer Program for Processing the TRUMP Thermal Property Data Computation (available from the NTIS, Springfield, Va., Report No. UCRL-50663).

[16] Brisbane, J. J., Heat Conduction and Stress Analysis of Solid Propellant Rocket Motor Nozzles (available from the NTIS, Springfield, Va., Report No. AD848594).

[17] Perry, Robert H., *et al*, John H. Perry's Chemical Engineers Handbook, 4th Edition (McGraw-Hill, New York, 1963).

[18] Myers, G. E., Analytic Methods in Conduction Heat Transfer McGraw-Hill Book Co., New York, 1971).

[19] Hansen, N., BEAMBUSTER: Program Solves for the Moment-Curvature Relationship of a Reinforced Concrete Cross-Section Subject to Axial Load and Bending, Portland Cement Association, unpublished (1971).

[20] Leckie, F. H., Some Structural Theorems of Creep and Their Implications, Advances in Creep Design, in Chapt. 4, A. I. Smith and A. M. Nicolson, Eds. (John Wiley and Sons, Inc., New York, 1971).

[21] Bizri, H., Structural Capacity of Reinforced Concrete Columns Subjected to Fire Induced Thermal Gradients, Report No. UL SESM 73-1, Structural Engineering Laboratory, University of California, Berkeley, Calif. (1973).

[22] Dorn, J. E., Mechanical Behavior of Materials at Elevated Temperatures, esp. Chapt. 14, Creep Under Non-steady Temperatures and Stresses, by S. S. Manson (McGraw-Hill Book Co., New York, 1961).

[23] Zener, C. and Hollomon, J. H., Effects of Strain Rate on the Plastic Flow of Steel, Journal of Applied Physics, Vol. 15 (1944).

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SMOKE AND CARBON MONOXIDE GENERATION FROM BURNING SELECTED PLASTICS AND RED OAK

Thomas Y. King[1]
Armstrong Cork Company, Lancaster, Pennsylvania

This paper presents preliminary results of simultaneous smoke and carbon monoxide measurements from burning selected plastics and red oak in the smoke density chamber. An attempt was made to correlate smoke optical density with mass concentration of smoke. Particulate shape and approximate size range of the smokes were obtained using a scanning electron microscope.

Key words: Carbon monoxide; electrostatic precipitation; particulate mass; scanning electron microscope; smoke.

1. INTRODUCTION

A material's flammability (i.e., flame spread, ease of ignition, etc.) has in the past been the primary consideration in fire safety evaluation. Now with a greater understanding of those factors which contribute to fire injuries and deaths, smoke and toxic products are becoming of increasing concern. Even a relatively good flame retardant or thermally stable material, which by itself would not ordinarily propagate a flame, should be considered in the total combustible system. In most actual fire situations other more flammable material will be available which could result in partial or full involvement of materials of low flammability.

The deleterious effects of smoke in a fire result from decreased visibility, both for the escaping occupant and the rescuing firefighter; inhalation of particulates which restrict respiration and can induce panic; and the toxic gases that accompany the smoke and account for a large fraction of fire deaths.

A study of the physical and chemical parameters which affect the smoke generating potential of various materials is important not only in assessing possible hazardous materials, but also in determining the means by which the hazard can be reduced.

This paper presents preliminary results of measurements of smoke and gaseous combustion products from selected materials in a smoke density chamber. Since the research described has recently been started, this paper is designed primarily to introduce the overall program and indicate its likely direction.

2. SMOKE AND CARBON MONOXIDE GENERATION

Smoke can be defined as the solid particulate and/or liquid aerosol generated from the incomplete oxidation of organic materials and the release of certain inorganic materials during the burning process. The gaseous combustion products are not included in the above definition of smoke. Factors which can affect the smoking tendency of materials include: composition, density and thickness, heat flux, air flow, oxygen availability, pressure, surface characteristics, and geometry. Carbon monoxide is formed from the incomplete oxidation of the decomposition products, and the same factors which affect smoke production might be expected to influence carbon monoxide generation.

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[1]The author was a Research Associate at the National Bureau of Standards, Washington, D.C. when the work reported here was performed.

In this paper, smoke was measured using the National Bureau of Standards' Smoke Density Chamber. [1] This is an 18 cubic foot enclosed chamber in which a vertically positioned photocell measures the amount of light absorbed (or scattered) from the smoke emanating from burning a vertical 3" x 3" sample. In the standard test method, the sample can be exposed to heat under either a flaming (2.5 W/cm^2 of radiant heat plus piloted ignition) or smoldering (radiant heat only) type exposure. The specific optical density is a measure of light obscuration for a specimen of given thickness and density, and is specific for the sample area exposed.

Although normally only the maximum specific optical density (D_m) is reported, other measured parameters of interest include: the time at which D_m occurs (T_m), the time at which the specific optical density equals 16 (T=16), and the maximum smoke production rate averaged over a two minute period (R_m).

Carbon monoxide (CO) was measured continuously and simultaneously with the smoke using an infrared analyzer connected to the chamber (fig. 1). Results are reported graphically in parts per million (ppm).

Throughout these studies the flow rate from the chamber to the infrared analyzer was maintained between 1 to 1-1/2 liters/min. A delayed response time due to dead air spaces (dry ice trap, particulate filter assemblies, and sample lines) for 90-95 percent CO response in the analyzer was approximately 30 seconds. None of the carbon monoxide curves shown in this paper were corrected for this factor.

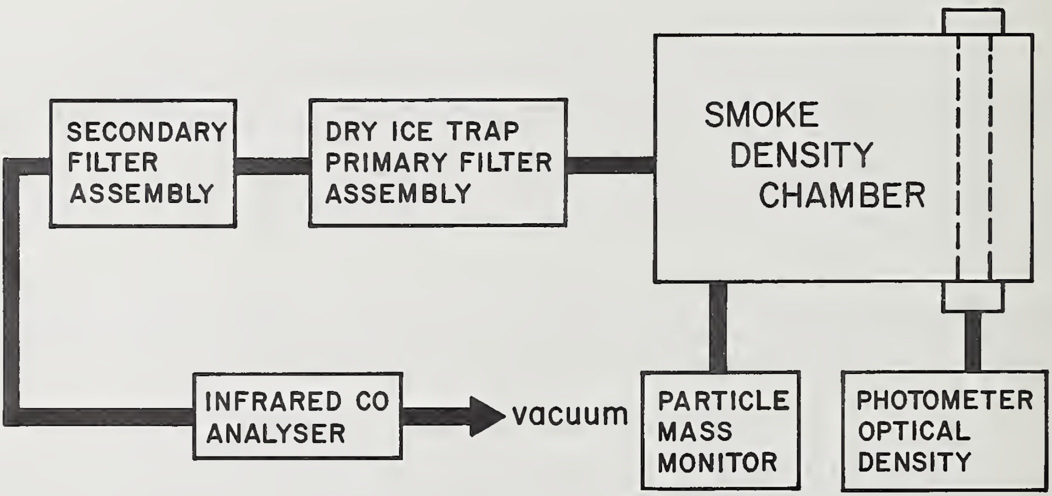

Figure 1. Smoke analysis system.

2.1. Sample Design

Samples for this study (table 1) included: red oak, acrylonitrile-butadiene-styrene (ABS), and rigid and plasticized polyvinylchloride (PVC). (Polystyrene and a polyurethane will be included later in the program.) These materials were chosen to represent typical cellulosic and polymeric materials. The plastics, however, are not truly representative of actual building and furnishing compositions since they contain no fillers and only a minimum amount of the other components necessary for fabrication. This allowed the comparison between different materials without undue concern for fillers, flame retardants, and other components which in practice could comprise a large percentage of the actual composition and have a significant effect on the results. Since smoke and carbon monoxide concentration would be expected to increase with sample weight, the samples were compared at approximately the same weight (4.1 to 4.4 grams). Sample weights were relatively small so that the heat transfer into the sample and resultant smoke generation would occur rapidly without allowing excessive time for particulate deposition to occur during the build-up stage. The maximum specific optical density (D_m) can be regarded as the point at which equilibrium exists between smoke production and particulate deposition.

Table 1. Materials Studied

Material	Approximate Thickness (in)	Approximate Density (g/in^3)
Rigid Polyvinylchloride[a]	0.023	20.3
Plasticized Polyvinyl-chloride[a]	0.022	21.2
Acrylonitrile-Butadiene-Styrene[a]	0.031	15.1
Red Oak	0.045	10.4

[a]Materials were specially prepared for this study.

2.2. Effect of Composition on Smoke and Carbon Monoxide Generation

The relationship between smoke (dotted curves) and carbon monoxide (solid curves) with time for red oak, ABS, and rigid and plasticized PVC samples burned under non-flaming exposure is shown in figure 2. The curves shown were averaged from three separate determinations. At a heat flux of 2.50 W/cm^2, rigid and plasticized PVC and ABS generate carbon monoxide very slowly (1-2 ppm/min) at a constant cumulative rate over the time interval described. Since there is little difference in the rate of CO build-up for these three materials, but a substantial difference in the maximum smoke densities, one can conclude that no simple relationship exists between smoke and carbon monoxide for materials under these conditions. Carbon monoxide appears to be liberated in each case only after a substantial amount of smoke has been generated. Whether this is due to the slow oxidation of carbonaceous char and/or smoke and gaseous decomposition products is not yet clear. The six-fold increase in smoke obtained from burning plasticized PVC compared to rigid PVC can be attributed to the significant contribution of the plasticizer to the non-flaming smoke evolution.

Comparatively, red oak liberates large quantities of carbon monoxide under smoldering conditions. The rate, however, was slow initially until the onset of glowing combustion, then rapidly increased (approximately 80 ppm/min).

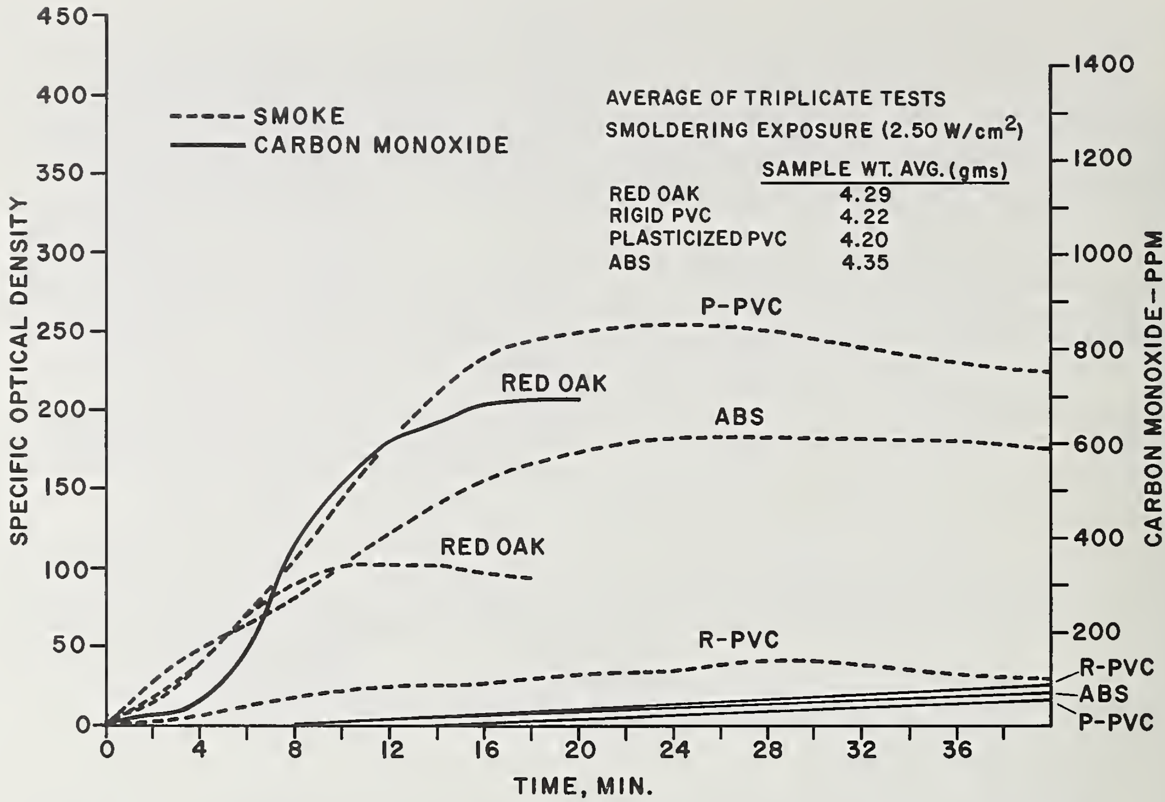

Figure 2. Smoke and carbon monoxide concentration for various materials.

Figure 3 illustrates similar curves for the four materials under flaming conditions. Under this exposure the carbon monoxide generated from the pilot burners was subtracted from the actual CO curve measured from the material. With the exception of red oak, more smoke and CO are produced under flaming compared to smoldering exposures. After the maximum smoke density had been reached the carbon monoxide curves for red oak and ABS reached a plateau which was consistent with the observation that little char remained at that point.

For rigid and flexible PVC there appear to be two distinct slopes on the CO curves, one corresponding to the rapid rate of CO generation until the maximum smoke density has been reached, the other occurring after the smoke begins dissipating which apparently results from carbon oxidation of the remaining char.

2.3. Sample Probe Position

In the previous studies continuous sampling for carbon monoxide had been accomplished from the top of the chamber. It is conceivable that under certain circumstances the convective heat flow might be such that the gases would tend to stratify at the top of the chamber before mixing. To determine this, CO was monitored at the middle and bottom in addition to the top to represent a cross sectional area of the chamber. The CO produced from red oak and rigid PVC samples was evaluated under flaming exposure at these three positions (fig. 4). Results indicated that there was a carbon monoxide concentration gradient only during the first few minutes of the test. After this initial time period concentration was essentially uniform throughout the chamber.

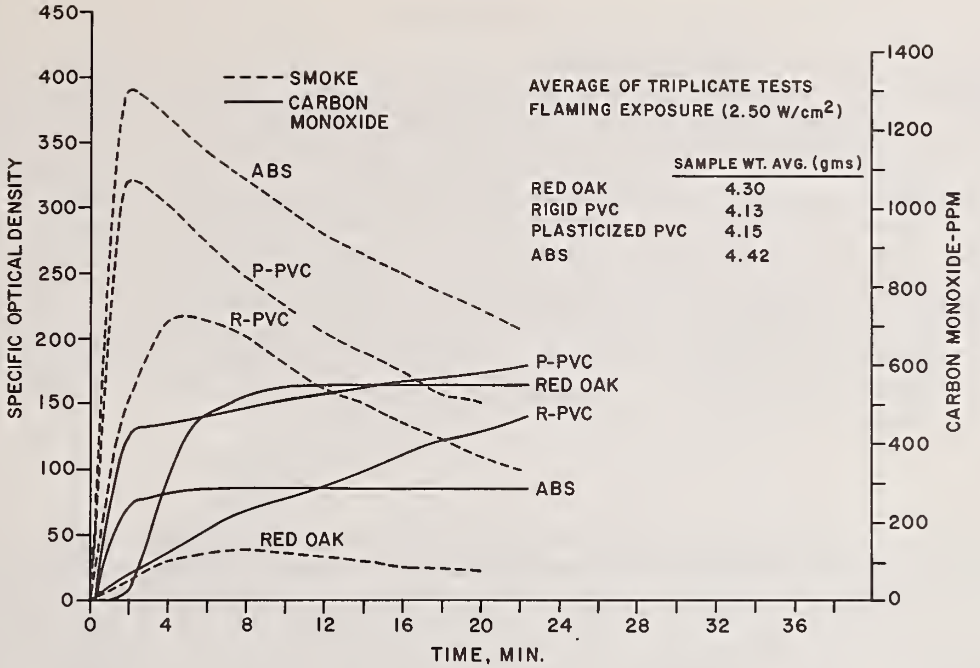

Figure 3. Smoke and carbon monoxide concentration for various materials.

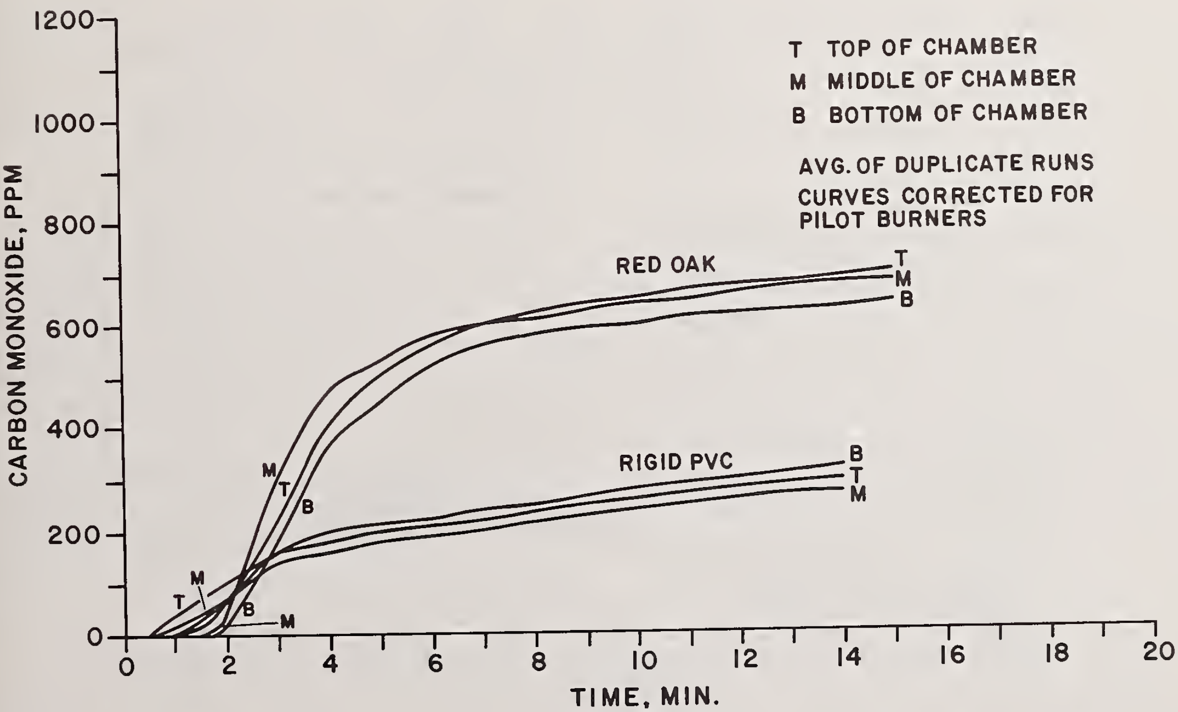

Figure 4. Effect of probe position on carbon monoxide concentration from red oak and rigid PVC (flaming exposure).

2.4. Heat Flux

Smoke and carbon monoxide concentrations from burning rigid PVC samples were studied as a function of heat flux (flow rate of energy across or through a surface). Radiant heat flux levels were varied from 1.87 to 3.07 W/cm^2 under flaming type burning conditions while the gas and air mixture to the ignition burners was constant. As shown in figure 5 as the heat flux increased the maximum specific optical densities were increased, the maximum rates of smoke and carbon monoxide generation were increased, and the times to reach D_m were decreased. The marked two-fold increase in maximum smoke density resulting from increasing the radiant heat from 1.87 to 3.07 W/cm^2 can be attributed in part to a greater total weight loss (ca. 70 percent and 84 percent respectively). Other factors which could contribute might be that less time for particulate decomposition on the chamber surface is available and there are possibilities of different reaction pathways which favor more smoke production at higher temperatures.

3. SMOKE MASS

Smoke mass density has been related to optical density measurements in the smoke chamber by using frequency monitored electrostatic precipitation. The change in frequency during a given time interval is directly proportional to the total particulate mass. In this study smoke was sampled at a point half way up the chamber wall under steady state conditions after reaching the maximum smoke density. A plot of smoke optical density per meter versus smoke mass density (milligrams per cubic meter) for red oak (flaming and smoldering exposure) and ABS, and rigid and plasticized PVC (smoldering exposure) is shown in figure 6.

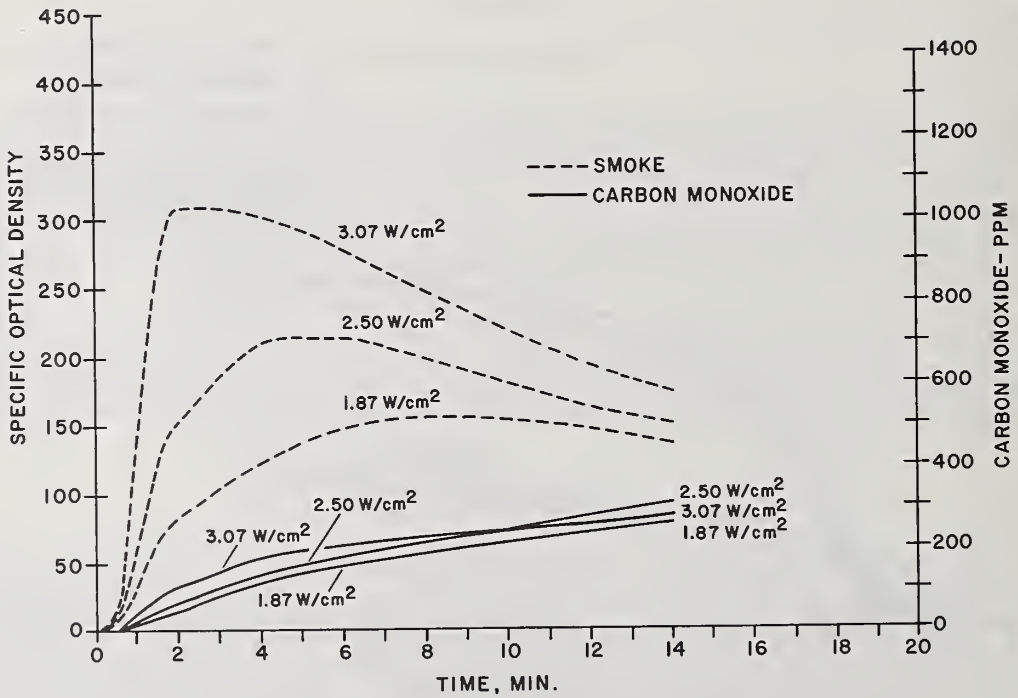

Figure 5. Effect of heat flux on smoke and carbon monoxide generation from rigid PVC samples (flaming exposure).

