

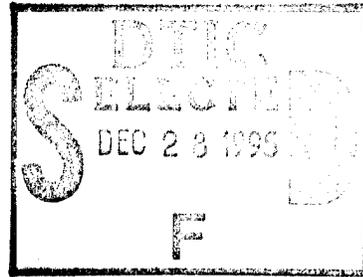
*Carl Sandrock*

NBSIR 81-2382

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# Fifth Annual Conference on Fire Research



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U.S. DEPARTMENT OF COMMERCE  
National Bureau of Standards  
National Engineering Laboratory  
Center for Fire Research  
Washington, DC 20234

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issued October 1981

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NATIONAL BUREAU OF STANDARDS

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NBSIR 81-2382

## **FIFTH ANNUAL CONFERENCE ON FIRE RESEARCH**

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Sonya M. Cherry, Editor

U.S. DEPARTMENT OF COMMERCE  
National Bureau of Standards  
National Engineering Laboratory  
Center for Fire Research  
Washington, DC 20234

August 1981

Final Report

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*  
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

## FOREWORD

In this, the Fifth Annual Conference on Fire Research, we will continue the pattern of concentrating alternately on the basic and applied science of fire. This year, it is basic science which is emphasized.

It is our intent that the distinction be temporary. As we progress, the careful observer of these meetings should notice a gradual blurring of the borders between basic and applied work. For example, we are learning to predict fire growth in an increasing variety of real situations; this prefigures the evolution of fire modeling into an engineering tool. In seeking an understanding of material fire properties, we are also seeking the information necessary for better fire safe materials and products.

The laboratory scientist and the fire protection engineer don't always speak the same language, but the common vocabulary is growing. Someday that language will be the same -- although the accent will be different.



Frederic B. Clarke  
Director  
Center for Fire Research

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FIFTH ANNUAL CONFERENCE ON FIRE RESEARCH

August 19-21, 1981

Sonya M. Cherry, Editor

Abstract

This report contains extended abstracts of grants and contracts for fire research sponsored by the Center for Fire Research, National Bureau of Standards, as well as descriptions of the internal programs of the Center for Fire Research.

Key words: Combustion; decision analysis; fire models; flame spread; human behavior; ignition; polymers; smoke; soot; toxicity; wood.

AD HOC WORKING GROUP ON MATHEMATICAL FIRE MODELING  
CENTER FOR FIRE RESEARCH

Professional Personnel

Robert S. Levine, Chairman of Steering Committee  
John A. Rockett, Chairman of Computer Committee  
Irwin A. Benjamin, Chairman of Users Needs Subcommittee  
James G. Quintiere, Chairman of Models Subcommittee

Note: The Modeling Committee is chaired by Professor Howard Emmons of Harvard University, and the Subprogram Committee by John deRis of Factory Mutual.

A number of CFR personnel are members of the technical committees.

Program Objectives

The objectives of this committee are to facilitate the development and use of mathematical models of fire and to coordinate and facilitate research needed to improve the models. The steering committee includes members from other Government agencies who have influence on their agencies' R and D in this field. The coordination, of course, is voluntary.

Project Areas

Each applicable area is included in another program abstract. The major portion of the CFR effort is in the Fire Modeling Program.

Associated Grants

1. Harvard University/Factory Mutual Research Corporation,  
Howard Emmons and John deRis - "Home Fire Project"
2. Several others as listed elsewhere.

DESIGN CONCEPTS RESEARCH  
FIRE SAFETY ENGINEERING DIVISION  
CENTER FOR FIRE RESEARCH

Professional Personnel

Harold E. Nelson, Head  
Bernard M. Levin, Research Psychologist  
A. Jeffrey Shibe, Operations Research Analyst  
Leonard Y. Cooper, Research Fire Protection Engineer  
Daniel M. Alvord, Math/Programmer  
Roseanne L. Paulsen, Social Scientist

Program Objectives

The objectives of the Program are to synthesize and integrate research and technology to develop technically based rational approaches toward providing safety from fire in buildings of various types of usage, and to provide operating mechanisms for using these approaches in setting fire safety requirements in these facilities.

Project Areas

1. Egress from Fires

The purpose of this project is to investigate the state-of-the-art of egress from fires; to conduct experiments related to egress for the purpose of establishing an improved data base, thereby providing a sound basis for hazard assessment approaches; and to determine specific engineering solutions which would yield emergency escape criteria for means of egress arrangements.

The first stage of the project was completed this last year with the publication of three reports. The first of these was, "The Measurement of the Smoke Leakage of Door Assemblies During Standard Fire Exposures," NBSIR 80-2004. by L. Y. Cooper. This work, carried out in cooperation with Underwriters Laboratory, involved an evaluation of a method for leakage measurements which was proposed by ISO. The second report was "Fire Tests of Stairwell-Sprinkler Systems," NBSIR 81-2202. by L. Y. Cooper and J. G. O'Neill. This work addressed the problem of open stairway protection, and it involved tests which were conducted in a full-sized open stairwell test facility at NBS. The last report was entitled, "Estimating Safe Available Egress Time From Fires," NBSIR 80-2172, by L. Y. Cooper. This was an initial study on enclosure fire modeling as applied to the basic life safety problem of safe egress from fires.

The latter study laid the framework for an important area of applied enclosure fire modeling. A series of new initiatives which extend this study are now in progress. Two reports of this new work were presented at the 20th National Heat Transfer Conference. The first of these was

entitled, "An Experimental Study of Upper Hot Layer Stratification in Full-Scale Multiroom Fire Scenarios," by L. Y. Cooper, M. Harkelroad, J. Quintiere, and W. Rinkinen. This was a report of a series of full-scale experiments which were carried out at NBS. The second report was entitled "Heat Transfer from a Buoyant Plume to an Unconfined Ceiling," by L. Y. Cooper. This work developed an applications-oriented methodology to be used in enclosure fire models, for estimating heat transfer from fires to ceilings for early times after fire ignition. An extension to the latter work is near completion. This will remove the above "early time" restriction.

Other work in progress concentrates on delivering available egress time computation methodology to the end user. In this vein, a "user friendly" computer code with a user's manual is under development. In another activity, readily accessible and practically usable graphical descriptions of fire growth phenomena are being developed. These graphical descriptions will be based on mathematical simulation of conditions which would develop during a large class of realistic fire scenarios.

## 2. Rational Approach to Fire Safety in Health Care Facilities

A multi-faceted program to extend the ongoing program on health care facilities. Major areas include: 1, extending the decision analysis and evaluation system approaches to facilities that provide board and care to the developmentally disabled, the disabled elderly and the mentally ill in a residential setting; 2, investing and providing technical support for improved values in specific subsystem parameters of the existing Fire Safety Evaluation System; 3, continuing work on fundamental modeling of fire development and smoke and heat propagation in health care facilities; 4, emergency preparedness criteria; and 5, initiating major investigations in fire safety through control of building contents.

The approach includes operations research application particularly as relates to decision analysis and emergency preparedness. The approaches are being directed at combining technical information, statistics and other historical information with the consensus of professional experts. The improvement of subsystem parameters and the development of predictive calculation on fire threat development will extensively use established engineering technology and the most current math modeling techniques and research developed data with emphasis on the development of engineering and design tools. Developments in the furnishing area will concentrate on use of oxygen calorimetry and bench tests to establish rates of heat release, total energy, and companion measurements on smoke and toxic species.

## 3. Fire Safety for the Developmentally Disabled

A recent development in the care of the mentally retarded, the disabled elderly and the handicapped persons, is to provide for their custodial care in small home-like facilities in the community rather than in

large remote institutions. Life/fire safety requirements have not been specifically developed for these types of facilities so the responsible authorities are using regulations designed for other purposes, including the NFPA Life Safety Code standards for private homes, boarding houses and hospitals. The objective of this project is to develop life/fire safety performance criteria specifically geared for these board and care homes.

This program started in July 1977 with a project directed at small group homes for the developmentally disabled. During the past year, the program was expanded to include larger buildings and a full range of disabilities.

The approach is to develop a variation and modification of the Fire Safety Evaluation System. This system will permit flexibility in the selection of fire safety features, and the fire protection requirements will depend, in part, on the level of capabilities of the residents. The criteria is being developed with the advice of experts throughout the country.

A preliminary version of the evaluation system is now developed. A major field test is being conducted in the summer of 1981 and recommendations will be made in January 1982 to the National Fire Protection Association for inclusion in the next edition of the Life Safety Code.

#### 4. Multi-Family Housing Life/Fire Safety Evaluation System

The objective of this project is the development of a fire safety evaluation system applicable to existing multi-family housing. The system is designed to evaluate equivalency of alternative fire safety approaches as compared to the normal requirements of the Department of Housing and Urban Development Minimum Property Standards.

The project is nearing completion. The evaluation system is based on the relevance of the various elements of building design to the performance objectives of fire safety (e.g., prevention of ignition, and extinguishment, and escape and rescue). A working evaluation system that may be used as an alternative to the existing explicit requirements has been developed and is now being tested.

#### 5. Life/Fire Safety Evaluation Manual-Inmate Housing and Confinement Facilities in Penal Occupancies

The purpose of this project is to develop a fire safety evaluation system and supporting manuals to determine the relative level of safety in inmate housing facilities in prisons and similar penal institutions. The approach will be modeled after the other types of fire safety evaluation systems prepared or underway by the program. The project includes full scale test of the rate-of-energy release of fully involved prison cells. The tests have been completed. The data has been used to develop smoke removal criteria for prison cell blocks that have been included in the 1981 Life Safety Code. The evaluation system is targeted for inclusion in the 1984 Life Safety Code.

## 6. Coal Mine Fire Safety Evaluation

This is a three-year project to develop a methodology for determining alternative means for providing fire safety in coal mines. The objectives are both to protect the lives and health of the miners and to preserve the national resources involved. Phase I is directed at the development of an event logic tree and other descriptions of the overall organization of elements and interrelationships involved in fire safety in coal mines.

The approach in Phase I consists of joint analysis by NBS and the Bureau of Mines of the fire histories, available statistics, experience of Bureau of Mines in coal and coal mining activities, and the experience and knowledge of NBS in fire protection and fire safety system principles to develop the resultant tree and supporting documentation. This phase is now completed and both the tree and a state transition model have been developed.

## 7. Extra-CFR Activities

A major portion of the activities of Design Concepts Research are conducted outside of the Center for Fire Research. These include:

### Center for Applied Mathematics, NBS

1. "System for Cost Comparison of Fire Safety Alternatives," Robert Chapman.
2. "Time-based Provisions for Emergency Escape in Public Occupancy Buildings," Fred I. Stahl.

### Associated Grants

1. University of Maryland, John Bryan - "The Determination of Behavior Response Patterns in Fire Situations - Project People II".
2. North Carolina State University, Richard Pearson - "Occupant Response Variability in Escape from Residential Fires."
3. University of Maryland, Norman Groner - "Guidelines for Preparing Fire Plan for Group Homes."
4. University of Washington, John Keating and Elizabeth Loftus - "Post Fire Interviews: Development and Field Validation."
5. AIA Research Corporation, Earl Kennett, - "Second National Conference on Fire Safety and the Handicapped."

Exploratory Fire Research  
Center for Fire Research

Professional Personnel

Walter L. Zielinski, Jr., Acting Head  
William L. Earl, Research Chemist  
Takao Kashiwagi, Guest Worker  
Takashi Kashiwagi, Materials Research Engineer  
W. Gary Mallard, Research Chemist  
Michael J. Manka, Chemist  
Bernard J. McCaffrey, Mechanical Engineer  
J. Houston Miller, Postdoctoral Fellow  
George W. Mulholland, Research Chemist  
Thomas J. Ohlemiller, General Engineer  
William M. Pitts, Research Chemist  
Kermit C. Smyth, Research Chemist

Program Objectives

- (1) Improve the understanding of the chemical, physico-chemical, and physical processes which underlie macroscopic fire phenomena by carrying out research studies covering both gas and solid phase processes, char formation, smoldering, ignition, transition from smoldering to ignition, formation and properties of smoke particulates and toxic gases, mass and energy transport in flames, fire plumes, the mechanism of action of fire retardants, and flame spread and flame extinguishment processes.
- (2) Devise new techniques for studying these phenomena.
- (3) Furnish fundamental scientific information to support the activities of the Fire Safety Engineering Division and the Fire Performance Evaluation Division.

Project Areas

1. Radiative Ignition

Before a liquid or solid fuel can ignite, it must absorb a significant quantity of energy. In many circumstances, the dominant transfer mechanism supplying this energy has involved exposing samples of n-decane, PMMA and laser, with and without a pilot heat source present. It has been shown that significant absorption takes place in the fuel, presumably by vapors derived from

High speed photography of liquid fuel surface and complex bubbling phenomena determine the vapor concentration in the gas phase during the ignition period.

1  
in

conditions, evolution of the distributions of fuel vapor concentration and gas phase temperature is being measured by a two-line holographic interferometer technique.

Transient gasification characteristics of polymeric materials are being investigated at a fire level radiant heat flux using a large blackbody source. The effect of gas phase oxygen on gasification of polymethylmethacrylate is being measured in the first phase of this study.

## 2. NMR Studies of Combustion of Solids

The basic capabilities for high resolution  $^{13}\text{C}$  nuclear magnetic resonance (NMR) in solids using magic angle spinning have been developed in collaboration with the NBS Center for Materials Science. Initial work focused on methodology assessments, including studies of the magnitude of line broadening and investigations of peak positions. These studies served to define the information available from the technique and potential for instrumental modifications to improve the methodology. A series of experiments on wood, wood products, and different forms of cellulose were conducted to provide the necessary background data for studies of the thermal decomposition of wood.

A set of isothermal pyrolyses in nitrogen was then performed on spruce, oak and cellulose, carried out by five-minute exposures to temperatures between 275 and 390°C and subsequent analysis by the  $^{13}\text{C}$  solid state NMR technique. The results indicated that spruce is slightly more resistant to pyrolysis than oak, that the cellulose component of wood decomposes more rapidly than the lignin, and that the chars formed have high aromatic character, even for pure cellulose which has no aromatic content. These preliminary studies show a significant promise for the use of solid state NMR in the analysis of chars in pyrolysis and combustion experiments.

## 3. Smoldering Combustion of Cellulosics

The propensity for smoldering exhibited by cellulosic materials continues to be a subject of major concern. The smolder characteristics of cellulosic insulation (made from wood pulp) represent the present focus for this work. Smolder propagation through a thick horizontal layer of such insulation has been investigated. Temperature, oxygen, and remaining solid fuel distributions have been measured as a means of determining the factors controlling propagation. The overall structure appears to be determined by the diffusion of oxygen. Boric acid slows the propagation and alters the smolder wave structure, but does not cause extinction in these thick layers.

The source of the exothermicity that initiates smoldering in the insulation is being investigated with thermal analytical techniques.

The oxidation behavior of the wood fibers and their components (cellulose, lignin, etc.) is being compared. It appears that cellulose is the major (but not the only) heat source.

#### 4. Fire Plume Characterization

Traditionally, a fire has been treated as a thermodynamic energy source with a spatially uniform heat release. Measurements show significant differences, however, between measurements of plume parameters near the base of a buoyant diffusion flame and predictions based on current, far field models. We are now preparing to measure the time-averaged flow, temperature and concentration fields in order to determine the validity of the classical representation and to refine these models.

It is realized that the plume is not well-mixed, and that it is highly likely that the flame-determining physics and chemistry are dominated by the local fuel-air ratio. Thus we are in the process of determining the fluctuation magnitudes and frequency distribution of the temperature and reactant concentrations in turbulent plumes.

#### 5. Soot Formation and Evolution

Smoke from fires dominates the flame radiation process, is a major factor in hindered egress from the fire vicinity, and is the prime basis for early detection. We have been conducting two studies concerning the fundamentals of smoke and its evolution.

We are in the second year of a long-term study of the basic chemistry of soot formation, carried out jointly with the NBS Thermal Processes Division in the Center for Chemical Engineering. Using the opto-galvanic effect in flames, we have observed enhanced ionization signals with long time delays, which correspond to laser-induced thermal ionization of very small soot particles. This phenomenon only occurs in a narrow stoichiometric range near the sooting limit in premixed flames. From mobility measurements, both mass (2300-6100 amu) and size (1.6-2.2 nm diameter) estimates can be made. In addition, extensive data have been obtained on the laser-induced fluorescence observed in sooting diffusion flames for a series of hydrocarbon fuels. Concurrently we will be characterizing the radical pool in various flames to determine the relevance of premixed flame data to diffusion flames.

Quantitative characterization of hazards associated with smoke, and of smoke detection, requires a knowledge of the properties of the smoke aerosol and development of predicting capabilities for the dynamic processes controlling the movement of the smoke and its growth. We previously have compared various instruments for measuring the physical properties of smoke cooperated in a study of particulate coagulation in a buoyant plume, and studied the smoke-filling process in a room. Recently, we developed a research plan

concerning smoke properties and visibility degradation to develop a quantitative model for predicting visibility degradation with time for a room-sized compartment. In addition, we have studied the characteristics of smoldering smoke from a realistic size scale smoldering source, with the findings that: (1) particle size was much larger than observed for smaller smoldering sources, resulting in lower sensitivity for ionization-type detectors; and (2) that the smoke particulate production rate was time-dependent. Collaborative work has also been conducted in the development of a smoke particulate coagulation model.

#### 6. Turbulent Chemically-Reacting Flow

In a large fire plume, the combustion region is turbulent and is characterized by highly variable (both spatial and temporal) distributions of temperature and species concentration. In such cases the flame properties are dominated by the substantial temperature and species concentration fluctuations. Due to the scarcity of measurements on such systems and the complexity of the phenomena, the understanding of turbulent fire plumes is poor. We have initiated an investigation of turbulent chemically-reacting flow for the purpose of enhancing the understanding of the nonlinear coupling which occurs between chemical reaction and turbulent flow mixing. Currently, as a first step in a planned series of experiments, the turbulent mixing of two different gases is being studied in the absence of chemical reaction by the use of a laser Rayleigh scattering technique. Subsequent steps will incorporate chemical reaction into the experimental system coupled with a numerical and theoretical modeling effort.

#### Associated Grants and Contracts

1. Clemson University, Michael J. Drews - "Ternary Reactions Among Polymer Substrate-Organohalogen-Antimony Oxides in the Condensed Phase Under Pyrolytic, Oxidative and Flaming Conditions."
2. SRI International, Sharon K. Brauman - "Polymer Degradation During Combustion."
3. University of Montana, Fred Shafizadeh - "Chemistry of Smoldering Combustion and Control."
4. Princeton University, Irvin Glassman - "An Experimental Investigation of Flame Spread Over Condensed Combustibles: Gas Phase Interactions."
5. Lawrence Berkeley Laboratory, Patrick Pagni - "Fire Modeling."
6. Lawrence Berkeley Laboratory, C. L. Tien - "Thermal Radiation of Luminous Flames and Smoke."

7. AeroChem Research Laboratories, Hartwell F. Calcote, "Soot Nucleation Mechanisms in Fires."
8. Princeton University, Forman A. Williams - "Studies of Flame Extinction in Relationship to Fire Suppression."
9. University of California, Simon L. Goren - "Dynamics of Smoke and Inert Tracers Produced in Porous Fuels."
10. University of Maryland, T.-M. Shih - "Theoretical Investigation of Large-Scale Turbulent Pool Fires."

FIRE HAZARD ANALYSIS  
FIRE SAFETY ENGINEERING DIVISION  
CENTER FOR FIRE RESEARCH

Professional Personnel

Alan Gomberg, Acting Head  
Louis Clark, Operations Research Analyst  
S. Wayne Stiefel, Operations Research Analyst  
Victoria Shaw, Programmer

Program Objectives

The work carried on in this program is based on two major objectives. The first is to characterize fire hazards and fire risk by analytical means and to evaluate strategies for reducing fire losses on a cost/benefit basis, both to help establish research priorities and to guide the development of test methods for codes and standards. The second objective is to provide access to fire loss data for CFR.

Project Areas

1. Decision Analysis

Decisions on the choice between strategic alternatives for reducing fire losses should be based on a systematic consideration of all benefits, risks and costs. However, because of the complexity of safety problems and the uncertainties inherent in the evaluation of strategies for reducing accidental losses, the choice among strategies is difficult. We have developed analytical techniques for assessing the risks and avoided damages associated with different fire safety alternatives, and the economic costs of these alternatives. Decision analysis provides the analytical framework for the combination of these loss and cost assessments in choosing the most cost effective strategy for addressing a particular fire problem. The initial decision analysis study of alternatives for the reduction of upholstered furniture fire losses served to establish the utility of this approach for fire hazard applications. A major decision analysis study is underway on the residential fire problem. Decision analysis is also being applied in other fire safety areas including health care facilities and arson.

2. Risk Analysis

This project area focuses on the development of risk assessment tools and methodologies designed to enable users to perform risk management functions. Emphasis is on developing means by which the strengths of various risk estimation methods can interact in a comprehensive approach

to fire risk assessment. The initial effort in this area involves the development of a risk assessment based management system to assist in the allocation of fire safety project funds in national park facilities.

### 3. Special Studies

The growth of the National Fire Data Center at the U.S. Fire Administration has provided more and better data for fire hazard analysis. Using these data as a basis, we perform special studies related to the characterization of specific fire hazards. Current special study topics include the following:

- Identification of factors associated with high fire death rates in rural areas and certain geographical areas.
- Feasibility of linkage of fire incident report files with demographic data bases, to permit future analysis of fire incident data as a function of population characteristics.
- Assessment of potential cost effectiveness of residential sprinkler systems and development of methods to improve sprinkler cost effectiveness.

#### Associated Contract

1. SRI International, Fred L. Offensend - "Continuation of Decision Analysis Studies in Fire Hazard Analysis"

FIRE MODELING  
FIRE SAFETY ENGINEERING DIVISION  
CENTER FOR FIRE RESEARCH

Professional Personnel

James Quintiere, Group Head  
Howard Baum, Research Physicist  
Daniel Corley, Physicist  
Margaret Harkleroad, Physicist  
Walter Jones, Physicist  
William Rinkinen, Engineering Technician  
Kenneth Steckler, Physicist  
Takeyoshi Tanaka, Visiting Scientist, B.R.I., Japan

Program Objectives

Through our research and grant program we aim to develop mathematical solutions to problems in fire growth so that they may be applied in fire safety design analysis and in the quantification of a material's contribution to fire. Our approach includes a range of mathematical techniques from exact to experimentally derived correlations as well as experiments designed to verify, elucidate, or measure significant fire growth parameters required in modeling.

Project Areas

1. Advanced Computational Methods

This work aims at developing computational methods and models to predict the detailed features of fire phenomena. A joint method with the Center for Applied Mathematics (R. Rehm) has developed a model [1,2] which predicts the large scale transient features of temperature and flow in a closed two-dimensional room subject to an idealized fire source. It is being further developed to include the effects of fire particulate distribution [3] using Lagrangian "particle-tracking" techniques. An alternative method based on analytical and finite Fourier series techniques is being examined. It has been applied to model fluid mechanics and combustion problems [4]. An ultimate goal of this work is to establish practical computer-based models for three-dimensional geometries.

References:

1. Baum, H., Rehm, R., Barnett, P., Corley, D. and Lewis, J.:  
Finite Difference Calculations of Buoyant Convection in an Enclosure  
- Part I, NBSIR in review.

2. Rehm, R.G. and Baum H.R.: Numerical Model of Convection in a Room Fire, presented at the Eastern Section Combustion Institute Meeting, 1980.
3. Mulholland, G.W. and Baum, H.R.: Effect of Initial Size Distribution on Aerosol Coagulation, Phys. Rev. Let., 45, 1980.
4. Baum, H., Corley, D., and Rehm, R.: A Parabolic Spectral Method for Combustion and Convection Problems, presented at the SIAM Meeting, June 1981.

## 2. Compartment Fire Dynamics

Overall and discrete features of compartment fire dynamics are being examined by control volume (zone) analyses and by experimental methods [1]. A review and assimilation of the various zone models for the prediction of fire growth in compartments are being made. Developments of our own code have addressed the case of crib fires in a compartment and results were compared with data [2,3]. Recent comparisons of multi-room fire codes have been made with corridor smoke filling experiments [4]. Also Dr. Tanaka, visiting from BRI, Japan, is refining his multi-room analysis and has succeeded in obtaining preliminary results for a large (five-story) building. Our experimental study of fire induced flows into rooms is obtaining the effect of fire location and room opening configuration on (orifice) flow coefficients [5] and fire plume entrainment [6]. Also a simple correlation was developed to predict the temperature rise in a room due to energy release from a fire [7].

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1. Quintiere, J.: Overview of Fire Modeling, SFPE Symposium Proceedings, University of Maryland, March 1981.
2. Quintiere, J.G., and McCaffrey, B.J.: The Burning of Wood and Plastic Cribs in an Enclosure: Volume I. NBSIR 80-2054, November 1980.
3. Quintiere, J., Steckler, K., and McCaffrey, B.: A Model to Predict the Conditions in a Room Subject to Crib Fires, First Specialist Meeting (Int.) of the Combustion Institute, France, July 1981.
4. Cooper, L.Y., Harkleroad, M., Quintiere, J. and Rinkinen, W.: An Experimental Study of Upper Hot Layer Stratification in Full-Scale Multi-room Fire Scenarios, The American Society of Mechanical Engineers, ASME Paper 81-HT-9.
5. Steckler, K., Quintiere, J. and Rinkinen, W.: Fire Induced Flows Through Room Openings - Flow Coefficients, presented 1980 Eastern Section Combustion Institute Meeting, NBSIR in review.

6. Quintiere, J.G. and Rinkinen, W.J. and Jones, W.W.: The Effect of Room Openings on Fire Plume Entrainment, Combustion Science and Technology, to be published 1981.

7. McCaffrey, B.J., Quintiere, J.G. and Harkleroad, M.F.: Estimating Room Temperatures and the Likelihood of Flashover using Fire Test Data Correlations, Fire Technology, to be published 1981.

### 3. Fire Spread

This area encompasses work to develop new methods for measuring flame spread on materials in a form suitable for inclusion in mathematical fire growth models (e.g.,  $V_f = C_f (T_{ig} - T_s)^n$ ) [1,2]. Under Federal Aviation Administration (FAA) sponsorship we are examining test method strategies for "creeping" (lateral or downward) and "wind-aided" (upward or under) flame spread on six varied materials. A wall fire spread model has also been incorporated in our zone model for a room [3], and an experimental ( $\sim 1/3$  scale) study of compartment wall fire burning behavior has been initiated for further development and validation of that analysis.

#### References:

1. Quintiere, J.: An Approach to Modeling Wall Fire in a Room, Fire Safety J, 3, 1981.
2. Quintiere, J.: A Simplified Theory for Generalizing Results from a Radiant Panel Rate of Flame Spread Apparatus, Fire and Materials, to be published 1981.
3. Steckler, K.: A Calculation of Wall Fire Spread in a Compartment, NBSIR in review.

### 4. Fire Performance and Risk

This area attempts to synthesize and analyze measurements of material performance in test methods, their relationship to real fire performance, and to develop methods for calculating specific risks in fire. A critical review of flammability and smoke test methods and their ability to correlate full-scale fire test data is underway for the FAA. The ultimate application of test procedures for aircraft interior material is being considered. An allied effort with the CFR Toxicology program examined smoldering fires in closed spaces, and developed an analysis that predicts the CO development for specific smoldering items. Mass loss and decomposition data are required, and general agreement with cotton and polyurethane smoldering fires was achieved [1].

#### Reference:

1. Quintiere, J.G., Birky, M., Macdonald, F. and Smith, G.: An Analysis of Smoldering Fires in Closed Compartments and their Hazard due to Carbon Monoxide, report in review.

### Associated Grants

The following grants are in support of the goals of the fire modeling program:

1. "Modeling of Wind-Aided Fire Spread", F.E. Fendell, Engineering Sciences Laboratory, TRW Systems, (monitor: H.R. Baum).
2. "An Investigation of Fire Impingement on a Horizontal Ceiling", G.M. Faeth, The Pennsylvania State University, (monitor: H.R. Baum).
3. "Computer Modeling of Aircraft Cabin Fire Phenomena", K.T. Yang, University of Notre Dame, (monitor: W.W. Jones).
4. "Flame Spread and Spread Limits", J.S. T'ien, Case Institute of Technology, (monitor: J.G. Quintiere).
5. "Experimental Study of Environment and Heat Transfer", California Institute of Technology, E.E. Zukoski, (monitor: J.G. Quintiere).
6. "Computer Modeling of Aircraft Cabin Fire Phenomena", R.L. Alpert, Factory Mutual Research Corporation, (monitor: K.D. Steckler).
7. "Home Fire Project", H. Emmons / R. Friedman, Harvard University / Factory Mutual Research, (monitor J. Rockett\*).
8. "Effects of Material Properties on Burning and Extinction Fires", M. Sibulkin, Brown University, (monitor J. Rockett\*).

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FIRE PROTECTION SYSTEMS RESEARCH  
FIRE SAFETY ENGINEERING DIVISION  
CENTER FOR FIRE RESEARCH

Professional Personnel

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Warren D. Hayes, Fire Prevention Engineer  
John H. Klote, Mechanical Engineer  
John G. O'Neill, Fire Prevention Engineer

Program Objectives

An integrated approach to fire protection design includes considerations for 1) alerting the occupants prior to the attainment of adverse environmental conditions, and 2) actively prohibiting or reducing the growth and spread of the fire and combustion products. The principal objective of this research group is to provide the engineering basis necessary to rationally incorporate hardware technology which addresses these considerations into a broader, more integrated fire protection design.

The current focus of this work rests in three areas: fire detection, fire suppression, and smoke control. Primary activities in these areas encompass the development of engineering design, installation, performance, and reliability requirements which will lead to appropriate test methods upon which to judge system capabilities, and overall design technology.

Two key factors in developing technology for fire protection systems are the ability to extend research results to innovative uses, and the need to create cost reductions through refinements in system designs. To do this, parallel research efforts are being pursued to provide a basic understanding of both the physical phenomena to which hardware systems must respond, and the design and performance of the systems themselves.

Project Areas

1. Smoke Detector Effectiveness in Health Care Facilities

Last year a survey and subsequent analysis of the field experience of smoke detectors in health care facilities were completed. A report includes discussion, based on information received through the survey, of the frequency of real and false alarms, installation practices, types of detectors installed, general maintenance, and insitu testing procedures.

## 2. Performance of Sprinklers in Health Care Facilities

One occupancy type of particular interest to CFR in examining sprinkler performance is the patient room - health care facility. An extensive series of full-scale tests was conducted last year to examine the performance of sprinkler systems in extinguishing bedding and combustible wardrobe fires in a patient room. Key design parameters which were considered included sprinkler spray density, water flow, room ventilation and the use of privacy curtains. The results were analyzed in terms of "life safety" criteria, and appropriate design recommendations were submitted to the project sponsor, Health and Human Services, and to the related standards committees. Work continues in this area in an effort to provide comprehensive guidance regarding sprinkler design requirements for health care facilities.

## 3. Sprinkler Protection of Open Stairways

A uniquely different project involved the conduct of full-scale experiments to determine the performance of selected water curtain sprinkler systems and spray nozzle systems in reducing the flow of heated smoke into an open stairwell. This work was designed to refine and update test results dating back to the 1940s which serve as the basis for design methods currently used in the National Fire Protection Association (NFPA) sprinkler and life safety codes. Experimental full-scale testing was conducted in a specifically constructed four-story facility. Cooling effectiveness, efficiency of water usage, and flow of combustion gases were measured and performance curves were developed, based on temperature effects for these systems, to indicate their capacity to inhibit the passage of combustion gases into the stairway resulting from the convective heat flow from the burner. A report has been completed on this work.

## 4. Sprinkler Response to a Compartment Fire

An ongoing project of a more fundamental nature is a full-scale study to examine the response characteristics of sprinkler heads at different locations in a compartment to various simulated fire growth rates. The experiments have been designed to examine the variation in the activation time of pendent and sidewall sprinkler links of different thermal mass in a typical room/corridor configuration. Limited measurements of temperature effects on simulated links of varying mass are also included. It is intended that the data provided from this work will lead to engineering guidelines for the use of sidewall sprinkler installations, where delays in activation due to sprinkler location may significantly affect fire control at low water supply rates.

## 5. Fire Suppression Systems for Offshore Platform Blowout Fires

A substantial effort was initiated in 1980 to examine the problem of suppression of blowout fires on offshore oil and gas platforms for the U.S. Geological Survey. A moderate term research plan has been prepared,

with the initial focus towards scaled experimental studies of the necessary flow rates for particular suppression agents and the appropriate delivery mechanisms to extinguish large flowing hydrocarbon fires.

#### 6. Stairwell Pressurization Systems

The use of stairwell pressurization systems has grown in the U.S. over recent years. Field tests, including sulfur-hexafluoride (SF<sub>6</sub>) tracer gas tests, pressure-velocity tests, and smoke candle tests have been conducted by NBS in buildings in Nashville, Tennessee which incorporate multiple injection systems. As an adjunct to this project a computer based model was developed to simulate smoke migration in stairwells having pressurization systems. This model provides a useful tool for the design of stairwell pressurization systems in multistory buildings. A progress report of this effort was prepared during 1980. During 1981-82, a joint effort will be conducted with CSTB (France) to verify the stairwell pressurization model with empirical data. In addition, the model will be extended to include analysis of elevators and vestibules.

#### 7. Smoke Control Manual

NBS is monitoring the development of a smoke control handbook under a grant to Integrated Systems, Inc. This handbook will contain practical design information suited for mechanical systems designers in designing smoke control systems. The availability of this manual should help to reduce failures in smoke control systems and thereby improve the potential for saving lives during building fires.

#### 8. Computer Modeling of Smoke

Two computer programs designed to model smoke movement in buildings have been developed under contract to Integrated Systems, Inc. (ISI). One of the programs, designed to evaluate steady-state conditions, is currently undergoing verification testing by comparing results with other computer models and with manual calculations. Upon successful completion of this exercise, verification of the transient model will be initiated. These programs will serve as a basis upon which to develop a methodology for analysis of building designs in order to optimize the design of the smoke control systems.

#### 9. Smoke Penetration of Acoustical Tile Ceilings

A project was initiated in 1980 to examine the smoke penetration of acoustical, fire rated ceilings under actual fire conditions as would typically occur in a hospital patient room. A test facility consisting of four hospital rooms and a section of corridor was built within another building. The test facility has a ventilation system which will simulate the air movement from a hospital HVAC system. The project is designed to determine whether smoke will penetrate the ceiling or flow into other hospital areas. A report of this work will be completed during 1981.

## 10. Smoke Movement on Merchant Ships

In addition, field tests have been conducted using pressure mapping and SF<sub>6</sub> tracer gas to simulate the movement of "cold smoke" on board merchant ships. Evaluation of this data is ongoing to determine the suitability of applying smoke control techniques for buildings to merchant vessels, and necessary modifications. A progress report will be prepared during 1981.

### Associated Grants/Contracts

1. University of Maryland, H. E. Hickey and J. E. Alleman - "An Investigation of the Water Quality and Condition of Pipe in Existing Automatic Sprinkler Systems"
2. University of Massachusetts, E. H. Nober - "Waking Effectiveness of Household Smoke and Fire Detectors"
3. Integrated Systems, Inc., New Brunswick, Maryland, J. Fothergill - "Mechanical Designer's Smoke Control Manual"

FIRE RESEARCH INFORMATION SERVICES  
FIRE RESEARCH RESOURCES DIVISION  
CENTER FOR FIRE RESEARCH

Project Leader

Nora H. Jason

Program Objective

The Fire Research Information Services (FRIS) is an on-going project within the Center for Fire Research (CFR), National Bureau of Standards. It was started in 1971 and incorporated several personal collections at the National Bureau of Standards, as well as the Federal Fire Council collection. Over the years it has grown and now contains approximately 30,000 reports, documents and books. (On an average, 2000 items are added to the collection each year.) It reflects the programmatic needs of the Center for Fire Research, as well as developing a national and international fire research collection for use by NBS staff, researchers, fire departments, fire science students and the fire community at large.

An extensive document distribution program is carried on, both on a regular basis and on a demand basis. The publication and distribution of grantee reports (in the NBS Government Contract Report series) to selected subject interest groups is part of this program. All NBS report series are listed in the automated bibliographic data base and available through the Government Printing Office or the National Technical Information Services.

The journal collection contains approximately 120 titles. The focus is on the research activities of the CFR, as well as fire-related research needs. The titles are quite unique to FRIS.

For interested people who cannot come to the FRIS, an extensive Interlibrary Loan program is carried out with participating libraries throughout the United States. FRIS is located at the National Bureau of Standards, Building 224, Room A-252. The telephone number is (301) 921-3249.

FIRE TEST METHODS RESEARCH  
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Program Objectives

The objectives of Fire Test Methods Research are to conduct research and development studies to evaluate the fire and high temperature performance of materials and products used in construction assemblies and transportation systems and to reduce the probability of the growth and spread of fire by developing fire test methods and acceptance criteria for furnishings and construction materials and assemblies. In addition, the Program manages the Center's large-scale experimental fire test facility.

Project Areas

1. Shipboard Fire Research

The objectives of this project are to evaluate the potential fire hazard of shipboard and submarine hull insulations and to improve the application of laboratory fire tests for screening compartment lining materials. The approach is to subject the variety of shipboard and submarine hull insulations, some of which are protected with fire resistant materials, to laboratory fire tests on ignitability, flame spread, rate of heat release, and potential heat. The performance of these insulations are then examined in quarter- and full-scale compartment fires. By comparing the time to flashover or the maximum temperature reached in the full-sized compartment with the results of the laboratory fire test methods, improved acceptance criteria for materials can be derived. By comparing the performance of the material between the full- and reduced-scale fire test, the usefulness of the quarter-scale model as a screening tool can be evaluated. At the same time, analytical and experimental studies are being carried out to improve the ability of the quarter-scale model to predict full-scale fire behavior. A standard test procedure based on the quarter-scale model is being developed.

## 2. Flame Retardant Permanency of Cellulose Insulation

The objective of this project is to study the effect of temperature and humidity cycling on the flammability characteristics of cellulosic loose-fill insulation. Based on the analysis of climatological data for regions of the country having widely differing weather conditions, various test cycles (time, temperature, humidity, number) are being imposed on cellulose insulation having different flame retardant compositions. Performance will be based on measurement of the critical radiant flux and the resistance to ignition by a smoldering cigarette. A proposed test method for inclusion in the Department of Energy Residential Conservation Service standard for cellulosic insulation will be written with recommended acceptance criteria.

## 3. Fire Safety of Amtrak Furnishings

The objective of this project is to develop and test cost beneficial concepts for reducing fire hazards in passenger rail vehicles. Specimens of passenger rail vehicle interior components have been obtained and are being assembled into sectional mock-ups for full-scale testing. Taking into account fire scenarios, usage geometry, and specific applications in railroad cars, mock-ups will be tested. An attempt will be made to predict the mock-up performance on the basis of small-scale laboratory tests. In addition, assessment will be made of the proposed fire safety guidelines being promulgated by the Transportation Systems Center of the Department of Transportation for rail vehicles. NBS will assist the Federal Railroad Administration in the conduct of full-sized burn experiments in actual rail vehicles by recommending "improved" materials and appropriate instrumentation of the test facility and recommending appropriate ways of analyzing and interpreting the resultant data.

## 4. Flame Spread

The objective of this project is to contribute to the development of test methods and procedures which can provide the input data required by mathematical models for predicting the downward, lateral, and upward flame spread in aircraft cabin fires. These methods include a flame spread test which can produce the empirical constants for the flame spread rate equations for downward and lateral flame spread and a heat release rate calorimeter for determining the effective heat of combustion, the effective heat of vaporization, the stoichiometric oxygen to fuel ratio, and the mass loss rate as a function of incident heat flux, which would all be used in calculating the flame spread rate in the direction of air flow. An attempt will then be made to calculate the empirical constants from more fundamental properties of the materials and, thus, predict the results of the test methods. This work is being done in cooperation with the Fire Modeling group.

## 5. Solar System Fire Risk Assessment

The objective of this program is to evaluate methods for determining the tendency of materials to self-heat after prolonged exposure to moderately elevated temperatures. Material tests will be conducted using several candidate test procedures and results compared with data in the literature and available field experience on the effects of long-term heating. In addition, tests will be conducted in which materials are heated by convection, radiation, and conduction separately to determine if the mode of heating affects the rate of degradation which may lead to self-heating. Materials examined will be those commonly found in solar collectors and the test results will be tabulated so as to be useful to the designers of solar collectors.

## 6. Fire Test Standards

The objective of this project is to develop laboratory test methods for the ignitability, flame spread rate, and rates of heat release and smoke production of construction and furnishing materials. These tests are intended to supply the input data on the fire properties of a material needed by the analytical models being developed for fire growth and spread in buildings. The tests must meet the criteria for ASTM Fire Test Standards, and their precision and accuracy must be demonstrated. The current fire test methods used in CFR will be maintained and improved in conjunction with the ASTM task group activities.

Work will continue on the development of the ease of ignition test which measures the time to ignition for vertically oriented interior finishing and furnishing materials by flame impingement. Some important improvements have been suggested as a result of preliminary round robin tests carried out on this test method.

Test methods for measuring the lateral and downward flame spread rates along a vertical surface as a function of the surface temperature ahead of the flame will be developed. In addition, a test method is needed to characterize the flame spread rate in the direction of air flow up a wall or across a ceiling. Some experiments are planned in this area which involve measuring the flame heights above vertical specimens as a function of their heat release rate.

Work will continue on the development of the heat release rate calorimeters. An internal round robin will be run on a range of materials on all of the calorimeters at NBS in each of their modes of operation. In addition, a furniture calorimeter has been built which can measure the heat release rate of full-size furnishing items by this technique.

## 7. Fire Test Criteria

The objective of this project is to develop acceptance criteria for materials and assemblies which will provide an acceptable level of fire safety in specific applications. This involves the selection of a suitable set of test methods and setting limits on the fire performance of the materials or assemblies in these tests. The acceptance criteria will be derived from a correlation between the results of the fire tests on the materials and assemblies and their full-scale burning behavior. The output of this project will be used by building code officials and the government regulatory agencies to reduce the incidence and severity of unwanted fires within their jurisdiction.

The analytical models being developed for room fire growth will be modified to take into account the spread of flame over the combustible interior finish materials and their heat release rates. Well instrumented reduced-scale and full-scale room fire tests will be run with interior finish materials whose fire properties have been measured in order to validate or upgrade the computer models for predicting the contribution of interior finish materials to fire growth. The acceptance criteria for these materials can then be based on their predicted performance in a standard room fire test or other enclosure fire of concern. The analytical model serves as a guide for correlating the results of the laboratory tests with the full-scale burning behavior.

This project is also responsive to other applications which may arise due to the incidence of or recognized potential for serious fires in the field. Through investigation and/or analysis of these real or potential fires, scenarios are developed which can form the basis for (1) an analytical model which can predict the hazard based on small-scale laboratory tests or (2) a mock-up test which captures the essential features of the real life hazard.

## 8. Oxygen Consumption Calorimetry

The objective of this project is to improve the instrumentation used to determine the heat release rates by oxygen consumption for the various applications encountered in CFR, to establish the accuracy of the method and its sensitivity to the test variables, and to make recommendations as to the optimum instrumentation for a particular application in order to achieve an acceptable balance of simplicity, accuracy, time response, etc. The output of this work will be to refine the oxygen consumption calorimeter and the measurement of heat release rate in the full- and reduced-scale room fire tests, the fuel contribution in the ASTM E 84 tunnel, and the heat release rate of assemblies in the ASTM E 119 furnace.

A systematic study is in progress on the accuracy, sensitivity, and time response of the oxygen consumption calorimetry technique by burning solids, liquids, and gases of known chemical composition and heat of combustion at various heat release rates in the oxygen consumption calorimeter. The effect of gas pressure, temperature, chemical composition,

and flow rate through the analyzer on the measured concentration of O<sub>2</sub>, CO<sub>2</sub>, and CO is being determined for the different types of analyzers available. A comparison of different types of volume flow rate measurements in the exhaust duct--such as orifice plates, bidirectional probes, and pitot tubes--will be made.

## 9. Large-Scale Fire Research Facilities

The following large-scale testing facilities are available at the Gaithersburg site for use by CFR programs as needed:

### Building 205:

This is a 60-ft. by 120-ft. test building with controlled environmental conditions; a large smoke collection hood serves the individual experimental facilities and is connected to a large stack with afterburner. The following facilities are contained within the building.

A room burn and smoke test facility. This is a two-story structure, 20 ft. by 20 ft. in plain view, which may be used for fire growth studies and for examining fire and smoke spread through ducts, dampers, doors, etc.

A corridor test facility. This is a 12-ft. wide, 30-ft. long corridor with several burn rooms attached which can be used for a variety of studies, including the contribution of furnishings and interior finish, as well as sprinkler performance.

A research fire resistance furnace. This furnace is designed to meet the essential requirements of ASTM E 119 as well as to provide for more rapid heating of walls (10 ft. by 8 ft.), floor/ceilings (10 ft. by 8 ft.), and columns (8 ft. high). Structural loads up to 30 tons may be applied, and furnace pressure may be adjusted from -0.05 in. to +0.15 in. water gage. The furnace may be used to test components, innovative constructions, and the effects of joints in wall/floor assemblies.

Building 205 also houses rooms for specialized calorimeters, small furnaces, and model enclosures. Laboratories are available for keeping and testing rats for toxicology studies in conjunction with large-scale fire experiments. Shops, instrument rooms, and service areas are also located in the building.

Mobile homes specially instrumented and outfitted to permit repetitive tests of fire growth and smoke movement and detection are adjacent to Building 205.

NBS Annex:

This is a former DOD facility adjacent to the NBS site which is available for special tests. It has a three-story stair tower which can be used for smoke spread and sprinkler studies; a dormitory building containing a 60-ft. long loaded corridor with lobbies at each end; a large laboratory designed for smoke detector testing; and, an electrical testing laboratory.

Instrumentation and Staff:

Each of the facilities is equipped with automatic data recording systems to collect a wide variety of information from the large-scale tests. A staff of five technicians and an instrumentation specialist are available to support CFR research programs. An instrumented van is available for field testing at distant sites.

Associated Grants

1. University of Michigan, George S. Springer -- "Degradation of Mechanical Properties of Wood During Fire"
2. University of California (Berkeley), R. Brady Williamson -- "Intra-laboratory Evaluation of a Standard Room Fire Test"
3. Northwestern University, A. C. Fernandez Pello -- "Fire Propagation in Concurrent Flows"
4. Factory Mutual Research Corporation, A. Tewarson -- "Determination of Fuel Parameters for Fire Modeling"
5. Portland Cement Association, Michael Gillen -- "Extension of Short-Term Creep Tests at Elevated Temperatures"

FIRE TOXICOLOGY RESEARCH  
FIRE SAFETY ENGINEERING DIVISION  
CENTER FOR FIRE RESEARCH

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Program Objective

The objective of research in fire toxicology is to reduce human fire losses from inhalation of toxic combustion products by providing test methods and recommended practices for predicting and reducing the hazard.

Project Areas

1. The development of a toxicity test method.
2. The correlation of small scale toxicity test system with large scale fire experiments.
3. Involvement in MGM, Hilton and Stauffer Hotel Fires
4. The development of performance criteria for portable "sniffers" to be used in arson investigation.

1. Development of Toxicity Test Method

A toxicity test method has been developed to identify those materials that produce unusually high toxic combustion products as distinguished from those materials that produce products that are equal to or less toxic than wood combustion products. The toxicity of combustion products is determined at 3 decomposition temperatures, 1 flaming mode and 2 non-flaming modes. Heat stress and oxygen deprivation are not included as part of the toxicity assessment. Six male rats are exposed in the head only at each product concentration. The three biological end-points examined during the development of the test method were incapacitation during the thirty minute exposure, lethality during the thirty minute exposure, and lethality during the thirty minute exposure and a 14 day post-exposure period. An ad-hoc toxicity committee agreed that the lethality end-point based on the 30 minute exposure and 14 day post-exposure period provides sufficient data with which to distinguish those materials which produce combustion products that are much more toxic than Douglas fir. To determine if the combustion products of any material would act extremely quickly, a 10 minute animal exposure at a mass loading of

30 mg/l would be carried out on any material in which the  $LC_{50}$  for the 30 minute and 14 day exposure was between 2 and 30 mg/l. The  $LC_{50}$  is the concentration which causes lethality in 50% of the animals.

Blood chemistry (carboxyhemoglobin, pH, and other blood parameters) is correlated with specific toxicant analysis to help determine the cause of incapacitation and death. Evaluation of a limited number of materials that produce different toxicological syndromes has demonstrated the applicability of the proposed test method.

Seven laboratories selected from academia, industry and government used the NBS test method for measuring the toxicity of combustion products in order to evaluate the reproducibility of results. The experimental design specified that each laboratory was responsible for Douglas fir plus three other materials from a total of 12 natural and synthetic samples. NBS determined the toxicity of all 12 materials.

The materials were chosen by an ad-hoc committee and distributed by NBS. All laboratories were required to determine the toxicity of the materials under both flaming and non-flaming conditions; and to measure blood carboxyhemoglobin. Toxicity was determined on the basis of incapacitation (hindleg flexure) during the 30 minute exposure and of lethality during the exposure and 14 day post-exposure period. NBS calculated the  $EC_{50}$  results [mass-loading/chamber volume (mg/l) necessary to induce incapacitation of 50% of the rats] and  $LC_{50}$  results (mg/l necessary to cause lethality in 50% of the rats) from the data supplied by the participating laboratories. The results were statistically analyzed by both a t-test and a z-test. We conclude from the inter-laboratory evaluation that the NBS toxicity test method will provide consistent results among various laboratories. Also, the results show that the division of materials into various toxic classifications is the same regardless of whether incapacitation or lethality data are used.

As indicated in the listing of associated grants, George Washington University has been involved in the toxicological efforts at NBS with two major objectives: (1) to provide toxicological support to NBS in the development of the proposed combustion toxicity test method, and (2) to investigate the applicability of histologic and various physiological techniques to identify target organ(s) to be studied in the protocol development. The first objective has been adequately discussed above.

The interest in the second objective is to help define the mode of action of toxic agents in order to identify early indications of developing toxicity and the levels at which significant functional disability or dysfunction occurs. The work involves the establishment of a logical series of screening tests with particular emphasis on those applicable to materials that produce unusually toxic combustion products, although the techniques would be applicable to other materials as well.

Present evidence suggests that smoke from some materials is capable of exerting both acute and delayed effects. Therefore an attempt will be

be made to establish threshold levels for accurate descriptions of the event of incapacitation, deferred toxicity and acute death.

## 2. Correlation of Small Scale Toxicity Test System with Large Scale Fire Experiments

Smoldering combustion of two materials, flexible polyurethane foam and cotton, has been carried out in large scale (closed room) experiments for comparison with the protocol procedure (small scale). Chemical analysis of the products generated and animal exposures in both systems are used as a basis for determining whether toxic products generated in the protocol system are consistent with self-smoldering combustion in large scale. Smoldering combustion of cotton and polyurethane was chosen since smoldering ignition of these two materials is the principal fire scenario that leads to loss of life.

In the case of flexible polyurethane foam, the yield of carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) is very nearly the same in the large scale and protocol experimental procedures. Total hydrocarbon production is somewhat lower in the large scale self-smoldering case, while hydrogen cyanide (HCN) is higher. However in both cases, the HCN concentrations are not high enough to be the primary toxicological factor. "Fingerprint" profiles of the products from the two types of combustion are qualitatively very similar.

Animal experiments confirm the relative significance of the CO and HCN results. However, the LC<sub>50</sub> results show the protocol to be toxicologically more severe than the self-smoldering large scale experiments. The toxicological syndrome also appears to be different in the two cases.

To investigate these differences, measurements of TDI concentrations in the protocol and in the self smoldering large scale experiments have been made. In the protocol, peak concentrations of about 10 ppm were observed while in the self smoldering large scale experiments, TDI concentration was less than 0.3 ppm. However these differences alone probably do not account for the different toxicological syndrome.

In the cotton comparison, the yields of degradation products between the two scales are very similar to CO and CO<sub>2</sub>. Preliminary toxicological data suggests that the two experiments are similar, although again post-exposure deaths occurred in the small scale experiments that did not occur in the large scale experiments.

Preliminary flaming combustion of two materials, wood and modacrylic, has been carried out in large scale experiments for comparison with the protocol procedure. Chemical analysis of the products generated in both systems are used as a basis for determining whether toxic products generated in the protocol system are consistent with flaming combustion in large scale. Animal exposures were not made.

In the case of wood, the yield of CO is higher in the protocol procedure than in flaming combustion in the large scale. However a wider range of flaming conditions in the large scale test needs to be investigated. In the case of modacrylic, the yield of HCN is very nearly the same in the large scale and protocol experimental procedures.