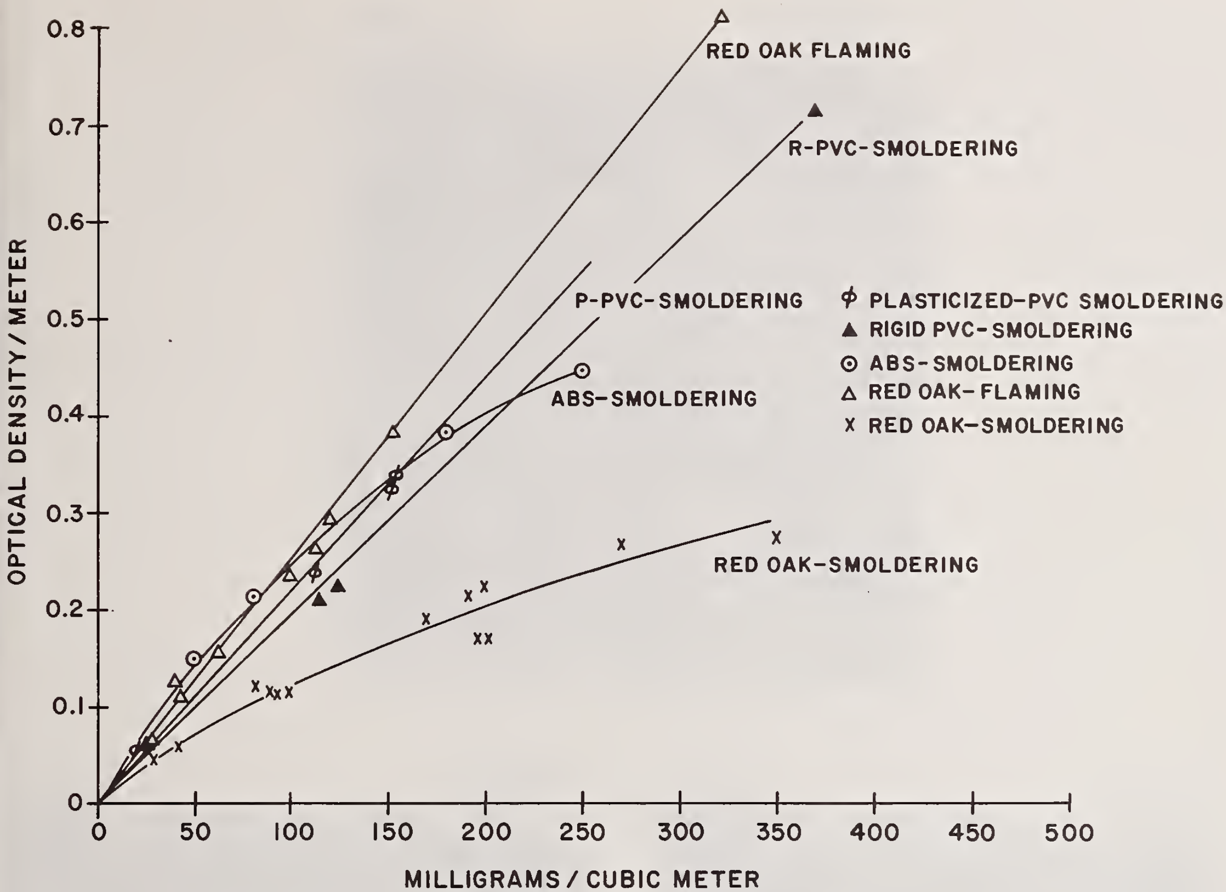

Figure 6. Optical density vs. smoke mass density.

Initial sample weights were varied by changing the sample area exposed, keeping thickness constant, to obtain a range of optical densities in the chamber. With the exception of red oak and ABS under non-flaming burning conditions, smoke mass density was found to be linearly related to optical density over the range explored. The non-linearity observed with the red oak and ABS specimens under smoldering conditions is not fully understood. It might result from the particular properties of the pyrolysis products contributing to more rapid agglomeration. However, by varying the sample area and therefore weight, a possibility exists that edge effects and heat flux gradients could have led to the observed results. It is interesting to note that in the case of red oak a considerably lower smoke mass to optical density ratio was found under flaming compared to non-flaming burning conditions.

4. PARTICULATE SIZE AND SHAPE

To complement the smoke optical density and mass studies, scanning electron microscope pictures were taken of smokes from rigid and plasticized PVC, red oak, and ABS (figs. 7 to 10 respectively) under flaming burning conditions. Samples were prepared by electrostatic precipitation (aerosol sampler) of the smoke particles from the chamber on an electro-polished titanium metal surface. By using a pulsed precipitating electric field in the sampler, smoke deposition was relatively uniform without preferential size separation.

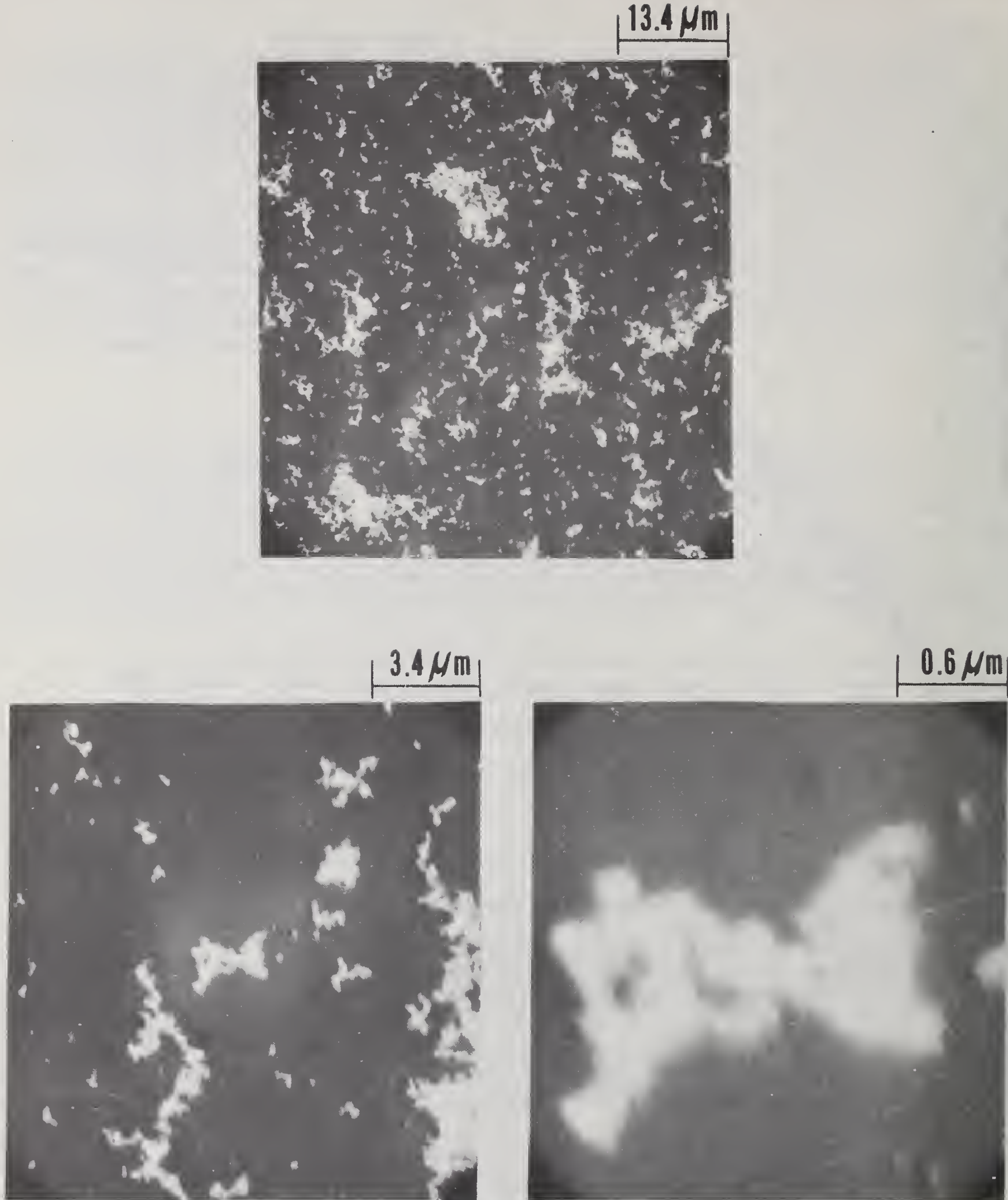

Figure 7. Rigid PVC "flaming exposure" smoke particulate, scanning electron microphotographs.

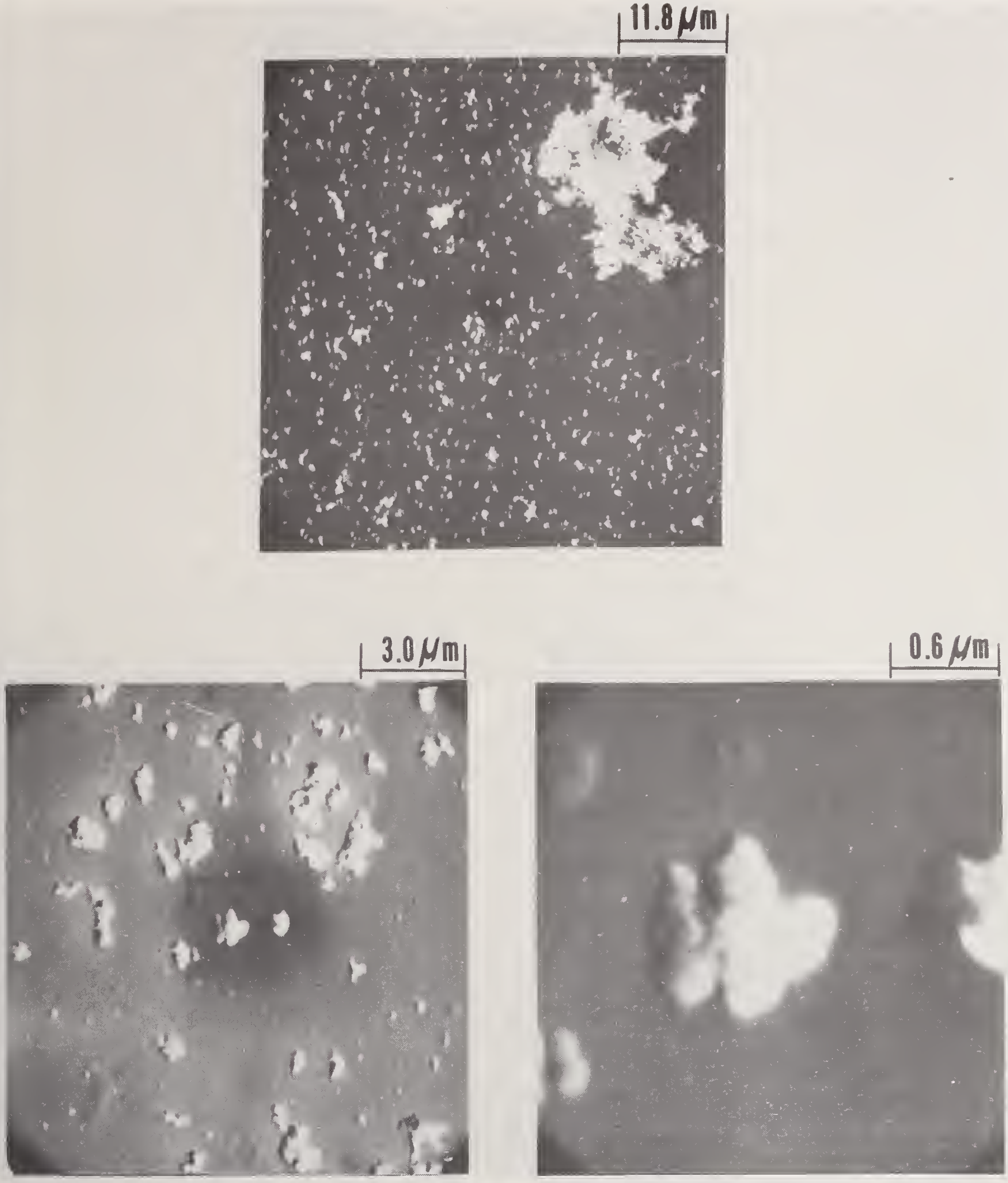

Figure 8. Plasticized PVC "flaming exposure" smoke particulate, scanning electron microphotograph.

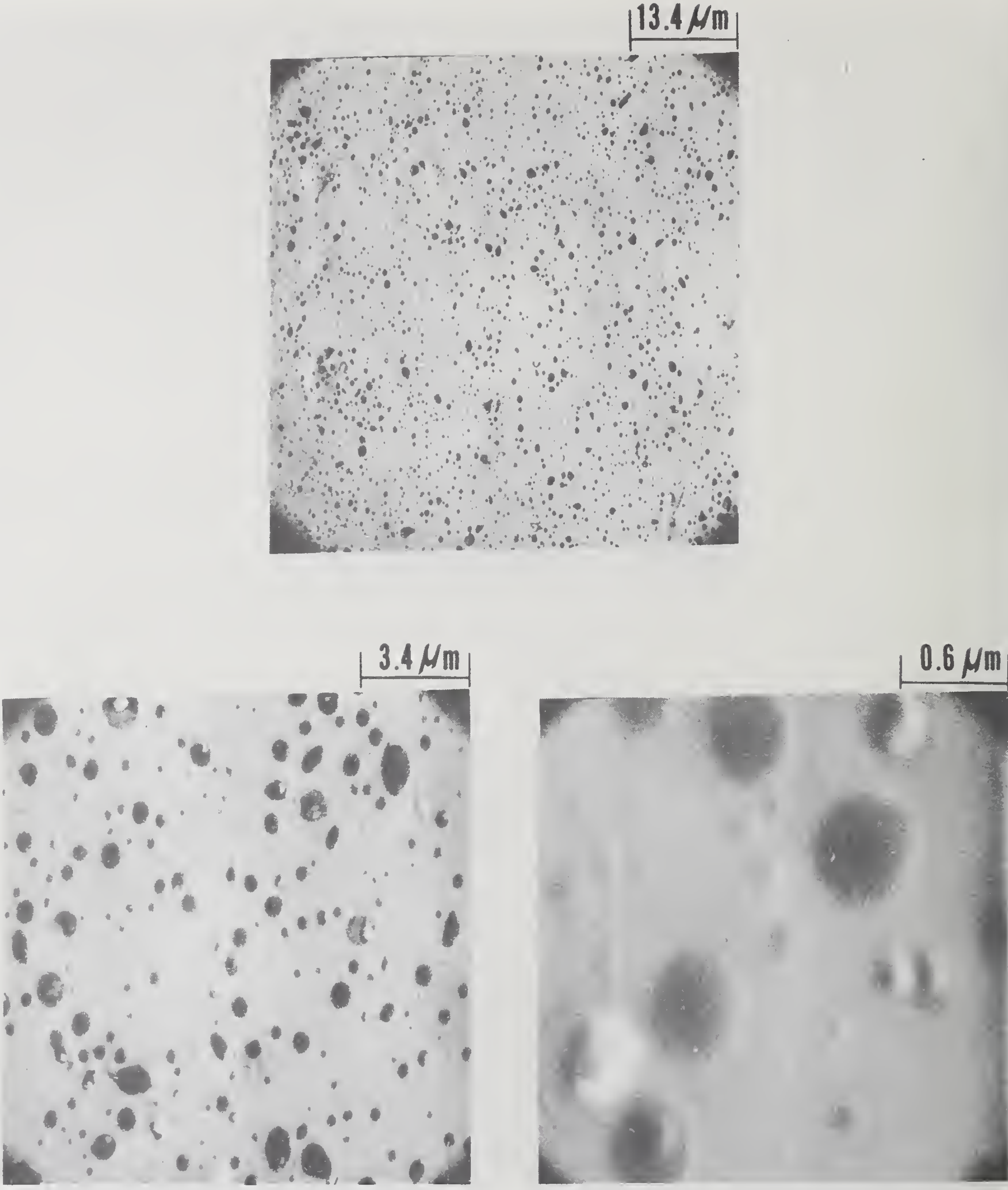

Figure 9. Red oak "flaming exposure" smoke particulate, scanning electron microphotograph.

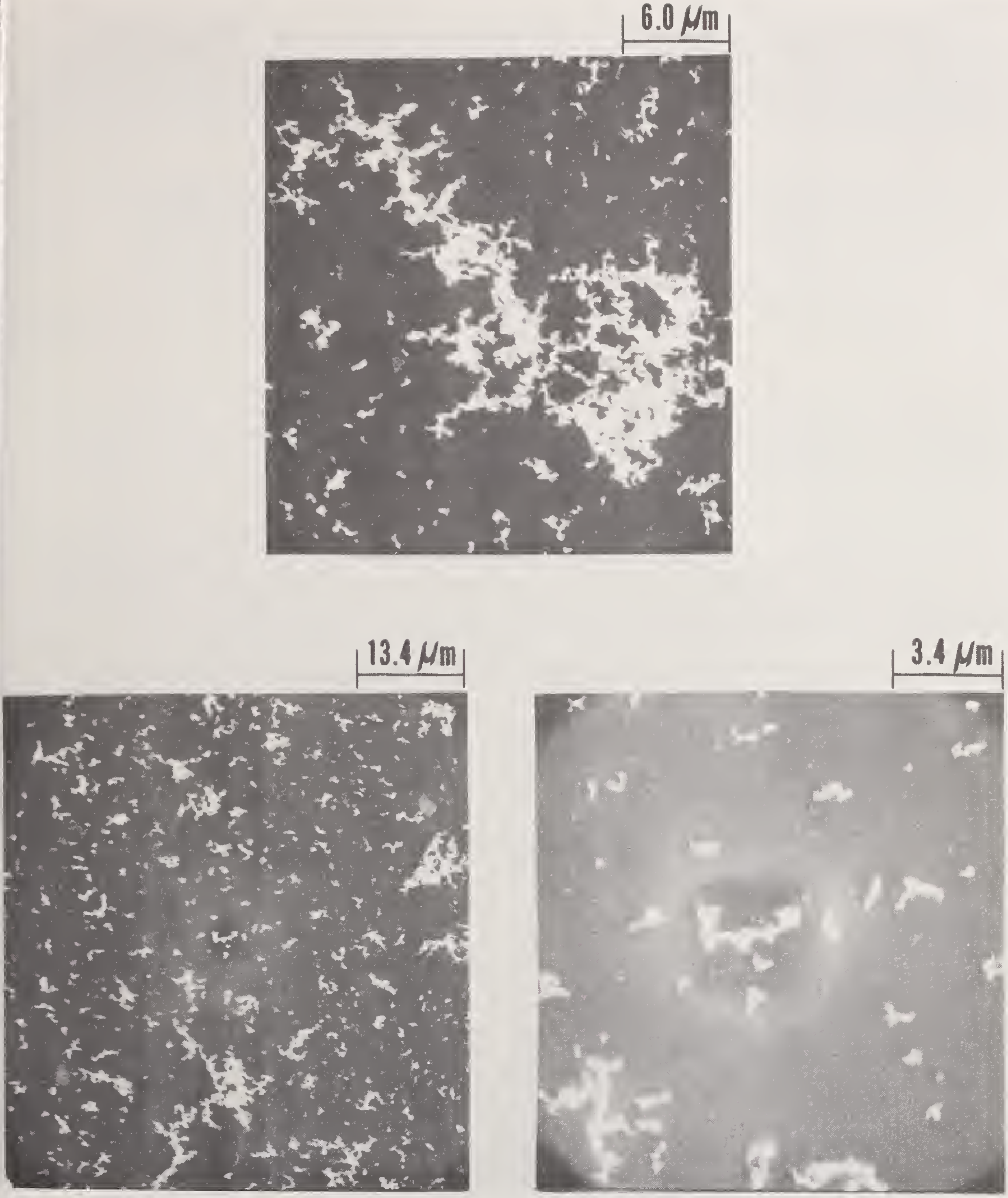

Figure 10. ABS "flaming exposure" smoke particulate, scanning electron microphotograph.

Particle shapes ranged from "stringer" type smokes containing discrete spherical units forming chains for rigid PVC and ABS to the elliptical shaped liquid residue for red oak. Through a knowledge of the magnification of the scanning electron microscope photographs, typical particle sizes were estimated as follows:

Composition	Estimated Maximum (μm)	Estimated Minimum (μm)
rigid PVC	15	0.15
plasticized PVC	24	0.10
red oak	2	0.30
ABS	30	0.15

No attempt was made at this time to estimate particle size distributions. It is interesting to note, however, that there appears to be a noticeable difference in shape between rigid and flexible PVC smoke particles, the former containing relatively long aggregated chains while the latter has a greater number of smaller aggregates more spherical in nature.

5. FUTURE STUDIES

The research described in this paper has recently been started and represents only a part of the overall program. The program will be limited to the six materials described earlier and will consist of three phases:

1. The determination of the effects of heat flux, oxygen depletion, material composition, and weight loss on smoke and carbon monoxide evolution.

2. The determination of the relationship between optical density and smoke mass density for each material under both flaming and non-flaming burning conditions.

3. The determination of smoke particulate shape and size distribution (if possible) for each material under flaming and smoldering exposures.

The study is designed to provide information relating to the following questions:

1. What are the relative smoke and carbon monoxide generating characteristics of these six materials and do they change significantly with higher temperatures and oxygen deficiencies?

2. From a knowledge of weight loss, heat flux, and oxygen availability can the maximum smoke densities and CO generation rates be estimated on samples of similar composition to those studied?

3. After experimentally determining the relationship between optical density and smoke mass density over a narrow range can these data be extrapolated to include higher optical densities so that one might predict total airborne smoke mass?

4. How does smoke particle shape and size vary with material composition and burning conditions?

6. CONCLUSIONS

Based on the limited study to date, carbon monoxide accompanies smoke development in the flaming combustion process, but there does not appear to be a unique relationship between the two products for materials of different composition.

In the case of red oak, it is possible to produce considerable amounts of CO without much smoke if the burning process remains in the flaming mode. The rate of carbon monoxide evolution for the plastic materials studied under non-flaming conditions was observed in all cases to be relatively low.

The complex interrelationship between smoke mass, optical density, and particulate size and shape appears to be strongly dependent upon material composition.

7. REFERENCES

[1] Lee, T. G., Interlaboratory Evaluation of Smoke Density Chamber, Nat. Bur. Stand. (U.S.), Tech. Note 708 (Dec. 1971).

[2] Gross, D., Loftus, J. J. and Robertson, A. F., Method for Measuring Smoke from Burning Materials, Symposium on Fire Test Methods -- Restraint and Smoke 1966, American Society for Testing and Materials, Philadelphia, Pa., 1967, pp. 166-204.

NATIONAL BUREAU OF STANDARDS SPECIAL PUBLICATION 411, Fire Safety Research, Proceedings of a Symposium Held at NBS, Gaithersburg, Md., August 22, 1973, (Issued November 1974)

A FIELD STUDY OF NON FIRE-RESISTIVE MULTIPLE DWELLING FIRES

Francis L. Brannigan[1]
Montgomery College, Rockville, Maryland

A field study was made of structural and building design factors contributing to the spread of fire in more than 40 non fire-resistive, multiple occupancy dwellings, typically "Garden Apartments". Most deficiencies could be corrected by preserving the integrity of a gypsum board sheath serving as a fire barrier. Examples are given of penetrations and openings in fire barriers which permitted substantial fire spread.

Key words: Apartments; building codes; fire; fire walls; garden apartments; gypsum board; insurance; livability; multiple dwellings.