### 3. Involvement in MGM, Hilton and Stauffer Hotel Fires

Three accidental hotel fires involving substantial loss in human life occurred during the past year. Investigations of these fires included the identification of various materials that contributed to the fire in the hotels, analysis of blood samples from victims and consulting with various investigators including the U.S. Fire Administration.

While the studies on these fires are incomplete, the information obtained from these activities has provided additional insights into the toxicological consequences of accidental fires.

### 4. Performance Standard for Hydrocarbon Vapor Detectors (Arson)

A method of detecting and locating residual flammable liquids absorbed in fire debris of porous materials (e.g. wood, carpets, upholstery, and cellular plastics) is a vital step for detection of arson initiated fires. Portable hydrocarbon vapor detectors are devices which can be and are often used to locate debris that is slowly evolving vapors of residual flammable liquids. However, evaluation of the sensitivity and selectivity of vapor detectors to hydrocarbon vapors in an environment containing fire debris has not been made. Knowledge of vapor detector response under a range of conditions is essential for effective use and appropriate selection of these instruments.

The basic types of detectors used the following means of sensing organic vapors:

1. catalytic combustion,
2. flame ionization, and
3. photoionization.

A commercial instrument using each of the methods of vapor detection is being used in this investigation.

A performance standard for vapor detectors was designed and is in preparation. The research leading to this standard includes the determination of the sensitivity of the three basic types of detectors (commercially available) to vapor standards consisting of one and two components common to petroleum distillates. The vapor standards were prepared dynamically by continuously mixing constant flows of hydrocarbon vapor and air using the method recently developed and reported ("Hydrocarbon Vapor Standards for

Performance Evaluation of Combustible Gas Detectors", NBS Special Publication 480-43, in press).

Because fire debris of many materials also liberates low levels of combustible vapors, a method was designed and is being used to determine the levels of these vapors. This phase of the research includes measurement of the response of the detectors to vapors from simulated fire debris which was prepared from several materials without an accelerant and similar materials containing a liquid accelerant.

#### Associated Grants

University of Maryland, Maryland Institute for Emergency Medical Services, Roy Myers, "Fire Casualty Study".

University of Pittsburgh, Yves Alarie, "Toxicity of Plastic Combustion Products".

Colorado School of Mines, Kent Voorhees, "Characterization of Aerosols from Fires".

George Washington University, Richard A. Kenney, "Toxicological Studies of Combustion Products".

PRODUCT FLAMMABILITY RESEARCH  
FIRE PERFORMANCE EVALUATION DIVISION  
CENTER FOR FIRE RESEARCH

Professional Personnel

Richard W. Bukowski, Head  
Vytenis Babrauskas, Fire Protection Engineer  
Emil Braun, Physicist  
John Krasny, Textile Technologist  
Joseph Loftus, Research Chemist  
Richard Peacock, Chemical Engineer

Program Objectives

One objective of the Product Flammability Research Group is to obtain a better understanding of the fire hazards posed by products and materials through the development of standard test methods which evaluate their performance under fire conditions. Another is the characterization of energy-consuming systems, appliances, and wiring as ignition sources to devise ways of reducing the likelihood of ignitions from them.

Project Areas

1. Spontaneous Ignition of Coal (DOE)

The objective of this project is to reduce the incidence of spontaneous ignitions of coal by identifying the causes for such ignition, developing procedures to predict the propensity of various coals to spontaneous ignition, and methods which can be employed to prevent ignition.

2. Fire Safety Aspects of Wood as a Fuel (DOE/CPSC)

This project involves the study of hazards associated with the operation of wood-burning appliances, wood stoves, fireplaces, and fireplace inserts. Specific areas being investigated include clearances to combustible surfaces, protective devices used with reduced clearances, and creosoting/chimney fires.

3. Upholstered Furniture Flammability (CPSC)

Two unique test methods are being developed to provide improved measurements of the hazards posed by furniture at significantly reduced testing costs. The first is a furniture calorimeter in which full-scale items are burned to obtain heat release data which can then be used to predict fire spread and flashover potential in rooms. This calorimeter could obviate the need for much more costly room burn tests but with comparable results. The second is a laboratory-scale cone calorimeter which would

be used to obtain similar rate of heat release measurements on small samples. This calorimeter uses the oxygen consumption principle of sensing and is eventually expected to have wide application, not restricted to furniture. Data from the calorimeter will be useful both for acceptance testing of materials and as input data into room fire models.

4. Test Methods for Explosion-Proof Equipment for Mines (BOM)

In this project, an evaluation of current test methods for the approval of explosion-proof electrical equipment in mines by MSHA will be evaluated against the statutory requirements of Part 18 of 30 CFR. Comparisons to the procedures followed by other laboratories (U.S. and foreign) for similar equipment will also be made, with differences in approach and the significance of these differences to the safety provided to be determined.

Associated Grants

1. Auburn University, Timothy T. Maxwell - "Investigation of the Safety Problems Associated With Fireplace Inserts"
2. Underwriters Laboratories, Incorporated, Wayne Terpstra - "Investigation of Fire Hazards of Fireplace Inserts in Factory-Built and Masonry Fireplaces"

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: AeroChem Research Laboratories, Inc.

Contract No.: NB 80 NADA 1038

Contract Title: Soot Nucleation Mechanisms in Fires

Principal Investigators: Dr. H.F. Calcote  
Dr. D.B. Olson  
AeroChem Research Laboratories, Inc.  
P.O. Box 12  
Princeton, New Jersey 08540

NBS Scientific Officer: Dr. Kermit Smyth

Technical Abstract

Soot formation is characteristic of all fires. Radiative heat transfer from soot plays a dominant role in maintaining the fire and inhalation of smoke is a major cause of fire casualties. Yet the mechanism by which soot forms is not understood.

This program is aimed at understanding the mechanism of soot formation in laminar diffusion flames with the ultimate goal of understanding sooting in fires. The hypothesis being investigated is that an ionic reaction mechanism dominates the nucleation and initial growth of soot particles. Ion concentration profiles in gaseous diffusion flames of several small hydrocarbon fuels are being measured mass spectrometrically, supplemented by Langmuir probe and temperature measurements. Neutral species concentration profiles in the same flames will also be obtained.

The mechanism of soot formation has been the subject of considerable research and much speculation for many years. Recently,<sup>1-3</sup> it has been concluded that an ionic mechanism may be important in the initial phase of the overall process. Figure 1 shows a schematic of the proposed mechanism. We are performing experiments in this program to extend the flame structure studies performed in premixed flames to include diffusion flames, since these systems more closely relate to real fire situations.

Work to date has consisted of flame ion mass spectrometric and Langmuir probe sampling of rectangular and cylindrical one atm diffusion flames of propane and ethylene. Experimental techniques used previously to sample flame ions from low pressure rich and sooting premixed flames<sup>2,3</sup> were found to perform poorly when applied to atmospheric pressure diffusion flames. The low velocity and low heat flux diffusion flames are easily perturbed by the mass spectrometer sampling cones. Several alternative sampling cone styles were designed and tested. Orifice clogging and the possibility of ion-molecule reactions in the quench zone were

additional problems encountered when sampling under the heavy sooting conditions previously studied by Haynes and Wagner.<sup>4</sup> Under leaner conditions the mass spectra show a series of heavy hydrocarbon ions similar to those obtained in premixed flames, providing preliminary evidence that the soot formation process may follow the same mechanism under both conditions.

Langmuir probe measurements were used to obtain absolute total ion concentrations in a rectangular sooting propane flame. Care was necessary to obtain data unperturbed by soot deposition on the probe. These probe data were analyzed to give ion concentration profiles across the flame front at several heights above the burner. Peak ion concentrations were typically  $5 \times 10^{10}$  to  $10 \times 10^{10}$  ions  $\text{cm}^{-3}$ , considerably lower than peak soot particle number densities measured by Haynes and Wagner. It has yet to be demonstrated that this steady state ion concentration is sufficient to support an ionic nucleation mechanism.

PCAH in Soot: Literature data on polycyclic aromatic hydrocarbons adsorbed on soot from various fuels and combustion sources (premixed flames, burning solids, and turbojet engine exhaust) have been analyzed for similarities and to test for correlations between PCAH emissions and fuel composition, physical configuration, or combustor type. Overall it was found that the emitted PCAHs are relatively insensitive to fuel or combustor type. Premixed gaseous flames emitted predominantly the lower molecular weight compounds indene and naphthalene. Kerosene and burning (nonflaming) PVC emitted the highest quantities of the most prevalent PCAH compounds (fluorene, phenanthrene, anthracene, and pyrene), whereas wood fires, the turbojet engine (kerosene fuel), and a benzene flame emitted the highest levels of benzopyrene (a and e isomers combined).

#### References

1. Calcote, H.F., "Mechanisms of Soot Nucleation in Flames - A Critical Review," to be published in *Combust. Flame*.
2. Olson, D.B. and Calcote, H.F., "Ions in Fuel Rich and Sooting Acetylene and Benzene Flames," Eighteenth Symposium (International) on Combustion (The Combustion Institute Pittsburgh, in press).
3. Olson, D.B. and Calcote, H.F., "Ionic Mechanisms of Soot Nucleation in Premixed Flames," Particulate Carbon: Formation During Combustion (Plenum Press, New York, in press).
4. Haynes, B.S. and Wagner, H.Gg., "Sooting Structure in a Laminar Diffusion Flame," *Ber. Bunsenges. Phys. Chem.* 84, 499 (1980).

Reports and Papers

Olson, D.B. and Calcote, H.F., "A Comparison of Polycyclic Aromatic Hydrocarbons in Soot Produced from Various Sources," presented at the Fall Technical Meeting, Eastern Section: The Combustion Institute, Princeton, NJ, November 1980; in preparation for publication.

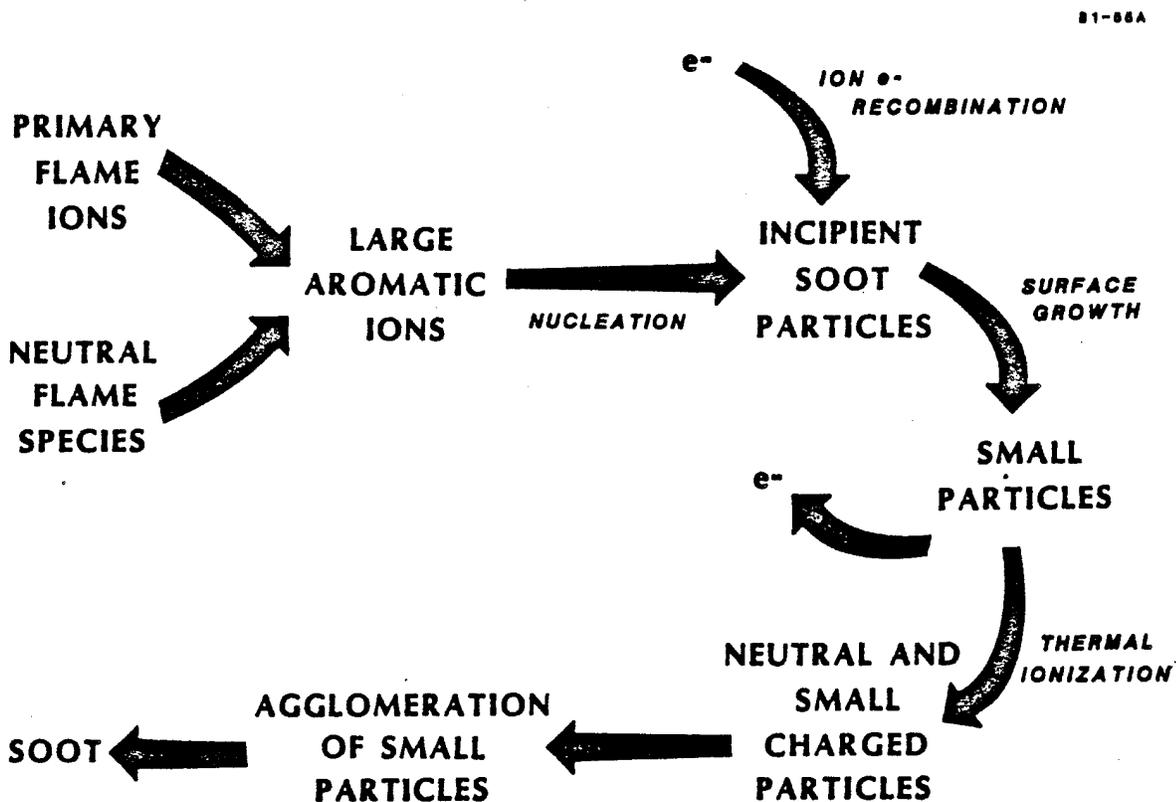


FIGURE 1 PROPOSED MECHANISM OF SOOT FORMATION

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: The National Task Force on Life Safety and the Handicapped  
(NTF/LSH)  
The AIA Research Corporation (AIA/RC)

Grant No.: NBS Grant NB8ONADA 1058

Grant Title: The 1980 National Conference on Life Safety and the  
Handicapped

Principal Investigators: Howard Teich  
National Task Force on Life Safety and  
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Harold Nelson (NBS)  
Bernard Levin

Guy Clark (Veterans Administration)  
Daniel Hollyfield

Jan Thomas (FEMA)

NBS Scientific Officer: Bernard Levin

Technical Abstract

Our society has made a conscious decision to integrate the handi-  
capped into the "mainstream" of everyday life. This decision is embodied  
in the Architectural Barriers Act of 1968 (P.L. 90-480), the Rehabilita-  
tion Act of 1973 (P.L. 93-112), and the Rehabilitation, Comprehensive  
Services and Developmental Disabilities Amendments of 1978 (P.L. 95-602).  
Significant progress has been made toward making buildings accessible to  
the handicapped. But this very success brings a concomitant responsi-  
bility for dealing with the problem of protection and emergency exit.

Simply stated, ingress implies egress.

The 1980 Conference on Life Safety and the Handicapped was another step in an ongoing process of responsibly addressing this issue.

The objectives of the 1980 Conference on Life Safety and the Handicapped were education, articulation, and formulation: education as to the overall existence of the issue, articulation of specific problems and needs, and formulation of a national agenda for how to address the issue. More specifically, the objectives were:

- ° to educate a large, broad-based constituency as to the overall goals, problems, and needs related to life safety for the handicapped;
- ° to demonstrate the existence of such a constituency by the number and type of associations represented at the Conference, and to build on that constituency for furtherance of solutions;
- ° to compile Conference presentations and to produce a document which will represent the state-of-the-art of work and products related to the field; and
- ° to formulate a National Agenda for dealing with the overall issue, to be initiated by presentation of an implementation plan matrix based on proceedings from the 1979 Conference on Fire Safety for the Handicapped, held at the National Bureau of Standards (NBS) with the participation of:
  - ° the AIA Research Corporation (AIA/RC)
  - ° the Federal Emergency Management Agency (FEMA)
  - ° the National Task Force on Life Safety and the Handicapped (NTF/LSH)
  - ° the Veterans Administration (VA)
  - ° the National Fire Protection Association (NFPA)

Toward the goal of formulating a National Agenda a significant portion of the Conference was devoted to workshops. In all, there were twelve workshops. The following list identifies ten of these: six elements--building design, transportation systems, public education, emergency planning, emergency services, and products; and four forces--social, technological, legal/administrative, and economic. The remaining two workshops were related to university concerns and the NBS proposal to structure a technical fire research program.

#### Reports and Papers

Papers presented at the 1980 Conference on Life Safety and the Handicapped (included in Proceedings).

Howard Teich, "National Task Force on Life Safety and the Handicapped"

Irwin Benjamin, "Life Safety Codes--Current State of Regulations Providing Safety Considerations in Buildings Accessible to the Handicapped"

Harold Nelson, "1979 Conference on Life Safety and the Handicapped"

Everett Blizzard, "Emergency Planning"

Jerry Kuns, "Public Education"

Fred Jameson, "Notification and Alarm Systems--The Las Vegas Story"

Rexford Wilson, "Fire Protection Strategies"

Philip Favro, "Implications to Fire Services"

Jo Anne Simon, "Panel on University Concerns--Toward a State-of-the-Art"

Gwen H. Callas, "Panel on University Concerns--A Model for Fire and Emergency Evacuation Training"

"Panel on University Concerns--Handicapped Student Evacuation Plan"

Susan O'Hara, "Panel on University Concerns--Fire Safety and Disabled Students at the University of California, Berkeley"

"Panel on University Concerns--Panel Notes"

Clarence Nicodemus, "A Case Study"

John Weber for David Dibner, FAIA, "Implications for Federal Buildings-- Safe Environments - What Does It Take?"

Peter Waldman, "Mental Disabilities"

Arnold Gangnes, AIA, "Developmental Disabilities"

Robert J. Lynch, FAIA, "Compliance"

J. Armand Burgun, AIA, "Life Safety Codes"

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Auburn University

Grant No.: NB 80 NADA 1012

Grant Title: Investigations of the Safety Problems Associated with  
Fireplace Inserts

Principal Investigators: Glennon Maples, Professor  
David Dyer, Professor  
Timothy T. Maxwell, Assistant Professor  
Department of Mechanical Engineering  
Auburn University, AL 36849

NBS Scientific Officer: Richard Peacock

Technical Abstract

Wood burning has become a very popular means of home heating in the last few years. But there are problems with wood burning stoves and fireplaces. Fireplaces are typically very high excess air devices, and thus, they possess a very low energy efficiency. Stoves, on the other hand, are generally much more efficient; however, when properly and safely installed, the free-standing stove requires a large amount of floor space. One solution has been the development of fireplace inserts--an appliance that operates at relatively low levels of excess air and requires little or no floor space from the room in which it is installed. Basically, the fireplace insert is an airtight woodburning appliance that is designed to fit into the firebox of an existing fireplace. The original fireplace provides a noncombustible encasement and chimney for the insert and the airtight design coupled with a proper heat exchanger provides improved energy efficiency and heating capacity over that of the original fireplace.

The fireplace insert is not without its problems. Masonry fireplaces generally operate quite safely in the way that they were intended to function; however, when they are essentially converted to an airtight appliance and the mode of operation likely is changed from a few hours in the evening to a 24 hour operation, overheating of nearby combustibles can result. When operating as an airtight appliance, the insert-fireplace combination does not have the large amount of excess combustion air typical of an open fireplace passing through the system; thus, the appliance and chimney operate at higher temperatures. Also, because of the intermittent operation typical of most open fireplaces, they never approach steady state thermal conditions; inserts are typically run 24 hours a day when the weather requires heating, thus, the fireplace and chimney reach much higher temperatures. Finally, as with all airtight woodburning appliances, fireplace inserts tend to achieve less than complete combustion. The unburned fuel

collects in the chimney as creosote. This creosote can at a later time ignite and burn inside the chimney producing much higher chimney temperatures than normal.

The overall objective of this project is to assess the limitations and capabilities of various types of fireplace inserts in various types of fireplaces. Hence, the first task was to classify the existing inserts according to generic types. A similar classification study on fireplaces was carried out by Underwriters Laboratory. A Masonry was designed to be a minimal unit but conform to the letter of existing building codes. This fireplace and several "zero-clearance" or manufactured fireplaces were used as the test fireplaces. Once the inserts and fireplaces were classified, typical units were selected and tested by performance and safety in various fireplaces. Also, some qualitative field tests were carried out during the project.

The results will be analyzed to determine what, if any, basic safety problems are associated with the use of fireplace inserts in either masonry or manufactured fireplaces. The results will also be made available to code and standard groups for their use in forming and evaluating relevant codes and standards.

#### Reports and Papers

Burch, T., Dyer, D. F., Maples, G., and Maxwell, T. T., "Fire Safety Of Wood-Burning Appliances, Part II: Fireplace Inserts, A Design Review" National Bureau of Standards, 1980.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Brown University

Grant No: NBS Grant NB80NADA 1024

Grant Title: Effects of Material Properties on Burning and Extinction-Fires on Vertical Fuel Surfaces

Principal Investigator: Professor M. Sibulkin  
Division of Engineering  
Brown University  
Providence, RI 02912

Other Professional Personnel: S. Malary, Graduate Research Assistant  
S. Tewari, Graduate Research Assistant

NBS Scientific Officer: J. Rockett

Technical Abstract:

The objective of this program is to determine the effects of changes in material properties on the burning rates and extinction limits for flaming combustion of solid fuels. A vertical geometry is used because it provides the best opportunity to compare experimental results with detailed mathematical analyses. Work on a previous grant resulted in a computer program for modelling a free convection, diffusion flame on a vertical fuel surface. Using this program it was found for small-scale fires that radiation from the fuel surface was more important than flame radiation to the surface. Even in the analytical limit of infinite chemical reaction rate, it was found that surface radiation could lead to extinction. Finite rate chemistry was subsequently modelled using a one-step global reaction, and was found to have little effect on burning rates. The action of a gas phase fire retardant was simulated by changing the chemical reaction rate. The results gave qualitative agreement with measurements in which  $\text{CF}_3\text{Br}$  (Halon 1301) was added to the ambient gas mixture.

Calculations of the effects of water droplet sprays on the burning of vertical fuel surfaces have been completed during this grant period. The analysis considers three physical effects: the injection of steam into the boundary layer, a surface heat sink due to water evaporation, and the reduction in surface radiation due to partial coverage of the surface by water droplets. A simple theory was devised to estimate an upper limit for the fraction of the fuel surface covered by water droplets in steady state burning as a function of water application rate. The boundary layer computer program was used to calculate the burning rate of PMMA slabs as a function of water application rate  $\dot{m}_W''$  (see Fig.1). The calculations show that the burning rate  $\dot{m}_F^*$  ( $\equiv \dot{m}_F'' \times 1/4 / \rho_r v_r c_l$ ) decreases with increasing values of  $\dot{m}_W''$ , and that extinction occurs at  $\dot{m}_W''$  between  $2.7$  and  $4.2 \times 10^{-4}$  g/s  $\text{cm}^2$  depending on the estimate of surface

radiation used. Published experimental results have given extinction limits of  $\dot{m}_W'' \approx 2 \times 10^{-4}$  g/s cm<sup>2</sup> for PMMA slabs.

During this period the boundary layer analysis and computer program were extended to obtain results for nonunity Lewis number. (For this situation the mathematical simplifications given by Schvab-Zeldovich theory no longer apply.) A range of Lewis numbers from  $Le = 0.5$  to  $2.0$  was chosen for investigation. Results were calculated for PMMA burning in air. It is found (see Fig. 2) that there is a 15 percent increase in burning rate  $m^*$  over this range. The corresponding increase in flame temperature is 30 percent. The chemical reaction rate is found to have a negligible effect on the burning rate.

The results discussed above were obtained using the local similarity approximation which reduces the mathematical problem to the solution of ordinary differential equations. During this period, calculation of the nonsimilar, partial differential equations was programmed. Solutions were obtained using either a forward difference or a Crank-Nicolson algorithm. Both difference techniques give the same results. The local similarity approximation solutions for burning rate  $m^*$  are compared with the exact nonsimilar results in Fig. 3 where  $x$  is downstream distance. Results are shown for both infinite chemical reaction rate, and for a finite chemical reaction rate derived from the literature. The results show close agreement between the approximate and exact solutions for the burning rate.

Papers based upon the results of the nonunity Lewis number and non-similar solutions will be prepared.

Experimental preparations for the study of the effect of ambient oxygen concentration on completeness of combustion ( $CO/CO_2$  ratio) have reached a final stage. Measurements will begin shortly. Our major experimental effort in the future will be a study of the effects of solid phase fire retardants on flaming combustion. The family of materials used will be fire retarded cellulose. A technique has been developed for the manufacture of homogeneous cellulose cylinders. After molding under pressure and subsequent vacuum drying the cylinders have a specific gravity which varies from  $0.45$  for a  $50$  psig load to  $0.48$  for a  $250$  psig load. We are in the process of surveying the qualitative effects of a range of retardants on burning behavior.

#### Reports and Papers

"Effects of radiation on the burning of a vertical fuel surface," M. Sibulkin, A. K. Kulkarni and K. Annamalai, Eighteenth Symp. (Int.) on Combustion, 1981.

"Burning on a vertical fuel surface with finite chemical reaction rate," M. Sibulkin, A. K. Kulkarni and K. Annamalai, Combustion and Flame (in press).

"Burning rate measurements on vertical fuel surfaces," A. K. Kulkarni and M. Sibulkin, Combustion and Flame (in press).

"Free convection diffusion flames with inert additives," M. Sibulkin and C-Y. Wang, ASME - 1981 Winter Annual Meeting (submitted for publication); a portion of this work was presented at the Eastern Section Meeting/Combustion Institute, Nov. 1980.

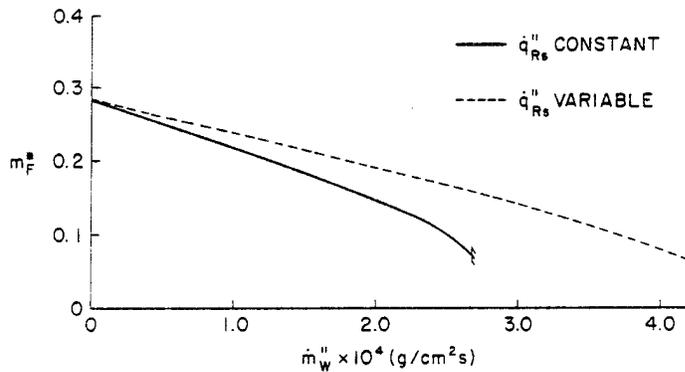


Fig. 1. Effect of water application rate on burning and extinction of PMMA slabs.

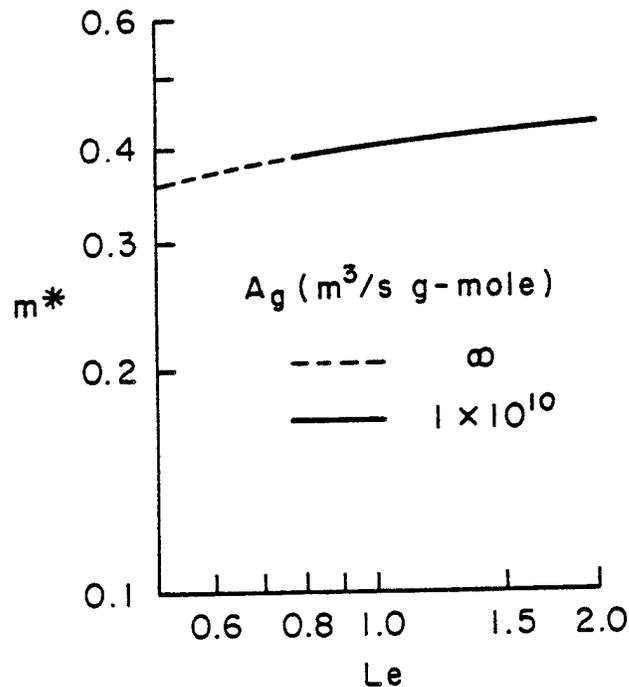


Fig. 2. Variation of burning rate with Lewis number.

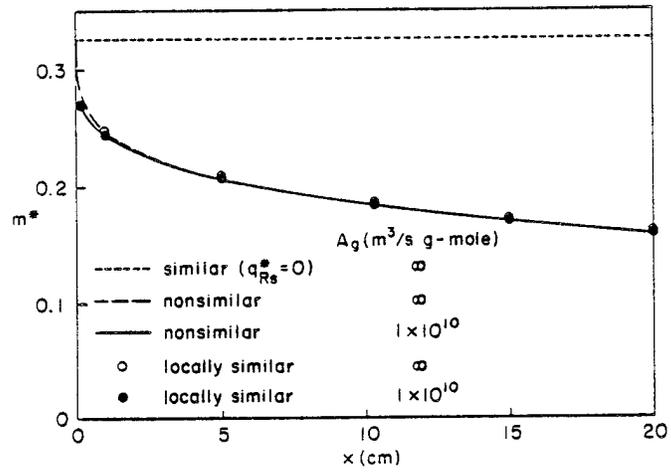


Fig. 3. Comparison of local similarity solutions with nonsimilar boundary layer calculations.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: California Institute of Technology

Grant No: NBS Grant G8-9014

Grant Title: Experimental Study of Environment and Heat  
Transfer in a Room Fire

Principal Investigator: Professor Edward E. Zukoski 301-46  
California Institute of Technology  
Pasadena, CA 91125

Other Professional Personnel: Professor Toshi Kubota  
William Sargent, Ph.D. Candidate  
Baki Cetegen, Ph.D. Candidate  
California Institute of Technology  
Pasadena, CA 91125

NBS Scientific Officer: Dr. J. Quintiere

Technical Abstract

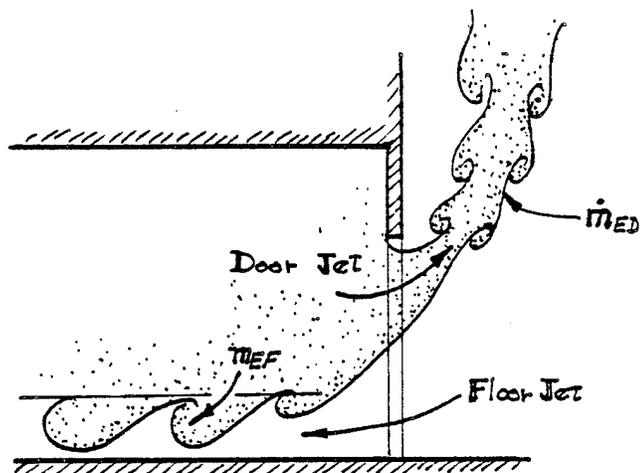
We are investigating a number of fluid dynamic problems associated with the movement of smoke and air through a multicompartmented building as a result of a fire in one of the compartments. We are primarily interested in rooms in which a pre-flashover condition exists and in developing experimental data for turbulent flow processes for which good models do not now exist. Our selection of experimental problems has been guided in part by problems which arose during our efforts to develop a simple numerical model for gas motion produced by fires in a multicompartmented building. Our current research work is outlined below.

Computer Model. We have continued to develop our computer model of the spread of smoke through a multi-room building with arbitrary internal and external connections. The program, in a previous incarnation, has been successfully transferred to the Fire Research Center of NBS; Livermore and Los Alamos Laboratories of DOE; and to the Naval Research Laboratory.

In the present form of the program, we are extending the calculation to include the capability of describing the flow in N rooms, doorway mixing phenomena and temperature variations in the cool layer. Currently, the model contains a description of the near field of the fire as described below. We are still working on a simplified heat transfer model which will include radiative and convective heat transfer to walls.

Experimental Program. We have completed an investigation of entrainment of mass by streams of gas flowing through openings. The experiments were carried out using salt water-water mixtures to model the buoyant flows. One problem involved a hot jet of fluid flowing out through the top of a door and into a cooler (and hence more dense) fluid in the adjoining room. (See  $\dot{m}_{ED}$  of Sketch 1) This door-jet behaved like a simple buoyant point source plume. The door-jet entrainment follows the law for our far-field point source plumes to within a multiplicative constant whose value changes when the door-jet changes from a separated jet (Sketch 1) to a jet attached to the wall.

Sketch 1.



We also used the salt water-water technique to examine the mixing produced by a thin door-jet of cool air entering a room along the floor and with a very deep ceiling layer of hot gas above it. Mixing occurs at the interface between the hot "stagnant" gas of the ceiling layer and the "high" speed, cooler floor jet and entrains gas into the cooler layer at a rate  $\dot{m}_{EF}$  (see Sketch 1). We found that a Richardson Number scaling parameter could be used to correlate these results.

Given the success of this study (which results will be reported in Zukoski et al, Reference 1 listed below), we are now investigating the entrainment rates of both of these flows in a 1/2 scale test facility in which hot air (100-150°C) is used to model the smoke and a chemical tracer ( $\text{CO}_2$ ) is added to aid in making the determination of the entrainment rates.

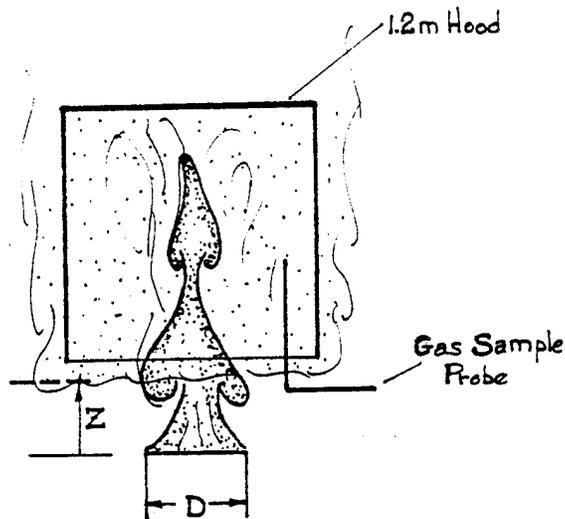
Our major effort during the past year has been a study of entrainment in the buoyant plumes produced by fires. We have completed our studies of entrainment rates in the plume above the fire and conclude that our simple point source model gives a good approximation for this region without any requirement for offset of the origin.

These experiments have emphasized results obtained with no disturbances present in the ambient atmosphere. Entrainment rates in real fires can be much larger due to disturbances in the ambient flow. Thus,

for a fire plume located in a room with a strong inflowing jet of fresh air (produced by the flow through a doorway), we have found that entrainment rates are as much as two times larger than the values obtained with no disturbance. We are examining these problems now and a report of some results is given in Zukoski et al, 1981, Reference 2 listed below.

The entrainment in the region of the fire where rapid heat release occurs is much more complex. We have used a slight modification of our standard technique for this zone. In the new technique, the ceiling layer is formed within a hood held over the fire as before but we now use chemical analysis of the gas to determine the entrainment rate because of the difficulty of handling ceiling layer gases as hot as 1000-2000°K. (See Sketch 2) The interface height is determined with aid of an optical technique. This work is described in detail in the report by Zukoski et al, listed below as Reference 3. Porous bed burners with

Sketch 2.



diameter  $D$  of 0.10-0.50 m and total heat release rates of 10-100 kw were studied in a cubical hood 1.25 m on edge.

The results suggest that entrainment in the first  $1/2$  to 1 meter above the fire scale as  $Z^{3/4} D$  where  $Z$  is the distance from the burner bed to the interface and  $D$  is the burner diameter. An integral analysis of the buoyant diffusion flame-sheet formed between an accelerating fuel jet on one side and quiescent air on the other agrees with the scaling law and thus leads us to believe that molecular transport processes such as those which occur in a buoyant diffusion flame dominate the entrainment process in this initial region of the flame.

In the initial region, entrainment rates for small values of the ceiling layer height,  $Z$ , are still large enough to insure that the overall fuel-air ratio in the ceiling layer will be less than the stoichiometric value even when the  $Z/D$  ratio is as small as 2. We also found that even when most of the visible flame lies above the ceiling layer interface, the combustion processes in the vitiated gas within the ceiling layer (i.e., in the 1.2 m hood) still occur with almost 100% efficiency and that no visible soot is formed until the fuel-air ratio

in the hood rises above 80%. This high combustion efficiency occurs under conditions for which the average residence times for gas in the hood is greater than 1 second.

In a second region, between the top of the initial region and the top of the flame, the entrainment process is similar to that in the far field. That is the entrainment rate at a given height  $Z$  above the burner is proportional to the plume centerline velocity and a scale for the plume which is proportional to height,  $Z$ . However, we assume that, in this region of the flame, heat addition keeps the average gas temperature relatively constant. This leads to an entrainment rate which scales as  $Z^{5/2}$  as compared with  $Z^{5/3}$  for the far-field plume.

This work is discussed in detail in the paper by Zukoski et al, Reference 3 listed below, and is being continued in the present contract year.

#### Reports and Papers

1. Zukoski, E. E., Sene, K. and Peterka, D., "Entrainment Rates in Flows Through Openings Produced by Room Fires," Report for Center For Fire Research, NBS, California Institute of Technology, August 1981.
2. Zukoski, E. E., Kubota, T. and Cetegen, B., "Entrainment in Fire Plumes," Fire Safety Journal, 3 (1980-81) 107-21.
3. Zukoski, E. E., Cetegen, B. and Kubota, T., "Entrainment in Buoyant Flames and Their Plumes," Report for Center For Fire Research, NBS, California Institute of Technology, July, 1981.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Case Western Reserve University

Grant No.: DA-1017

Grant Title: Flame Spread and Spread Limits

Principal Investigator: Professor James S. T'ien  
Department of Mechanical and Aerospace  
Engineering  
Case Western Reserve University  
Cleveland, Ohio 44106

Other Professional Personnel: Robert Borgeson (Graduate Student)  
Charlie Chen (Graduate Student)

NBS Scientific Officer: Dr. James G. Quintiere

Technical Abstract

The overall objective of this research program is to develop basic understanding on flame spreads and spread limits. The work involves experimental and theoretical modeling efforts for both downward (opposed flow) and upward (concurrent flow) flame spreads.

At the present time, the modeling effort is concentrated on the extension of an existing opposed-flow flame spread model [1] to include the external radiation effect and the pyrolysis kinetic effect for multi-component fuels. The dominant effect of external radiation on spread limits was found to be through the increase of unburnt fuel temperature (for reasonably long radiation exposure time). Since it is easy to establish a relationship between external radiative heat flux level and the surface temperature for a given sample geometry and orientation, the spread limit is computed in terms of fuel surface temperatures. The numerical computation is still continuing.

Simultaneous with the addition of external radiation, the model in Ref. 1 is modified to include fuels with more than one component (e.g. primary fuel and inert). The different components may have different pyrolytic kinetics. The interest here is to find the pyrolytic kinetic effect on flame spread limit.

Experimentally, upward propagations were measured for paper and rigid polyurethane samples of various widths. Steady-state flame spreads have been obtained in laboratory size paper samples with narrow sample widths. The spread rate, pyrolysis length, preheating distance, surface temperature vs. distance and spread limits were

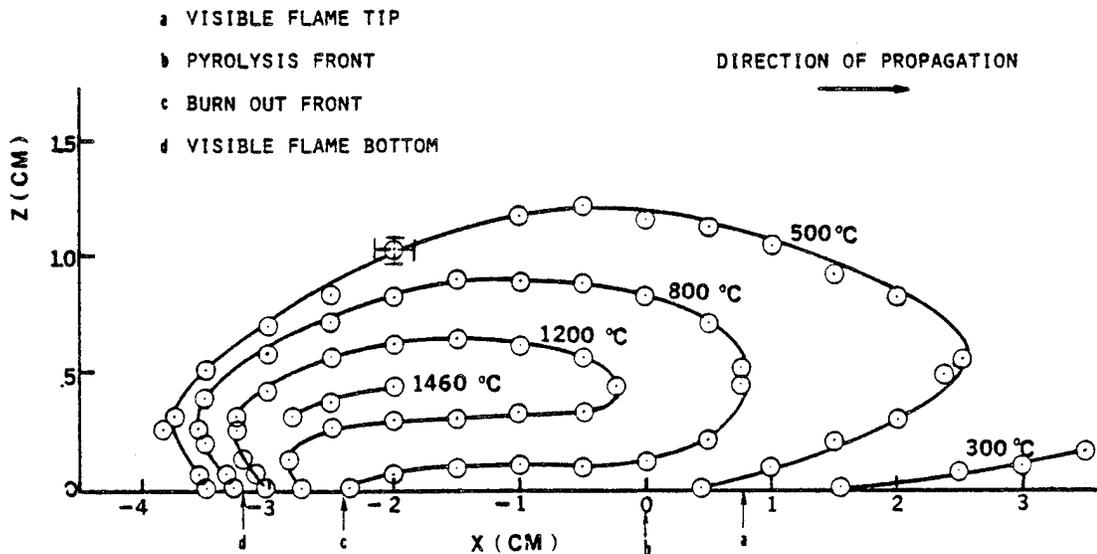
measured as a function of total pressure and oxygen mole fraction.\* In selected cases, gas phase temperature profiles and surface heat flux were also measured. The upward flame spread over narrow samples has been found to be three-dimensional in nature, i.e. the lateral cold air entrainment into the fire plume is very important. In order to quantify this effect, the surface heat flux is being measured at off-centerline positions for different size samples. The work is still being continued. Such detailed measurements could provide more understanding of the mechanisms of upward flame spreads and spread limits as well as provide the data for comparison with model predictions.

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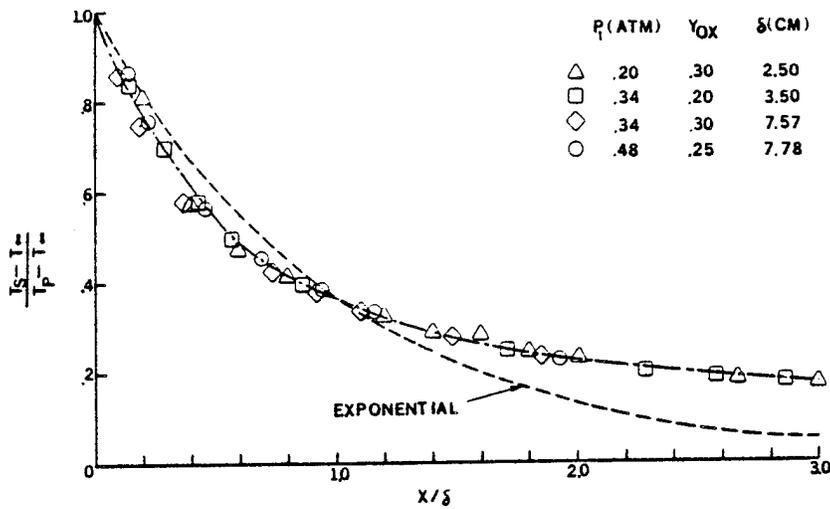
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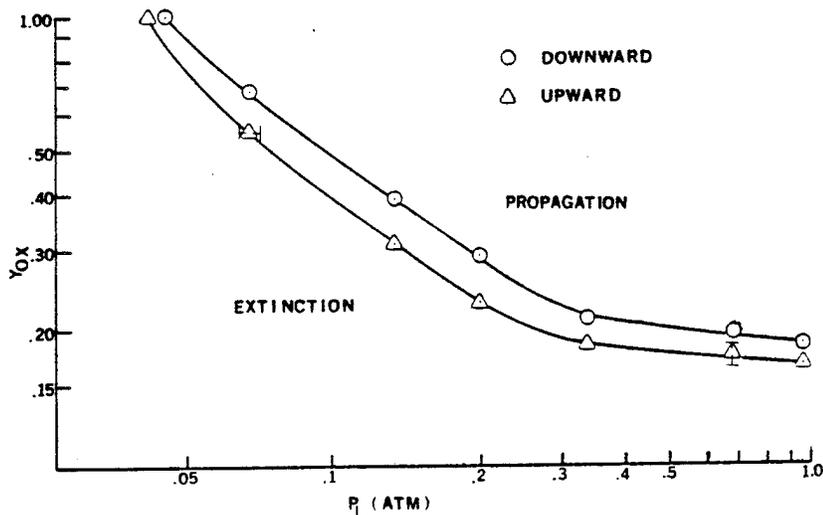


Centerline Isotherms in an Upward Spreading Flame over Paper Surface, Sample A,  $P_t = 0.20$  atm,  $Y_{ox} = 30\%$ , paper width = 1 cm.

\*See figures.



Nondimensional Centerline Temperature Profile in the Preheat Zone of an Upward Spreading Flame at Various Gas-Phase Conditions, Sample A,  $D=1$  cm.  $\delta$  is the pyrolysis length.



$\log Y_{Ox}$  (Limiting Oxygen Mole Fraction) vs.  $\log P_t$  (Limiting Total Pressure). Flammability Limits of Upward and Downward Propagation for paper Sample A, paper width = 1 cm.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Clemson University

Grant No.: NBS Grant NB80NADA1042

Grant Title: Ternary Reactions Among Polymer Substrate-Organohalogen-Antimony Oxides in the Condensed Phase Under Pyrolytic, Oxidative and Flaming Conditions.

Principal Investigator: Dr. M. J. Drews  
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Other Professional Personnel: Dr. C. W. Jarvis, Co-principal Investigator  
Ms. J. D. Hansel, Graduate Assistant

NBS Scientific Officer: Dr. W. Earl

Technical Abstract:

The objective of the two-year research plan is to determine the contributions of solid phase interactions, occurring in antimony oxide/organohalogen/thermoplastic, polymer substrate compositions, to the overall system chemistry during combustion. Of particular interest is the role of the polymer substrate in the generation of volatile antimony and halogen containing species. Small scale degradation data are to be integrated with the results from a series of laboratory scale flaming combustion experiments conducted at the Center for Fire Research of the National Bureau of Standards. The flaming combustion and degradation data are to be used in an attempt to develop a comprehensive model for the chemistry which occurs in the condensed phase, under both flaming and non-flaming degradation conditions. This model is to be used in the identification of the controlling parameters for optimizing the efficiency of organohalogen/antimony oxide flame retardant combinations in specific polymer substrates.

The research plan is divided into two concurrent pathways. The first pathway consists of small scale degradation studies to be conducted throughout the two-year lifetime of the project. These degradation studies are designed to characterize the thermally initiated ternary reactions, which could affect halogen and antimony release in the condensed phase, occurring in mixtures of polymer substrate/organobromine additive/antimony oxide. These data will then be correlated with the previous results obtained in studies of the reactions involving the individual components and binary mixtures. From these two data sets, the changes in the rates of antimony and/or bromine

volatilization, the temperature profiles for antimony and bromine release, and the relative concentrations for the various volatilized bromine and antimony species will be used to define the role of the polymer substrate structure in the halogen and antimony loss from the solid phase. Three polymer substrates are to be studied: polymethylmethacrylate (PMMA), polypropylene (PP) and polyethylene terephthalate (PET). Three organo bromine compounds will be used as model organo-halogen additives: hexabromocyclododecane (HBCD), tetrabromobisphenol-A (TBBPA) and decabromodiphenyl oxide (DBDPO). The study of mixtures of each of the above with antimony trioxide or antimony pentoxide consists of a sequence of experiments including but not limited to, dynamic (at three different heating rates) and isothermal (at two different temperatures) decomposition studies in three different atmospheres: pyrolytic (nitrogen), catalytic (1% oxygen) and ambient (21% oxygen).

The second pathway in the research plan includes a series of laboratory scale flaming combustion experiments to be conducted at the Center for Fire Research at the National Bureau of Standards during the first project year. In these experiments, the effects on combustion parameters such as sample thickness and geometry, as well as polymer substrate additive concentrations, are to be studied. The apparatus to be used for these flaming combustion experiments is the cone calorimeter developed by Parker, Babrauskas, and Swanson. Several combustion parameters are to be measured for each sample including time to ignition, rate of flame spread, rate of heat release, mass consumption rate, and the gravimetric smoke yield. Three intrinsic sample parameters are to be varied: polymer type, flame retardant additive, and antimony oxidation state.

Because the flaming combustion experiments were to be completed during the first project year, the results obtained from them were to be used in the later small scale degradation studies. Particular emphasis was to be placed on determining the environmental, flow conditions, and sample sizes to be used in the subsequent small-scale degradation experiments so as to maximize utility of the information obtained from them. Using analytical techniques developed since our previous work, binary mixtures of PP/DBDPO, PP/Sb<sub>2</sub>O<sub>3</sub> and DBDPO/Sb<sub>2</sub>O<sub>3</sub> have been studied. In addition, the ternary mixture PP/DBDPO/Sb<sub>2</sub>O<sub>3</sub> has also been studied with these revised analytical procedures. The bromide ion distribution between the thermal analyzer sample pan, furnace tube, and the off gas bromide ion trap and the corresponding antimony distributions have been measured. In addition, kinetic analysis of the thermogravimetric data for these decomposition experiments has been initiated.

These data and results form the basis for a masters thesis to be completed in August 1981. Since the evaluation of these data has not been completed at this time, it is possible to draw only general conclusions. These data do, however, appear to demonstrate the importance of the ternary reactions in the volatilization of an antimony containing species from the ternary mixture of PP/DBDPO/Sb<sub>2</sub>O<sub>3</sub>.

In all of the DBDPO binary mixture data no evidence has been found of significant interaction between antimony oxide and organobromine additives which would account for the formation of a volatile antimony species. In every case, the kinetic analysis and product distribution data lead to the conclusion that little direct interaction occurs between the organobromine and antimony oxide. On the other hand, when all three reactants are present at the same time, the kinetics of the volatilization processes and the distribution of the degradation products change measurably.

Because of experimental difficulties which have been experienced, only a limited number of samples have been burned in the cone calorimeter. These include PMMA, PP and PP loaded with 10% DBDPO and 5%  $Sb_2O_3$ . The data available for these samples consist of the melt temperatures of the samples, the flame temperatures above the surface of the samples, the mass burning rates, the relative smoke concentrations, the oxygen consumptions, and carbon dioxide and carbon monoxide formation. In addition to these numerical data, there were also visual observations made of the burning behaviors and an assessment made of the relative difficulty of, or relative times to, ignition for the different materials.

In comparing the burning behavior of the PP and PMMA, the following observations have been made. The PP burned with a significantly more luminescent flame than the PMMA in the cone calorimeter. This is substantiated by the increase in smoke observed on going from PMMA to PP. The mass burning rate of PMMA is approximately 50% greater than that observed for PP. In addition, the PMMA melt temperatures and flame temperatures are approximately 100°C lower than those observed for PP. Perhaps the most significant observation in comparing the burning behavior of PP to PMMA in the cone calorimeter is that, while neither polymer produces a significant quantity of carbon monoxide (less than .01%), and as expected, the oxygen depletion observed for PP is greater than that observed for PMMA; the carbon dioxide production is approximately 15% lower for PP than PMMA in this burning environment. These data imply that for PP, a significantly greater fraction of polymer is used to produce oxygenated combustion products other than carbon dioxide and carbon monoxide relative to PMMA.

As expected, the PP sample containing DBDPO and  $Sb_2O_3$  burned with a much more luminescent flame and generated a considerably greater quantity of smoke than PP alone. Quite unexpectedly, the melt and flame temperatures for both samples were almost identical. The mass burning rate also was apparently unaffected by the presence of 15% DBDPO/ $Sb_2O_3$ . In addition, a significant amount of carbon monoxide was produced ( $.063 \pm .07\%$  during the steady state burning). However, this increase in carbon monoxide was not sufficient to account for the observed oxygen depletion. This observation was similar to that which was observed for PP alone. Again this indicates the formation of significant oxygenated combustion products which are not carbon monoxide or carbon dioxide. In addition, even though the mass burning rate was

unaffected, the oxygen depletion for the flame retardant sample was significantly lower than the oxygen depletion observed for PP alone, as was the exhaust stack thermocouple temperature.

While these results obtained on the cone calorimeter so far are extremely interesting, because such a limited amount of data is available, it is difficult to draw any conclusions regarding some of the observations that have been made. It appears more promising than ever, however, that when combined with the thermal analysis results these data will lead to a significant increase in the understanding of the effects of antimony/halogen systems on the combustion performance of polymer substrates.

The results of this systematic investigation are intended to make available new basic information in several important areas: formation of volatile antimony species from reactions of antimony oxides with organo halogens that cannot by themselves eliminate hydrogen halide; the effect of the polymer substrate on the reactions which produce volatile antimony halides and oxyhalides; and the first systematic study on the controlled combustion of thermoplastic materials containing organohalogen/antimony oxide flame retardants. The systems description which this research program seeks to develop should make it possible to model more accurately combustion performance of these materials in fire situations and lead to a greater understanding of the thermal characteristics necessary for the more efficient flame retardation of thermoplastic material.

#### Reports and Papers:

Drews, M. J., Jarvis, C. W., Leibner, E. A., "Organobromine/Antimony Oxide/Polymer Substrate Interactions in the Solid Phase. Part I. Binary Interactions," Organic Coatings and Plastics Preprints, 43, 181 (1980).

Hansel, J. D., "Solid Phase Interactions Among Antimony Oxides, Decabromodiphenyl Oxide and Polypropylene Under Pyrolytic Conditions," Masters Thesis, August 1981.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Colorado School of Mines

Grant No.: NB81NADA2020

Grant Title: Characterization of Aerosols from Fires

Principal Investigator: Professor Kent J. Voorhees  
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Other Professional Personnel: Dr. R. Tsau, Post-Doctoral Associate  
Mr. S.A. Durfee, Ph.D. Candidate

NBS Scientific Officer: Ms. Maya Paabo

Technical Abstract

The work on this project began May 1, 1981. The following is a short description of the proposed work.

Aerosols produced from the thermal degradation of polymers are primarily composed of lower molecular weight fragments of the original polymer. Based on our previous work on atmospheric particles, it is proposed to use Pyrolysis/Mass Spectrometry (Py-MS) to generate patterns from the aerosols which are characteristic of the initial polymer structure. Initially single polymers will be degraded in the Potts furnace; however, after the uniqueness and reproducibility of patterns plus variability from changes in the degradation scheme are established, aerosols from composite samples will be studied. By using the Py-MS data from the single samples as reference spectra, the composition of the composite sample can be determined by pattern recognition techniques.