1. INTRODUCTION

From January 1971 till the present the author has been under contract to the National Bureau of Standards to investigate serious multiple dwelling fires to determine what structural elements or practices contributed to the extension of fire beyond the area of origin.

Several local fire department radio channels are routinely monitored by the author, and he responds to fires of interest. In addition, he keeps in close touch with fire officials in the local area, and is notified of fires of interest. All investigations were made either while the fire department was still in possession of the premises, or if later, accompanied by a fire official and with the permission of and access provided by the owners' representative. Wherever possible firefighters early on the scene were interviewed.[2] A few observations are based on examination of buildings under construction.

No attempt was made to determine the extent to which any particular building conformed to the code in effect at the time the particular building was built. Obviously, not all the defects cited exist in all jurisdictions, or in all structures examined.

Each report provides a capsule description of the building, the fire, the manner in which the fire spread from the point of origin, appropriate 35mm slides, and any recommendations the investigator might have on how modifications of present practices might improve the fire containment design of similar buildings. The reports are circulated to the appropriate staff members and provide a body of information which aids the staff in developing and supporting improved building design.

Through other channels the investigator shares his findings and fire tactical recommendations with firefighting forces. If a fire department is well aware of the defects of a building or types of buildings it may be possible to "plug the gap" tactically and reduce the consequences of the designers' errors.

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[1]Mr. Brannigan serves as a consultant to the Program for Fire Control - Construction, Programmatic Center for Fire Research, National Bureau of Standards, Washington, D.C.

[2]Appreciation is expressed to the Montgomery County Department of Fire and Rescue Services and the Fire Departments of Bethesda, Kensington, Silver Spring, Rockville, Gaithersburg, Prince Georges County, Anne Arundel County, Clarkesville and Annapolis in Maryland, Arlington and Fairfax Counties in Virginia and the District of Columbia.

2. PRIVATE HOMES VS. MULTIPLE DWELLINGS

"A man's home is his castle" is a long established principle of our common law. This principle is carried forward into statute law such as building codes, in that fire protection aspects of building codes bear very lightly on single family dwellings. Regulations calling for masonry exterior walls and spacing between buildings limit one's "right" to burn down his neighbor, though recent relaxation of rules against wooden shingles have restored this "right" in some areas. Generally, inspection laws don't give the Fire Inspector access to private dwellings. The principal impact of the statutes is in the regulation of the initial installation of electricity and heating appliances, but there is generally no warrant for reinspection to determine that installations have not been substantially altered after initial approval. Even when requirements are upgraded, usually no attempt is made to apply them retroactively to existing dwellings. For example, current efforts to legislate installation of combustion products detectors in one-family homes are limited to *new* homes; little thought is given to ordering installation in *existing* homes.

It is impossible to house each family in the United States in its own individual "castle". Multiple dwelling units are necessary.

In the multiple dwelling unit there is an *interaction* between a fire in any unit, and the safety of the occupants in all the other units. In addition, multiple dwelling units contain common areas accessible to all occupants, and to varying degrees, to any outsider. A fire in the common area threatens all the occupants.

Historically, multiple dwellings in many cities were created by the subdivision of large one-family homes into smaller units as the former owners moved away and neighborhoods deteriorated. In cities like New York, the supply of deteriorated housing was insufficient to meet the needs of hordes of immigrants, so tenements were built to house several family units, structurally indistinguishable from the multi-story one-family house of the well-to-do (the typical New York "Brownstone").

The first official recognition of any special fire safety problem was the requirement that outside fire escapes (vertical ladders, with a platform at each floor level) be provided. Terrible losses of life occurred in these tenements (now "old-law" tenements in New York parlance).[1]

About 1903, as a result of sociological pressures, sweeping tenement house legislation was passed in New York giving rise to the "New Law" tenement. Though not so stated, the principle which underlay the requirements was that no person should lose his life due to a fire which started outside his apartment. The entire thrust was towards easy escape of the occupants, and for many years there was no loss of life in such a building due to extension of fire.

While the fire protection emphasis was almost exclusively directed towards safe escape, requirements for life safety also tended to limit extension of fire. Fire resistive stairways, self-closing fire resistive apartment doors and similar requirements for dumbwaiters together with the universal *complete* plastering of all interior surfaces, served to contain almost all fires to the apartment of origin, for many years. The provisions for easy escape of occupants lightened the burden of rescue operations so that firefighters were available to swiftly check for, and suppress, any extension of fire. Exterior fire escapes provided direct secondary *access* to all apartments.

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[1]For a further discussion of the circumstances of the New York City Tenement House Act see Brannigan, F. L., "Building Construction for the Fire Service", National Fire Protection Association (1971), pp. 146-150.

Unfortunately, building codes are parochial and so as communities shift from individual to multiple dwellings, the same error of regarding a multiple dwelling as simply a larger version of a single family house is repeated. Typically, in 1966 the District of Columbia asked the National Bureau of Standards to investigate possible methods of improving, *in situ*, the fire resistance of existing wooden apartment doors. Tests indicated that improved fire performance was an attainable but costly solution; a simple alternative was to remove the door and frame and substitute metal, a determination made two-thirds of a century earlier in New York.[1]

The multiple dwellings in which the fires were investigated are of a post World War II type known generally as garden apartments. The exterior structural walls are of solid masonry or of brick veneer over platform wood frame.[2] In some cases portions of the exterior surface, typically the spandrel spaces directly between vertical lines of windows are of wood. No completely wooden exterior buildings were involved in any of the fires studied. The usual nominal height is limited to three stories, but by taking advantage of terrain the building can be four stories on one elevation.

Balconies are customary, either extended or reentrant, and variously of combustible or noncombustible construction. Common gable roof attics usually extend over the entire structure, broken in area only to the maximum permitted by the local code when the building was built, and by barriers as inadequate as the code or inspections will permit.

Regardless of exterior construction the interior construction is almost totally of wood, using identical construction techniques to those used in one-family homes. The addition and stacking of units multiplies many times fire extension potentials which are inherent in current construction techniques.

Bathrooms provide an excellent illustration. Years ago, the bathroom was fully plastered and the bathtub stood independently on "feet". "Glamorizing" the bathroom brought about the development of the built-in bathtub. Because of its contours, such a tub interconnects the void spaces of one wall, the void spaces of the wall at right angles, and the void spaces under the floor. These void spaces are interconnected with vertical voids which must be of substantial dimensions to accommodate waste and vent piping. In the layout of the apartments the plumbing facilities are consolidated for economy. This can result in four bathrooms being located in four quadrants around a point.

Vertical and horizontal voids three or four stories high are, thus, fully interconnected. In installing plumbing fixtures, it is often the practice to cut and, thus, weaken structural members. The result is that any fire which starts in or penetrates this void will extend rapidly to as many as 16 family units, and the attic above. In one fire, interior collapse occurred very early in the bathroom area. The weight of fixtures, cutting of structure for accomodation of plumbing, and the air supply due to interconnected voids would make early collapse not unexpected. The contrast between the potential ultimate effect of an initially identical fire in a one-family ranch house and a garden apartment is startling, yet no code provision really takes this into account. "Fire stopping" even if mandated is usually nonexistent, or at best ineffectual.[3]

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[1]Shoub, H. and Gross, D., Nat. Bur. Stand. (U.S.), Bldg. Sci. Ser. 3, "Doors as Barriers to Fire and Smoke (March 1966).

[2]See Brannigan, "Building Construction...", p. 93, for a discussion of the impossibility of distinguishing brick veneer from brick masonry by exterior observation in modern construction.

[3]See Brannigan, "Building Construction...", pp. 64-65, for a discussion of the difference between "Inherent" and "legal" firestopping.

3. THE INTERIOR FIRE RESISTIVE SHEATH

A few years ago New York subway riders were startled to read "car card" ads which urged them to "Keep New York Plastered". Many tried, in more than one sense, but their effort failed. The reference was to the fact that the city was about to embrace a new building code which would permit the use of gypsum board or "drywall" for interior finish. Prior to this, wet plastering had been required. The all plaster, essentially continuous sheath of the wood lathed "New Law" tenement provided (until the plaster deteriorated with age) an almost complete and usually adequate barrier to the extension of fire to the combustible inner structure of the building.

Today, almost universally, interior finish is of "drywall" or gypsum board.

Gypsum board consists of a layer of gypsum, sandwiched between two sheets of paper. It is offered commercially in sheets from 3/8 to 5/8 inch thickness, 4 feet in width and 7 to 10 feet long. By including vermiculite or glass fibers in the gypsum, the time a given thickness of gypsum will resist fire can be increased. If thicknesses greater than 5/8 inch are desired, successive layers of gypsum board are used.

Gypsum itself provides negative Btu yields of as much as -580 Btu per pound, measured by the "bomb" calorimeter method.

Underwriters' Laboratories "Fire Resistance Index" (see fig. 1) contains a number of fire resistive (combustible) wall and "floor and ceiling" assemblies, tested and rated according to the standard fire test, ASTM E119. In most cases the essential protective element is gypsum board.

The test assemblies are simple structures. Walls are of vertical wood studs, without any offsets, and are *fire stopped*. Floor and ceiling assemblies are usually on 2 x 10 inch wood joists *fire stopped*.

Building codes contain various requirements for fire resistive (combustible) construction.

The "as built" wall and floor ceiling assemblies are far more complex than the test assemblies. It appears that builders, building officials, and inspectors are quite unfamiliar with all the details of the assemblies which passed the tests and were rated.

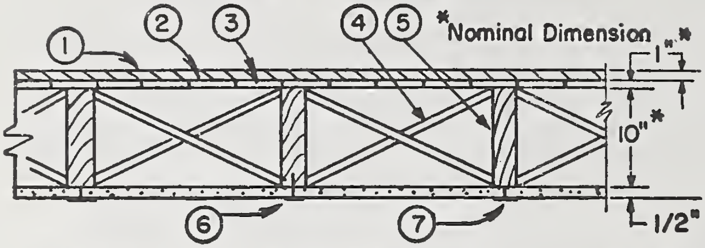
One of the most persistent and dangerous errors is the assignment of the fire resistance rating to the gypsum board itself rather than to the assembly as erected in the test facility. Another error is the failure to understand the meaning of "combustible" when added to a fire resistance rating.

Gypsum board walls and ceilings competently installed under the watchful eye of inspectors who understand the *full* installation requirements can and have performed remarkably well. An excellent example can be found in the Harbour House project in Annapolis. There, at least 11 fires have made substantial attacks on the gypsum sheathing, but in no case was the sheath penetrated. (An aluminum soffit permitted an "end around" extension.)

Up to this point the author has, artfully he supposes, led the reader to believe that there is such a concept as a continuous fire resistive sheath protecting the combustible structure from a fire in the contents. In fact, there is apparently no such conception on the part of those who build, regulate, supply materials or test. The building is simply never looked at as a whole. This is another example of component testing as opposed to systems safety.

While the chief problem appears to be the failure of continuity of what could be an adequate protective sheath, there are some other areas of design construction and layout features which contribute to the extension of a typical confinable fire, to a building conflagration (see fig. 2).

Design No. L506
(Formerly Design No. 1—45 Min.)
Unrestrained Rating—3/4 Hr. Combustible
Finish Rating—See Item 6.



1. Finish Flooring—1 by 4 in. T&G: laid perpendicular to joists, or 5/8-in. plywood, minimum grade "underlayment," with T&G long edges, and conforming with PS 1-66. Face grain of plywood to be perpendicular to joists with joints staggered.
2. Building Paper—Commercial rosin-sized, 0.010 in. thick.
3. Subflooring—1 by 6 in. T&G, fastened diagonally to joists, or 1/2-in. plywood, minimum grade "standard," with exterior glue, and conforming with PS 1-66. Face grain of plywood to be perpendicular to joists with joints staggered.
4. Cross-Bridging—1 by 3 in.
5. Wood Joists—2 by 10 in., spaced 16 in. O.C. firestopped.
6. Wallboard, Gypsum*—1/2 in. thick. Sheets of wallboard installed with long dimension perpendicular to joists and fastened to each joist with 1 5/8 in. long 5d, cement-coated nails spaced 6 in. O.C.
   Big Horn Gypsum Co.—Type A (finish rating 18 min), Type B (finish rating 20 min) or Type C (finish rating 15 min).
   Flintkote Co.—Type III (finish rating 20 min).
   Republic Housing Corp.—Type RG-1 (finish rating 15 min) or RG-3 (finish rating 20 min).
7. Finishing System—Fiber tape embedded in compound over joints and exposed nail heads covered with compound, with edges of compound feathered out. As an alternate, nominal 3/32 in. thick gypsum veneer plaster may be applied to the entire surface of Classified veneer baseboard. Joint reinforced.

*Bearing U.L.I. Classification Marking.

Figure 1. Design L 506 P 265 Underwriters' Laboratories Fire Resistance Index, Jan. 1973. "The firestopped 2" x 10" joists, the spacing and setting of nails and the taping of joints are all essential elements of the rating achieved by the floor and ceiling assembly. It appears that in the field, the gypsum board is considered to be the essence of the fire resistance rating, and the other equally important elements are ignored."

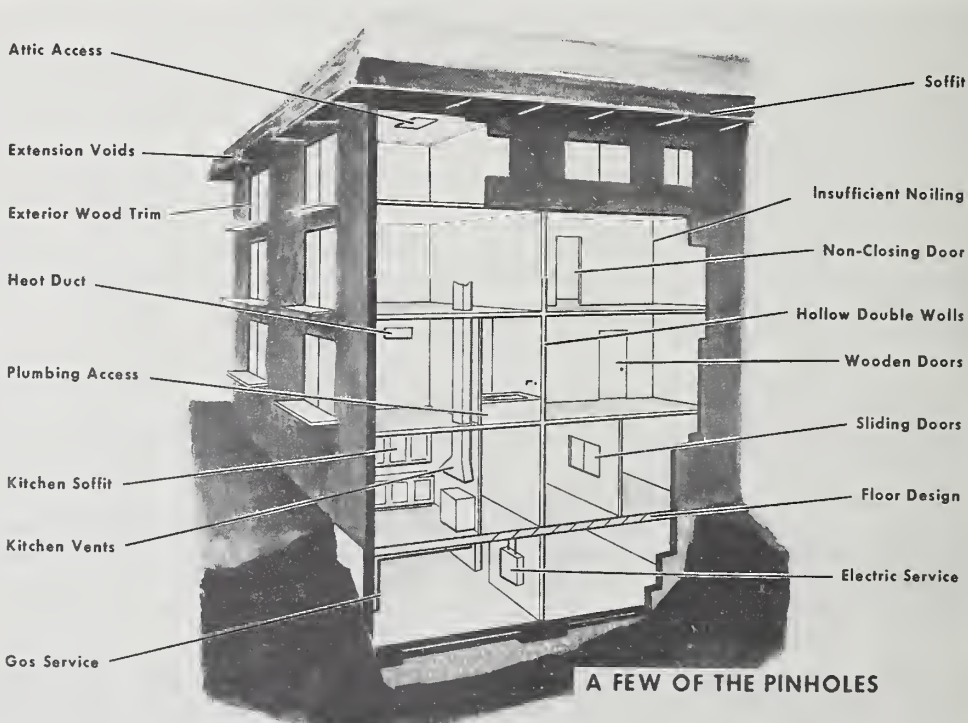


Figure 2. Sketch of garden apartment house showing all pinholes in the sheathing. "Any lack of continuity in the sheathing permits fire to enter the interior voids of the building where it can spread unchecked." (Courtesy of Montgomery College, Learning Resources)

The various modes of failure are interrelated, but it is possible to break down the discussion into a few headings for convenience.

1. Ways in which fire penetrates the gypsum sheath and enters the inner structure of the building.

2. Fire spreading substantially in combustible voids, within the inner structure of the building, usually interconnected with the huge combustible void of the attic.

3. Fire extension through or around fire walls and barriers between buildings.

While loss of life was not very common in the fires studied, a few observations of life safety, both of occupants and firefighters are warranted.

4. FIRE PENETRATION MODES

1. Inadequate *nailing*, particularly of ceilings is common. At times, entire 4' x 8' panels of gypsum board fell early in the fire, before the board should have failed by fire exposure. Examination showed that nailing was short, as little as 12 inches on centers versus the 6 inches usually required.

2. The only U.L. listed standard for floor and ceiling assemblies using trusses rather than joists, requires two 1/2 inch layers of gypsum board. Ceilings nailed to gusset plate trusses are nailed only on the 24 inch spacing of the trusses rather than 16 inch spacing. Single layer 1/2 inch or 5/8 inch ceiling constructions permitted under trussed roofs appear to be unwarranted extrapolations from the tested constructions.

3. Gypsum board was found of less than the required *thickness*, 3/8 inch in some cases.

4. *Two* (gypsum board) *layer* construction in which the underlayer was made up of incomplete "scraps" with large areas uncovered, was noted.

5. *Plywood* panels are used to cover openings. The commonest example is the omnipresent wooden panel which gives access to the bathtub plumbing. Many access panels to attics are of plywood. Most of the buildings involved were heated by hot air heat. In one case hot or chilled water was delivered to convectors. One convector in an interior wall between two bedrooms served the two rooms. A 3' x 4' plywood panel gave access to the convector for maintenance. A typical "child set" fire in the bedroom entered the wall space through the plywood, extended upward through the walls along the water pipe openings to the next floor level, broke through the corresponding plywood panel. The extended fire did more damage to the upper apartment, than to the apartment of origin.

6. An attractive *pass through* between the kitchen and dining area could be closed off by sliding louvered doors. The doors slid back into a space provided by doubling the wall, much like old fashioned sliding doors. The fire entered the wall space through the opening, and extended to other apartments by interconnected voids. A picture taken at the time the fire department was "turning out" shows that the smoke was already coming from two other apartments.

7. In a number of cases fire penetrated the drywall sheath around hot air heat register openings, and light fixtures.

8. Penetrations were noted around door frames.

9. The basement areas of garden apartments are used for utility meter rooms, rubbish rooms, coin laundry rooms, and storage rooms. The typical storage room has a series of wire cages, one per tenant, individually locked.

The storage area particularly can represent a substantial fire load. These areas are arranged to be usually locked with a key provided to each tenant, but are often found open. They are a common point of origin of incendiary fires.

10. Because of many utility openings, the integrity of the gypsum sheath on the basement ceiling is particularly dubious.

11. Utility meters are commonly grouped for convenience. In one case the gypsum ceiling was cut short 2 inches from the wall. The gap was made up by a piece of wood 1" x 2". The electric cables passed upward through holes drilled in the wood. The fire extended upward by burning out the wood.

12. The difficulty of fitting gypsum around the gas pipes caused the area around the gas meters to be left unprotected. The fire extended upward through the unprotected area.

13. Oversized holes for plumbing pipes, or unclosed openings in the ceiling for repairs also permitted extension.

14. Fire came into a building following the main electrical service. The fire department sized the fire up as an electrical fire. Following cables, which went up through an opening in the ceiling, the fire extended upward through the building and involved a dozen or more apartments.

15. Access plates are sometimes provided in basement ceilings for access to plumbing. In one incendiary fire it was believed that an access plate had been deliberately opened to permit extension of the fire.

16. The built-in metal bathtub "substitutes" for the drywall sheath. In one fire, studied before this investigation, it was evident that fire extended into the apartment from the wall by conduction through the bathtub. At least one building code requires that drywall be complete behind a *plastic* bathtub, but I have not seen sheathing behind a steel or cast iron tub.

17. A wooden floor joist with plywood nailed on top and gypsum nailed on the bottom (the ceiling) serves as a stop to the spread of fire at right angles to the joist. In earlier construction practices, a double joist was placed under each partition wall to carry the weight of the plaster. This practice is not necessarily followed in current construction. Floor joists are laid on 16 inch centers and the partitions of the floor above are laid out as directed by the architect. As a result a partition wall between apartments may rest on the plywood floor, *between two joists*. In two cases a fire starting in one apartment close to the partition wall burned down through the floor to the joist void, which was common to the next apartment.[1] The fire then burned up into the next apartment. In one case this was how the fire was discovered.

18. Plywood surfaces are installed for decorative effect. Often the plywood is the *only* wall sheath, and thus, the void space is quickly penetrated. Walls of hardboard decorated to look like plywood have also been noted.

19. More expensive detailing does not necessarily produce greater fire safety. In low cost work the walls are finished and then kitchen cabinets are hung on the wall. In more costly work, *soffits* are built down from the ceiling

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[1]The entire testing concept of "fire-resistive combustible" floor and ceiling assemblies is open to question. The test fire attack is made only against the gypsum board ceiling. No assemblies are tested by a fire attacking the wooden floor. Fires in fact burn downward through floors quite readily. Those constructions which provide huge voids under the floor, such as trussed floors, provide a potential for disaster when the floor is penetrated from above.

Figure 3. Kitchen cabinets. These "built-in" cabinets are attractive in appearance, but the only barrier between a kitchen fire and the inner voids of the building may be 1/8 inch of hardboard forming the top of the cabinet.

line. Gypsum board is applied to the ceiling and the vertical surface of the soffit. The bottom of the soffit is left open. The cabinets are then installed. The only barrier between a kitchen fire and the void spaces is the thin top of the kitchen cabinet, often 1/8 inch hardboard (see fig. 3). The determining factor in the confinement of a kitchen fire to the kitchen is often, whether the cabinet doors are open or closed. Where kitchens are back-to-back these soffits are common voids. Soffits are also provided to conceal heat ducts. Along interior apartment partition walls they are often back-to-back creating another void common to two or more apartments. These voids are often interconnected to vertical voids discussed further on.

20. Fire extended through the narrow vertical void formed by gypsum board furred out from a masonry wall on 1" x 2' strips.

21. While no fire extension has been noted, some apartments are built with "sunken living rooms". The offset between the rest of the apartment floor and the living room floor is covered by a vertical board nailed in place. It appears likely that this would pass fire sooner than a floor all in one plane. There is no listed construction of this type.

5. ATTIC AND OTHER CONCEALED VOIDS

1. In a few cases nominally flat roofs are used. Even such a roof has interconnected void spaces because a pitch must be provided to run the rain off the roof. The difference between the pitched roof and the horizontal ceiling joists creates openings so that the roof joists do not serve as fire stops. In one case there was no void (see fig. 4). The roof was of plank on beam construction and the interior followed the room pitch. It did not fail structurally, but fire charred the entire surface, possibly due to the use of a high flame spread finish.

2. The usual attic is a high pitched gable roof, of sheet plywood on lightweight gusset plate trusses. When the attic is involved the fire is spectacular (fig. 5), and often is stopped only by a true fire wall or by the end of the building.

The attics are provided only for heat relief, architectural effect and sometimes utility services. They are not used for storage. Access is usually by a scuttle hole in the top floor stairway ceiling.

Fire can reach the attic in several ways.

Figure 4. Penetration of the attic void permits fire to attack the top floor ceiling from the upper side - note the burning on the bottom chords of the roof trusses. Water required to extinguish the fire causes the ceiling to drop. Water damage down through the building is often severe.

Figure 5. A typical garden apartment fire. The combustible attic makes a spectacular show, for the passerby, but not for the many families victimized by incompetent design.