During the first year 20 polymer samples plus 3 wood samples will be investigated in both flaming and non-flaming modes. The composite samples will be selected from these specimens. At the end of year one, aerosols will be generated, using the previous sample suite, in a large scale facility. The same sample collection, analysis and data work-up developed during the Potts experiments will be used on these aerosols.

A study to investigate the effects of an accelerant on the composition of the aerosol will also be conducted during the first year. This study will involve understanding the composition of the aerosol produced from the accelerant as well as its effect when decomposed with a polymer, on the composition of the resulting aerosol. Py-MS and GC/MS will be used in this phase of the study.

Successful completion of these studies should provide the following deliverables:

1. An understanding of the effects of varied thermal decomposition on the high molecular weight portion of aerosols from polymers.

2. An analytical technique for assessing the fuels involved in fires.
3. A better method for assessing the presence of an accelerant in a fire situation.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Factory Mutual Research Corporation

Grant No.: NB81NADA2007

Grant Title: Computer Modeling of Aircraft Cabin Fire Phenomena

Principal Investigator: Dr. R. L. Alpert  
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Other Professional Personnel: Dr. M. A. Delichatsios  
Ms. M. K. Mathews

NBS Scientific Officer: Dr. Kenneth D. Steckler

Technical Abstract

The objective of this project is to develop the elements of a computer code required to predict flame spread and fire growth inside an airplane fuselage that is being heated by an outside exposure fire through an open side door. Integral models for burning and flame spread on flammable walls and ceilings will be developed in order to minimize computation time. These models, coupled with radiation calculations from the exposure fire and the walls involved in burning, will provide the necessary ingredients for predicting the fire growth in an airplane fuselage.

1. Turbulent Wall Convective Flows.

A two-layer integral model has been developed for the prediction of convective flows (including burning wall conditions) on a vertical wall. The turbulent wall flow is divided into three regimes: 1) a laminar flow regime close to the wall; 2) a turbulent wall flow next to the laminar flow regime; and 3) an outer, free-turbulent flow. In similarity to Von Karman's logarithmic wall law, universal wall law profiles for the flow properties are proposed for the turbulent wall flow. These profiles depend on the boundary conditions at the wall. Simple integral relations are written for the outer free-turbulent flow with the inner flow conditions taken into account by appropriate matching at the limits of each flow regime. The model has been applied to a convective flow over an adiabatic wall induced by a line source of constant buoyancy flux attached to the wall. The present approach allows the calculation of turbulent wall convective flows without the need for assuming similarity profiles for the properties throughout the wall flow.

## 2. Flame Spread Correlations

Based on a simple similarity assumption for the flame spread, we have developed an expression for the flame spread velocity in the presence of an outside applied heat flux (for example from a pool fire):

$$\frac{\tau(x_p, t)}{x_p} \frac{dx_p}{dt} = C \ln \left( \frac{x_f}{x_p} \right) \quad (1)$$

In equation (1)

$x_p$  is the location of the pyrolysis front from the bottom edge of the wall

$x_f$  is the location of the flame tip from the bottom edge of the wall

$\tau(x_p, t)$  is a characteristic ignition time of the wall defined later

$t$  is the time from ignition

$C$  is a constant.

The ignition time,  $\tau$ , can be determined from the following relation:

$$\tau(x_p, t) = \tau_f(x_p) [1 - \tilde{t}]^2 \quad (2)$$

where

$$\tau_f(x_p) = \frac{k_w}{2} \frac{\sqrt{\pi}}{\alpha_w} (T_p - T_\infty) / \dot{q}_f'' \quad (3)$$

and

$$\tilde{t} = \frac{t}{\tau_o} \quad (4)$$

$$\tau_o = \frac{k_w}{2} \frac{\sqrt{\pi}}{\alpha_w} (T_p - T_\infty) / \dot{q}_o'' \quad (5)$$

In equations (3) and (5)

$k_w$  is the conductivity of the wall

$\alpha_w$  is the thermal diffusivity of the wall

$\dot{q}_f''$  is the heat flux to the unburned wall from the flames

$\dot{q}_o''$  is the outside applied heat flux

$T_p$  is the pyrolysis temperature of the wall material

$T_\infty$  is the ambient temperature.

It is obvious that in order to use equation (1), the wall properties as well as the flame properties (flame height and radiation properties) for turbulent conditions in the presence of an outside heat flux must be known. A test method (in a separate program) is being designed at Factory Mutual Research Corporation to obtain this information.

For the flame height ( $h_f$ ) ratio to the pyrolysis height ( $h_p$ ), we have proposed a relation based on dimensional arguments and the assumption that the flame height in free buoyant flows is independent of the chemistry. The latter assumption is based on calculations in turbulent buoyant jet flames<sup>1</sup>, which indicate that the flame height is independent of the stoichiometric ratio of the fuel. This result is obtained by observing that the ratio of the heat of combustion of the fuel to the stoichiometric ratio is approximately constant, i.e. independent of the type of fuel. The proposed expression for the flame height is:

$$\frac{x_f}{x_p} = fcn \left[ \frac{g x_p}{(gQ/w\rho_\infty C_p T_\infty)^{2/3}}, \frac{(\dot{Q}/\rho_\infty C_p T_\infty w)}{v_\infty}, \frac{\dot{m}''/\rho_\infty}{(gQ/w\rho_\infty C_p T_\infty)^{1/3}} \right] \quad (6)$$

In equation (6):

$g$  is the gravitational constant

$w$  is the width of the wall

$Q$  is the total heat release rate =  $\dot{m}'' \cdot H_c \cdot x_p \cdot w$

$\dot{m}''$  is the average burning of the wall

$v_\infty$  is the viscosity of the air

$\rho_\infty C_p T_\infty$  are properties of the air at ambient conditions.

#### Reports and Papers

1. Delichatsios, M.A., "Flame Height and Virtual Source in Turbulent Diffusion Flames" Presented at the Eastern Section Meeting of the Combustion Institute, Princeton, New Jersey, 1980.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Factory Mutual Research Corporation

Grant No.: NB79NADA0014

Grant Title: Determination of Fuel Parameters for Fire Modeling

Principal Investigator: Dr. Archibald Tewarson  
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Other Professional Personnel: Mr. J.S. Newman, Senior Research Scientist  
Mr. M.M. Khan, Research Scientist  
Mr. R.F. Pion, Assoc. Research Scientist

NBS Scientific Officer: Dr. David D. Evans

Technical Abstract:

The objective of the study is to obtain fuel properties in a generalized fashion for fire modeling, for fire hazard evaluations of materials (FR treated and untreated), for basic understanding of fires, and for reliable fire testing of materials. Data have been obtained for the following physico-chemical and combustion/pyrolysis properties for overventilated fire conditions [1]: chemical formulae, stoichiometric air-to-fuel ratio, net heat of complete combustion, heat required to generate a unit mass of vapors, surface reradiation loss, surface temperature, combustion efficiency including its convective and radiative components, product yields, light obscuration parameter, flame convective and radiative heat flux to the surface, Spalding's B-number modified for radiation and for combustion efficiency, normalized flame heights, ratio of CO<sub>2</sub> concentration to gas temperature above ambient (for fire detection), ratio of optical density per unit path length to gas temperature above ambient (for fire detection), and energy required to generate combustible vapor-air mixture near the surface. (1-7).

The dependency of the fuel properties on fire environment and fire size has also been investigated using three apparatus, shown in Figure 1 [7], identified as FM small-, intermediate- and large-scale combustibility apparatus (fuel surface areas, ~0.007, ~0.07, and ~7 m<sup>2</sup> respectively).

The continuation of the study involves measurements of the properties: 1) for under-ventilated fire conditions; 2) in the presence of water sprays; 3) in the presence of air contaminated by fire products, especially CO<sub>2</sub> and 4) for changing fire sizes. In addition, the reliability of the apparatus would be tested for possible use of the apparatus as a

"standard" small-scale fire test apparatus. (Char-forming fuels are emphasized.)

The following are some examples of the data for the fuel properties.

1. Energy Required to Generate Combustible Vapor-air Mixture Near The Surface [1]

Fuel	Energy (kJ/m <sup>2</sup> )
Red oak (solid)	420
Chlorinated polyethylene (granular)	920 to 970
PVC (granular)	1600
Flexible polyurethane foams (IA, GM-21)	670 to 730
Rigid polyurethane foams (GM 29 and 31)	830 to 870
Polystyrene foams (GM 49,51, and 53)	1500 to 1700

The lower the energy, the easier the ignition and the faster is the expected flame spread. Materials with higher energy are thus preferred for reduction of fire hazard.

2. Mass Transfer Number and Normalized Flame Heights [1]

Figure 2 shows the data. The mass fraction of oxygen is increased for flame radiation scaling. The higher the values of mass transfer number and flame height, the higher is the expected fire hazard. Thus, materials with lower values are preferred for reduction of fire hazard.

3. Combustion Efficiency [1]

Fuel	Combustion Efficiency	
	Over-ventilated	Slightly Under-ventilated
Polymethylmethacrylate (granular)	0.97	0.85
Flexible polyurethane foam (GM-21)	0.81	0.61
Red oak (solid)	0.70	-
Polystyrene (granular)	0.67	-
Rigid polyurethane foam (GM-37)	0.64	-
Rigid polystyrene foam (GM-51)	0.53	-
PVC (granular)	0.35	-

Materials with lower combustion efficiency, heat of complete combustion and the mass transfer number are preferred because the heat release rates for such materials are lower in fires.(1,2).

4.1 Product Yield Expressed as Product Generation Efficiency  
(CO and "Smoke") [1]

Fuel	Product Generation Efficiency			
	CO		"Smoke"	
	Over-Ventilated	Under-Ventilated	Over-Ventilated	Under-Ventilated
Red oak (solid)	0.003	-	0.03	-
PVC (granular)	0.038	-	0.22	-
Flexible polyurethane foam (GM-23)	0.016	0.024	0.03	0.37
Rigid polyurethane foam (GM-29)	0.023	0.048	0.10	0.23
Polystyrene (granular)	0.021	-	0.20	-
Rigid polystyrene foam (GM-47)	0.009	0.024	0.36	-

Materials with lower values for yields of CO, "smoke" or other toxic products and mass transfer number are preferred because the generation rates of "smoke" and toxic products from such materials are lower.

4.2 Average Soot Fraction in "Smoke" [1]

Fuel	Soot fraction in "smoke"
Rigid polystyrene foam (GM-47)	0.98
Rigid polyurethane foam (GM-29)	0.92
PVC (granular)	0.79
Polystyrene (granular)	0.75
Red oak (solid)	0.55
Flexible polyurethane foam (GM-23)	0.45
Polymethylmethacrylate (granular)	0.17

5. Fuel Properties and Fire Size

1. Asymptotic value of mass loss rate in pool fires [7]

Fuel	Pool Area (m <sup>2</sup> )	Mass Loss Rate (g/m <sup>2</sup> s)	
		Measured <sup>a</sup>	By Radiation Scaling <sup>b</sup>
Methanol	2.37	19.5	20
Polymethylmethacrylate	2.37	29.6	28
Polystyrene	0.93	33.5	38
Heptane	1.17	65.7	63

<sup>a</sup> FM large-scale combustibility apparatus

<sup>b</sup> FM small-scale combustibility apparatus; radiation scaling by increasing the oxygen concentration in inlet air

2. Ratio of heat release rate and product generation rate to mass loss rate [7]

Fuel	Pool Area (m <sup>2</sup> )	$\left[ \frac{\dot{Q}_a''}{\dot{m}_b''} \right]$ (kJ/g)	$\left[ \frac{\dot{Q}_c''}{\dot{m}_b''} \right]$ (kJ/g)	$\left[ \frac{\dot{G}_{CO_2}''}{\dot{m}_b''} \right]$ (g/g)	$\left[ \frac{\dot{G}_{CO}''}{\dot{m}_b''} \right]$ (g/g)	$\left[ \frac{\dot{G}_{HCN}''}{\dot{m}_b''} \right]$ (g/g)	$\left[ \frac{\dot{G}_{Hydrocarbon}''}{\dot{m}_b''} \right]$ (g/g)
Methanol	4.68	18.7	15.6	1.29	<0.001	-	<0.001
	2.32	18.8	15.7	1.30	<0.001	-	<0.001
	0.007	19.4	17.1	1.32	<0.001	-	<0.001
Polymethyl- methacrylate	2.37	24.2	15.8	2.11	0.008	-	<0.001
	0.073	23.8	14.9	2.10	0.010	-	<0.001
	0.007	24.4	17.9	2.15	0.011	-	<0.001
Heptane	0.93	41.2	26.8	2.83	0.015	-	0.001
	0.007	37.7	19.9	2.80	0.034	-	0.010
Rigid poly- urethane foam	~7	16.4	10.8	1.50	0.027	0.010	0.005
	0.007	15.8	6.5	1.51	0.036	0.012	0.003

$\dot{Q}''$  = heat release rate; a: actual; c: convective;  $\dot{G}''$  = generation rate of product;  $\dot{m}_b''$  = mass loss rate

Establishment of agreement between data from small- and larger-scale fires is important, because 1) data measured in the small-scale apparatus can be used with confidence for fire modeling of large-scale fires to assess the fire hazard and evaluate means to reduce it; and 2) such agreement is required for the reliable assessment of fire hazard of materials in small-scale tests, as well as for "standardizing" the tests.

6. Basic Understanding of Fires

All the data are being examined in order to establish the relationship between fuel properties and fire and flame extinction. For example, the ratio of heat of complete combustion to heat of gasification or the ratio of stoichiometric yield of individual products to heat of gasification are properties independent of fire size and conditions, but depend on the chemical structure of materials and their treatment. On the other hand, properties such as combustion efficiency, individual product generation efficiencies, radiation, etc. depend not only on the materials but also on fire conditions. A knowledge of the dependency of the fuel properties on various conditions is useful for the improvement of materials in order to reduce the fire hazard.

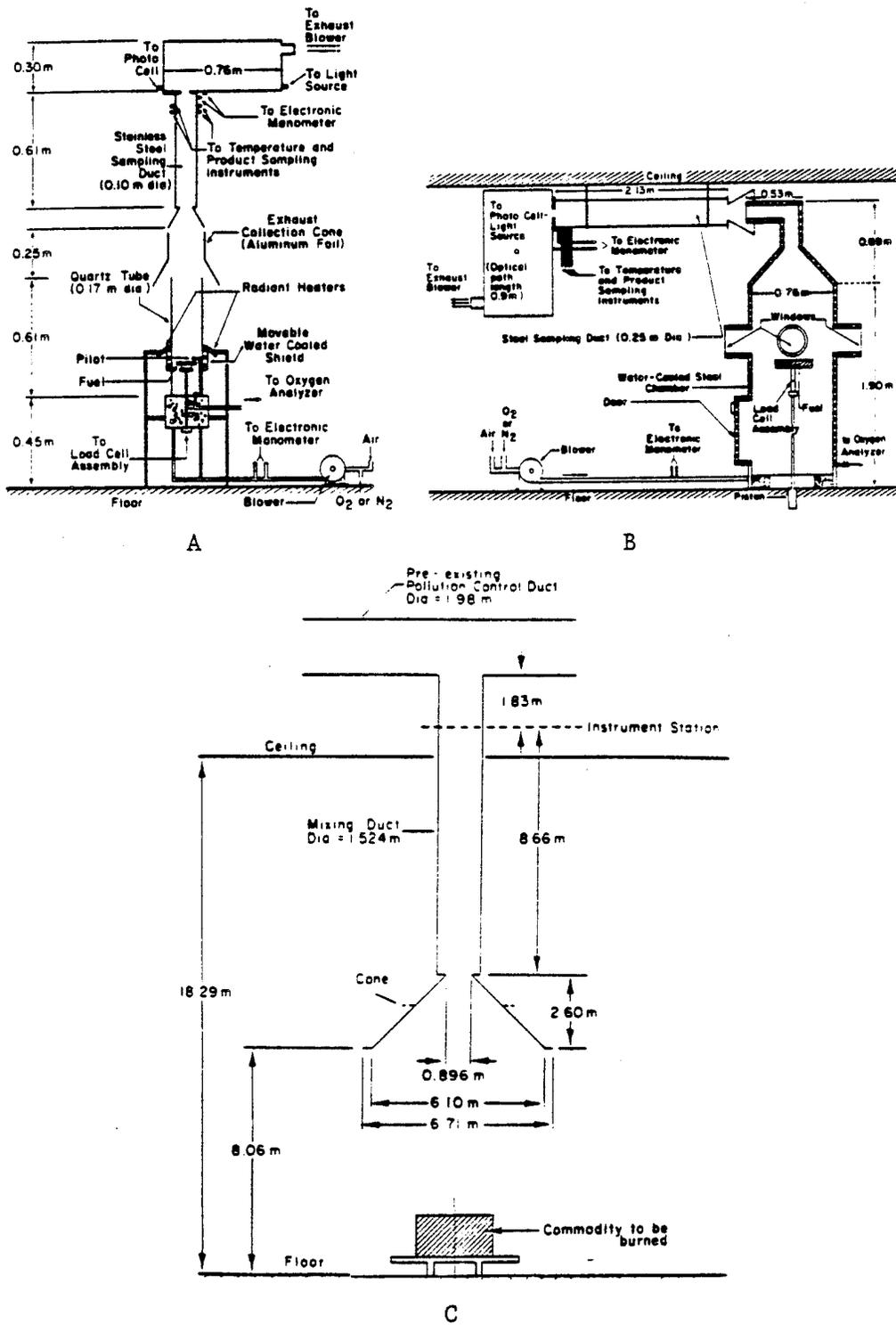


FIGURE 1

FM COMBUSTIBILITY APPARATUS - A, SMALL; B, INTERMEDIATE; C, LARGE

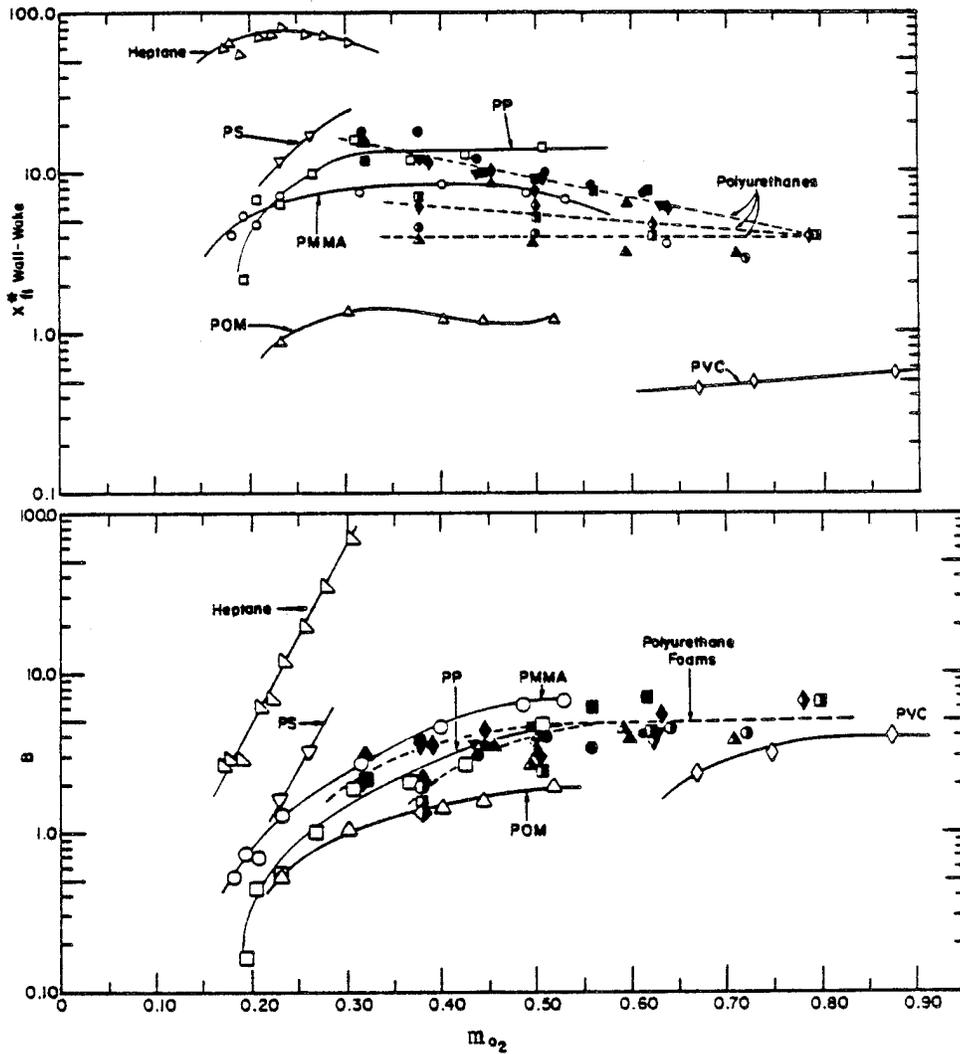


FIGURE 2 FLAME HEIGHT UNDER FORCED AIR FLOW ( $x_{fl}^*$  wall wake) AND MASS TRANSFER NUMBER ( $B$ ) AS FUNCTIONS OF OXYGEN MASS FRACTION,  $m_{O_2}$ , IN THE INLET AIR

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2. Tewarson, A., Lee, J.L., and Pion, R.F., "The Influence of Oxygen Concentration on Fuel Parameters for Fire Modeling," 18th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa. (in press).
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4. Tewarson, A., "The Factory Mutual Combustibility Apparatus for Reliable Fire Testing of Materials on a Small-Scale," Modern Plastics, p. 58, November 1980.
5. Tewarson, A., Lee, J.L., and Pion, R.F., "Fuel Parameters for Fire Modeling and Fire Hazard Evaluations," 1980 International SPI/FSK Polyurethane Conference, Strasbourg, France, June 1980.
6. Lee, J.L., Tewarson, A., Pion, R.F., "Indexing Method for Cable Classification Using FM Laboratory-Scale Combustibility Apparatus," 29th International Wire & Cable Symposium, Cherry Hill, N.J., November 1980.
7. Tewarson, A., "Combustibility Evaluations-Part I - The FM Small-, Intermediate-, and Large-Scale Combustibility Apparatus and Data Compilation (No. 1A7E4.RC); Part II - Heat Release Rate in Fires - Oxygen Depletion and Carbon-Dioxide Generation Techniques (No. 1A7E4.RC); Part III - Quantitative Correlations of Fire Test Data from the Three FM Combustibility Apparatus and Simplified Test Procedures," (No. OFOE3.RC), Factory Mutual Research Corporation, Norwood, Massachusetts, Technical Reports (to be issued).

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Harvard University

Grant No.: NB81NADA2026

Grant Title: "Computer Modeling of Aircraft Cabin Fire Phenomena"

Principal Investigator: Professor Howard W. Emmons  
Gordon McKay Professor of  
Mechanical Engineering  
Abbott and James Lawrence  
Professor of Engineering  
Pierce Hall  
Harvard University  
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Other Professional Personnel: Henri E. Mitler, Ph.D.

NBS Scientific Officer: Dr. Leonard Cooper

Technical Abstract

When a fire occurs in an aircraft cabin, the flames and hot air plume rise toward the ceiling, strike the ceiling, and spread out in all directions as a layer of hot smoky gas. This growing hot layer is soon confined on two sides by the cabin walls, and then spreads longitudinally along the cabin ceiling.

This ceiling layer is heated by the burning of excess fuel which it contains, and is cooled by convective and radiative heat transfer to the ceiling above and by radiation to the floor below. The flow may contain large-scale turbulent eddies. The chemical composition is complex, and the hot layer movement is sometimes obstructed by class separation partitions and service areas.

The goal of the present project is to develop a computer code which could be used to mathematically simulate the above mentioned phenomena which develop during the growth of fires in aircraft cabins. The work is in its initial stage of progress.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Harvard University and Factory Mutual Research Corporation

Grant No.: NBS Grant 7-9011

Grant Title: The Home Fire Project

Principal Investigators: Professor Howard W. Emmons  
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Seng-Chuan Tan, Ph.D. Candidate, H.U.

Dr. John de.Ris, FMRC  
Dr. Michael Delichatsios, FMRC  
Dr. George Markstein, FMRC  
Dr. Lawrence Orloff, FMRC

NBS Scientific Officer: Dr. John Rockett

Technical Abstract

The ultimate purpose of this project is to improve the fire safety of our built environment, homes and work buildings, by using scientific principles to compute the growth of a fire in a high-rise building.

The tasks are of two types: 1. The construction of a sufficiently general, sufficiently numerically robust program to compute the fire growth from an arbitrary ignition in an arbitrary building (Task 2); To develop some of the missing pieces of the science of fire as required for the developing computer program (Tasks 1, 3, 4, 5). The various tasks are being carried out jointly at Harvard (Tasks 2, 5) and at FMRC (Tasks 1, 3, 4). The progress on these five tasks is reviewed below.

Task 1: Vitiation and Entrainment in Pool Fires

Task Leader: Dr. Michael A. Delichatsios FMRC  
(Former task leader F. Tamanini)

## Technical Abstract

The objective of the present task is to measure the influence of vitiation on turbulent flames and provide experimental results and theoretical models for calculating the plume properties when the flames are immersed and quenched by a hot layer of ceiling gases.

The 1.2-m diameter enclosure<sup>1</sup> constructed for this task, including a flame-quenching heat exchanger, was put in operation near the end of 1980. The test apparatus has been employed to measure radiation and rate of burning of propane diffusion flames produced by a 12.7 mm diameter nozzle as a function of height. Two propane flow rates were investigated, corresponding to theoretical heat release rates of 16 kW and 31 kW. The results<sup>2</sup> are presented in a dimensionless form in Figs. 1, 2, 3 and 4.

In these figures the prefix  $\Delta$  indicates the value of a property integrated from the exit of the nozzle to the corresponding height. The normalized length  $L_{.5}$  is the distance at which half of the fuel has been burned. Although only two flow rates were tested in a specific geometry, the tentative conclusions from these figures are:

1. The rate of burning, the radiation per unit height and the species concentrations (yields) are self similar.
2. The radiative fraction of the burning rate expressed in terms of the integrated properties over the distance from the exit of the nozzle increases with height.

These conclusions are encouraging because they support turbulence models<sup>3,4,5</sup> for the flaming region of a diffusion flame which all are based on a similarity-type assumption for the turbulent flow. The second conclusion is difficult to explain. Before any explanation is proposed, the error introduced by the presence of the catcher-quencher will be evaluated. Notice that the error increases for measurements taken close to the exit of the nozzle.

Similar measurements have been taken for a 38-cm diameter propane burner. The propane flow rates were the same as the flow rates produced by the 12.7 mm nozzle. In this case, fifty percent of the heat release occurs within 6 cm of the burner surface. To further investigate the effects of the pool size, a 17-cm propane burner has been built and a theoretical model is being developed.

Three different integral models<sup>3,4,5</sup> for a turbulent diffusion flame were developed last year. In all these models, an important parameter was the entrainment of combusting air by the diffusion flame. Since there is not a theoretical or experimental investigation on the value of the entrainment coefficient vs. height in turbulent diffusion flames, the objective of this task has been extended to include experiments on the combustion air entrainment.

Technical Reports and Papers

1. Tamanini, F., "A New Experimental Technique for Measuring the Burning Rate and Product Yield in Fire Plumes," Eastern Section Meeting, The Combustion Institute, 1980, Princeton, N.J.
2. Tamanini, F., "Height Dependence of Burning Rate and Product Yield in Fire Plumes," paper presented at First Specialist Meeting of the Combustion Institute, Bordeaux (France), July 20-25, 1981.
3. Tamanini, F., "An Integral Model of Turbulent Fire Plumes," Eighteenth Symposium (International) on Combustion, Waterloo, 1980.
4. de Ris, J., "A Stochastic Combustion Model for Fire Plumes," Journal of Fire Safety Vol. 3 No. 4, March 1981, pp.287-297.
5. Delichatsios, M.A., "Flame Height and Virtual Source in Turbulent Diffusion Flames," Eastern Section Meeting, The Combustion Institute, 1980, Princeton, N.J.

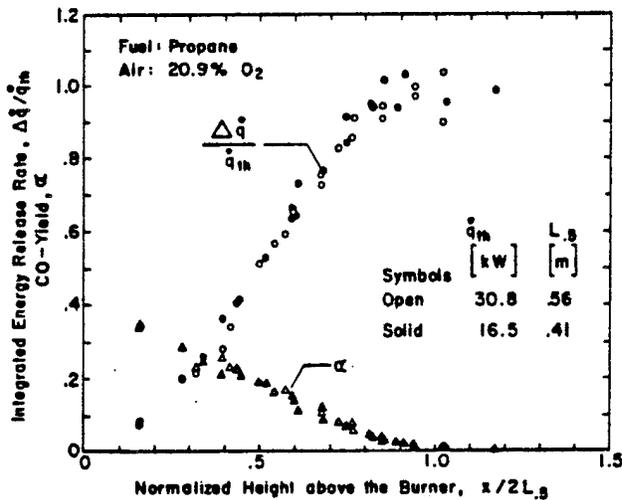


Figure 1. Normalized energy release rate and CO-yield plotted as a function of normalized height above the burner.

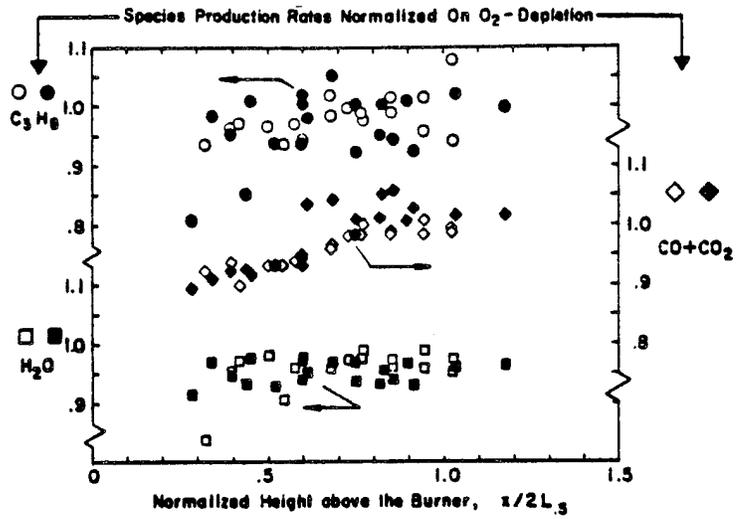


Figure 2. Rates of production of H<sub>2</sub>O and CO+CO<sub>2</sub> and rate of C<sub>3</sub>H<sub>8</sub> depletion divided by the stoichiometric equivalent based on the rate of O<sub>2</sub> depletion (see legend in Figure 2).

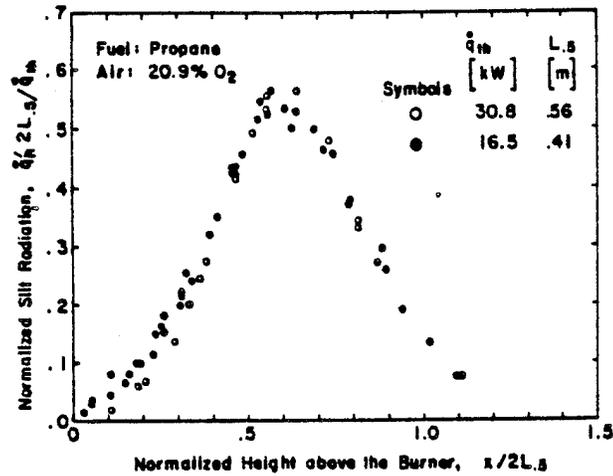


Figure 3. Normalized Slit Radiation as a function of height in the flame.

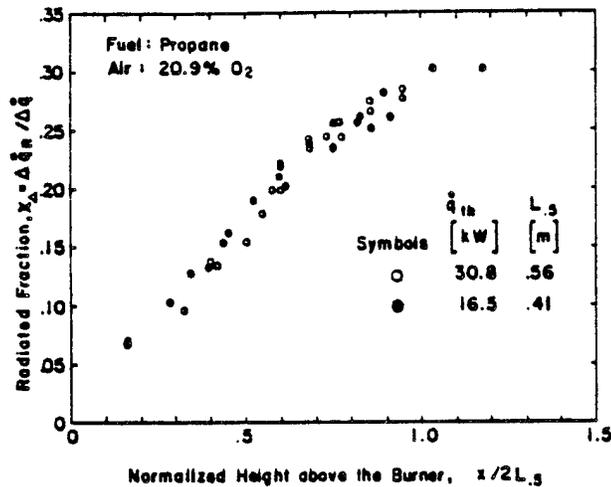


Figure 4. Variation of integrated radiant fraction,  $x_\Delta$ , with height in the flame.

## Task 2a: The Prediction of a Fire

Task Leaders: Dr. Henri E. Mitler, Prof. Howard W. Emmons H.U.

### Technical Abstract

The fifth version of the Harvard Computer Fire Code has been completed. This version (Mark V or CFC V) of the mathematical model permits the computation of the development of a fire in a vented enclosure. The fire can be one of three kinds: a growing fire (ignited at a point), a pool fire, or a burner fire. The room may have up to five vents. Mass flows through the vents are calculated; species concentrations (CO, CO<sub>2</sub>, H<sub>2</sub>O, O<sub>2</sub>, soot) are found for the hot layer, as well as its depth, temperature, and absorptivity. The surface temperatures of up to four objects (besides the original one) can be found, and they may ignite either by piloted (or auto-) ignition, or by contact with a (growing) flame. The calculation can be carried forward as far as desired; for a limited fuel mass, this means through flameover, burnout, and cool-down. No provision is yet made for the burning of walls or ceiling (hence no collapse).

Some of the detailed improvements for this version are: the particle concentration and water vapor concentration in the layer are now calculated; hence a subroutine due to A. Modak can be used (as an option) to find absorptivity of the layer. The difference in the results between using this and the simpler (default) option for the absorptivity is very small. The flame-flame interactions have been included, although they are small. The view factors of flames, walls, and ceiling have been recalculated explicitly, and other improvements in radiation subroutines also made. Ignition by contact with a flame is new, as is the burner fire. Reradiation from a burning surface as well as its convective heating, are now included. The alteration in flame shape which occurs during the fire is now included. (The flame gets smaller as the fuel burns out.) Flame parameters have been changed to agree with Orloff's data.

The input has been made more flexible and forgiving; the output format has been made more flexible. The fire-spread parameter  $A$  and the initial time increment  $\Delta t$  can now be input at run-time.

The tape of CFC V has been sent to NBS, and is available for wide distribution. The documentation is 80% finished as of this writing, and (hopefully) will be available by this summer.

Plans are in preparation for the next increment of improvement which will result in the development of CFC VI. The equations required to compute the growth of fire in a multiroom high-rise structure are being assembled. A report "Computer Fire Code VI-Plus" is in preparation and will discuss the present understanding of what is involved in the general building fire problem.

### Reports and Papers

1. Mitler, H.E., "Computer Fire Code V," Program Tape, Harvard University, 1981.
2. Mitler, H.E. and Emmons, H.W., "The Fifth Harvard Computer Fire Code," Technical Report # 45, The Home Fire Project, Harvard Univ., 1980 (in preparation).

### Task 2b: A Computer Fire Code - General Study

Task Leader: John Ramsdell

### Technical Abstract

We want to restructure the fire program with three goals in mind:

1. To improve transportability;
2. To reduce the difficulty of modifying the program; and
3. To reduce the numerical work required to find a solution at each time step.. .

We plan to improve transportability by using a standardized programming language. We intend to use FORTRAN 72 now, and consider ADA when it is available. A modular design of the line code has been done, using standard practices of software engineering, and it has yielded a program that is easier to modify. The efficiency of the numerics can be improved by eliminating variables. An algorithm for finding a good way of eliminating variables has been designed and coded [1]. We plan to test this code with new variable elimination problems.

Progress: We have written a fire code which implements all of the above ideas for a reduced set of physics [2]. The next task is to implement the above ideas for the physics of Fire Code V. During the process of creating this new fire code, we intend to document the entire procedure.

### Reports and Papers

1. Ramsdell, J.D., "Finding Minimal Feedback Vertex Sets," Home Fire Project Technical Report No. 47, April 1981.
2. Ramsdell, J.D., "Variable Elimination in the Home Fire Code," to be published in the Conference proceedings of the Heat Transfer Conference, Milwaukee, Wisconsin, August 1981.

### Task 3: Chemical Modeling of Pool Fires

Task Leader: L. Orloff FMRC

## Technical Abstract

This task is part of a concerted effort to predict the burning behavior of large pool fires using measured flame property data obtained from small pool fires. The present study emphasizes the development of simplified scaling relationships based on measurement techniques that are convenient and easily introduced to outside laboratories. The motivation for this and related tasks is to provide fire protection engineers with practical techniques for evaluating the potential fire hazard of a wide variety of fuels.

A simplified (homogeneous) radiation model was previously applied to 381 mm diameter PMMA pool fires. When applied to those fires the model offers the convenience of simple analytic expressions for radiant transfer to the fuel surface and to remote target locations. The simplified model requires average flame property values: temperature,  $\bar{T}_f$  and absorption coefficient,  $\bar{k}_f$  and a flame size parameter,  $L_m$ , the mean beam length.

This model has been further simplified in the current task and applied to typical sooty (propene) and moderately "clean" (methane) fires. The experimental design includes two sintered bronze burners (381 mm and 762 mm diameter) to evaluate scale effects and adjustable lip sizes to study lip effects. In the current model  $\bar{T}_f$  and  $\dot{Q}'''$ , the theoretical chemical heat release rate per unit volume is assumed constant and both  $\bar{k}_f$  and  $L_m$  are derived from measurements that can be obtained with a simple "slit radiometer." This is a wide angle radiometer viewing the flames through a horizontal slit, which measures the radiant power per unit height as a function of flame height.

Figure 1 shows a fairly well-correlated linear increase in  $L_m/R$  ( $R$  is the pool radius) with  $\dot{Q}'''$ , the theoretical chemical heat release rate, for the combined 381 mm pool methane and propene data. Calculated absorption coefficients vary about 20% across the range of burning rates and lip sizes for the respective fuels.

Investigations of 730 mm PMMA pool fires in related tasks show a marked temperature drop and local absorption coefficient increase near the fuel surface. This effect is associated with high concentrations of pyrolysis gases. Radiation blocking by pyrolysis gases can strongly affect burning rates for large ( $>1$  m) pool fires. Measurements of time-average local molecular species concentrations in turbulent pool fires are being made to develop scaling relationships accounting for radiation blockage effects.

A prototype improved gas sampling probe was constructed for those measurements. The probe design considers requirements for constant mass sampling rate and isokinetic sampling, quenching and transient response. A premixed  $O_2-C_3H_8$  burner providing a well-defined axisymmetric plume has been constructed to test this probe under conditions where the plume species concentration should be exactly correlated with plume temperature.

Current efforts are directed toward obtaining spatial distributions of local temperature and time-averaged molecular species concentration parametric in pool diameter, lipsize and actual combustion heat release for two different fuels ( $\text{CH}_4$  and  $\text{C}_3\text{H}_6$ ). The data will be analyzed to determine whether it correlates with soot and local absorption-emission coefficients obtained from the Task 4 study. Correlations of the mixture-fraction variable with respect to pool scale and lip size will also be sought.

#### Technical Reports and Papers

1. Orloff, L., "Simplified Radiation Modeling of Pool Fires," Eighteenth Symposium (International) on Combustion (in press).
2. Modak, A.T., "The Burning of Large Pool Fires," Journal of Fire Safety Vol. 3, No. 3, February 1981, pp. 177-184.

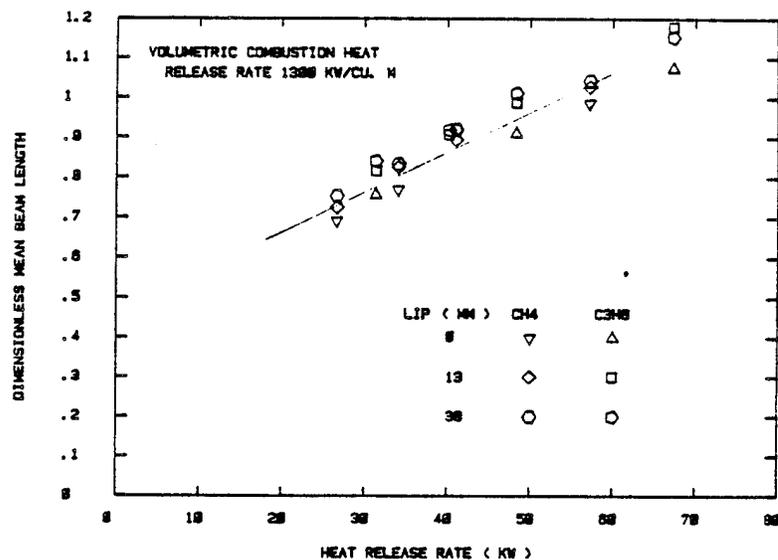


Figure 1. Dimensionless mean-beam-length,  $L_m/R$ , as a function of theoretical chemical heat release rate for methane and propene 381 mm pool fires.  $L_m/R$  based on assumed  $\dot{Q}''' = 1300 \text{ kW/m}^3$  and  $T_f = 1200 \text{ K}$ .

#### Task 4: Radiation from Flames

Task Leader: George H. Markstein FMRC

#### Technical Abstract

In many fires, energy transfer from the flame to the fuel and to the surroundings occurs predominantly by thermal radiation. The main objective of the present task is the development of techniques for measuring the pertinent radiative properties of fires, and to provide a quantitative basis for predicting the resulting radiative energy transfer. The rate of fire growth and the spread of fire to new fuel elements depends critically on this energy transfer, and its quantitative assessment is thus essential for estimating fire losses and threat to life safety.

Earlier work under this project had shown that for sufficiently large fires, e.g., pool fires with diameters exceeding about 0.3 m, it is essential to take nonuniform distribution of radiation sources within the fire into account. In the present task, three instruments have been developed recently for the measurement of nonuniformly distributed radiative properties of fires.

One of these, the scanning radiometer, has been described previously, and data obtained with this device have been reported. The instrument is currently being used extensively in Task 3 for measurements on gaseous-fuel pool fires.

Another instrument, a water-cooled and nitrogen-purged fiber-optic absorption probe that can be inserted into a fire to measure the local absorption coefficient, has also been described earlier. Further work with this probe is planned: new measurements on gaseous-fuel pool fires will be compared with absorption data obtained by the indirect method of Abel inversion of transmittance data.

Recent work has concentrated primarily on the development and use of the third instrument, a modification of the Schmidt method for measuring radiation temperatures and emissivities of fires. The conventional Schmidt method uses a furnace blackbody source of background radiation, and is therefore slow and cumbersome, since the measurements must be repeated at several settings of the source temperature. The present "fast-Schmidt" instrument employs a tungsten-filament source with a sapphire window that permits rapid change of effective source temperature. Digital feedback control is used for matching the effective background temperature automatically to the flame radiation temperature. An analysis showed that the use of a nongray background source in the Schmidt method requires the flame to be a gray emitter. Comparisons of results obtained with gaseous-fuel ( $C_2H_6$ ,  $C_3H_8$  and  $C_3H_6$ ) pool fires by the conventional and the new method showed agreement of radiation temperatures within about  $\pm 2$  percent and thus indicated that for sufficiently luminous (sooty) flames the restriction to gray emission is not a serious limitation.

The fast-Schmidt method has been used to obtain vertical traverses along the flame axis, and horizontal traverses near the pool surface, for 0.762 m-diameter propylene pool fires at several fuel flow rates. The results showed that at the flame axis near the pool surface, the radiation temperature decreases with increasing fuel flow rate. Near the flame periphery, as well as at axial locations at heights above the pool surface exceeding about  $1/3$  pool diameter, the trend is reversed. The emissivity was found to increase with fuel flow rate everywhere within the flame. The horizontal traverse near the pool surface also showed a minimum of radiation temperature at the axis and maxima at lateral distances of about  $1/4$  pool diameter, while the emissivity maximum occurred at the axis.

On the basis of the axial symmetry of the flame, the horizontal traverses of radiation temperature and emissivity can be inverted

numerically, to yield the more fundamental radial distributions of the absorption coefficient and the volumetric radiant power.

It is planned to continue measurements with the fast-Schmidt method on gaseous-fuel pool fires. This work, as well as the measurements with the absorption probe, will be coordinated with the work under Task No.

3. A portion of the work will also be devoted to the development of a fast-response flame-ionization probe to measure local total hydrocarbon concentration in flame gases. In combination with a fast-response thermocouple, this probe should permit the determination of the fluctuating value of the conserved Shvab-Zeldovich variable in fires.

#### Technical Reports and Papers

1. Markstein, G.H., "Rapid Measurements of Fire Radiative Properties with a Feedback-Controlled Tungsten Source of Background Radiation," Paper No. 20, Eastern Section, The Combustion Institute, Princeton, N.J., November 1980.
2. Markstein, G.H., "Recent Advances in the Measurement of Radiant Transfer from Fires," Paper 81-14 (Invited Review), Spring Meeting, Western States Section, The Combustion Institute, Pullman, Washington, April 1981.
3. Markstein, G.H., "New Methods for Radiation Measurements in Fire Research." To be presented at the First Specialists Meeting of the Combustion Institute, Bordeaux, France, July 1981.

#### Task 5a: Experimental and Theoretical Study of Horizontal Fire Spread on Wood

Task Leader: Arvind Atreya H.U.

#### Technical Abstract

In a room on fire, objects that are not involved are being heated by direct radiation from the flames of the burning objects and by the hot layer in the room. In the lab this situation is simulated by using radiant heaters and by circulating oxygen depleted air. The present study is limited to Fire spread on horizontal surfaces of wood under various levels of external radiation and vitiation.

In contrast with commonly studied synthetic materials, wood is anisotropic and inhomogeneous. This greatly affects the dynamics of fire spread. There are four major differences:

1. It forms an insulating layer of char (to date there does not exist experimental data and a theory for any charring material).
2. The rate of flame spread was found to be related to the orientation of the grain. Combustible gases that are generated in the combustion zone are liberated ahead of the flame front allowing the flame to spread faster in that direction.

3) Woods like pine that have a lot of resin content form spots wetted with resin on the surface when heated. As the flame approaches this resin pool it spreads on the liquid surface much faster than elsewhere.

4) Sometimes woods like redwood have vastly different growth ring patterns in the same sample, accounting for a very nonhomogeneous material. Flame speed is an order of magnitude lower when such a dense year ring pattern is encountered. At times the flame has even extinguished.

Several experiments on fir, pine, redwood, red oak, maple and mahogany have been done. The measurements include the following as a function of time: 1) Weight loss; 2) Fire radius; 3) Total energy released (exhaust and radiant); 4) CO<sub>2</sub>; 5) O<sub>2</sub>; 6) CO; 7) Total hydrocarbons; 8) Temperatures at various depths; 9) External radiation level. The data is presently being analyzed, and only a few results are available at this moment. Figure 1 shows results from two different experiments on maple. Spread rates are considerably higher for higher initial temperatures of the slabs.

A charring theory was developed by assuming the existence of a "pyrolyzing surface." At this surface the pyrolysis rate is infinite and the temperature is the pyrolysis temperature. This heat conduction problem was solved for a constant surface temperature moving boundary condition. This solid phase solution has yet to be combined with the gas phase to yield a complete theory.

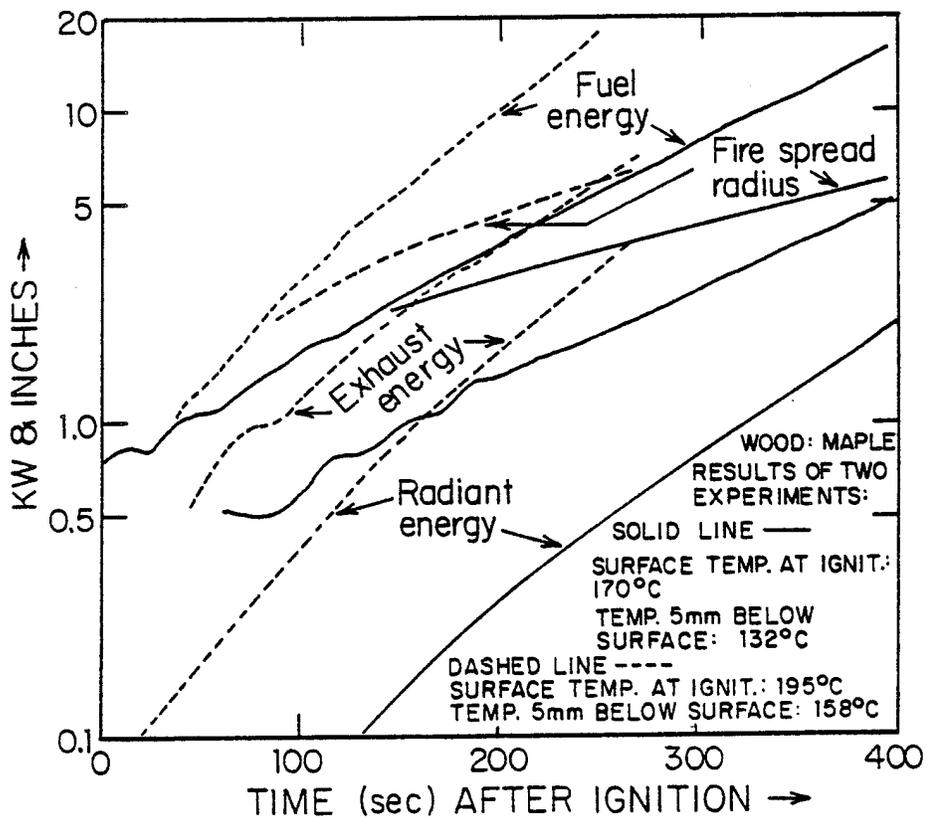


Fig. 1

Task 5b: Experimental and Theoretical Study of Horizontal Fire Spread on Plastics

Task Leader: Seng-Chuan Tan, H.U.

Technical Abstract

Work on the understanding of the fire growth and burning of cellular plastics continued with the measurement of the following rate data for a number of plastic foams:

- 1) Radial spread rate;
- 2) Pyrolysis weight of the sample;
- 3) Convective and radiative energies evolved by the fire;
- 4) CO, CO<sub>2</sub>, O<sub>2</sub>, HC and H<sub>2</sub>O gas concentrations in the exhaust.

These data are obtained from transient fire spread tests performed on 24" square samples in 3 broad categories with the following conditions:

- 1) No external radiation or vitiation (ambient conditioning);
- 2) External radiation and preheat of material;
- 3) Fire-vitiated air.

The following test conditions were standardized:

- 1) All tests were carried out on freshly cut surfaces to avoid the problem of surface aging.
- 2) The foams were ignited using a single wax match with an insertion depth of 10 mm. This method of ignition is reproducible and the time flaming ignition begins is when the lower edge of the match flame strikes the foam surface.

The apparatus used is the same as that for Task 5a. Transient fire growth tests for category 1) have been completed on the following PRC materials: GM22, 24, 26, 28, 32, 42, 48, 50, 52 and 54. The Tenneco Chemicals #7004 foam used in the Home Fire Project Test Series 1973-1977 has also been measured.

Systematic tests for category 2) have been started on the same foams with uniform ( $\pm 5\%$ ) external radiation levels up to .85 W/cm<sup>2</sup> and preheat times up to 7 minutes. The limits of "sustained flaming" of the above materials were determined earlier using small-scale (6" square) transient tests under different preheat times and radiation levels.(Fig1) For some foams there appears to be a minimum threshold of radiation level below which sustained flaming does not occur. This is the radiation level necessary to balance heat losses to maintain a minimum surface temperature for flame spread.

Following the completion of the tests for category 2), a few additional tests will be performed to include fire-vitiated conditions.