Requirements for attic ventilation are often met by the provision of a screened opening along the soffit under the roof overhang. In one fire, a top floor tenant returned home late at night, started cooking, fell asleep, and awoke to find the kitchen in flames and the apartment filling with smoke. He opened the balcony door (this probably saved his and his father's life). This gave the fire immediate access to the attic as flames rolling out of the living room engulfed the vent. Other tenants fleeing the building found pieces of the roof falling on their heads as they came out of the stairway.

3. Little attention is given to fire resistance of the roof overhang soffit. Soffits are constructed variously of plywood, hardboard, and aluminum. Flame pouring out a top floor window or balcony doorway, and even from the floor below the top floor, have attacked and penetrated such materials with ease.

Balcony overhangs are a particular problem. In the case of reentrant balconies, there are varying practices. Wire lath and plaster, with the customary nullifying attic ventilator has been noted. In some cases gypsum board painted with a moisture resistant has been used. In most cases plywood or hardboard is used. Most jurisdictions have laws against the use of charcoal grills on balconies, as much for the protection of those passing below as a fire protection measure. The enforcement of the law is usually in response to complaints, and the transgressor righteously points to the caution on the charcoal bag that it not be burned indoors. In one fire the top floor tenant apparently accelerated his fire with gasoline and then went in to prepare the food. On arrival the fire department found a full blown attic fire which burned off the entire attic. Necessary water damage made the lower floor apartments uninhabitable.

In another case children playing with matches and charcoal lighter fluid on a top floor balcony started a fire which entered the attic via a plywood soffit with ventilation opening. The attic was fully involved on arrival of the fire department.

4. "Noise Pollution" is not a new complaint. Over half a century ago the double wall to prevent noise transmission between apartments was developed. This is an arrangement of a double row of studs; alternate studs are offset so that the separate wall surfaces do not share the same stud. Earlier, sea grass was inserted for a sound deadener. Currently, mineral wool or glass fiber is used. This arrangement, of course, negates the "fire stopping" which is an integral part of the "rated" dry wall-wood stud construction.

At the top floor ceiling, the channel between the two stud walls is open to the attic. Fire in the void space extends into the attic.

5. Earlier in the paper we noted the use of vertical channels for plumbing piping; these often serve the purpose of double walls for soundproofing.

When kitchens are installed in the interior of the building, vertical exhaust ducts are provided leading to the roof. The voids for these ducts are often interconnected with soffits above the kitchen cabinets, and soffits around heat ducts so that there is a truly huge amount of interconnected void space, all of which is connected to that big overall void, the attic.

6. When extension of fire through vertical voids is considered by fire departments, it appears that attention is devoted almost exclusively to the very evident potential for *upward* extension. In fact, in addition to the traditional "conduction-convection-radiation"[1] methods of fire extension, fires often extend by flaming material, moving upward, downward, or laterally.

[1]These are more accurately the methods of heat transfer, not the mechanism of fire spread.

An electrical defect started a fire within such a void between two first floor apartments. Flaming material fell out onto an upholstered chair in the basement. First arriving volunteer fire units assumed that the chair fire was the full extent of the problem; additional responding units were returned to quarters by radio, and it was necessary to recall them when fire was detected coming from the attic.

6. FIRE WALLS

The use of masonry walls to limit the spread of fire is as old as the republic. The first building code of the City of Washington, signed by President Washington, required that the outer walls of all buildings be built of brick or stone. "Trade-offs" were not unknown even then; the wall was directed to be a "party wall"[1] and the second person sharing the use of the wall was required to reimberse the original builder of the wall.

Fire walls or barriers are intended to provide a physical limit to the area involved in a fire.

The ideal fire wall is free standing masonry wall, parapetted through the roof, projecting through the exterior wall, or tightly joined to an exterior masonry wall which is unpierced for a distance of several feet on either side of the fire wall. Such a wall should be capable of stopping the extension of fire independent of the operations of the fire department.

The following deficiencies have been noted. For most of them specific examples of fire extension are contained in the reports.

1. Fire wall used as bearing wall. Main wooden girders of adjacent townhouse were lodged in common wall sockets. In one case these were photographed before a fire had occurred. When a fire occurred over 20 units were destroyed. A perhaps apocryphal story quotes an official of the construction company as saying, "Those fire walls were terrific; they were the only thing left standing" (see fig. 6).

2. Fire walls complete only to the underside of the roof. There is rarely a "meeting of the minds" between the masons and the carpenters as to where the underside of the roof will be. The gap has been seen to be as much as four inches. Given the basic gas relationship of Temperature, Volume and Pressure, it is obvious that pressurized heated gases will pour through this void, but few building inspectors or tradesmen are familiar with elementary chemistry.

3. Lewis Mumford called the Mansard the "crowning indignity of the seventies", and that was a hundred years ago. The Mansard provides a fire path around the end of the fire wall, unless a cantilevered beam supports a masonry extension of the wall.

4. Where officials are stern supporters of fire wall integrity, utilities are installed in trenches parallel to the buildings and each building is served by laterals. At times the easier method of running the utilities through the fire walls is permitted, thus, providing a hidden fire extension path. In one case the gas main passes through the attics and service is dropped down into the apartments. The fire walls in this case extend only to the top floor ceiling. The attics are overlapping truncated wooden pyramids, and the opening around the gas main provides a fire path from attic to attic.

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[1]See Brannigan, "Building Construction...", p. 119, for a discussion of the fire deficiencies of the party walls.

Figure 6. The firewalls were all that was left.

5. This matter of fire walls extending just to the top floor ceiling line has a history. As "New Law" apartment houses of larger size were being built in New York during the 30's, the limitation of building area was maintained. Larger buildings were created by joining together two or more units with a common ground floor lobby. The concept of life safety was paramount and thus, it was felt necessary to extend the fire walls only to the top floor ceiling. In several disastrous fires, fire spread through the common "cockloft" (shallow attic). Eventually fire walls were required to be parapetted.

6. In some cases one common facility such as the laundry may be under one unit, while the storage rooms may be under the next. To provide all weather access, swinging fire doors are provided in the fire wall between units. These are almost invariably found propped open. While no fire extension was noted due to this defect, in one case smoke in dangerous quantities filled the stairway of the next unit. The occupants were rescued from balconies. In hindsight this risky operation was unnecessary but it is difficult to explain this fact to a panicky citizen threatening to jump.

7. Soffit roof overhangs are constructed beyond fire walls, thus providing a fire path out of access of hose streams and out of sight.

8. Fire barriers in attics are often constructed of gypsum on studs. Defects include failure to construct barrier in the overhang, failure to fit tightly to the roof, failure to tape and set nails, and openings cut by maintenance personnel for passage from unit to unit. In one case the inadequate fire stop did serve to *hinder* the extension of the fire, but the fire did extend to the roof over the adjacent units on each side. Necessary water use and the partial damage to the roof made 12 apartments uninhabitable in addition to the 6 directly affected by the fire.

9. In rolling terrain the roof line of the lower unit may be several feet below the top of the masonry wall of the next and higher unit. The fascia board on the sloping edges of the higher roof has been ignited by fire coming through the lower roof.

10. One Florida condominium could have been an excellent building, but there were two weaknesses. The building was of concrete block construction, the floors were of reinforced concrete, and the units were separated by block walls, to the top floor ceiling. Unfortunately, the attic fire stops were of gypsum applied to the sides of the trusses, where they *happened* to be located. Thus, the fire stop did not continue the vertical plane of the fire wall between units. No matter, the fire barriers extend only to the building line, and do not penetrate the overhanging void.

7. EXTERIOR EXTENSION

Combustible balconies figured in several vertical fire extensions. Combustible separators between two adjacent apartments sharing the same balcony have also provided an extension path.

1. Plastic shutters burned and extended fire downward to shutters below.

2. Wooden paneling in the spandrel space between windows permitted extension to the floor above.

3. Fire lapping out the window passed a masonry spandrel and entered the floor above. As noted elsewhere fire lapping out of second floor window bypassed the third floor and entered the attic via the soffit vent.

4. In one case a concrete balcony was credited by the fire department with preventing extension to the floor above of a particularly severe fire.

5. In one group of apartments, second floor windows project beyond the first floor. The underside of the projection is plywood. A first floor fire, rolling out the windows will probably soon enter the second floor through the plywood.[1]

In one group of wood frame apartments the sheathing is of gypsum. This is defeated, however, by huge two story "dormers" which create a monstrous unfirestopped, inaccessible, combustible void on the exterior of the building.[1]

For some unaccountable reason, codes often require true fire walls between separately *owned* row units, but permit common attics over similar "townhouse" units (apartment with rooms on two floors) being *rented*. The conversion of rental to condominium units has required building alterations to provide fire separation between units.

In one case related to the writer, a selective insurer refused to write contents insurance for a tenant of a garden apartment due to lack of fire walls.

A local fire marshal was examining the housing authority's plan for "townhouses". The fire separations conformed to the code for rental housing. He convinced them to install fire walls between each dwelling by arguing that at some future date they might want to sell them to the occupants.

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[1]Both of these were noted outside the area in which the fire investigations were made. This author is not aware as yet of any fires in which these designs are a factor.

Permitted distances between separations are usually stated in square feet, not in number of dwelling units. It is up to the ingenuity of the designer to see how many units he can cram into one fire subdivision. This is a menace to all in the area, and in some cases a loss of "livability", if not direct fire damage to all units, is an almost predictable result of any fire which involves so much as one room. If this situation is to remain unchanged, perhaps the victims of official neglect should at least be warned.

8. LIFE SAFETY AND FIREFIGHTING

1. Only a few fatalities occurred in the fires investigated and none could be directly attributed to any building defect; however, there were some injuries and "near misses".

2. Non self-closing doors permitted smoke or fire to escape into the stairway from the apartment of origin. This often forces other occupants to the refuge of the balconies. Rescue efforts slow down the control of the fire, and ladder rescues are always hazardous.

3. Fire involving the attic can soon cause roof overhang structures to fall on persons escaping from the building.

4. While nominally three stories high, garden apartments are often four stories high on one side due to rolling ground. When this fourth floor is in the rear it is inaccessible to truck mounted aerial ladders. The raising of a 40 or 50 foot ground ladder requires the efforts of a well drilled crew of several men which has worked together. This is not often delivered early in a fire by volunteers, and paid departments often do not have enough men in ladder companies.

5. Complicated street layouts and cul-de-sacs may improve the livability of garden apartments, but if the first due fire unit commits itself to the wrong driveway, the building can be lost. Fire departments expend great effort to get maps of all projects and to drill drivers, but direction signs do not take fire problems into consideration, and building numbers follow no standard pattern.

6. A fire hydrant is a useless obstruction until a fire pumper hooks into it, but hydrant locations are rarely coordinated with firefighting procedures.

7. In a number of cases substantial quantities of smoke were distributed through hot air ducts and the void spaces around them.

8. Current design developments feature economy of material, often by substituting geometry for mass.

Gusset plate roof trusses are now commonplace. Standard firefighting procedures, based on the reserve strength in conventional wood rafters, often call for men to get onto a roof to open it to release pent up heat ("ventilation" in fire parlance). To the best of the writer's knowledge, no firefighter has been injured carrying out this practice on the fast to collapse, truss roofs. The usual reason assigned is that fire is "through the roof" on arrival.

Recently we have seen floors made of wooden gusset plate trusses (see fig. 7). These provide a common unfirestopped void over (and under) the entire area of four apartments on each floor. If, as is probable, the voids are interconnected by vertical voids, the entire building can be involved in fire very rapidly (see fig. 8). The possibility of early structural collapse cannot be discounted.

"I" beams rolled of steel develop their characteristic shape from the flanges provided to resist the maximum compression (found in the top) and tension (found in the bottom). Until recently, there was no wooden "I" beam. Now such

Figure 7. These trussed floors permit a combustible void over and under the four apartments on a floor. Vertical channels may interconnect the several voids. In such a structure it is possible to envision collapse not long after fire penetrates the void.

Figure 8. The combustible attic forms a vast horizontal flue.

beams are offered; 2" x 4" lumber forms the top and bottom flanges; the web is plywood. Such a beam may carry the same load as its sawn counterpart, but it appears self-evident that it could not make the same contribution to a fire resistive (combustible) assembly as a solid sawn beam.

9. Many gas meters are often located in one room for ease of reading. In one case the twenty or so lines leading to apartments were grouped together overhead in the passage between storage cages. They were supported by horizontal pipes attached to the joists by pipe strapping. The failure of one nail dropped all the pipes on advancing firefighters and caused a massive gas leak. A serious tragedy was narrowly missed.

10. In one fire extensive areas of brick veneer fell off during the fire. This falling masonry is hazardous both to escaping occupants and firefighters, even though the building is not impaired structurally.

9. CONCLUSIONS

A meeting of builders is hardly complete without a speaker who raises the shibboleth, "Buildings would cost far less if we didn't have those terrible *specification* codes. New *performance* codes would let us use imagination and technology." Here is a suggested "performance code":

> "A combustible multiple dwelling should be so designed and built that the "design basis fire" will be confined to the area of origin for 30 minutes."

The design basis fire would be a typical garden apartment fire based on a study of fire loads. Such a requirement would lead to the elimination of many penetrations of the protective gypsum sheath. Where openings are necessary, there would be a demand for listed devices to provide openings equivalent to the protective sheath in fire resistance. Sociologically, the requirement should have great appeal. Since each of us is entitled to do "his own thing" in his apartment, the *living conditions* of others are equally entitled to be protected (see fig. 9). To have the tenants barely escape alive is no longer an adequate design criterion.

What can be done to improve existing buildings to deliver the right to "livability" to their occupants?

Work should be done to determine whether a few strategically placed high temperature sprinklers, fed from readily available domestic water, could not create a steam condition within vertical and horizontal voids which would act to control the free movement of fire through these areas.

A lightweight field foamable gypsum would provide a ready means of fire stopping voids, after the installation of all utilities. No such material is known to exist.

Retroactive[1] legislation should require:

1. The installation of supervised automatic sprinklers fed from the domestic system in all laundry, storage, rubbish and similar rooms. Fire officials are unanimous as to their efficacy.

2. The equipping of all apartment doors with door closers.

3. Renailing of poorly nailed gypsum, particularly ceilings.

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[1] "Retroactive" safety legislation is not "ex post facto" legislation and is constitutional.

Figure 9. Xmas Tree. The tenants of this apartment lived 200 feet away from the apartment where the fire started. Should not the building "system" protect them from the other tenant? "Fire Prevention" will not help these innocent victims. Architectural awareness, adequate code requirements, and competent enforcement are required to assure the right to live in peace.

4. Elimination of all plywood not mounted on gypsum board.

5. Elimination or adequate firestopping of all voids common to more than one apartment.

6. Elimination of all exterior wood balconies, sheathing and soffits.

7. Painting of all combustible attics with fire retardant coating.

Greater efforts should be made to educate fire departments in the deficiencies of these buildings. Adequate education, leading to realistic prefire planning, should contribute to cutting off the extension of a fire closer to the origin.

Questioning of tenants discloses that probably less than half have personal property fire insurance. Such insurance is usually quite cheap, so there is little incentive to anyone to "sell" it. If the owner was required to provide a personal property insurance policy up to some limit for each tenant, the insurer would now be examining a much larger risk, and there might be some pressure from this quarter for improvement. This is not a foregone conclusion; without a doubt, the buildings are insured.

In summary, since most of our population must be housed in multiple dwellings, the constitutional right of a citizen to be secure in his apartment home must be extended to protect him from a fire caused by his neighbor exercising his "constitutional right to be careless".

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THE CURRENT STATUS OF FIRE DETECTION

George Sinnott
National Bureau of Standards, Washington, D.C.

The status of residential fire detection systems is presented in terms of the major problems encountered in their use. This includes a discussion of risk benefit considerations, false alarms, and the effectiveness of alarms. The impact of these considerations on acceptance standards for residential fire detection systems is pointed out.

Key words: Alarm communications; false alarms; fire alarms; fire detectors; risk benefit; smoke detectors; standards.

Common to much of what you have heard here today is the high expectation of the ability of technology to solve many social, human problems, even those created by contemporary technology itself. This is so much in us that we find ourselves surprised, for example, when what seemed like routine engineering problems years ago have yet to come to fruition. This is true not only of the so called "big" problems like breeder reactors or automated transportation systems but also of specialized ones like automatic fire detection. A number of articles and testimony before the National Commission on Fire Prevention and Control, and before Congress have described the potential benefits of modern fire detectors and have expressed disappointment that for some reason fire detectors have not become widely used. I want to describe here what might be called a "hangup analysis" of fire detection. That is, I want to explore the hangups, those untoward social and technological side effects, that have prevented the wide acceptance of residential fire detectors.

A good place to start is with an appraisal of the risks that one runs of fire at home. Of the 12,000 fire deaths in the United States each year, a little over half occur in homes. There are about 700,000 residential fires each year and since there are about 65,000,000 residences in the country this means that as an overall national average the mean time between fires per residence is about 100 years. This gives us the first hint of a problem. There are very few devices commonly used by man with a mean time between failure of more than 100 years. We must then face the situation of installing in our home (or requiring others to do so in theirs) devices that have a much larger chance of failing than of being useful, or else of creating devices of exceptional reliability by any standard. What's more, these exceptionally reliable devices, as we shall see later, must be exceptionally cheap.

The two ways of looking at the statistics, then, is perhaps the first hangup. At meetings like this we discuss the 6,000 lives lost and perhaps 10 times that many injuries and $874,000,000 direct financial loss each year. Fire is nevertheless a rare occurrence for any one family. The average family perhaps intuitively senses the 10,000 years mean time between fire caused death per residence or the annual average $14 financial loss per residence and relegates fire well down on its hierarchy of fears. However, three major model building codes in the country as well as the Department of Housing and Urban Development's minimum property standards do now or will soon require fire detectors in residences. How alarmed should a person be at this hazard? Are there rational implications as far as public policy is concerned? That is, is there a statesmanlike position somewhere between being cynical and hysterical? Some rather nice insights to this problem have been presented in recent years in several articles by Chauncey Starr. [1,2] The argument here is put in terms of the risk of fatalities even though injuries are certainly an important consideration. The problem with discussing injuries is that the severity of injuries is difficult to measure and the statistics are haphazard.

Natural disasters (floods, earthquakes, tornadoes, and storms -- "acts of God") cause 5 to 10 deaths per million population per year. Over the years, the human attitude has adjusted itself to this so that this tends to set a base level for noticeable risk. Man-made risks at this level can be considered almost negligible. On the other hand, fatalities due to disease are the major cause of man's mortality and a hazard of this magnitude appears to represent the level of a fearful risk. As indicated in figure 1, that is about one per hundred years on a population average. (There are 8,766 hours in a year or 114 years per million hours). Starr adduces evidence that on a per hour of exposure basis, society adjusts its activities in terms of risk and perceived benefits in a rather consistent manner and notices a factor of a thousand difference in the apparent level of acceptable risks between those activities that an individual voluntarily undertakes and those activities forced on him by the makeup of the economy, that is those activities undertaken collectively. The two levels of risk, disease, and natural disasters, are indicated by the dashed lines in figure 2. The two lines indicate Starr's conjecture on society's risk-benefit trade off levels for voluntary and involuntary activities. I will not go into his calculation of the benefits of the various indicated activities. [1,2]

With this point of view as background, then, let us look into the risk-benefit situation for fire detectors. It has become part of the folklore of fire protection that fire detectors could save about a third of the residential fire fatalities. This is based on some studies done more than 10 years ago. [3] This is probably a reasonable estimate, but it is complicated by some unfortunate correlations with senility, alcoholism, and other disabilities. For example, the Baltimore City Medical Examiner and the Johns Hopkins Applied Physics Laboratory in Howard County have some preliminary statistics based on detailed autopsies conducted on fire victims in that area that indicate that many of the victims had significant levels of blood alcohol. It is not easy to determine how much good fire alarms would do in many of these situations. Nevertheless, let us assume that fire detectors in every residence in the country would prevent 2,000 fatalities per year, which is to say that the risk of fire fatality would be lowered by about 2×10^{-9} per person per hour at home. Or in other words we can estimate one life will be saved per year for every 30,000 installed detector systems.

We can compare the added risks of not having a fire detector in a home to the benefit of not having to pay for such a detector. The only present voluntary standard for fire detection systems in homes is the National Fire Protection Association #74 which requires heat sensors throughout the house and a smoke detector in a central hall. A system meeting this standard is an expensive one often costing more than $1,000. Amortizing this, adding for maintenance and assuming each system protects three people you arrive at an annual cost of about $40 per person. On the other hand, a good single station smoke detector very well might give almost as much protection at an annual cost of $5 per person. Over on the left hand side of figure 2, in the region of small risks and costs, I have located fire detectors. The model codes and the Department of Housing and Urban Development are all going in the direction of single station detectors because of the low cost. Presumably sporting types such as hunters and skiers and even smokers would conclude that not having a single station smoke detector in the house is a foolish risk considering the small cost. A member of the Bureau staff is now chairman of this NFPA committee that maintains #74 and they will be looking into appropriate changes in that standard. I hope that I have made the point that the problem of benefit versus costs places severe restrictions on the proposals that one can entertain for new improved fire detection methods.

The cost of installation, however, is not the only cost that has to be considered for fire detection systems. There is also the question of false alarms, perhaps hangup number two. Good statistical information on this is unavailable. As an example of field experience, however, tables 1 and 2 present some data compiled in England. [4] The general experience is that there are somewhat more than 10 false alarms per real fire. The English data are for

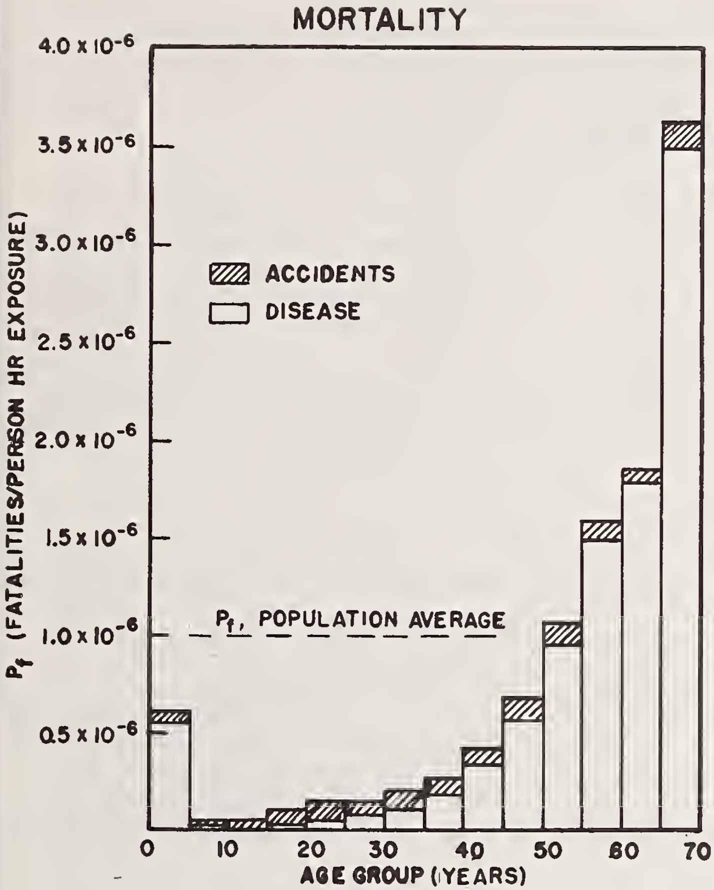

Figure 1. The overall mortality rate provides a reference against which particular hazards can be compared. For simplicity, in this paper, we refer only to the population average.

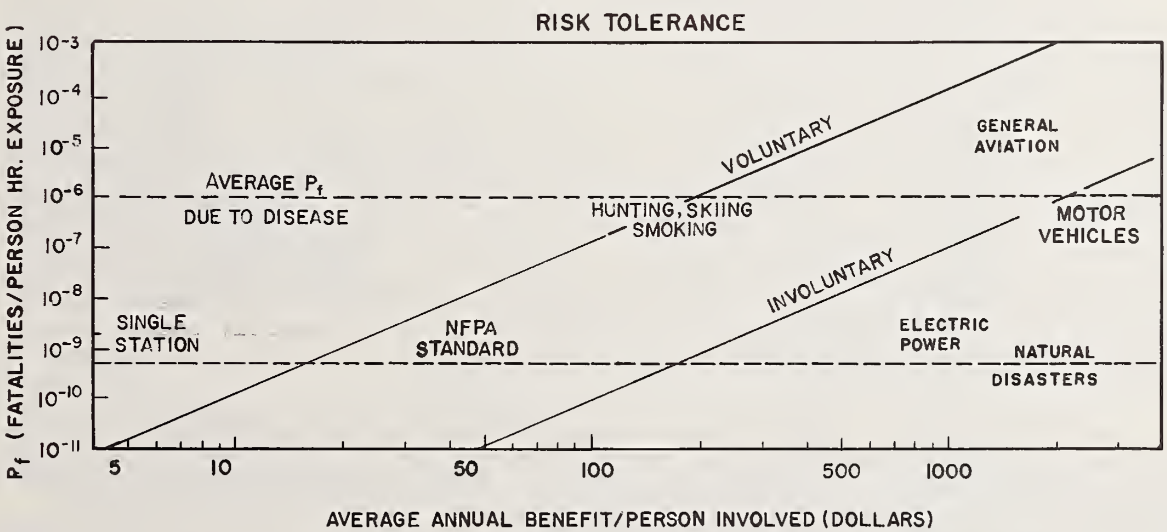

Figure 2. With the exception of fire detectors, this figure is taken from Starr [1]. The location of fire detectors on the graph indicates the lowered risk of fatality provided by fire detectors compared to their cost. The NFPA Standard #74-1972 does not allow for a range of trade-offs by the consumer. (This has been modified in the 1974 edition of the Standard.)

commercial systems and are not directly applicable to residential situations. The reasons for false alarms will be different in residential situations, however, our general experience is that there are a lot of them. This limits the application of fire detectors in homes to modes where the cost of responding to an alarm is very low. One handle that we have that can be used to improve detectors and their false alarm problems is standards.

Historically, fire detection has been associated with the melting of fusible links or other mechanical, temperature-sensing devices. Getting the required speed of response and sensitivity in these devices is a design problem and the standards that have evolved over the years have been primarily sensitivity standards. These standards have also been directed towards the free burning open fire that produces a lot of heat and develops rapidly. These fires are characteristic of some of the industrial and commerical hazards, but the pattern of loss in homes is quite different. Forty percent of residential fire casualties come from fires that start in bedding or mattresses or upholstery. [5] These fires are not the kinds of fires that we are accustomed to thinking about, but these represent the hazards that potentially might be reduced by detectors. These fires develop very slowly, giving off smoke and carbon monoxide but little heat. The detectors that are effective for this kind of fire are the electrically-operated, smoke detectors. These detectors can easily be made with virtually any sensitivity, limited only by their incidence of false alarms. Deciding on a figure of merit and an acceptance standard for this kind of detector requires the incorporation of the concept of signal to noise ratio into the standard. A research associate from Underwriter's Laboratories will be with us for the coming year to make use of our facilities and resources in the generation of performance standards relevant to these needs. It is a technical task of no mean proportions. There are two levels of trade off involved. First, there is sensitivity to fire versus false alarm rate. Then there is the false alarm rate versus effectiveness of response. That is, there are situations where it would be advantageous to have a less sensitive, slower responding detector in exchange for a more effective response such as alerting the entire apartment house or one's neighbors when it did alarm.

Smoke aerosols are very complicated, being a mixture of organic liquids and tars, carbon particles, water, etc. Undoubtedly, there are many subtle ways - composition, droplet structure, size distribution - by which the aerosol maintains some clues to its origins. At present there are two types of smoke sensors in common usage. One is the so called ionization type. It consists of a small ionization chamber where the air is kept weakly ionized by a radioactive source, usually on the order of a microcurie of americium 241 or radium 226. An electric field produced by two electrodes in the chamber induces a current on the order of a nanoampere which is monitored. The magnitude of this current is determined by the competition between collection of the ions by the electrodes and gas phase recombination. Diffusion of gaseous ions to the surface of any aerosol particles that are present alters this balance in favor of recombination and reduces the collected current. This type of detector has a sensitivity bias towards very small particles. On a per mass of aerosol basis, the sensitivity is proportional to one over the particle radius squared for particles of 100 Å diameter and up.

The other common type of smoke aerosol sensor is the optical type. This type sends a pencil beam of light into a chamber that is protected from stray light but where smoke is allowed to enter and detects the presence of aerosol particles via the scattered light. This type has a maximum sensitivity for particles whose diameter is of the order of the wavelength of light with decreasing sensitivity for larger or smaller particles. Further development of these devices as well as possibly the invention of new detection principles in the future, may well exploit some of the subtle characteristics of smoke aerosols to greatly improve the discrimination against false alarms by smoke detectors.

Table 1. Summary of Calls Received

Type of system	No. of calls to fires: By system installed	No. of calls to fires: By other means	No. of false calls	False calls per fire calls
All types	489	288	5,440	11.1
Heat	193	105	2,146	11.1
Smoke	101	37	1,429	14.1
Sprinkler	101	125	1,048	10.4
Manual	55	10	243	4.4
Mixed	18	6	137	7.6
Heat and smoke	18	2	410	22.8
Unspecified	3	3	27	9.0

Note: There was also one false call from gas detector equipment.

Table 2. Summary Table of Reasons For False Calls

Reasons for false calls	Totals (all types of equipment): No.	Totals (all types of equipment): Percent
Ambient conditions		
Extraneous heat and smoke	951	17.5
High ambient temperature	233	4.3
Condensation, snow, rain, etc.	153	2.8
Low ambient temperature	37	0.7
Steam, vapor	29	0.5
Draught, high wind	7	0.1
Total	1,410	25.9
Mechanical and electrical		
Defective wiring on control unit	602	11.1
Defective head	539	9.9
Surge in mains	411	7.6
Miscellaneous (e.g. broken pipe)	293	5.4
Direct impact on head	244	4.5
Vibration of system	215	4.0
Shock (e.g. falling weight)	151	2.8
Voltage drop, power cut	42	0.8
Defective push button, etc.	10	0.2
Total	2,507	46.1
Communication		
Testing, maintenance not notified	478	8.8
G.P.O. activity	335	6.2
Defect in connection to brigade	88	1.6
Total	901	16.6
Unspecified and unknown	623	11.5
Total (all reasons)	5,441	100

The last and in a way the most wide open problem is what should happen when the fire sensor senses a fire. It has a sort of an E.T.I.P. (Experimental Technology Incentives Program) kind of flavor in that it is a question of stimulating the invention of, the testing and evaluation of, and finally the implementation of suggestions for new modes of alarm. I think that this is a very important technical problem in fire detection.

As an example, consider a telecommunications aspect. It is widely recognized that it would be better to alert the fire department or the neighbors in addition to a potential victim near the fire rather than only having a local alarm. Many of these schemes require some kind of telephone communication. This normally now requires a leased telephone line which often is by far the most expensive part of the system. The cost of the leased telephone line, in fact, usually makes these schemes impractical. But dedicating a telephone line to this service is something like building a separate set of highways for exclusive fire truck use. It is much cheaper to pre-empt existing roads for emergency use with a siren. For telephone lines this would require the availability of a control function or what is known in the computer trade as an interrupt capability. What prevents this is not so much the technical problem but rather the absence of an economic or social pressure to advocate this provision in the telephone tariffs.

In summary then, there are three major points that must be kept in mind when attempting to make progress in the business of fire detection and alarms. One is the dilute nature of the hazard. This is a fact of life in the fire safety business that we must learn to live with gracefully. I present it not as a source of discouragement but as a challange to our cleverness. Lest we find ourselves tilting at windmills, action in this area must be based on a more thorough analysis of our fire loss experience.

The second is that the sensitivity or quickness of fire alarms is limited by our tolerance of false alarms. Improvements in this regard require either that we envision ways of being more tolerant of false alarms or that we develop detectors that produce fewer false alarms. In this latter category are those nice gadgeteering types of activity where we in the science-engineering fraternity feel so much at home.

The third is the observation that, as can easily be shown in the laboratory, ringing a bell does not in itself put out a fire. The effectiveness of an alarm must be viewed in terms of some series of actions, if any, that the alarm initiates. It is possible that effort spent on devising alarm systems that trigger more constructive responses to the emergency might be among the most promising opportunities that we have to make improvements in fire detection systems.

REFERENCES

[1] Starr, Chauncey, Social Benefit versus Technological Risk, Science, Vol. 165, 1,232 (1969).

[2] Perspectives on Benefit-Risk Decision Making, National Academy of Engineering (1972).

[3] McGuire, J. H. and Ruscoe, B. E., The Value of a Fire Detector in the Home, Fire Study #9 of the Division of Building Research, National Research Council, Ottawa, Canada (Dec. 1962).

[4] Fry, J. F., The Problem of False Alarms from Fire Detection Systems, Problems of Automatic Fire Detection, Institut fur Elektrische Hachrichtentechaik, Technischen Hoshschule, Aachen, Germany, Conference Proceedings, 37 (Oct. 1972).

[5] Pingree, Daniel, Material Ignited and Fire Casualties, Fire Journal, Vol. 65, No. 3, 8 (Mar. 1971).

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SEQUENCING THE PURCHASE AND RETIREMENT OF FIRE ENGINES

Patsy B. Saunders and Richard Ku
National Bureau of Standards, Washington, D.C.

A mathematical model and solution method are presented for the problem of determining an "optimum" manner of sequencing the purchase and retirement of fire engines. The method calculates that stream of "buy and retire" decisions which, subject to certain natural constraints (such as limits on annual acquisitions), minimizes the operating cost of the fleet of engines over a prescribed planning period. Implemented as an efficient computer program, the model has been applied to illustrative data from the Washington, D.C. Fire Department. The approach carries over to problems dealing with the replacement of other types of items (e.g., ambulances, small fleets of aircraft, typewriters) whose reliability-maintenance becomes increasingly expensive with age.

Key words: Dynamic programming; equipment replacement; fire engines.

1. INTRODUCTION

This paper describes a method to determine an "optimum" manner of sequencing the purchase and retirement of fire engines (hereafter simply called "engines"), with specific application to the Washington, D.C. Fire Department. The model developed, however, has more general applicability as regards both the equipment type and the fire department. Because of the apparent similarity of the present problem to conventional equipment replacement problems, we first will review briefly some of the ideas in the equipment replacement literature.

Equipment replacement problems have a long history in industrial engineering and operations research. The reader is referred to [1] for a comprehensive bibliography on this subject. One class of equipment replacement problems balances the cost of failures against the cost of planned replacements [2]. If units are to operate continuously over some time period [0, t] and are replaced upon failure, then typically the expected cost C(t) during [0, t] may be given by

$$C(t) = c_1 E[N_1(t)] + c_2 E[N_2(t)], \qquad (1)$$

where

c_1 = per unit total cost resulting from a failure and its replacement,

c_2 = per unit total cost of replacing a non-failed item ($c_2 < c_1$),

$N_1(t)$ = the number of failures in [0, t], a random variable,

$N_2(t)$ = the number of replacements of non-failed units, a random variable,

and E denotes expected value. The problem is to minimize eq (1) over the possible replacement procedures available within a given policy of replacement. Examples of replacement policies are: strictly periodic replacement, random periodic replacement and sequentially determined replacement. Electronic components typify the equipment to which this well developed mathematical theory applies.

A second class of equipment replacement problems, called "preparedness" problems, assumes that a piece of equipment is kept in a readiness state for use in case of emergency. The objective is to maintain the equipment in a state of operational readiness at minimal cost. Thus, a sequence of inspection and replacement actions that minimizes the ratio of expected cost per unit time to proportion of "good"[1] time, would constitute an "optimal" decision stream [1,3]. Large military hardware provides examples of the type of equipment to which this class of models may be applied.

One of the basic underlying concepts of the two classes of equipment replacement models discussed so far is that of a *reliability function*[2]. This is the probability R(t) that the equipment is "good" at time t (measured from a time at which the equipment is considered to be "new") and is exemplified by the negative exponential form

$$R(t) = \exp(-\lambda t). \tag{2}$$

A closely related concept is the failure rate, defined for any reliability function R(t) as $\rho(t) = -R'(t)/R(t)$, where the prime denotes the derivative. For the negative exponential, the failure rate is the constant λ.

A third class of equipment replacement problems deals with the replacement of items that deteriorate. Mathematical models to solve this class of problems typically trade off the increasing operational and maintenance costs (and decreasing resale value) of an aging item against the cost of a new purchase, i.e., the "optimal" replacement time is that time at which these opposing forces are equalized. Dreyfus [5] used a dynamic programming approach to solve this problem under the additional complication of technological change.

The main concern of this paper is the development of a model to determine purchase and retirement decisions over a planning period, subject to certain constraints, which would minimize the cost of operation of a fleet of engines during that period. The concern of the Washington, D.C. Fire Department was not with the cost of failure or the distribution of failures of fire engines *per se*, primarily because of the negligible number of engine failures and the inability to measure the "cost" of a single engine failure. The model developed may be regarded as an extension of the ideas represented by the third class of equipment replacement problems discussed above.

Section 2 describes a simple calculation, which serves to introduce the data at hand and compares the results of this calculation (as applied to Washington, D.C.) to those of a study [6] from which the data were obtained. A dynamic programming (DP) model is formulated and given illustrative application in section 3, and directions for further investigation are suggested in section 5. Section 4 lists formulas for computing upper and lower bounds on the variables of the dynamic programming model. For the derivation of these bounds, as well as for an integer programming analog to the DP model, the reader is referred to [7].

2. INITIAL CONSIDERATIONS

Aside from personal communications with members of the staff of the Washington, D.C. Fire Department, the main source of data was a report by Balcolm [6]. That report also proposes a model for determining the life-span of an engine, which will be described later.

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[1]It is implicitly assumed that the equipment is either in a "good" or a "failed" state.

[2]See [4] for a discussion of the statistical theory of reliability.

A linear relationship between engine age and maintenance cost was used in [6], and least-squares regressions yielded three sets of coefficients, corresponding to "high usage," "medium usage," and "low usage" engines. Balcolm then obtained a "composite" equation -- a weighted average (by the number of engines in the three categories) -- which this paper also uses. This equation is of the form:

$$u_a = U_0 + U_1 a, \tag{3}$$

where

a = engine age,

u_a = the maintenance cost of an engine entering its $\underline{a}^{th}$ year of service,

U_0 = 24.17,

U_1 = 122.46/year.[3]

Values of u_a are listed in table 1. This relationship was adopted as the basis of the data for maintenance cost since it was felt that a more complex function could not be supported by the observed cost figures.

Table 1. Data For the Dynamic Programming Model

a	Q_a	u_a*	v_{at}* t=1 (1971)	t=2 (1972)	t=3 (1973)	t=4 (1974)	t=5 (1975)
1	4	147	14,474	8,684	5,211	3,126	1,876
2	0	269	8,477	5,086	3,052	1,831	1,099
3	10	392	4,961	2,977	1,786	1,072	643
4	5	514	2,902	1,741	1,045	627	376
5	0	636	1,696	1,018	611	366	220
6	5	759	991	595	357	214	128
7	10	881	578	347	208	125	75
8	0	1,004	337	202	121	73	44
9	5	1,126	197	118	71	42	25
10	5	1,249	114	69	41	25	15
11	3	1,371	67	40	24	14	9
12	4	1,494	39	23	14	8	-
13	4	1,616	22	13	8	-	-
14	4	1,739	13	8	-	-	-
15	5	1,861	8	-	-	-	-

*Values have been rounded to the nearest dollar.

A linear relationship was also used in [6] for the purchase price of a new engine, given by

$$P_t = P_0 + P_1(t - 1900), \tag{4}$$

where

P_0 = -16258.18,

P_1 = 576.87.

[3]All monetary quantities are expressed in dollars.

Values of P_t are given in table 2. The choice of the "base" year 1900 is not explained, but it accounts for the surprising (negative) value of P_0. The index t refers to the year for which a value of the purchase price is desired.

Table 2. Purchase Price of a New Engine

t	P_t*
1 (1971)	24700
2 (1972)	25276
3 (1973)	25853
4 (1974)	26430
5 (1975)	27007

*Values have been rounded to the nearest dollar.

Using these data, simple calculation can be made to determine an "optimum" life-span for a single engine. Assuming a zero salvage value (for simplicity)[4] and a constant purchase price P, the accumulated total cost of keeping an engine for n years is

$$TC(n) = \sum_{a=1}^{n} (U_0 + U_1 a) + P$$

$$= nU_0 + U_1 \sum_{a=1}^{n} a + P$$

$$= nU_0 + [n(n+1)/2]\, U_1 + P. \qquad (5)$$

Thus the *average* annual cost of keeping an engine for n years is

$$AC(n) = TC(n)/n$$

$$= U_0 + [(n+1)/2]\, U_1 + P/n. \qquad (6)$$

Clearly, the longer an engine is kept, the longer the time to amortize the price P, so that portion of the cost per year will decrease with n. However, the maintenance costs increase year by year. Thus, with the "optimum" life-span defined as that value of n which minimizes eq (6), the standard calculus technique of setting the derivative of (6) equal to zero and solving for n yields:

$$(d/dn)[AC(n)] = U_1/2 - P/n^2 = 0, \qquad (7)$$

whence

$$n = (2P/U_1)^{1/2}. \qquad (8)$$

Since $P > 0$ and $n > 0$, the second derivative $2P/n^3$ is positive so that the value of n given in eq (8) ensures a minimum value of eq (6). Figure 1 indicates contours of the optimum value of n in the (U_1, P)-plane.

[4] Constant salvage values (with respect to age) can be represented by subtracting them from U_0.

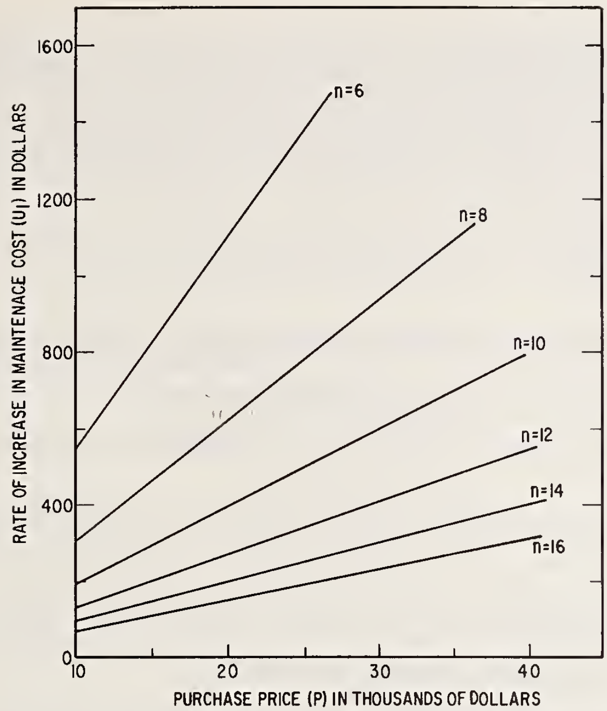

Figure 1. Contours of the optimum engine life.

For Washington, D.C., using the 1969 purchase price, eq (8) yields n = 19.6, considerably larger than the present life-span of 15 years. Balcolm [6] recommends a life-span of 10-11 years, depending on the number of years over which an engine is linearly depreciated, using as his criterion the equality of current (resale) value and accumulated repair cost, i.e., n is chosen so that

$$P - n(P - S)/N = \sum_{a=1}^{n} U_a,$$

where N is the number of years over which an engine is depreciated and S is the salvage value of an engine after N years. (Note that Balcolm assumes that the number of years over which an engine is depreciated (N) and the number of years it is kept (n) need not be the same.) No rationale for this criterion is offered in [6], but the large difference between the "optimum" life-span in [6] and the one derived from the present calculation [eq (8)] indicates a significant difference between the two models.

3. A DYNAMIC PROGRAMMING MODEL

The dynamic programming (DP) model described in this section takes a somewhat different approach to the problem of equipment replacement. Instead of determining an "optimum" life-span which would be applied to all engines, the DP model begins with the existing scenario and prescribes purchasing and retiring decisions over a T-year planning horizon. (The index t = 1,...,T is used in this model and appropriate notation changes are made in the relevant formulas presented in section 2.) In this sense, the model may be "tailored" to fit the initial state of affairs of any urban fire department. The reader interested in DP in general is referred to the text by Nemhauser [8]. For other DP formulations of equipment replacement problems, see [9] and [10].

In accordance with the concerns and objectives of the Washington, D.C. Fire Department, the DP model determines the purchases and retirements to be made during the planning horizon such that the total cost incurred during this period is minimized. The model accounts for various constraints with which a fire department must operate, e.g., constraints on the number of purchases and/or retirements which may be made in any year, the total fleet size and the maximum allowable engine age.

The DP "state variables" (those which describe the system at each stage, or year in this case) are

x_{1t} = the number of engines in the initial fleet which remain in year t-1,

x_{2t} = the number of new engines purchased in years 1,...,t-1,

x_{3t} = the maintenance cost in year t-1 on engines purchased in years 1,..., t-1.

(Note that $x_{1t} + x_{2t}$ is the fleet size in year t-1.) The "decision variables" are

d_{1t} = the number of engines retired from the initial fleet in year t,

d_{2t} = the number of engines purchased in year t.

It should be emphasized that retirements are made only from engines in the initial fleet, i.e., none of the engines purchased during the planning period are considered for retirement. Since the Washington, D.C. Fire Department indicated interest in a planning horizon of at most five to ten years, restriction to retiring engines from the initial fleet only is not considered a limitation.