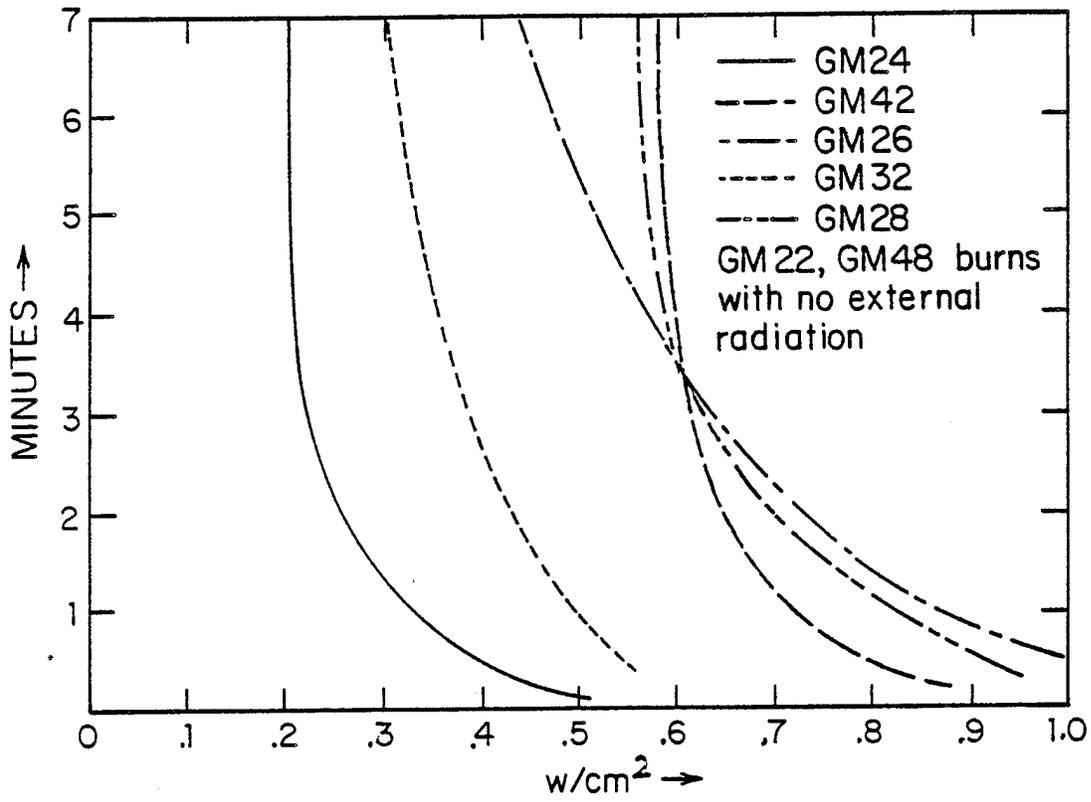


Figure 1

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Integrated Systems, Inc. (a maryland corporation)

Grant No.: NB-79-SAC-A0230

Grant Title: Mechanical Designers' Smoke Control Manual

Principal Investigator: John W. Fothergill, Jr.  
Integrated Systems, Inc.  
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318 West Potomac Street  
Brunswick, Maryland 21716

Other Professional Personnel: Patricia A. Fothergill  
Hun-Ya Lee  
Henry DuBay  
Margaret A. Johnson

NBS Scientific Officer: John Klote

Technical Abstract

The physical fundamentals, principles, procedures, equations, constraints, design variables, data, definitions, etc., necessary to design proven smoke control measures are being organized into a manual. Suitable forms of presentation, such as graphs, tables, nomographs, etc., are being developed and integrated into written text to allow easy use by mechanical designers. An overall format for presentation of the material has been developed which will provide a user with an understanding of the principles involved. Samples or examples of effective smoke control techniques of different levels of protection will be included. The manual will also contain the calculational steps, procedures, and data necessary to determine fan sizes, effective relief vent areas, and other design variables, with appropriate examples of applying each such calculational procedure.

This manual will provide the means for mechanical designers to design state-of-the-art smoke control systems. This, in turn, should reduce the injury and death rate due to smoke and toxic gas inhalation.

Reports and Papers

Fothergill, J. W., Jr., "A State-of-the-Art Smoke Control System Test Procedure," presented at the Semi-Annual ASHRAE Meeting, Chicago, Ill., 25-29 January 1981.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Lawrence Berkeley Laboratory, University of California,  
Berkeley

Grant No.: NB 80 NAG-E6839

Grant Title: Fire Modeling

Principal Investigator: Professor Patrick J. Pagni  
Mechanical Engineering Department  
University of California  
Berkeley, California 94720  
Telephone: (415) 642-0729

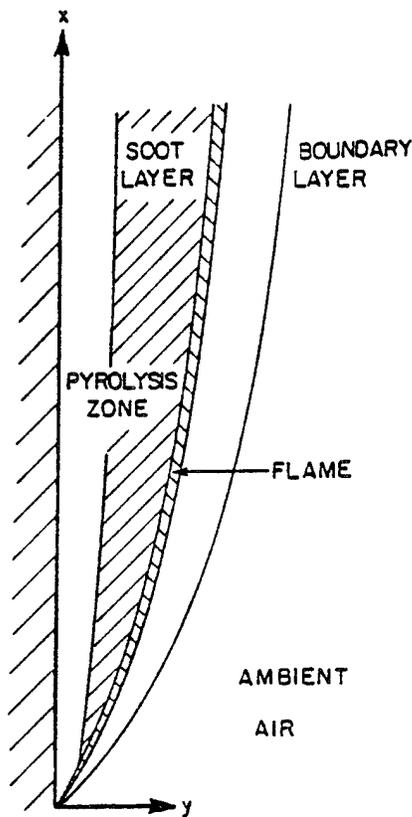
Other Professional Personnel: Richard A. Beier, Ph.D. Candidate  
Clement I. Okoh, Ph.D. Candidate  
Catherine Cagle, M.S. Candidate

NBS Scientific Officer: W. Gary Mallard

Technical Abstract:

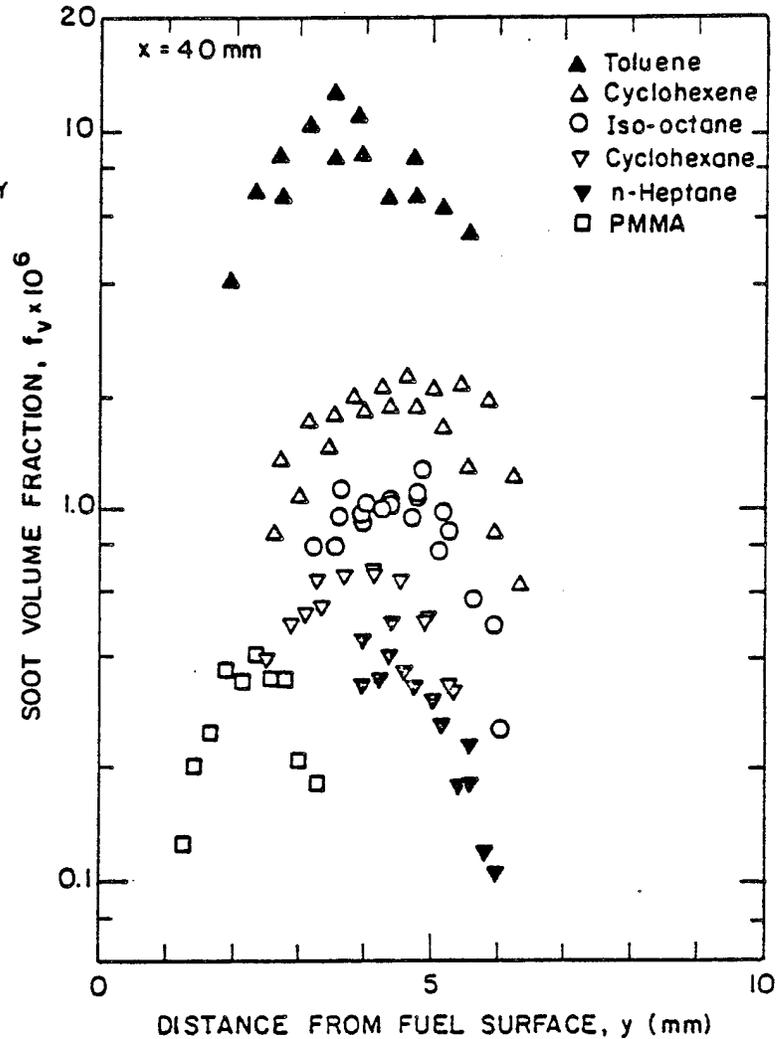
The overall goal of this project is to develop physical and mathematical models of the detailed combustion phenomena which control a fire's growth within a compartment of origin and its subsequent propagation through a structure. These experimental and theoretical studies will provide bases for development of test methods and for evaluation of the real fire hazard of materials. This year's report concentrates on incorporating radiation in the modeling of combusting systems and the measurement of a key parameter to quantifying radiation in fires, the flame soot volume fraction.

Experimental values of  $f_v$ , the local volume fraction of the flame occupied by combustion generated carbon particulate, have been reported for small turbulent pool-fire flames [7,8]. Measurement of the attenuation at several wavelengths of monochromatic laser beams passing through a flame also determines approximate detailed size distributions for the carbon particles within the flame. Recent results are given in Fig. 2 for the detailed profiles of  $f_v$  in the free combusting boundary layer shown in Fig. 1. The liquid hydrocarbon fuels rank as expected from toluene down to n-heptane. Formation near the fuel and oxidation near the flame lead to a maximum in  $f_v$  near the converging streamline. These data and detailed velocity, temperature and species fields, calculated with methods currently under development here for incorporating radiation effects in the Shvab-Zeldovich combusting boundary



XBL 813-5397

Figure 1.



XBL 813-5399

Figure 2.

layer analyses [5,6], will permit modeling of the soot formation process and accurate prediction of flame radiation.

Calculations of flame radiation back to polyurethane in a pool fire geometry yield good agreement with experimental mass pyrolysis rates [1]. Flame radiation is well accepted as the dominant heat transfer mode in full scale fires. This radiation is in turn controlled by the amount of soot in the flame which now can be measured in both laboratory and full scale flames by the techniques described here [7-9]. The next step is to determine proper soot scaling laws to allow small scale laboratory results to be accurately extrapolated to full scale fires. Efforts will also be directed toward extending flame height analyses to include radiation and turbulence. Additional non-dimensional

radiation parameters will emerge, but previously identified groups remain important [3,6].

Reports and Papers:

1. C.M. Kinoshita and P.J. Pagni, "Laminar Wake Flame Heights," Journal of Heat Transfer, Trans. ASME, Series C, 101, 104-109, 1980.
2. C.M. Kinoshita, P.J. Pagni and R.A. Beier, "Opposed Flow Diffusion Flame Extensions," Proceedings of the Nineteenth (International) Symposium on Combustion, in press, The Combustion Institute, Pittsburgh, PA, (1980).
3. C.M. Kinoshita and P.J. Pagni, "Stagnation-Point Combustion with Radiation," Proceedings of the Nineteenth (International) Symposium on Combustion, in press, (1980).
4. P.J. Pagni, "Diffusion Flame Analyses," Fire Safety Journal 3, 273-285, 1981.
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7. R.A. Beier and P.J. Pagni, "Soot Volume Fraction Profiles in a Free Combusting Boundary Layer," American Society of Mechanical Engineers Paper, in press, (1981).

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Lawrence Berkeley Laboratory, University of California,  
Berkeley

Grant No.: NB 80 NAGE 1653

Grant Title: Thermal Radiation of Luminous Flames and Smoke

Principal Investigator: Professor Chang-Lin Tien  
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Telephone: (415) 642-0877

Other Professional Personnel: S. C. Lee (Ph.D., 1981)  
G. S. Shiralkar (Ph.D., 1980)  
T. W. Tong (Ph.D., 1980)

NBS Scientific Officer: Dr. Takashi Kashiwagi

Technical Abstract

The objective of this project is to establish a simple physical framework for the calculation of radiation from complex fire and smoke phenomena. The basic research approach aims at developing approximate formulations by systematic experimentation and analysis of the fundamental aspects of the problem. In particular, the research is focussed on three topics: (1) experimental and theoretical investigation of the soot properties affecting soot radiation from flames and smoke, (2) analysis of radiative heat transfer in scattering media, and (3) computation of fire radiation and plume convection in an enclosure.

Flame and Smoke Radiation. Soot particles play an important role in the radiative heat transfer from flames and smoke. It is necessary to know detailed information on the soot optical properties, size distribution, and shape for accurate calculation of soot radiation. A dispersion model has been established to predict the optical properties of soot from in-situ flame data. Experiments are also performed of the visible and infrared radiation attenuation in small-scale diffusion flames of solid, liquid, and cellular fuels to provide information on the extinction characteristics, as well as size distributions of soot from the various fuels. Successful application of the optical properties to predict accurately the radiative characteristics of the soot particles indicates that these properties are indeed representative of that of soot from different fuels. Study on the effect of soot shape on soot radiation reveals that the shape effect is more pronounced at low temperature, i.e., typical of smoke, than at high temperature, i.e., typical of flames. The polydisperse and spherical assumptions of

soot particles are also found to be appropriate for radiation calculation at elevated temperatures. Experimental investigation of the shape effect is being currently pursued.

Analysis of Radiative Transfer with Scattering. Soot particles absorb and scatter visible and infrared radiation. Radiative heat transfer in flames and smoke can be modeled on the basis of dispersed particles acting as independent absorbers and scatterers in the gaseous medium. Simple, convenient representation of the absorption-scattering field is being investigated. In particular, the resistance network representation of radiative heat transfer, an absorbing-scattering system has been developed on the basis of the two-flux and the linear anisotropic scattering model. The mean beam length formulation for anisotropic-scattering media is being investigated.

Computation of Enclosure Convection and Radiation. Progress has been made in achieving simple approximate solution for radiation heat transfer in one-dimensional, non-planar geometries and multi-dimensional geometries. Computation schemes for enclosure convection have been examined carefully with their respective strengths and limitations. Interaction between enclosure convection and radiation is being pursued currently.

#### Reports and Papers

S. C. Lee and C. L. Tien, "Optical Constants of Soot in Hydrocarbon Flames," Eighteenth Symposium (International) on Combustion, The Combustion Institute, 1159-1166 (1981).

S. C. Lee and C. L. Tien, "Effect of Soot Shape on Soot Radiation," Paper No. 80-54, Western States Section/The Combustion Institute Fall Meeting (1980). Submitted for publication.

C. L. Tien and S. C. Lee, "Flame Radiation," to appear in Progress in Energy and Combustion Science (1981).

T. W. Tong and C. L. Tien, "Resistance-Network Representation of Radiative Heat Transfer with Particulate Scattering," J. Quant. Spect. Radiat. Transfer, 24, 491-503 (1980).

W. W. Yuen and C. L. Tien, "A Successive Approximation Approach to Problems in Radiative Transfer with a Differential Formulation," J. Heat Transfer, 102, 86-91 (1980).

G. S. Shiralkar and C. L. Tien, "A Numerical Study of Laminar Natural Convection in Shallow Cavities," Journal of Heat Transfer, 103, 226-231 (1981).

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: National Fire Protection Association, Quincy, MA

Contract No.: EMW - C - 0252

Contract Title: Investigation and Analysis of Major Fires

Principal Investigators: A. Elwood Willey, Project Administrator  
Richard L. Best, Senior Fire Analysis  
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Steven W. Hill, Fire Analysis Specialist  
Fire Investigations Department  
National Fire Protection Association  
Batterymarch Park  
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Other Professional Personnel: James R. Bell, Legislative Technical  
Specialist  
James K. Lathrop, Life Safety Code  
Specialist  
Wilbur Walls, Flammable Gases Specialist  
Martin Henry, Flammable Liquids  
Specialist  
Robert Benedetti, Chemical Specialist  
Joseph Redden, Assistant Vice  
President, Public  
Protection  
Robert Carter, Chief Fire and Arson  
Investigations  
Specialist

NBS Scientific Officer: Irwin A. Benjamin  
(COTR: Thomas Klem, Federal Emergency  
Management Agency, U.S.  
Fire Administration,  
National Fire Data Center)

Technical Abstract: Under a cost-sharing contract between the National Fire Protection Association, National Bureau of Standards and Federal Emergency Management Agency, in-depth field investigations are conducted of selected fire incidents. For each investigation an analysis is made of fire causal factors, spread factors, materials contributing to fire and smoke propagation, people movement and actions taken, fire propagation as a function of time, factors affecting fire propagation, performance of fire protection equipment, key life safety and property protection problems and of contributing factors resulting in loss of life and property damage. In addition to field work by investigators with fire protection engineering background, other specialists are consulted, including NBS

researchers. In some cases, samples from fire scenes are tested for fire hazard characteristics at NBS and results included in reports. Briefings by fire investigations are provided FEMA/NBS regarding incident facts and technical aspects of interest.

Following submittal of contract reports to FEMA/NBS, reports are published and distributed by NFPA to ensure that the facts and lessons learned are made available to the fire community in a timely manner. In addition to the literature, background data from the investigations is available at NFPA for research purposes.

This contract is the fifth in a series of NFPA/NBS fire investigation contracts since 1972. The three most recent contracts have also involved the FEMA, with funding shared between the two agencies and NFPA in a cooperative effort. Since the original contract, 79 incidents have been investigated and reports prepared.

### Potential Applications

This in-depth investigation and analysis activity gives an improved understanding of fire growth and development, smoke development and spread, and the actions of people in actual fire situations. The information gained has many uses both in the fire safety field and in the research community.

Reports contain commentary on the performance of fire detection and extinguishing equipment, building assemblies and systems and various measures of fire control. The studies provide an opportunity to measure the performance of requirements in national consensus fire safety codes and standards. Lessons learned from these investigations are of use to fire safety practitioners and researchers. Indicators for additional research are often included in reports.

In addition to the use of information by NFPA technical committees and in technical programs, information from investigations is utilized in training films and slide packages for use by the fire service and fire safety practitioners.

### Future Milestones

Investigations are in progress on three incidents and reports will be prepared. These active studies include:

- o A fire in the MGM Grand Hotel, Las Vegas, Nevada killed 85 and injured 678. The incident which occurred on November 21, 1980 involved large portions of the ground level Casino area and produced large quantities of heat and smoke throughout the guest room areas. Although victims were found throughout the complex, the major concentration of deaths occurred on the top five floors.

The fire started in a restaurant area and progressed to the large open Casino and Arcade levels. Smoke from the fire was transmitted to upper levels via interior stairways, other vertical openings, and by the building's HVAC system.

In conjunction with the incident investigation of the MGM Hotel fire, a separate study of the human behavior elements of that fire is being conducted. This survey of individual emergency situation reactions encompasses nearly 2000 people who were involved in the November 21, 1980 fire.

- o On the evening of February 10, 1981, 8 people died and approximately 350 were injured as a result of an incendiary fire in the Las Vegas Hilton Hotel. This hotel is the largest in the United States.

This was a very technically significant fire incident due to exterior fire spread that involved 22 floors of the 30-story building. This exterior fire spread was attributed to a combustibile interior finish in the form of carpeting on the walls and ceilings of elevator lobbies along with other fuels such as combustibile drapes and furnishings.

- o On December 4, 1980, a fire of incendiary origin occurred within the Conference Center at the Stouffer's Inn, Harrison, New York. The critical location of the fire in the exit access, the rapid development of fire, and the lack of a second means of egress from the small meeting rooms were significant factors which contributed to the 26 fatalities and some 40 injuries.

Reports and Papers: Under this contract the following investigation reports have been submitted to FEMA/NBS:

Bell, James R., "High-Rise Building Fire - New York City, New York - 137 Injuries - June 23, 1980."

Demers, David P., "Nursing Home Fire - Mississauga, Ontario - 24 Fatalities - July 14, 1980."

Bell, James R., "Hotel Fire - Bradley Beach, NJ - 24 Fatalities - July 26, 1980."

Bell, James R., " Donehue Adult Foster Care Home Fire - Detroit, Michigan - 5 Fatalities - November 30, 1980." (Summary Report)

Hill, Steven W., "Royal Beach Hotel Fire - Chicago, IL - March 14, 1981 - Nineteen Fatalities." (Limited Investigation)

### Preliminary Reports

"MGM Grand Hotel Fire, Las Vegas, Nevada, November 21, 1980"

"Stouffer's Inn of Westchester Fire, Harrison, New York,  
December 4, 1980"

Las Vegas Hilton Hotel Fire, Las Vegas, Nevada, February 10,  
1981"

### Published Reports

Best, Richard L., Reconstruction of a Tragedy - Beverly Hills  
Supper Club Fire, NFPA, 1978.

Demers, David P., Fire In Syracuse: Four Fire Fighters Die,  
NFPA, 1979.

A Study of the Baptist Towers Housing for the Elderly Fire,  
NFPA, 1973.

### Articles in NFPA Publications

Bell, James R. "Smoke Hinders High-Rise Fire Operations." Fire  
Command, February 1981.

Demers, David. "25 Die in Nursing Home Fire." Fire Command, March  
1981.

Best, Richard. "Howard University Hospital Fire, Washington, DC."  
Fire Journal, January 1981.

Demers, David. "25 Die in Nursing Home." Fire Journal, January 1981.

Bell, James R. "137 Injured in New York City High-Rise Building Fire."  
Fire Journal, March 1981.

Bell, James R. "25 Die in New Jersey Hotel Fire." Fire Journal, March  
1981.

"Fire at the MGM Grand - A Preliminary Report." Fire Journal, March  
1981.

### Recent Major Publications

Wiley, A. Elwood, "Lessons from Recent Hotel Fires",  
presented before the Opening Session, May 18, 1981, at the  
85th NFPA Annual Meeting, Dallas, TX.

Best, Richard L., "Mississauga Train Derailment", presented at the Annual Meeting of the Union of Furtherance of Fire Protection, Leverkusen, Germany, June 16, 1981.

Case Study NFPA Films and Slide Packages based on contract investigations:

Case Study Slide Packages:

- SL - 13, "LP-Gas Explosion, Kingman, Arizona, July 5, 1973"
- SL - 22, "Hospital Fire, Osceola, MO., December 3, 1974"
- SL - 26, "Three Nursing Home Fires" (Wincrest Nursing Home, Chicago, Illinois, January 30, 1976; Cermack House, Cicero, Illinois, February 4, 1976; Plaza Nursing Centre, Niles, Illinois, February 18, 1976)
- SL - 38, "Reconstruction of a Tragedy - The Beverly Hills Supper Club Fire"

Films:

- FL - 35, "Incendio!" (High-rise fire, Sao Paulo, Brazil, February 1, 1974)
- FL - 50, "The Beverly Hills Supper Club Fire . . . A Case for Code Enforcement"

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: The Pennsylvania State University

Grant No.: NBS Grant 7-9020

Grant Title: An Investigation of Fire Impingement on a Horizontal Ceiling

Principal Investigator: Professor G. M. Faeth  
Department of Mechanical Engineering  
The Pennsylvania State University  
214 M. E. Building  
University Park, PA 16802

Other Professional Personnel: S-M. Jeng, Graduate Assistant  
H-Z. You, Ph.D. Candidate

NBS Scientific Officer: H. Baum

Technical Abstract

The structure and heat transfer characteristics of turbulent fires and fire plumes impinging on a horizontal ceiling are being investigated in order to provide a better understanding of unwanted fires within structures. The results of the study have direct application to modeling fires within buildings, determining heat transfer rates to structural members during fires, and to estimating the environment of fire detectors and fire suppression devices mounted near a ceiling. Results of the study also provide basic information on the properties of buoyant, turbulent, combusting flows useful for the development of improved theoretical descriptions of these processes.

The objectives of the research are to complete measurements of convective and radiative heat fluxes to the ceiling and radiative heat fluxes to the surroundings when an axisymmetric turbulent fire plume impinges on a horizontal ceiling. The structure of the flow, in both the plume and ceiling jet regions is also being examined. These results are being employed to develop a differential (field) model of the plume portion of the flow, which utilizes higher-order turbulence closure; as well as simplified integral models which can represent the main features of both the plume and ceiling jet regions. The objective of the theory is to help summarize the experimental results and to provide more insight concerning simple correlations of the measurements that were found during earlier stages of the investigation.

Measurements during this report period emphasized flow structure in the plume portion of the flow. The measurements included profiles of mean velocity, velocity fluctuations and Reynolds stress using a laser-Doppler anemometer, mean temperature using fine-wire

thermocouples, and mean concentrations of gaseous species using isokinetic sampling and gas chromatography. A sampling system for soot concentrations and a method for measuring instantaneous concentrations by marker nephelometry were also developed during this report period, however, only limited measurements have been completed with these systems to date.

Measurements have been completed on two experimental apparatus. The first arrangement involves a 55 mm I.D. burner tube located 400 mm below a 1000 mm diameter water-cooled ceiling. Two flames have been studied with this apparatus, having flame tip Reynolds numbers 2000 and 8000. The second apparatus involved an open 1.2 mm I.D. burner with no ceiling present so that measurements could extend well beyond the combusting region. In this case, flame tip Reynolds numbers were varied in the range 5000-25000.

The main elements of the field model have been described in earlier reports. Briefly, a  $k-\epsilon-g$  turbulence model is employed using Reynolds averaged governing equations and a simplified radiation model. Buoyancy is considered in the mean flow equations, but the effect of buoyancy on turbulence properties is ignored. This model has demonstrated good agreement with combusting jet measurements, involving small buoyancy effects, during earlier work in this laboratory.

The integral model for the plume has been constructed to minimize its complexity and empiricism. Top-hat profiles are assumed using an entrainment expression involving two empirical constants. Turbulent reaction rates are estimated using an integral model simplification of the Magnussen and Hjertager model. The reaction expression requires one additional empirical constant.

The integral model in the ceiling jet is constructed in the same manner as the plume. The only additional empirical factor involves the friction factor at the ceiling. Convective ceiling heat transfer rates are found using the Reynolds/Colburn analogy.

The predictions of both models have only been compared with results in the literature and measurements using the 55 mm I.D. burner. The field model yielded fair predictions, however, the results were not as satisfactory as for forced flows. The main discrepancy involved underestimating the width of the flow. Currently, the model is being improved by introducing a beta function pdf and buoyant contributions to turbulence. Work is in progress to compare the revised model with the expanded data base available from the new measurements.

Both current measurements and those in the literature were reduced to obtain mean flow properties appropriate for comparison with the predictions of the integral model. Predicted and measured mean velocities, temperatures and concentrations were in reasonably good agreement for both the plume and ceiling jet regions. However, best results were obtained using slightly different values of the entrainment constant for noncombusting and combusting flows (0.140 and 0.182, respectively).

While the variation is not much worse than the accuracy of existing data, it does suggest effects of buoyant structure and Froude number that could be accommodated in an improved model. These modifications will be considered when all experimentation is complete.

Currently, a new apparatus is being constructed which employs a 5 mm I.D. burner. Several improvements over earlier arrangements have been incorporated in order to improve experimental accuracy. This includes cooling the burner to room temperature in order to eliminate extraneous natural convection flows along the sides of the plume and a screened enclosure that moves as the burner position is varied for LDA measurements. The moving enclosure serves to reduce disturbance of entrainment properties. This arrangement will provide a means of approaching conditions where both buoyancy and high Reynolds numbers are present at the same time, which eliminates an important gap in the current data base. Measurements with this system will involve both combusting and noncombusting flows using the LDA for velocities and marker nephelometry for concentrations. The capability of instantaneous measurements of both quantities will provide a means of testing the extensions of the differential model.

The results of this research provide benchmark flow structure data under well-defined experimental conditions which can be used to test both detailed differential models as well as simplified integral models of natural fires. The models examined thus far appear promising and exhibit the potential to reduce the need for expensive large scale tests during fire hazard evaluation as well as providing a more rational basis for standardized fire tests.