The data required by the model are

D_t = the minimum number of engines required during year t (checked against the fleet size after year t's decisions have been made)[5],

M_t = the maximum number of engines which may be purchased in year t,

N_t = the maximum number of engines which may be retired in year t,

R = the age by which engines must be retired,

P_t = the purchase price of a new engine in year t,

Q_a = the number of a-year-old engines in the initial fleet,

$m = \sum_a Q_a$ = the initial fleet size,

u_a = the maintenance cost of an engine during its a^{th} year of service,

[5]That D_t adequately measures the demand for fire service is a simplification.

v_{at} = the resale value in year t of an engine which was initially of age $\underline{a}$,[6]

a_i = the age of the $\underline{i}^{th}$ youngest engine in the initial fleet (e.g., a_1 is the youngest).

As in the simple model of section 2, the maintenance costs are calculated as

$$u_a = U_0 + U_1 a,$$

with the values of U_0 and U_1, as indicated earlier. The linear relationship leads to a recursive definition of u_a,

$$\begin{aligned} u_{a+1} &= U_0 + U_1(a+1) \\ &= U_0 + U_1 a + U_1 \\ &= u_a + U_1. \end{aligned} \tag{9}$$

Letting $x_t = (x_{1t}, x_{2t}, x_{3t})$, eq (9) may be used to obtain, as the stage transformation formula,

$$x_{t+1} = (x_{1t} - d_{1t}, x_{2t} + d_{2t}, x_{3t} + u_1 d_{2t} + U_1 x_{2t}). \tag{10}$$

The transformation for x_{1t} and x_{2t} is clear. The value of $x_{3,t+1}$, the maintenance cost in year t on engines purchased in years 1,...,t, is obtained by adding to x_{3t} both the cost of the first year of maintenance for engines purchased *in* year t ($u_1 d_{2t}$) and the incremental increase in maintenance cost on engines purchased in the preceding years ($U_1 x_{2t}$), the latter deriving from eq (9).

The "stage return" is the cost of operation in year t. With the notation $d_t = (d_{1t}, d_{2t})$, the stage return is calculated as

$$I_t(x_t, d_t) = (P_t + u_1)d_{2t} + \sum_{i=1}^{x_{1t}-d_{1t}} u_{a_i+t} - \sum_{i=x_{1t}-d_{1t}+1}^{x_{1t}} v_{a_i t} + x_{3t} + U_1 x_{2t}.\text{[7]} \tag{11}$$

[6]The convention is adopted that an $\underline{a}$-year-old engine in the initial fleet enters its $(a+1)^{st}$ year of service at t=1. It is assumed, for simplicity, that decisions are made at the beginning of a year, and that $a \geq 1$.

[7]Whenever the lower limit of a summation exceeds the upper limit, the summation is taken to be zero. This is a standard notational convenience.

The components of eq (11) have the following interpretations:

$(P_t + u_1)d_{2t}$ = the cost of purchasing d_{2t} engines in year t and maintaining them during the first year of service,

$\sum_{i=1}^{x_{1t}-d_{1t}} U_{a_i+t}$ = the maintenance cost in year t on engines which remain from the initial fleet,

$\sum_{i=x_{1t}-d_{1t}+1}^{x_{1t}} V_{a_i+t}$ = the revenue from retiring the d_{1t} *oldest* engines not previously retired[8],

$x_{3t} + U_1 x_{2t}$ = the maintenance cost in year t on engines purchased in years 1,...,t-1.

The linear form of the maintenance cost yields the pleasing result that the values of x_{3t} are all exact multiples of U_1.[9] This, together with the fact that x_{1t} and x_{2t} are integers bounded by the constraints, makes it computationally feasible to consider *all* of the combinations of values that the state variables may assume in any stage. It follows that the optimal solution is *exact*, rather than involving the sort of discrete approximation typically found in DP problems. This characteristic is explicitly noted here as a favorable feature of the model.

The recursive equations of the DP model are

$$f_t(x_t) = \min_{d_t} [I_t(x_t,d_t) + f_{t+1}(x_{t+1})/(1+r)],$$
$$f_T(x_T) = \min_{d_T} I_T(x_T, d_T). \tag{12}$$

The quantity r is a discount rate, so that division by (1+r) in the first relation of eq (12) renders $f_t(x_t)$ as the minimum present value cost of operations from years t through T, given that the state of the system in year t is x_t. Since the initial state is known to be $x_1 = (m,0,0)$, $f_1(m,0,0)$ is the optimal value of the objective, i.e., the minimum total cost of operations in years 1,...,T.

The constraints of the DP model are straightforward from the definitions of the variables and parameters:

$$0 \leq d_{1t} \leq N_t \quad (t=1,...,T), \tag{13}$$

$$0 \leq d_{2t} \leq M_t \quad (t=1,...,T), \tag{14}$$

$$x_{1t} + x_{2t} \geq D_{t-1} \quad (t=2,...,T+1), \tag{15}$$

$$\sum_{j=1}^{t-1} d_{ij} \geq n_t \quad (t=2,...,T+1) \tag{16}$$

[8]This assumption of retiring "oldest first" is supported by the Washington, D.C. Fire Department.

[9]The proof of this can be found in [7].

where $n_t = \sum_{a>R-t+1} Q_a$ is the number of engines which *must* be retired *prior to* year t because of the age limitation R. Note that by definition the initial conditions are: $x_{11} = m$, $x_{21} = 0$, $x_{31} = 0$ and $n_1 = 0$. With the definition $D_0 = m$, eqs (15) and (16) automatically hold for $t = 1$.

The constraints (13) - (16) and the relationships among the state and decision variables lead to interesting and computationally useful results which are detailed in [7]. Section 4 lists the bounds derived from these relationships. Suffice it to say here that a special computer code,[10] developed as a part of this effort, takes advantage of these results to make it possible to solve larger problems than could be handled by a general purpose DP code. Furthermore, experience thus far has indicated that computer running times are significantly shorter using the special code. For example, one of the runs to be discussed below took 12 seconds using the special code, while the general purpose code[11] took 227 seconds. (Both codes are written in FORTRAN V and runs were made on the National Bureau of Standards' UNIVAC 1108 computer under the EXEC II Operating System.)

In exercising the DP model, the maintenance costs and purchase prices were the same as those discussed previously (cf., section 2). The purchase price function was modified to

$$P_t = P_0 + P_1(70 + t), \qquad (17)$$

so that $t = 1$ would correspond to 1971. The values of P_0 and P_1 are unaffected by the modification and remain as listed under eq (4). The resale values v_{at} were calculated on the basis of eq (17), assuming an annual depreciation rate ρ, using

$$v_{at} = (1 - \rho)^{a+t-1} [P_0 + P_1(70-a+1)]. \qquad (18)$$

This allows the resale values of engines in the initial fleet (purchased prior to $t = 1$) to be calculated from the appropriate purchase prices.[12] Finally, values of Q_a were obtained directly from the Washington, D.C. Fire Department's inventory of engines. These data are given in tables 1 and 2 with $T = 5$ (a five-year planning horizon).[13]

For the remaining data specifications, it was suggested by members of the Fire Department staff to take $R = 15$ (the present maximum engine age in Washington), $D_t = 64$ for $t = 0,\ldots,5$ (i.e., constant minimum required fleet size equal to the present fleet size), and $M_t = N_t = 6$ for $t = 1,\ldots,5$ (constant and equal purchase and retirement ceilings).

A base run was made with no discounting, i.e., $r = 0$, and the resultant "optimal" decisions were to purchase and retire 6 engines in each of the first three years and to purchase and retire 2 engines in year 4, i.e., $d_{1t} = d_{2t} = 6$ $(t=1,2,3)$, $d_{14} = d_{24} = 2$, $d_{15} = d_{25} = 0$. Note from the age distribution Q_a in

[10] A listing of this code can be found in [7].

[11] This code is an extension of the code documented in [11].

[12] A geometric depreciation is not required by the model. It is incorporated in the code, but can easily be modified with minor coding changes.

[13] Members of the Fire Department staff advised that a planning period of more than five years is unreasonable.

table 1 that 20 engines reach the mandatory retirement age by year 5 (i.e., $n_6 = 20$). Since the maximum number of retirements permissible is 6 in each year, the optimal policy is to retire the 20 engines *as soon as possible* (ASAP policy), replacing them with new engines to meet the minimum required fleet size.

The above results are not surprising in view of the discount rate $r = 0$. Increasing maintenance costs, decreasing salvage values and increasing purchase prices all indicate early retirement. The same policy is optimal in the extreme case where the purchase price is always zero. It is intuitively obvious that in this situation the ASAP policy is optimal regardless of the value of r, since the newly acquired (free) engines are operated at a lower maintenance cost than are the old ones.

In order to study the effect of the discount rate r on the optimal decisions, a series of runs was made with U_1 as a parameter, taken from 62.46 to 162.46 in increments of 10.00. (Recall that the "nominal" value of U_1 is 122.46.) Initially, r was varied from 0.0 to 0.5 in increments of 0.1 (a very rough grid), and based upon these results, smaller ranges with finer increments were studied for certain values of U_1. The following observations were made consistently from the outputs of all the runs:

1. The only engines retired were the 20 which reach their maximum age during the 5-year planning period.

2. In every year, the numbers of purchases and retirements were the same. This may be attributable to the constant demand and to the constant and equal values of M_t and N_t over all t.

3. For those values of r considered, there was a value r_E such that for $r \leq r_E$ the ASAP policy was optimal, and a value r_L such that for $r \geq r_L$ the optimal policy was to retire *as late as possible* (ALAP policy). (The ALAP policy has $d_{11} = d_{12} = 5$, $d_{1t} = d_{2t} = 4$ ($t=2,3,4$), $d_{15} = d_{25} = 3$ for this particular problem.)

4. The values of r_E, r_L and $r_L - r_E$ are monotonically increasing functions of U_1.

The values of U_1 for which the behavior of the optimal policy, as a function of r, was studied in greater detail are listed in table 3 together with the relevant results. All other values of U_1 considered gave rise to values of $r_E = 0.0$ and $r_L = 0.1$ in the initial runs. It can be seen from table 3 that the finest analysis with the smallest increments for r was made for the "nominal" value of $U_1 = 122.46$. For $.080 < r < .089$ the optimal decisions were "mixed", i.e., neither an ASAP nor an ALAP policy. For example, with $r = .085$, the optimal decisions were

$$d_{11} = d_{21} = 5, \qquad d_{12} = d_{22} = 6,$$

$$d_{13} = d_{23} = 6, \qquad d_{14} = d_{24} = 3,$$

$$d_{15} = d_{25} = 0.$$

The "critical" range of r (.080, .089) is quite small, but it should be noted that the values $M_t = N_t = 6$ do not permit a drastic difference between the ASAP policy and the ALAP policy.

Table 3. Results of Finer Variation of r For Certain Values of the Parameter U_1

U_1	Range of r	Increment	r_E	r_L
62.46	.01 - .10	.01	.05	.06
122.46	.08 - .09	.001	.080	.089
152.46	.01 - .20	.01	.09	.11
162.46	.01 - .20	.01	.10	.12

It is clear that if a value of r is specified, then the DP model may be run to determine the optimal policy. If r cannot be specified, then the values of r_E and r_L may be determined for the given value of U_1. Then one need only specify whether $r \leq r_E$ or $r \geq r_L$ to conclude that the ASAP policy or ALAP policy, respectively, is optimal.

One run was made with $M_t = N_t = 10$ for all t, with the other data remaining the same. With r = 0, the ASAP policy resulted; in this case $d_{11} = d_{21} = d_{12} = d_{22} = 10$, $d_{1t} = d_{2t} = 0$ (t=3,4,5). Unfortunately, lack of time prevented further study of this case. Intuitively, one might expect a greater "critical" range of r since the larger values of M_t and N_t give rise to a greater difference between the ASAP and the ALAP policies.

4. BOUNDS ON DP VARIABLES

Dynamic programming models are frequently subject to criticism because although the formulation can be accomplished, the numbers of states and decisions to be considered make the model computationally unfeasible. Fortunately, for the model described in this paper, there are relationships among the variables which make it possible to examine a limited number of states and decisions for which the stage return $I_t(x_t,d_t)$ is calculated. Although technical in nature, this aspect of the problem is of great importance to computational feasibility in the sense that computer storage requirements and running time depend on the number of states and decisions that the algorithm must consider.

This section will simply present the set of formulas to be used in calculating upper and lower bounds on both the state variables and the decision variables. The full derivations and explanations of these formulas are given in [7].

Before presenting the bounds, certain notational conventions should be explained. Notations of the form $\lambda(x_{1t})$ and $\mu(x_{1t})$ will denote the greatest lower bound (GLB) and least upper bound (LUB) of x_{1t}, respectively. Notations of the form $(x_{3t}; \hat{x}_{1t}, \hat{x}_{2t})$ will denote the GLB of x_{3t}, given specific values of x_{1t} and x_{2t}, namely $x_{1t} = \hat{x}_{1t}$ and $x_{2t} = \hat{x}_{2t}$. As in section 3, it is understood that whenever the lower limit of a summation exceeds the upper limit, the summation is taken to be zero. With these notational conventions in mind, table 4 lists all of the formulas needed to calculate the ranges of the variables used in the dynamic programming model.

Table 4. Formulas For Ranges of the Dynamic Programming Model Variables

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$$\lambda(x_{1t}) = \max \{0, \max_{1 \le \tau \le T+1} [D_{\tau-1} - \sum_{j=1}^{\tau-1} M_j - \sum_{j=\tau}^{t-1} N_j]\}$$

$$\mu(x_{1t}) = m - \max_{t \le \tau \le T+1} [n_\tau - \sum_{j=t}^{\tau-1} N_j]$$

$$\lambda(x_{2t}; \hat{x}_{1t}) = \max_{1 \le \tau \le T+1} \{D_{\tau-1} - \sum_{j=t}^{\tau-1} M_j - \min [\mu(x_{1\tau}), \hat{x}_{1t} + \sum_{j=\tau}^{t-1} N_j]\}$$

$$\mu(x_{2t}) = \sum_{j=1}^{t-1} M_j$$

$$\lambda(x_{3t}; \hat{x}_{1t}, \hat{x}_{2t}) = \sum_{\tau=1}^{t-1} U_{t-\tau} (\bar{x}_{2,\tau+1} - \bar{x}_{2\tau})$$

$$\bar{x}_{2\tau} = \max [x^*_{2\tau}, \hat{x}_{2t} - \sum_{j=\tau}^{t-1} M_j]$$

$$x^*_{2\tau} = \max_{1 \le \sigma \le t} [D_{\sigma-1} - x^*_{1\sigma} - \sum_{j=\tau}^{\sigma-1} M_j]$$

$$x^*_{1\sigma} = \min [\mu(x_{1\sigma}), \hat{x}_{1t} + \sum_{j=\sigma}^{t-1} N_j]$$

$$\mu(x_{3t}; \hat{x}_{1t}, \hat{x}_{2t}) = \sum_{\tau=1}^{t-1} U_{t-\tau} (\tilde{x}_{2,\tau+1} - \tilde{x}_{2\tau})$$

$$\tilde{x}_{2\tau} = \begin{cases} \sum_{j=1}^{\tau-1} M_j & \text{for } 1 \le \tau < \sigma \\ \hat{x}_{2t} & \text{for } \sigma \le \tau \le t \end{cases}$$

σ is the *largest* value of k such that $\hat{x}_{2t} > \sum_{j=1}^{k-1} M_j$.

$$\lambda(d_{1t}; \hat{x}_{1t}) = \max [0, \hat{x}_{1t} - \mu(x_{1,t+1})]$$

Table 4. (Cont'd)

$$\mu(d_{1t};\ \hat{x}_{1t},\ \hat{x}_{2t}) = \min\Big\{N_t,\ \hat{x}_{1t} - \lambda(x_{1,t+1}),\ x_{1t} + x_{2t} + M_t$$

$$- \max_{1 \le \tau \le T+1} [D_{\tau-1} - \sum_{j=t+1}^{\tau-1} M_j - \sum_{j=\tau}^{t} N_j]\Big\}$$

$$\lambda(d_{2t};\ \hat{x}_{1t},\ \hat{x}_{2t},\ \hat{d}_{1t}) = \max\ [0, \lambda(x_{2,t+1};\ \hat{x}_{1t} - \hat{d}_{1t}) - \hat{x}_{2t}]$$

$$\mu(d_{2t}) = M_t$$

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5. CONCLUDING COMMENTS

It should be emphasized that the DP model has considerably greater generality than was indicated in the limited application to Washington, D.C. The only model constraint on the data is that they be self-consistent (e.g., M_t and N_t must be consistent with D_t). If, for example, an urban fire department sees fit to reduce its fleet size because of overkill capacity or perhaps because of declining demand, and the values of M_t and N_t fluctuate because of a fluctuating budget, then a greater portion of the model's generality could be exploited. The interactions among the variables and parameters of the model which are evident in section 4 should support this contention.

On the other hand, time limitations prevented any attempts to examine the model with particular relationships among the parameters. It seems reasonable that certain conditions, e.g., $M_t = N_t$ = constant, or D_t = a constant for all t, could lead perhaps to closed-form optimal solutions, or at least might simplify the necessary DP calculations. Further research along these lines is recommended. In addition to these basic issues, there is a need for further sensitivity tests, with respect to the discount rate and the value of U_1, for other values of the parameters M_t, N_t, D_t and R. For instance, the optimal values of the objective $f_1(m, 0, 0)$ could be compared for different values of R (in some reasonable range of maximum ages), leading to an "optimal" value of R (i.e., one which minimizes $f_1(m, 0, 0)$). Finally, runs with depreciation rate ρ varying, or using a different (perhaps linear) depreciation policy, would be desirable.

6. REFERENCES

[1] McCall, J. J., Maintenance Policies for Stochastically Failing Equipment: A Survey, Management Science, Vol. 11, No. 5, pp. 493-524 (1965).

[2] Barlow, R. E. and Proschan, F., Planned Replacement, Studies in Applied Probability and Management Science, K. J. Arrow *et al* (eds.) pp. 63-87 (Stanford University Press, Stanford, Calif., 1962).

[3] Radner, R. and Jorgenson, D. W., Optimal Replacement and Inspection of Stochastically Failing Equipment, Studies in Applied Probability and Management Science, K. J. Arrow *et al* (eds.) pp. 184-206 (Stanford University Press, Stanford, Calif., 1962).

[4] Zelen, M. (ed.), Statistical Theory of Reliability (The University of Wisconsin Press, Madison, Wis., 1963).

[5] Dreyfus, S., A Generalized Equipment Replacement Study, JSIAM, Vol. 8, No. 3, pp. 425-435 (1960).

[6] Balcolm, R. D., A Systems Analysis for the District of Columbia Fire Department Dealing with the Replacement of Wagon Pumpers, report to the Washington, D.C. Fire Department (1970).

[7] Ku, R. and Saunders, P. B., Sequencing the Purchase and Retirement of Fire Engines, Nat. Bur. Stand. (U.S.), NBSIR 74-513 (to be published).

[8] Nemhauser, G. L., Introduction to Dynamic Programming (John Wiley & Sons, New York, 1967).

[9] Ackoff, R. L., Progress in Operations Research (John Wiley & Sons, New York, 1961).

[10] Britten, A. A., Decision Making in Vehicle Management, Report No. S.15, Local Government Operational Research Unit, Reading, England (1971).

[11] Bellmore, M., Howard, G. and Nemhauser, G. L., Dynamic Programming Computer Model 4, The Johns Hopkins University, Baltimore, Md. (1966).

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FIFI -- FIRE INFORMATION FIELD INVESTIGATION[1]

F. James Kauffman and Martin E. Grimes
National Fire Protection Association, Boston, Massachusetts

The Research Phase of FIFI defined and evaluated those state-of-the-art investigation techniques used at the scene of fires to report on the cause and circumstances of those fires. The two most significant conclusions reached during the research phase were (a) that very little literature is available to an officer interested in studying methods of general fire cause determination, since most existing literature is arson oriented, and (b) that standardized training programs in systematic investigative practices do not exist. The Development Phase of the project isolated the most valid of the investigative techniques evaluated in the research phase, and synthesized them into a new, simplified, logical, process-of-elimination investigation sequence known as HEP (Hexagonal Elimination Process) based on the NFPA Standard 901, Coding System For Fire Reporting. Two prototype training packages were developed; designed to aid firefighters in carrying out the systematic HEP investigation sequence in their initial, on-scene, routine fire investigations. The prototype training packages were field tested in six fire departments of varying sizes and types.

Key words: Field investigation; fire information; fire investigations; fire training; programmed instruction.

1. THE PROBLEM

The National Fire Protection Association (NFPA) has maintained and published statistics and information on fire and its effects for many years. The information received is used by NFPA's technical committees in the preparation and evaluation of codes and standards. It is made available to any organization engaged in fire research. However, it has been quite apparent that much of the information on fire received by NFPA from various sources is deficient due to lack of adequate field investigation and that the reports received frequently do not contain material pertinent to research needs.

Recognizing this, NFPA employs investigators and utilizes its specialists to make field investigations of special incidents. This must, of necessity, be limited. If a higher standard of reporting from primary sources were available, its usefulness would be reflected, not only in NFPA's operations, but also in providing a sound basis of data for all research workers in fire protection.

In order to make progress towards a uniform national reporting system and with the obvious need for basic information for research purposes, a greater emphasis on sound information gathering in the field is essential.

2. PRIME DEFICIENCY

Fire research requires an input of valid qualitative and quantitative data on fire behavior.

[1]This work was done under a contract with the National Bureau of Standards.

The information required must include such items as cause, propagation, development, growth periods, contributory acts or omissions, performance of materials, and other factors, in order to provide a meaningful basis for research and statistical analysis.

The validity of fire data depends on consistent accuracy and quality by the primary reporting source.

The Fire Service attends by far the majority of all fires occurring and, considering the large number of incidents, would seem to be the most practical and economical source of quantitative basic information. This does not preclude reporting from other sources as a supplement. There is a need for separate in-depth studies of incidents of special research interest and regional studies for sociological and demographical purposes.

Most fire departments complete reports on fires attended, usually for local record purposes. There is no uniformity and very few departments ascertain information reliable enough for research purposes. This is partly due to lack of demand on a local basis but is also due to the fact that fire department personnel have not been indoctrinated or oriented to the need for such information.

The high incidence of fire has placed fire departments under pressures which have resulted in undermanning and a need to reduce time spent at the scene of a fire. As a result, officers often make only a cursory investigation of the cause and effect.

Special investigators are called in when arson is suspected, but they generally concentrate on the criminal aspects of the incident. They rarely get involved with information necessary for research purposes. It is impractical for specialist officers, such as fire prevention staff who might be better able to report, to visit every fire.

There are several logical reasons why the fire departments should be the primary field collectors of fire information. The firefighter, present at an early stage of the fire, sees much of its development and spread. He, of necessity, removes or disturbs much that is relevant to determining the circumstances of the fire. The firefighter sees, but is not aware of, many indicators that might be research potential. The officer charged with the responsibility of completing the fire report could, if trained in a systematic approach and with the assistance of properly oriented fire crews, easily obtain meaningful basic information with a minimum of time expended.

Further, if special interest studies are to be carried out, it will be vital that prompt notification be given in order that specialist investigators of interdisciplinary teams can respond. Properly oriented fire personnel could, in effect, provide reconnaissance to alert such investigators of incidents of probable research value.

In general, little or no training is given to alert fire personnel to the methods and value of identifying and collecting such information. They are certainly not yet oriented as to what might constitute research potential. This is also probably true of other agencies involved in fire reporting.

3. RESEARCH PHASE

Four tasks were designated as necessary research activities prior to the development of an optimum investigation system and training course:

TASK A: Review the availability of technical, scientific and educational resources to support project.

TASK B: Survey current practices in training and methods for field collection and investigation.

TASK C: To determine required information (quantitative and qualitative) at each of the levels necessary.

TASK D: Identification of problems associated with current field investigative techniques and establishment of criteria to be used as a basis for development of systems.

3.1. Task A -- Information Sources

Task A was a review and compilation of information available to support the development of sound fire information field investigation practices. This involved a complete search of the literature, files, and records of NFPA; a survey of those educational institutions which offered fire service courses and degrees; and a survey of allied organizations such as the American Insurance Association, Factory Insurance Association and the Federal Aviation Administration, for reference materials and procedures that they use in fire investigation.

We also sought information suitable for the development of a systems approach to fire investigation and fire investigation training.

3.1.1. Literature

A comprehensive literature search yielded 103 candidate books, articles, and papers numbering approximately 4,000 pages. Of these, 65 were considered reflective of the state-of-the-art in fire and arson investigation and were selected for further evaluation in Task D.

All reference materials and existing literature were found to be extensively arson oriented, with determination of fire cause becoming critical only if it was suspected that the fire cause was something other than natural or accidental.

3.1.2. Educational Establishments

One hundred fifty-two (152) colleges and universities in the U. S. offer courses in fire investigation or fire related subjects. Details on the type of training offered by these institutions is contained in the final contract report[1].

3.1.3. Allied Organizations

Ten agencies or organizations are, or were at one time, engaged in fire investigation and fire cause determination. Examination of their methodologies yielded useful information.

3.2. Task B -- Survey of Current Practices

Task B surveyed existing practices in fire investigation and available training in methods of fire investigation. To accomplish this, a mail survey of 2,268 fire departments was conducted. The data received from the 1,401 fire departments who returned the survey form indicates that thorough investigations

[1] National Fire Protection Association, FIFI-Fire Information Field Investigation, Phase I, Final Report, July 1972.

were mainly conducted on those fires which were suspicious or involved fatalities or major dollar loss. It also showed that fire department line officers are generally responsible for conducting the initial investigation. Special investigators responded only if requested. Formal training in investigative procedures is conducted in very few departments. Those having training programs generally rely on the lecture method by an "experienced" fire investigator since printed texts and publications are not widely available except in the limited scope of arson determination. State Fire Marshal agencies are heavily relied upon for assistance when special investigators are required, but very seldom are outside specialists such as engineers, chemists, etc. utilized in fire cause determination.

In addition to contacting the individual fire departments, all 42 State Fire Marshal Offices were surveyed by mail. Fire Marshal survey tabulations indicate a heavy emphasis on arson or on those fires regarded as suspicious, those involving fatalities, or those constituting large monetary loss. Fire cause and damage determination appear to be the main objectives of such investigations. Details of fire spread and contributing acts are often a secondary concern of the investigation. Outside specialists are seldom used in state fire marshal investigation activities.

In an effort to summarize the existing formal training in fire cause determination, 191 universities, colleges, and State Fire Service Training organizations were contacted by mail. Investigation courses offered by the respondents to the survey were very limited in scope or fire investigation was given only as part of another course. Courses were generally taught by individuals who had fire service backgrounds but not necessarily educational backgrounds or experiences. The advent of the community college has increased the availability of formal education in fire science or fire protection technology. However, very few courses are offered exclusively in fire investigation and those that are offered are highly arson oriented. Reference materials for such courses generally consist of texts with supplementary material occasionally developed on a local basis.

In our surveys of fire departments and the other agencies or institutions, several procedures which appeared to warrant detailed study were brought to light. These procedures were found in the San Diego, California; Portland, Oregon; Houston and Dallas, Texas; and Ashtabula, Garfield and Shaker Heights, Ohio fire departments. Special field visits were made to these fire departments to gather on-site material and for personal evaluation of methods and procedures practiced by the fire department personnel. Summaries of these field trips and the information obtained are included in the final report.

3.3. Task C -- Evaluation of Existing Fire Information Collection Systems and Methods

In order to determine the scope and extent of information that any system developed in the project should provide, a study was made of existing fire information collection systems and other relevant factors.

Lack of uniformity and absence of a national reporting system presented a problem of considerable proportion. Currently, reports of fires are entirely a local prerogative, depending mainly on the decision of the individual fire department as to extent of detail and quality of information. In some states fire departments are required to submit reports to a state level agency -- in some cases a State Fire Marshal, in others, an Insurance Commissioner. The variations in required information for fire reports, when viewed nationally, are wide ranging.

Increased interest and recognition of the need for collection of fire information has led to the development of reporting systems utilizing automatic data processing and in most such systems NFPA Standard 901, Coding System for Fire Reporting, is used as a basis.

The design of a system and training package on field fire information collection which would be compatible with the multiplicity of systems and report forms currently in use appears to be an almost impossible task unless it is based on a number of elements common to most systems.

Examination of a number of systems and forms in use indicated that if the required information was based on elements contained in Standard 901, even if used in conjunction with other coding systems, there would be enough commonality to make the systems compatible. The descriptors in 901 were such that even if used narratively without any coding, as is the case presently in the majority of fire reports, they would be satisfactory. Additionally, it was felt that use of the descriptors of 901, either coded or narratively, would assist in standardization and generally improve fire reporting nationally.

In reviewing 901, it was obvious that additional information relating to actual firefighting operations and other similar factors pertinent to the suppression of a particular fire should be available. As the means for reporting such information were so varied and well within the capability of local determination and reporting, they were considered as options and were not included in this program. In this respect, the Uniform Fire Incident Reporting System (UFIRS), developed by NFPA under contract to the Department of Housing and Urban Development, is a system which is based on 901 with additional information of particular value for local use. This system could ultimately become the basis of a national fire reporting system.

The type of fire information required by other research, code making, insurance, and allied organizations was also considered to be necessary input for this project. The final report contains statements of the requirements and statistical research information considered desirable by these agencies. In most cases the information desired was not suitable for mass collection and quantification. Rather, it would lend itself more suitably to separate studies.

The Report Summary and Recommendation of a Committee Appointed to Study the Arson Problem in California (Appendix Q of the Final Report) is a good treatise on the establishment of a state-wide fire investigation team. The report shows the financial considerations and the problems encountered when trying to establish such a team on a state-wide basis -- notwithstanding the problems that could be encountered in establishing such a team on a national basis.

Another part of this task was to explore the feasibility of the Interdisciplinary Team concept for in-depth investigation of fires of special interest. Our research indicated that some of the preconceived theories regarding this concept might not be practical. Meetings with the sponsor of the project, the National Bureau of Standards in Washington, D.C., further confirmed that any nationwide network of such teams at this time would be premature and unworkable.

3.4. Task D -- Problem Identification and Establishment of System Criteria

The principal goal of this task was to establish criteria for developing a system to identify problems associated with current fire investigation techniques. An evaluation was made of all current techniques employed by fire departments in the recognition and preservation of evidence as well as general methods of investigation. These studies led to the development of the objectives for the FIFI training package.

3.4.1. Usefulness of Existing Literature on Fire Investigation

Generally, the existing texts and publications all place a heavy emphasis on the arson-oriented investigation. Techniques to determine accidental fire cause are given a relatively minor role in most of these publications.

3.4.2. Published Articles and Textbooks

Close to 400 published articles and texts are listed in the International Association of Arson Investigators bibliography of investigation resource materials. Those titles considered to be most appropriate for our task of teaching practical investigation procedures were weeded out and subjected to closer review by FIFI project workers who had practical experience in fire investigation.

3.4.3. Materials Produced In-house by Fire Departments

Of the 1,401 fire departments who returned our questionnaire, 127 indicated that they used or printed their own investigation manuals, and 85 departments said they would send us a copy. Only 21 departments, however, actually sent copies of their own in-house fire investigation training materials. It is felt that the number of departments who actually use their own or locally produced training materials is closer to the percentage reflected by the "21" figure.

3.4.4. Conclusions

1. The vast majority of the 1,401 U. S. fire departments who replied to our questionnaire stated that they do not use any of the published articles or textbooks as direct teaching material for their firefighters or investigators.

2. Of the relatively few departments which use a published text for teaching investigation, the same four or five titles seem to be cited.

3. At least 21 of the 1,401 departments replying to our survey felt so strongly about the need for some practical fire investigation instructional material that they packaged their own. Because much of the content of these locally produced training materials is taken from well established and authoritative arson investigation textbooks, it is obvious that these textbooks were perceived by fire departments as authoritative but impractical teaching devices. At the same time, however, in their desire for a more streamlined, practical approach to teaching investigation, it is evident that most of these 21 locally-produced, mimeographed handbooks have serious gaps in content since they reflect the specialized needs or interests which pervaded each department at the time of their booklet's birth.

In short, there are 4 or 5 popular, authoritative, knowledgeable, and complete textbooks on arson investigation. They are excellent for gaining perspective on the art and science of fire investigation, and they are excellent for reference purposes, but, they fail as an instructional tool.

A textbook, by its format, allows for little or no rehearsal or use of the information read and processed by the student. Reading the textbook or looking at pictures in the textbook bears little resemblance to required on-the-job performance or behavior. Merely reading about a procedure or technique does not quarantee that the student will be able to retrieve that information at the appropriate time on the job.

What is needed is a programmed approach to teaching fire investigation. By programming we mean certain learning units or learning experiences set into meaningful arrays in order to achieve stated objectives. Typically, it is a format which forces the student to interact with the material just learned in a manner very much like the way he will have to interact with the material on the job. This was the philosophy which governed the instructional design of the prototype training package we developed.

3.5. Conclusions of Research Phase

1. Most emphasis has in the past been placed on field fire investigation when cause and circumstances are suspicious.
2. Little specialized training has been given to the firefighter on the role he can play in fire investigation.
3. Line fire officers have generally not been trained or given guidance which will expedite their work in obtaining information for fire reports.
4. Motivation of the firefighters to observe and preserve the scene is an essential factor in fire information collection.
5. The process of elimination is the only satisfactory method to use in fire investigation.
6. The elements of cause and circumstances of fire incidents contained in NFPA Standard No. 901 provide a satisfactory descriptor basis even when used in a narrative form.
7. Little use is made of specialists (structural engineers, chemists, etc.) to support routine fire investigations.
8. Very few qualified persons are available to carry out fire investigations.
9. Persons with a knowledge of fire behavior are vital to investigation.
10. A national network of interdisciplinary fire investigation teams is not yet feasible.
11. There are wide variations in fire reporting when viewed nationally.
12. A national Uniform Fire Reporting System would materially improve the availability of data on fires; in addition, it would initiate a greater interest and quality in routine fire investigation.
13. Any improvement in routine fire investigation would enhance the detection of arson.

4. DEVELOPMENT PHASE

The next four tasks utilized the information gathered in the research phase of the project and were concerned with establishing an appropriate training methodology and the development of a working prototype training package. The development tasks were:

TASK E: Develop systems approach techniques for use in training firefighters and fire officers.

TASK F: Develop systems approach techniques for use in training interdisciplinary fire investigation teams.

TASK G: Develop learner-centered training program and job aids for firefighters and fire officers.

TASK H: Develop program and job aids for interdisciplinary team investigation seminars.

The objective of Tasks E and F was to establish group behavior characteristics (skill clusters, performance objectives) of the projected study body in simulated fire incident situations. These findings provided justification for the technical approach used in Tasks G and H.

4.1. Task E -- Training Techniques For Firefighters and Fire Officers

In this task, various approaches to training system development were evaluated and the most appropriate training system design chosen. One of the first efforts needed to accomplish this was to establish a step by step sequence of events and decision points typically encountered by people involved in a fire occurrence. When viewed as a total system, the flow of information from person to person and from the scene to a national data collection agency becomes a very vital link. The development of such a system approach also clearly establishes the interrelationships of the various tasks which must be developed and taught in a training package.

4.1.1. Methods of Fire Loss Determination

The one factor for which there are no established criteria at the present time, except in some isolated local instances, is determination of dollar fire loss. A survey of existing practices and a realization of the complexity of such a task, clearly indicates the necessity for a separate in-depth study. Present methods for determining dollar fire loss are quite varied, localized and generally unreliable.

4.2. Task F -- Training Techniques For Interdisciplinary Teams

Originally this task was to develop a systems approach to the fire investigation techniques for use at the C-level (Interdisciplinary Team). Some preliminary work was accomplished, but the decision to delay recommendations for establishment of the interdisciplinary teams deprived this task of practical significance.

4.3. Task G -- Learner-Centered Training Program

In essence, this task represents the central goal of the project: the development of a prototype learner-centered training program which will make fire cause determination an easier and more reliable task. Materials, guides and aids developed for the training program are briefly discussed in the following paragraphs.

4.3.1. Training Package Audience

In keeping with our earlier objectives as defined in Task D, the training programs were divided into two basic levels: the Basic Unit (Level A) for firefighters and the Officer's Unit (Level B) for fire officers. Both packages can be used for small groups as well as large group instruction -- although small group instruction, by its nature, affords greater instructor attention to individual student comprehension. The programs are designed to be administered by a fire officer acting as instructor. Field testing suggests that any fire officer, properly motivated, can perform adequately in the role of instructor, regardless of formal training. It is intended that all fire service personnel will participate in the Basic Unit (Level A) training program and that fire officers or other fire personnel responsible for completing fire reports and making fire cause determinations will take the Officer's Unit (Level B) of the training program as well. The Officer's Unit can be given by itself, but the student will be missing some of the basic material concerning observing and preserving the fire scene which was covered in the Basic Unit. Field testing suggests that greater insight and motivation for fire scene observation and preservation can occur if the firefighter is also exposed to the Officer's Unit (Level B).

4.3.2. Contents of Prototype Training Package

The Basic Unit (A-Level) training program includes an Instructor's Guide, a cassette tape, a set of slides, and a participant workbook. The Instructor's Guide gives the instructor a detailed, written script of the contents of the tape to enable him to sequence the visuals (slides) with the recorded script.

The Officer's Unit (B-Level) includes an Instructor's Guide, a cassette tape, a set of slides, a participant workbook, the Investigating and Reporting Guide which contains the HEP[1] Checklist and FIFI Field Notes, and the HEP Chart which includes the Officer's Handbook. Since this level of instruction is directed at the fire officer who will be completing the fire report and who will be required to make a preliminary fire cause determination, there has been extensive development of visuals and aids which can assist in this task.

In addition to a script of the contents of the tape cassette, the instructor's guide in both training packages contains statements of the philosophy and objectives of each lesson being given, as well as suggesting what supplementary information or materials might be added to enhance each particular learning exercise. Including this information with each learning exercise is designed to encourage the fire service officer conducting the course to include specific supplementary information from his own experience, or the students' (i.e., war stories) which illustrate the instructional point being made, in order to preserve the spontaneity of the group and keep the instructor feeling useful without letting him wander off the point at hand.[2]

4.3.3. Instructional Philosophy and Design

The instructional design of the training program takes advantage of the intuitive reasoning capabilities of the students. It is designed to emphasize the knowledge that the firefighter students already have concerning fire behavior and its effects.

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[1]Hexagonal Elimination Process: a simplified sequence of investigation developed during this project.

[2]There is considerable evidence to suggest that using subject matter experts (such as experienced fire investigators) merely as "button-pushers" for canned mechanical presentations can have disastrous results. The hostility built up in the instructor alone is often enough to completely sabotage the program.

In short, our philosophy towards the firefighter is this:

> You already know quite a bit about fire behavior. We are about to expose you to a sequence of investigation, emphasizing those things you already observe at a fire which will enable you to draw some pretty exacting conclusions about the fire cause, its point of origin and whether or not it was accidental.

Once the firefighter has learned to be suspicious and vaguely hostile towards the incidence of fire, his natural mechanical aptitude (a characteristic of most firefighters) coupled with his first-hand (even if limited) experience with the way fire behaves, will enable him to intuitively ask and answer appropriate questions about a fire.

In administering the package, students are encouraged to draw conclusions and answer questions before formal instruction in that particular topic is given so that a degree of competitive interaction and useful involvement with the subject matter will be maintained. This is done by presenting case histories and asking for conclusions *before* any instruction is given. For example:

Was this window locked or unlocked at time of fire?

Was this door opened or closed?

Those who answer questions, such as the above, without formal instruction, are not branched onto a faster instructional track as is common in many packages where students show prior knowledge. This is for two reasons:

1. Students who are able to draw conclusions to investigative evidence are valuable class resources. They give out answers, create arguments, and promote a subtle air of in-class competition.

2. It increases student interaction and involvement -- a key to the success of any instructional design.

Likewise, it is hypothesized that firefighters who come up with answers to investigative questions in class will encourage similar mental speculation among peers about the causes and circumstances of the fires they are fighting once they return to the firehouse. This has been shown to be the case in several cities studied during the project.

Wherever possible, students are taught by example (several examples equal a concept) so that they will generate their own definitions of the concept -- the only definition which we can be assured they understand. Validity of their own definitions will be checked many times throughout the training program since students will be required to apply their "learned" definitions to problem situations as they go along.

In short, the on the job instructional design used in the development of this package is intended not merely to "create an awareness" of the cause and circumstances of the fires they are fighting, but also to interest firefighters in assuming a detective-like posture when fighting fire. Our goal is for firefighters and fire officers to begin to value their firefighting environment (the fire building itself) as an *intimate interaction with the evidence which they will be required to work with soon after extinguishment.*

4.3.4. Job Aids Developed

The fire officer has many tasks to accomplish on the fireground. His primary task is to direct the men under his command in their efforts to effect rescue, limit fire spread, extinguish the fire, and prevent unnecessary water and smoke damage. This is a large task and requires much of his time and his decision making processes. However, if fire data collection and prevention efforts are to have any meaning and validity, the officer's focus of attention must shift to determining fire cause as well.

The Hexagonal Elimination Process (HEP) was a system developed to give the fire officer a simplified sequence of steps to take in determining all the facts required for reporting a complete fire cause. HEP was also developed around the NFPA No. 901, Coding System for Fire Reporting, in an effort to make the training program as universal as possible. The six steps of HEP are the basic informational requirements of fire cause determination required by NFPA No. 901.

The role of the fire officer, both in the fire station and on the fireground, was carefully analyzed in the development of FIFI training and job aids.

4.3.5. The HEP Chart

The HEP Chart is designed to graphically relate the six steps of HEP to the proper recording of the fire cause determination. The Flip Chart method gives the fire officer an easy reference to all of the descriptors established by NFPA No. 901.

4.3.6. The Officer's Handbook

The Officer's Handbook is a detailed, step by step procedure manual on how to obtain the information necessary for determining each of the six steps of HEP on the fireground. The size of the booklet was designed for easy use as a pocket reference if the fire officer so desires. Common pitfalls which can lead to wrong fire cause determination are pointed out in the Officer's Handbook in an effort to maintain accuracy and realism.

4.3.7. Investigating and Reporting Guide

Each officer is equipped with an Investigating and Reporting Guide, a notebook designed to fit into his fire coat. It is a condensation of some of the tips and instructions (fig. 1) contained in the Officer's Handbook and contains space for making notes (fig. 2) at the fire scene.

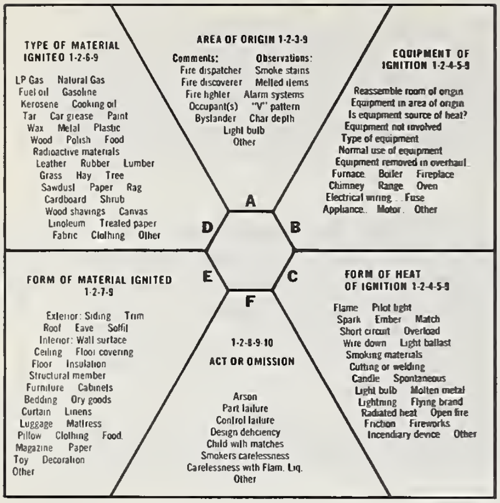
4.3.8. Present Training Package a Prototype

It is important to note that the development of any training package is incomplete without appropriate validating field tests. The product developed under this contract must be validated in the field for content clarity, content applicability, desired performance outcome, and teachability.

5. SUMMARY AND CONCLUSIONS

FIFI (Fire Information Field Investigation) was a one year Research and Development Project conducted by the National Fire Protection Association under contract to the National Bureau of Standards.

H.E.P. CHECK LIST FOR DETERMINING FIRE CAUSE



(1) For Question Areas, A, B, C, D, E, and F, record what is ALREADY KNOWN about fire (Interview Dispatcher, Fire Discoverer, Firefighters, Occupants, Bystanders).

(2) Verify this information by examining scene. **IF KNOWN INFORMATION IS INSUFFICIENT TO DETERMINE ALL SIX CAUSAL FACTORS, BEGIN SEQUENCE BELOW:**

(3) Find AREA OF ORIGIN (A). Work from area of no damage to area of most severe damage (read fire language; reassemble remains if necessary).

(4) Find EQUIPMENT (B) in area of origin. (Did ignition begin as result of equipment, or did fire spread to equipment?)

(5) What FORM OF HEAT (C) caused ignition of surrounding material?

(6) What MATERIAL (D) was first ignited?

(7) How was MATERIAL (E) used or shaped?

(8) What ACT OR OMISSION (F) brought together HEAT OF IGNITION and MATERIAL IGNITED?

(9) Complete Fire Report.

(10) If Incendiary, Suspicious, or Undetermined, notify appropriate authority.

Figure 1. The HEP Check List is one of the forms contained in the Investigating and Reporting Guide. It is a condensation of the instructions contained in the Officer's Handbook.

FIFI FIELD NOTES

INCIDENT NO.: DATE TIME

INCIDENT ADDRESS:

OCCUPANT(S) NAME(S):

OWNER:

OWNER'S ADDRESS:

INCIDENT: Fire Rescue False Alarm Public Service Other

BUILDING: Type Height Floor Area Age

VEHICLE: Year Make Model Style Lic.

DISPATCHER INFORMATION:

OBSERVATIONS ON ARRIVAL:

FIRE DISCOVERER: Name Address

COMMENTS:

WITNESSES: Name Address

Name Address

INJURIES: Type Name Address

Type Name Address

DEATH(S): Name Address

AREA OF ORIGIN: Floor Room Pt. w/in Room

SOURCE OF IGNITION: Equipment Form of Heat

IF EQUIPMENT. Year Make Model Ser. No.

MATERIAL IGNITED: Type Form

ACT OR OMISSION:

FACTORS CONTRIBUTING TO FIRE SPREAD. Non-fire Stopped Walls Open Stairs

Open Shafts Type of Fuel Stock Arrangement

Poor Water Supply Design Deficiencies

METHOD OF EXTINGUISHMENT: No. & Size of Streams

FORCIBLE ENTRY: Door Window Roof Other

VENTILATION: Door Window Roof Other

ESTIMATED VALUE: Building Contents Equipment

ESTIMATED FIRE LOSS: Building Contents Equipment

INSURANCE: Agent Address Amount

Figure 2. This form gives the officer space for recording information on the fireground which will be needed later to complete his fire report. It asks for the basic information necessary for completing any fire report form known to be in existence at the present time.

5.1. Research Phase

The objective of the research phase of FIFI was to define and evaluate those state-of-the-art investigation techniques used by public fire agencies at the scene of fires to report on the cause and circumstances of those fires. The two most significant conclusions reached as a result of this research were:

1. That most existing literature and practices were arson oriented; and

2. That standard investigative practices and training programs do not exist.

5.2. Development Objectives

After defining and evaluating the state-of-the-art of the many fire investigation techniques used in the field, the development phase was initiated with two objectives in mind:

1. To increase the probability that the firefighter will recognize and preserve useful fire scene information by enhancing the firefighters ability and willingness to observe those events and actions which assist in determining the cause and circumstances of the fire.

2. To improve the fire officer's effectiveness in determining the cause and circumstances of a fire and to assist him in the early identification and notification of research potential incidents.

5.3. The Products of the Development Phase

In fulfillment of these objectives, the development phase of the FIFI project:

1. Synthesized the most valid standard investigation techniques into a new, simplified, logical, 901-based[1] process of elimination investigation sequence. This system of investigation, entitled HEP (Hexagonal Elimination Process), was developed to give the fire officer a simplified sequence of steps to follow which enable him to determine all the facts required for reporting a complete fire cause. In an effort to make the system compatible with an existing reporting standard, HEP was developed around NFPA Standard 901, Coding System for Fire Reporting. By design, the six steps of HEP constitute the basic informational requirements of fire cause determination required by NFPA Standard 901.

2. Two pilot training packages were developed, designed to aid firefighters in carrying out the systematic investigation sequence known as HEP in their initial, on-scene, routine fire investigations.

5.3.1. Summary Description of Pilot Training Packages

Each of the two training packages consists of a series of slides accompanied by a 33 minute tape cassette containing instructional material sequenced with the slide progression. However, since there is no sense in turning qualified fire department instructors or fire service officers into button pushers for canned mechanical presentations, the Instructor's Guide gives the instructors suggestions for adding supplementary material with each slide shown, in order to enhance the concept being presented at any one time during the package sequence. This usually adds a minimum of 4-6 hours to each 33 minute core package.

[1]Standard 901, Coding System for Fire Reporting, NFPA, 1971.

For example, when the slide-tape program is explaining how the color of window panes can be used to gauge the heat of the fire and help in finding the area of origin of the fire, the Instructor's Guide states the learning objective as: "Given two pieces of glass, students will be able to pick the one closest to the hottest part of the fire". The Instructor's Guide also encourages the instructor at this point to bring in actual samples of cracked, syrupy glass which the students can examine at their leisure. The format is flexible enough so that at this point -- during the session on using window glass as heat indicators for instance -- the instructor is free to spend the whole day or a couple of days tackling the subject.

Our intention in formatting the package this way was to take advantage of the best of two possible worlds: the world of the fire service officer, who is often armed with a good theoretical base of knowledge as well as years of specialized experience in fire behavior -- and the world of the audiovisual package, which insures that all important concepts in fire investigation are covered in logical sequence, and as such, functions as a tool for the instructor.

5.3.2. Principle Objectives of Package #1

The principle objectives of the Basic Unit for firefighters are:

1. To convince the firefighter that he is a most valuable source of fire intelligence information; that he is a most valuable person in the whole scheme of valid fire incident reporting.

2. To create in the firefighters' mind an awareness of their firefighting environment to the extent that they begin to assume a detective-like posture when fighting fire; to be aware of the investigative significance of everything he sees during the course of the fire he is fighting.

3. To encourage the firefighter to preserve, insofar as possible, the original configuration of the fire scene, so that investigation is made easier for the fire officer who will be investigating the fire's cause. He will learn to value the fire building itself as evidence which he and his fire officer will have to work with soon after the fire is contained.

5.3.3. Principle Objectives of Package #2

The second training package is designed for fire officers (although firefighters find it useful) after they have been through package #1. The following objectives focus on the task of arriving at a fire cause determination, which is usually the job of the fire officer:

1. The fire officer will become familiar with the HEP sequence of investigation, a method whereby a process of elimination can be used to discover the cause and circumstances surrounding the fire he has just contained.

2. Although the package itself does not make a fire officer into a skilled fire investigator, it gives the student just enough practice in solving investigation problems to whet his appetite for practicing his investigative skills "on the job" which, realistically, is the only place where proficiency in fire investigation can occur.

In short, the training package provides the motivational setting as well as a step-by-step sequence of investigation to follow while he is practicing on the job.

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NATIONAL SCIENCE FOUNDATION RANN PROGRAM

Ralph H. Long, Jr.
National Science Foundation, Washington, D.C.

The fire research effort at NSF is part of the Research Applied to National Needs (RANN) Program of NSF, which provides funds for problem-oriented research on selected problems of national importance. The current effort is funded at $2 million and about 20 projects are under way. An outline of the thrust of the total program will be given. Also, several projects which are closely related to interests of the National Bureau of Standards will be indicated. Related activities within NSF will be mentioned.

Key words: Fire programs; fire research; National Science Foundation; RANN; research grants.

1. INTRODUCTION

The fire research effort of the National Science Foundation (NSF) is part of the Research Applied to National Needs (RANN) Program which was initiated early in 1971. It involves problem-oriented research rather than just meritorious research in a field of science or engineering.

2. RESEARCH OBJECTIVES

Without citing available data, a quotation from the National Fire Protection Association summarizes well the national situation: "In a word, the fire problem is that too many people die or are injured by fire and that the social and economic losses are an unnecessary burden on the American people." The general objectives of the Fire Research Program, within the Division of Advanced Technology Applications, are to reduce deaths, injuries and property damage due to unwanted fires and also to reduce the costs and improve the effectiveness of fire control.

Research is supported which develops understanding of mechanisms of ignition, fire spread and extinguishment sufficient to improve significantly fire safety in homes and urban areas, including special problems of tall structures. Some backup research is supported to complement efforts of the U.S. Forest Service on forest fires.

3. STRATEGY

The fire problem has several components; in effect, it consists of a series of interrelated problems. The spectrum covers public ignorance and apathy, combustibility of environment, building deficiencies, effectiveness and cost of fire protection and adequacy of fire statistics.

The proper NSF role in fire research is dependent on and complementary to the activities and interest of mission agencies, particularly the National Bureau of Standards, the Department of Housing and Urban Development, the General Services Administration and the Forest Service. The research needs outstrip the abilities and interests of any one agency, so a coordinated Federal approach is required.

The research emphasis of the program is directed at the fire problems of cities, where the losses occur, although some funds go to research that complements that of the Forest Service on forest fires. The general thrust addresses problems connected with the means to provide adequate fire protection for buildings. The research will lead to safer buildings through the improvement of design practices and of the test methods and standards for materials.

The research efforts focus on the understanding of the ignition of various materials, the fire spread mechanisms and extinguishing methods. Included are the modeling of fire propagation, effectiveness of fire fighting systems and the deleterious effects of smoke. Research that will improve the detection and suppression of fires will be supported. The NSF effort provides the research base that can be effectively addressed primarily by university researchers in many critical areas of importance to other Federal agencies and the fire protection community.

As the research base is improved and new technology developed, it will continue to be necessary to devise methods to make the fire protection community aware of the progress and induce cooperative experimentation in order to upgrade the system. Greater efforts will be exerted to initiate projects related to the direct needs of the fire services, including fire equipment technology where there is sufficient economic incentive.

The Foundation's research effort provides support for four comprehensive (multidisciplinary) fire research groups on projects where special competence is needed and for a larger number of smaller research grants.

4. ADVICE

The goals and strategy reflect advice from several qualified organizations and individuals, including the National Academy of Sciences-National Research Council Committee on Fire Research. Recommendations from meetings and workshops which were concerned with specialized areas are also considered.

Research proposals form the vehicle for implementation of the program. The advice of several experts is sought for each proposal and forms the basis for a decision.

5. SIZE OF FIRE RESEARCH PROGRAM

The RANN Fire Research obligations for fiscal year (FY) 1972 and FY 1973 are given in table 1. When RANN was formed early in 1971, nine existing grants (totaling $670,000 on an annual basis) were administratively transferred to the new Fire Research Program, two from the former Office of Interdisciplinary Research on Problems of Our Society and seven from the Engineering Division.

Currently there are 24 active grants. Four multidisciplinary groups (Harvard-Factory Mutual Research Corporation; Applied Physics Laboratory of Johns Hopkins University; University of California, Berkeley; and University of Utah) have major support, which ranges from $247,000 to $399,500 per year. There are 16 other research grants which average about $36,000 for a year and four special grants.

Table 1. RANN Fire Research Obligations[a]

	FY 1972		FY 1973	
	No.	Funding (Thou.$)	No.	Funding (Thou.$)
Multidisciplinary Grants	3	912	4	1,156[b]
Research Grants . . .	9	508	14	791
Special Grants. . . .	2	35	4	164
Total	14	1,455	22	2,111

[a]Note all grants do not have the same duration.
[b]Figure includes $113,000 from HUD.

6. AREAS OF FIRE RESEARCH

Seven sub-program areas will be briefly described. Some projects include more than one area and at times the classification of a particular grant may be a bit arbitrary.

6.1. Structure and Solid Materials Flammability

In order to improve fire safety, a fuller understanding must be developed of the conditions needed for ignition to occur on solid materials and structural components, including the effects of flame retardants. Results will be used to improve design practices and fire tests.

Empirical studies have been conducted for some time and have provided some knowledge of ignition, however, proper scientific understanding is lacking. Research that is being supported will lead to the use of materials and design of structures in a manner to provide improved fire protection. Moreover, improved bases for the setting of realistic ignition tests are being pursued. Both chemical and engineering research efforts on pyrolysis of cellulose, wood and polymers are under way.

6.2. Fluid and Fuel Flammability

This area deals with the development of the knowledge base concerning the fire potential and propagating characteristics of fuels and volatile fluids.

The ongoing effort consists of an experimental and analytical effort at Princeton and a complementary analytical program at Cornell University. A detailed understanding of the mechanism of flame spreading across liquid fuel is being sought. The research has advanced to the point where both gas phase and heat transfer aspects can be included simultaneously in the analysis.

6.3. Fabric Flammability

Research is being conducted in fabric flammability and the associated hazards for use by the National Bureau of Standards in setting flammability standards.

A two-year coordinated program with NBS has been completed. The effort included NSF funded research at Georgia Institute of Technology and Massachusetts Institute of Technology (MIT) and projects at Gillette Research Institute and Factory Mutual Research Corporation with funds from three industrial associations. A Government-Industry Research Committee on Fabric Flammability was formed to monitor the group of projects. The MIT project terminated during FY 1973 as did the ones at Gillette and Factory Mutual. Additional research was funded at Georgia Tech on the ignition of composite systems. The purpose of the analytical and experimental work is to relate the hazard from burning garments to laboratory test methods on fabrics for use in setting reasonable fabric flammability standards. The work is designed to lead to the prediction of the probability of garment ignition under given exposure.

A grant was recently made to the Textile Research Institute (TRI) to establish, in rigorous quantitative terms, the thermal and flammability characteristics of multicomponent fibrous polymer-systems. The research is complementary to the applied research normally done by TRI and funded by industry. The goal is to provide quidelines for the development of textile materials that will minimize the flammability hazards to the ultimate consumer.

6.4. Chemical and Physical Properties of Flame Propagation

A fuller understanding of the mechanism of flame spread, including chemical and physical properties, is needed in order to lead to improvements in building design and methods for combating fires. Results will also be used to improve flame spread tests. The movement of gases within structures is also included, as it is important in connection with fire safety and detection. This area includes research on fire spread in materials and systems, the role of radiation and the fluid mechanics of combustion products.

Brown University is conducting an experimental and analytical study of flame spreading over cylinders (round and rectangular cross-sections made of wood and plastic). A major long-range objective of the research being conducted at Harvard is to develop the capability to predict the history of fire progression from an assumed ignition point in a house. Under a subcontract from Harvard, the Factory Mutual Research Corp. is determining the range of application for a pressure method of modeling building fires and for approximate atmospheric pressure methods for modeling fires. Complementary research at Berkeley is directed at understanding a standard wall furnace fire endurance test. Another task is the prediction of the structural response to fire for reinforced concrete frames. A two-dimensional model has been developed which gives a realistic prediction of the stress history under different fire conditions. The convective flows of combustion products in building fires are being studied at California Institute of Technology. A recent grant to the University of Notre Dame has the primary objective to provide the foundation for the development and use of theoretical predictions for describing fire and smoke spread in corridors. The analyses will be coupled with small-scale experiments at Notre Dame and with data from the NBS corridor facility.

6.5. Fire Fighting Systems and Human Behavior

Here the aim is to develop knowledge that will contribute to controlling fires more effectively and that will reflect the human response to a fire situation.

Studies on the extinguishment of fires include the behavior of water droplets in a fire plume and the action of metal powders on flames. A project at the University of Washington, with participation from the University of California, San Diego and Washington State University, and in cooperation with the U.S. Forest Service, is directed at determining a rational understanding of wildland fire response to fire suppression measures for use in the development of proper equipment, attack strategies and management techniques that will minimize costs. Research at the University of California, Riverside is directed at some statistical problems connected with the development of a basic simulation model, for forest fire control, by the Forest Fire Laboratory of the Pacific Southwest Forest and Range Experiment Station of the U.S. Forest Service.

At Johns Hopkins' Applied Physics Laboratory, the development has proceeded on an economical and practical tactics case for use by fire departments. It is being tested at the Hillandale, Maryland Volunteer Fire Department, and several improvements have resulted. The case was a major element in the NSF/RANN Fire Research exhibit at the May 1973 Annual Meeting of the National Fire Protection Association in St. Louis. Plans call for further testing in several fire departments in the next few months. Efforts will be made to locate an organization for the manufacture and distribution of the case if an adequate potential market emerges.

At the University of California, Berkeley, part of the project is directed at the development of a computer simulation model of the unwanted fire process for use as a design tool for fire protection and fire control. In conjunction with this, field studies have obtained fire incident and human response data applicable to the simulation model. Using engineering psychology approaches, analyses and experimental studies of human response in fire situations will be made. The data obtained will be useful in practical fire safety and control design.

6.6. Smoke Effects

The effects of smoke on people are being studied so that attention can be concentrated on the most critical points that offer a payoff in the reduction of deaths and injuries.

Little information is available on the exact cause of death of fire victims, except in cases where severe burns, heart attacks or fractures have occurred. The clinical and pathological mechanisms are not understood when a person dies from the effects of by-product agents of a fire.

Under a grant at the Applied Physics Laboratory of the Johns Hopkins University, a cooperative program has been initiated with the Baltimore City Medical Examiner's Office and the School of Hygiene and Public Health of Johns Hopkins University. The project includes the post-mortem examination of fire victims in Maryland, chemical analyses of the lung tissues and fluids, and investigation of the fire scene in order to determine the sequence of events leading to death. In addition, the effects of the fire environments on fire fighters are being studied.

A related program at the Flammability Research Center of the University of Utah is directed at the physiological and toxicological aspects of smoke produced during the combustion of polymeric materials. The research team includes medical staff members at the University of Utah. The Salt Lake City Fire Department, the Fire Marshal of the State of Utah and the National Bureau of Standards are cooperating with the university group. The program is concerned with the problems connected with the burning of polymeric materials such as fabrics, elastomers and cellular plastics. Laboratory studies of the effect of smoke on rats are included. The research will provide the fundamental information necessary to develop improved materials and to devise better testing procedures to evaluate material hazards under realistic conditions.

6.7. Technology and Information Transfer

There is also a need to develop greater facility for the transfer of fire research knowledge between various sectors concerned with fire protection and control.

There are special problems in getting fire research knowledge into a form that will ensure use by the fire services community. Through increased communication and education, the process of updating fire codes and standards can be accelerated and the public can become more aware of fire safety.

An information dissemination plan is part of each research proposal. For a large grant, an advisory committee, including potential users, is formed to assure coupling to the user communities. Specialized meetings and workshops are arranged to facilitate information transfer, often in cooperation with other groups such as NBS. For example, a conference was held July 18-20, 1973, on "Firesafety for Buildings, Research-Practice-Needs" involving most RANN grantees and organized jointly by NSF, NBS, GSA, and HUD. Contact has been established with several associations, such as the National Fire Protection Association, the Society of Fire Protection Engineers and Society of the Plastics Industry (SPI). SPI is providing funds to supplement the NSF grant at the University of Utah on the toxicology of smoke from polymers.

7. OTHER NSF FIRE RELATED ACTIVITIES

Within the Engineering Division of the Research Directorate there is a special program for tall buildings. Some effort is directed at structural problems resulting from fire. While some combustion research is supported within the Division, research on unwanted fires is not.

Within RANN in the Social Systems and Human Resources Division, the Municipal Systems, Operations, and Services effort includes the delivery of fire protection. Two grants were recently made under Program Announcement NSF 73-4 for evaluation of policy-related research in fire protection with respect to technical quality, utility for policy-makers and potential for codification and wider diffusion. The result will be a synthesized base of evaluated information for potential use by agencies at all levels of government.

8. SUMMARY

The NSF Fire Research Program covers the spectrum from basic to applied research and is directed at critical elements of the nation's fire problems. Through close coordination with other Federal agencies, a research effort has resulted which is complementary and often permits study on longer term payoff areas than is usually possible in a mission agency. Projects contain utilization plans, coupling with potential users and periodic progress reviews in order to accelerate the transfer of research results to useful purposes and to provide the research people with a knowledge of needs of practitioners.

APPENDIX. LIST OF ACTIVE NSF RESEARCH GRANTS AND PRINCIPAL INVESTIGATORS, AS OF AUGUST 1, 1973

1. Brown University, Division of Engineering, Merwin Silbukin, Flame Spreading Over Solid Surfaces.

2. California Institute of Technology, Division of Engineering and Applied Science, Edward E. Zukoski, Convective Flows of Building Fires.

3. Cornell University, Department of Thermal Engineering, Kenneth E. Torrance, Flame Spread Over Liquid Fuels.

4. Georgia Institute of Technology, School of Mechanical Engineering, Wolfgang Wulff, Ignition of Fabrics.

5. Harvard University, Division of Engineering and Applied Physics, Howard W. Emmons (with Raymond Friedman, Factory Mutual Research Corp.), The Home Fire Project.

6. Johns Hopkins University, Applied Physics Laboratory, Robert M. Fristrom, Fire Problems Research and Synthesis.

7. National Academy of Sciences-National Research Council, Committee on Fire Research, Nelson T. Grisamore.

8. National Bureau of Standards, Conference on Firesafety For Buildings: Research, Practice, Needs, Joseph E. Clark.

9. New York City-Rand Institute, Edward H. Blum, Fire Research Needs and Priorities.

10. Northwestern University, Department of Mechanical Engineering, M. C. Yuen, Behavior of Water Droplets in Fire Plume.

11. Princeton University, Guggenheim Laboratories, Irvin Glassman, Flame Spreading Across Liquid Fuels.

12. State University of New York, Binghamton, Department of Chemistry, Walter E. Kaskan, Extinction of Flames By Metal Powders.

13. State University of New York, Department of Mechanics, Richard S. L. Lee, Fire Whirl and Firebrand in Mass Fires.

14. Student Competitions on Relevant Engineering, Charles M. McCuen, Students Against Fires.

15. Textile Research Institute, Bernard Miller, Thermal and Flammability Behavior of Multicomponent Fibrous Polymer Systems.

16. University of California, Berkeley, Department of Civil Engineering, R. B. Williamson, Firesafety in Urban Housing.

17. University of California, Riverside, Department of Statistics, F. N. David, Forest Fire Statistical Problems.

18. University of California, San Diego, Department of Applied Mechanics and Engineering Sciences, F. A. Williams, Fire Propagation Along Solid Surfaces.

19. University of Maine, Department of Mechanical Engineering, Ashley S. Campbell, Fire Rate of Spread in Paper Arrays.

20. University of Montana, Wood Chemistry Laboratory, Fred Shafizadeh, Chemistry of Cellulosic Fires.

21. University of Notre Dame, Department of Aerospace and Mechanical Engineering, J. L. Novotny, Fire and Smoke Spread in Corridors.

22. University of Utah, Department of Chemical Engineering, Norman W. Ryan, Mechanism of Fire Propagation on Polymer Surfaces.

23. University of Utah, Flammability Research Center, Irving Einhorn, Physiological and Toxicological Aspects of Smoke Produced During the Combustion of Polymeric Materials.

24. University of Washington, Department of Mechanical Engineering, R. C. Corlett, Mechanisms of Wildland Fire Suppression.

APPENDIX - CONTRIBUTING AUTHOR INDEX

Robert H. Barker
Clemson University
Clemson, S. C. 29631

M. M. Birky
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Francis L. Brannigan
Montgomery College
51 Manekee Street
Rockville, Md. 20850

Emil Braun
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Benjamin Buchbinder
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Laura Baker Buchbinder
Res. Assoc. - The Cotton Foundation
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

I. N. Einhorn
The University of Utah
Salt Lake City, Utah 84112

J. B. Fang
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Paul Gottfried
Consumer Product Safety Commission
5401 Westbard Avenue
Bethesda, Md. 20016

Martin E. Grimes
National Fire Protection Association
60 Batterymarch Street
Boston, Mass. 02110

D. Gross
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

M. L. Grunnett
The University of Utah
Salt Lake City, Utah 84112

John W. Hastie
Inorganic Materials Division
National Bureau of Standards
Washington, D.C. 20234

Clayton Huggett
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Lionel A. Issen
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Takashi Kashiwagi
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

F. James Kauffman
National Fire Protection Association
60 Batterymarch Street
Boston, Mass. 02110

Thomas King
Armstrong Cork Company
Research and Development Center
Lancaster, Pa. 17604

Richard Ku
Technical Analysis Division
National Bureau of Standards
Washington, D.C. 20234

B. T. Lee
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Ralph H. Long, Jr.
Advanced Technology Application Div.
National Science Foundation
1800 G. St., N.W.
Washington, D.C. 20550

Bernard Miller
Textile Research Institute
Princeton, N.J. 08540

S. C. Packham
The University of Utah
Salt Lake City, Utah 84112

W. J. Parker
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

J. H. Petajan
The University of Utah
Salt Lake City, Utah 84112

James Quintiere
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

J. A. Rockett
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Richard W. Roberts, Director
National Bureau of Standards
Washington, D.C. 20234

Patsy B. Saunders
Applied Mathematics Division
National Bureau of Standards
Washington, D.C. 20234

J. D. Seader
The University of Utah
Salt Lake City, Utah 84112

George Sinnott
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

James A. Slater
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

Allan Vickers
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

F. Karl Willenbrock
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

James H. Winger
Programmatic Center for Fire Research
National Bureau of Standards
Washington, D.C. 20234

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