#### Reports and Papers

You, H-Z. and Faeth, G. M., "An Investigation of Fire Impingement on a Horizontal Ceiling," Report under NBS Grant 7-9020, Department of Mechanical Engineering, The Pennsylvania State University, October 1980.

You, H-Z., "An Investigation of Fire Plume Impingement on a Horizontal Ceiling," Ph.D. Thesis, The Pennsylvania State University, March 1981.

You, H-Z. and Faeth, G. M., "Buoyant Axisymmetric Turbulent Diffusion Flames in Still Air," Combustion and Flame, in press.

You, H-Z. and Faeth, G. M., "A Simplified Model of Axisymmetric Turbulent Fire Plumes," in preparation.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Fire Research Department, Construction Technology Laboratories, Portland Cement Association

Grant No.: NBS Grant NB8ONADA1009

Grant Title: Extension of Short-Term Creep Tests at Elevated Temperatures

Principal Investigator: Michael Gillen  
Fire Research Department  
Construction Technology Laboratories  
Portland Cement Association  
5420 Old Orchard Road  
Skokie, Illinois 60077

Other Professional Personnel: None

NBS Scientific Officer: L. Issen

Technical Abstract

This program is an extension of a previous investigation, also funded by NBS, of the short-term creep behavior of concrete at elevated temperatures. The current program examines the influence of variables not studied in detail in the initial program, but that was observed to have a measureable effect on concrete strain behavior. In particular, the role of moisture in influencing creep behavior will be studied at a number of loads and temperatures. In addition, one test series will examine the effect of these variables on concrete compressive strength.

At the conclusion of the experimental portion of the program, an effort will be made to use the data to develop an analytical expression that will adequately model concrete creep behavior as a function of the variables studied. A suitable model for the short-term creep of concrete at elevated temperatures is essential for the accurate evaluation of the design of a concrete structure to withstand fire.

The experimental program includes 276 creep and compressive strength tests on concrete cylinders made from three types of mineral aggregates. Significant variables are:

- a. Aggregate type - calcareous, siliceous, and lightweight aggregates,
- b. Temperature - ambient to 649C (1200F),
- c. Static load - 0.3 to 0.6 $f_c'$ ,
- d. Concrete curing - 10, 50, and 100% RH, and
- e. Test duration - 6 to 24h.

The analytical portion of the program will begin with, but not be limited to, a comparison of test data to models proposed by other investigators in the field of creep of concrete at room and elevated temperatures. In addition, some alternative expressions will be examined in the course of determining the mathematical model that best matches experimental results.

Funding for the program was approved at the end of March, 1980. Work completed from that time has included the fabrication, curing, and testing of about 65% of the concrete specimens called for in the experimental portion of the program. Work has also been conducted on development of computer programs for processing the large volume of test data and performing much of the numerical analysis associated with the analytical portion of the program.

The overall program is anticipated to be completed in November, 1981.

#### Reports and Papers

##### Progress Reports

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Princeton University

Grant No.: NBS Grant 7-9004

Grant Title: An Experimental Investigation of Flame Spread Over Condensed Combustibles: Gas Phase Interactions

Principal Investigators: Prof. I. Glassman (Correspondent) Prof. F.L. Dryer  
Department of Mechanical and Aerospace Engineering  
Princeton University  
Princeton, New Jersey 08544

Other Professional Personnel: S. Ray, Ph.D. Candidate  
I. Kennedy, Research Staff Member

NBS Scientific Officer: B. McCaffrey

Technical Abstract

During the past year an investigation of the detailed mechanism of a flame spreading over a condensed phase fuel continued. In an effort to obtain a clearer picture of the competing processes involved, special attention has been focussed on the behavior of spreading flames in an opposing flow of oxidizer. This approach has shown the strong effects of both the opposed flow velocity and of the oxygen concentration in the atmosphere. Further, by comparing the behavior of thermally thick and thin fuels some insight has been gained as to the role of heat transfer in the process.

In the previous year the behavior of a spreading flame was quantified in terms of global parameters (Fernandez-Pello et.al. (1980)). These nondimensional terms separated the two competing effects of heat transfer and gas phase chemistry. The chemistry was described by a Damköhler number defined as

$$\bar{D} = \frac{C_u P^n A Y_o (\ln(1+B)/B)^{0.15}}{Le \rho_g^2} \exp(-E_g/RT_F)$$

while the heat transfer was addressed using the thermal flame spread model of de Ris (1969). The dimensionless spread rates were

$$\bar{v} = \frac{\rho_s C_{ps} \lambda V (T_v - T_\infty)^2}{\rho_g C_{pg} \lambda U (T_F - T_v)^2}$$

for a thick fuel, and

$$\bar{v} = \frac{\rho_s C_{ps} L V (T_v - T_\infty)}{2^{1/2} \lambda_g (T_F - T_v)}$$

for a thin fuel. The success of the approach was shown by the ability to correlate the measured spread rates over the entire range of opposed flowrate and oxygen concentration studied.

Present work is directed at extending and refining the above approach. It is felt that the correlation is a powerful tool for practical fire situations during its initial stages. It indicates the role of finite chemistry and the approach of extinction conditions. However, a true understanding of the detailed processes involved in stabilizing a flame over a fuel surface is still lacking. To this end we have directed attention to the behavior of the leading edge of a spreading flame, which is believed to be the key element determining the rate of spread.

The present view of the process is somewhat different from that held before, as diagrammed in Figure 1. It is postulated that the diffusion flame sheet is anchored near the fuel surface by a small premixed flame zone acting as a pilot. The conditions at this flame site are such that the laminar flame speed relative to the fuel/oxidizer mixture is equal and opposite to the opposed flow velocity at that particular height from the surface. This requirement is necessary for a steady flame to remain over the fuel. By knowing the laminar flame speed the gasified fuel concentration can be deduced at the flame location. By assuming the fuel vaporizes ahead of the flame into a boundary layer one can then calculate the extent of preheating of the fuel surface necessary to produce the required concentration of fuel vapor at the flame front. Using standard approaches the resulting expression for the preheat length,  $\ell$ , is

$$\ell = \left[ \frac{v}{d^2 U_\infty} \left( 1 - \frac{C_p \left( \frac{du}{dy} \Big|_o \right)^2}{\lambda X_o X_{F(o)}^A e^{-E/RT_F}} \right)^2 \right]^{-1}$$

One of the remaining questions is the mechanism by which the fuel surface is heated, be it by direct surface heating or by subsurface conduction from the postflame region. To investigate the relative importance of the various heating modes a series of surface temperature profiles were measured for opposed flow of oxygen of various velocities (Figure 2). If subsurface heating were the primary mechanism causing subsequent surface vaporization, one would expect the extent of preheat to increase with higher opposed flow velocities. The experimental results indicate that the preheat length decreases with increasing opposed flow. These findings seem to indicate that some other effect oc-

curs near the flame front not yet included in the conceptual model. It is quite possible that direct surface heating could be primarily responsible for the surface temperature behavior. In addition, the diffusion of vaporized fuel within the quench layer to the pre-flame zone could be more important than formerly believed. Work is presently underway on the development of a physical model incorporating these new ideas and results.

#### NOMENCLATURE

A	Arrhenius pre-exponential term	
B	Mass transfer number	
C	Constant term	
d	Quenching distance on flame standoff distance	
E	Activation energy	
$\ell$	Characteristic preheat length ahead of flame	
n	Order of overall reaction	
P	Gas phase pressure	
R	Gas constant	
$T_\infty$	Ambient temperature	
$T_F$	Flame temperature	
$T_v$	Surface vaporization temperature	
$u_m, u_\infty$	Flow velocity	
$\frac{du}{dy}\bigg _0$	Surface velocity gradient	
$X_O, X_F$	Oxidizer or fuel mole fraction	<u>Subscripts</u>
$Y_O$	Oxidizer mass fraction	g gas phase properties
$\lambda, \nu, \mu, C_p$	Thermophysical properties	s solid phase properties

#### REFERENCES

de Ris, J., "Spread of a Laminar Diffusion Flame", XIIth Symposium, p. 241 (1969).

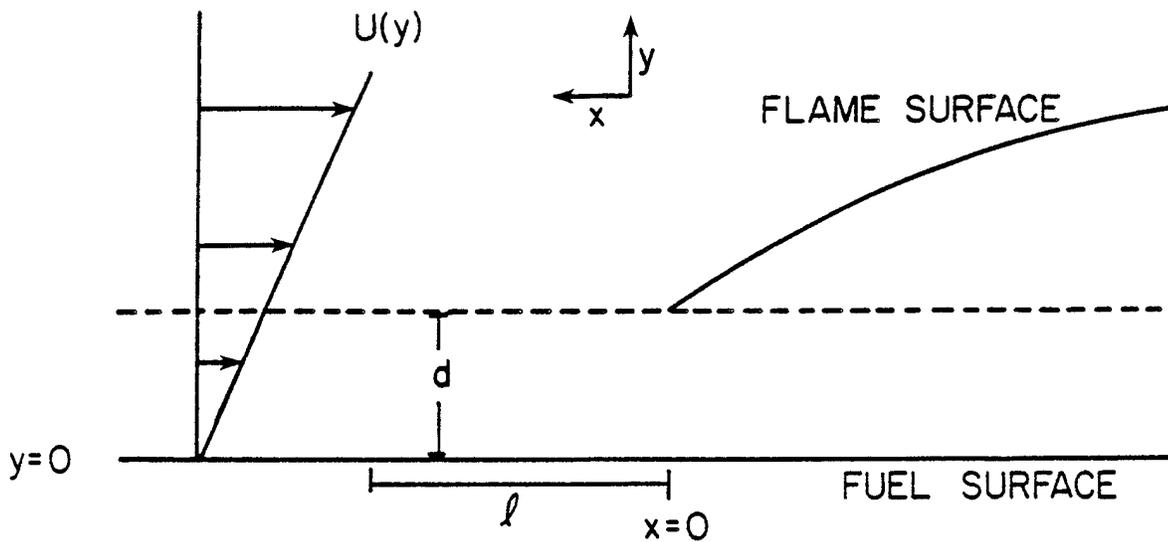
Fernandez-Pello, A.C., Ray, S.R. and Glassman, I., "Flame Spread in an Opposed Forced Flow: The Effect of Ambient Oxygen Concentration", XVIIIth Symposium (1980).

#### Reports and Papers

Glassman, I. and Dryer, F.L., "Flame Spreading Across Liquid Fuels", Fire Safety J. 3, 123 (1981).

Fernandez-Pello, A.C., Ray, S.R. and Glassman, I., "Flame Spread in an Opposed Forced Flow: The Effect of Ambient Oxygen Concentration", XVIIIth Symposium (Int'l) on Combustion, The Comb. Inst., p. 579(1981).

Ray, S.R., Fernandez-Pello, A.C. and Glassman, I., "An Analysis of the Heat Transfer Mechanisms in Horizontal Flame Propagation", J. of Heat Transfer 102, 357 (1980).



PHYSICAL FLAME SPREAD MODEL

FIGURE 1

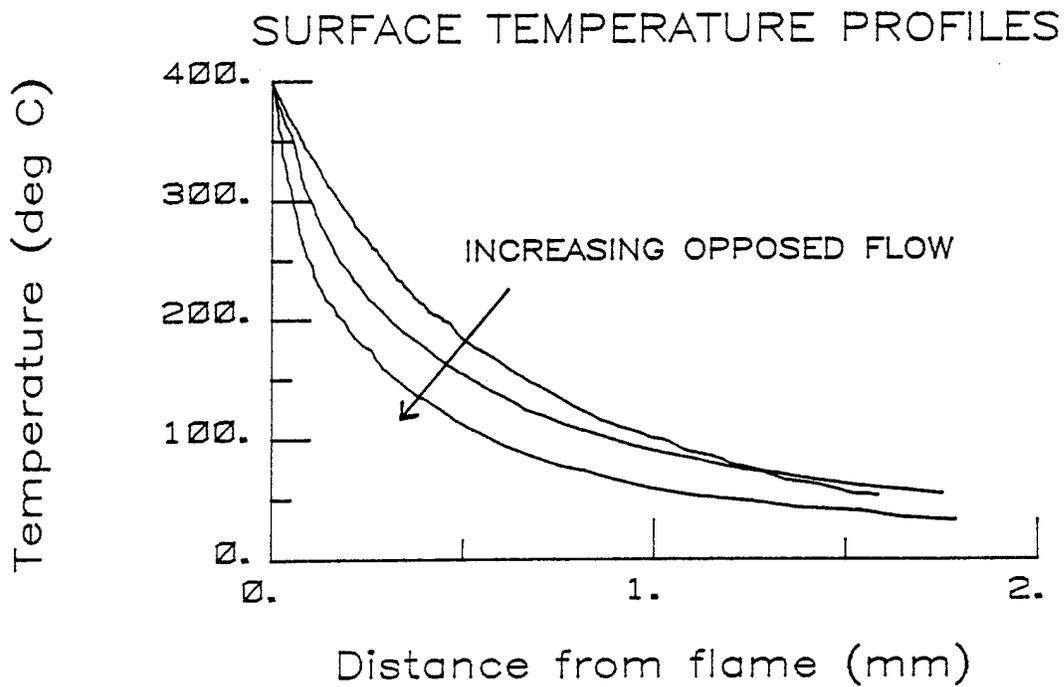


FIGURE 2

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: SRI International

Contract Number: EO-A01-78-00-3569

Contract Title: Continuation of Decision Analysis Studies in Fire Hazard Analysis

Principal Investigator: Fred L. Offensend, Ph.D.  
Director, Decision Analysis Group  
SRI International  
Menlo Park, CA 94025

NBS Scientific Officer: Alan Gomberg

Technical Abstract

The objective of this project is to develop and demonstrate a decision analysis model for evaluating alternative strategies for reducing residential fire losses. The model will ultimately be used to evaluate a variety of loss reduction strategies including basic research directions, design standards, prevention and detection programs, and suppression measures.

The decision analysis model has five sub-models. The implementation sub-model describes the loss reduction strategy under consideration and the degree to which its implementation is attenuated through manufacturing defects, user acceptance, and improper installation and maintenance. The demographics sub-model specifies the housing population under consideration. The fire loss sub-model calculates the annual residential fire losses for the target population in question, given a loss reduction strategy and its degree of implementation. The value sub-model introduces explicit value judgments to convert the physical losses calculated by the fire loss model to economic terms. The cost sub-model calculates the total economic cost of the loss reduction strategy under consideration. The output of the cost model is then added to the economic value of the losses to give the cost plus loss of the alternative in question. From an economic standpoint, the most attractive alternative is the one with the least total economic impact to society.

Probability trees are used to model uncertainty on fire and human behavior. Where possible, we use historical statistics to develop the probability assignments, but if such information is not available, we use expert judgment as that represents the best information available. The various sub-models are modular in format so that they can be replaced with more complex models as the need arises.

A preliminary version of the residential fire decision analysis model has been developed. The model is now being used to compare the cost-effectiveness of smoke detectors and residential sprinkler systems. We expect to have our preliminary results documented by autumn 1981.

#### Reports and Papers

Offensend, F. L. and Gomberg, A., "The Use of Decision Analysis Methods for Describing Residential Fire Hazards" paper presented at the ORSA/TIMS national meeting, Toronto, Canada, May 4, 1981.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: SRI International

Grant No.: NBS Grant NB80NADAL003

Grant Title: Polymer Degradation During Combustion

Principal Investigator: Dr. S. K. Brauman  
Polymer Sciences  
SRI International  
333 Ravenswood Avenue  
Menlo Park, CA 94025

Other Professional Personnel: I. J. Chen, M.S.

NBS Scientific Officer: Dr. Thomas J. Ohlemiller

Technical Abstract

The degradation of burning polystyrene is being investigated to provide understanding of the detailed degradation processes occurring in the condensed phase of a burning polymer that result in fuel production and to allow prediction of the effect of certain thermal or chemical variables on the rate or mechanism of fuel production. We are using a novel driven-rod apparatus with superimposed radiant heating to study steady-state linear regression of vertically mounted polymer rods degrading under nonflaming conditions that simulate those of combustion. Absence of the flame simplifies experiments and analysis.

During combustion in air (15 liters/min), a 1.35-cm-diameter rod of polystyrene containing 0.05 wt% carbon black burns from the top with a steady-state linear regression rate of  $0.058 \pm 0.001$  cm/min (71.9 mg/min). The temperature profile is determined with a 0.002-in. thermocouple embedded horizontally in the sample. The surface temperature, or temperature when the thermocouple appears at the surface, is  $461 \pm 2^\circ\text{C}$  (see Figure 1 for a representative temperature profile). The temperature gradient during steady-state combustion extends slightly more than 4 cm into the polymer. However, almost all the temperature rise occurs in the top 1.5 cm, and most of this rise happens rapidly once the polymer becomes fluid around  $150^\circ\text{C}$  at a distance of 8 to 9 mm below the surface. Only about the top 1 mm is actively bubbling.

We achieved the combustion linear regression rate for nonflaming degradation of the polymer rod in air and nitrogen (15 liters/min) by using superimposed radiant heating on the top of the polymer rod ( $1.35 \text{ cal/cm}^2 \text{ sec}$  for both atmospheres). To achieve a pyrolysis temperature

profile (see Figure 1) and melt depth resembling those during combustion, we had protected the length of the rod from the incident light with a water-cooled stainless steel shield; temperature profiles determined across the rod diameter are quite similar. Since the required radiant flux is independent of the atmosphere, polymer surface oxidation appears insignificant during pyrolysis and, presumably, during combustion in this top-burning configuration.

We calculated mass loss rates using the observed temperature profiles and kinetic parameters ( $E = 47.2$  kcal/mole, zero order kinetics) determined for isothermal (total<sup>a</sup>) volatilization of this polystyrene sample (Dow, Styron 666U) in nitrogen. These parameters are within the range of literature values for polystyrene. To calculate the rates, we treated the temperature profile as a series of isothermal cross sections taken at uniform temperature intervals, typically every two degrees along the profile. The gradient temperature corresponding to the section midpoint was used as the isothermal temperature for the section. The temperature dependence of the density was taken into account. The calculated rates are in very good agreement with the observed rate (Table 1), particularly considering the large extrapolation (above 345°C) to the high temperatures near the surface. We calculate that little degradation resulting in volatilization occurs below about 350°C (1.8 mm below the hot surface).

Table 1

RESULTS FOR COMBUSTION AND RADIANT  
PYROLYSIS OF POLYSTYRENE<sup>a</sup>

Conditions	Surface Temperature (°C)	Calculated Mass Loss (% of observed)
Combustion	461 ± 2	117 ± 18
Radiant pyrolysis, <sup>b</sup>		
nitrogen	460 ± 3	122 ± 14
air	451 ± 1	86 ± 2

<sup>a</sup>0.06 cm/min regression rate.

<sup>b</sup>1.35 cal/cm<sup>2</sup> sec.

However, degradation resulting in loss in polymer molecular weight without concomitant volatilization does occur at a greater depth. Radiant pyrolysis residues (nitrogen) are being analyzed to provide mechanistic information of the condensed-phase degradation processes occurring within the polymer under combustion-like conditions. Preliminary analysis by gel permeation chromatography indicates no change in molecular weight below about 285°C (3.0 mm below the hot surface).

In the future, we will attempt to fit these results to the observed temperature profile and degradation scheme.

The information obtained from this research will contribute to reducing the nation's fire loss by providing understanding of the chemistry of the combustion process of fuel production. With this knowledge, understanding of the effectiveness of and even prediction of improved fire retardants used to control fires by altering fuel production become possible.

#### Reports and Papers

Brauman, S.K., and Chen, I.J., "Polymer Degradation During Combustion," SRI International Annual Report, January 21, 1981.

Brauman, S.K., and Chen, I.J., "Polymer Degradation During Combustion," SRI International Quarterly Progress Report No. 5, April 6, 1981.

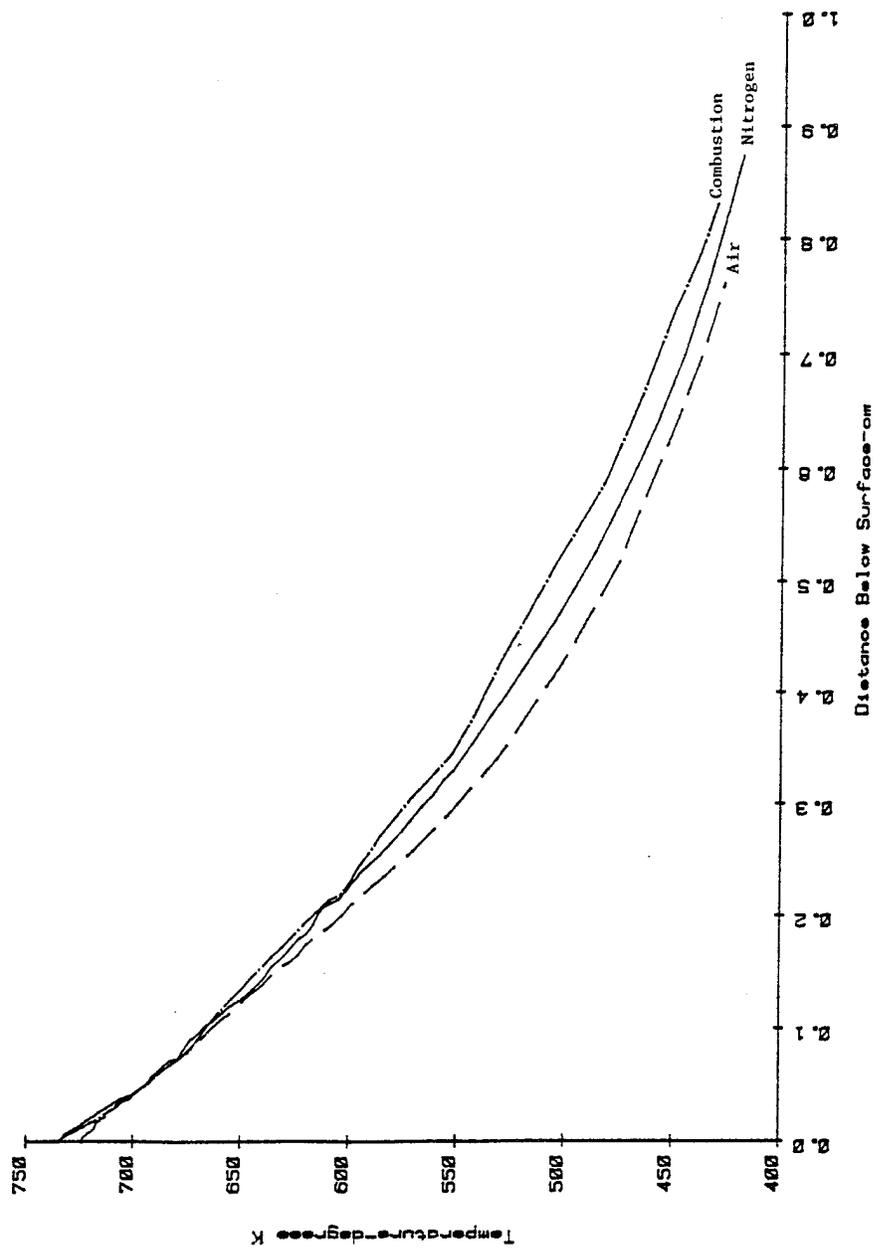


FIGURE 1 REPRESENTATIVE TEMPERATURE PROFILES FOR POLYSTYRENE BURNING OR PYROLYZING AT STEADY STATE.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Center for Urban and Public Affairs  
Tennessee State University

Grant No.: NB81NADA2017

Grant Title: "Tennessee Fire Research Project"

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NBS Scientific Officer: Irwin Benjamin

Technical Abstract

Within the United States, incidents of fire resulting in deaths, injuries, dollar and property loss have occurred disproportionately in the southeastern portion of the U.S. as compared to the rest of the nation. The chances of death resulting from fires in the southeast region are 60% greater than in any other portion of the U.S. There is even a greater disparity among the minority communities of this region. Consequently, federal, state and local government fire departments and agencies across the nation are endeavoring to identify the problems of these fires, their probable causes as well as reducing the number of fires which occur every year.

This is a seed proposal that is in its initial stage of work. Its overall objective is to provide access to available data on fires and the sociological-psychological disparity of fires between minority and non-minority communities. One of the first steps in accomplishing this objective will be to identify and assess pertinent data related to incidents of urban and rural fires provided by the Center for Fire Research and the U.S. Fire Administration.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: TRW Defense and Space Systems Group

Grant No.: NB8ONADAL065

Grant Title: Modeling of Wind-Aided Fire Spread

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Other Professional Personnel: G. F. Carrier, Consultant  
P. S. Feldman, Numerical Analyst

NBS Scientific Officer: H. Baum

Technical Abstract

This project, just under way for one quarter, undertakes progress toward the ultimate goal of predicting the rate of wind-aided flame spread across a horizontal fuel slab (e.g., the ceiling of a corridor) from knowledge of (1) the chemical and physical properties of the slab, and (2) the modest speed, slightly reduced oxygen content, and appreciable enthalpy of the vitiated air (taken to be initially fuel-vapor-free) flowing across the slab. More particularly, what is sought is the time rate of change of the extent of the involvement of the slab, taken to be the area over which significant outgassing of (at least partially) combustible fuel vapor is occurring.

For specificity, and because it serves a useful adjunct goal, the modeling concentrates on a simplified unsteady, two-dimensional formulation of the ASTM E84 test, carried out in a so-called Steiner tunnel. In this extensively utilized, ten-minute-duration test, hot (up to 1150K) air continuously flows along a slab, ceiling-mounted in a sealed duct; the air cools radiatively as it proceeds downstream at about 1.2 m/s. The formulation is simplified in that it employs laminar diffusion in the boundary-layer approximation, convective transport in the Oseen approximation (though nonlinearity is necessary to account adequately for interphase mass transfer), and chemical kinetics in the Burke-Schumann thin-flame limit. Nevertheless, the problem entails the complexity of three independent variables; of inherent coupling of the gaseous and solid phases; and of radiative, diffusive, and convective transfer of heat. More importantly, the problem is of an unconventional Stefan-type, in that a moving boundary is present in a heat-and-mass-transfer process. The moving boundary, whose position is to be found in the course of solution as the principal output, is the separatrix between the nonpyrolyzing portion of the sample (undergoing preheating

to a pyrolysis temperature) and the pyrolyzing portion of the sample (from which combustible vapor is evolved to sustain the exothermic gas-phase combustion and thus to perpetuate the endothermic gasification of the solid).

In previous work, already reported in the literature, an analytic-numeric methodology was introduced for solving such problems. Briefly, introduction of Fourier transform over the coordinate transverse to the two-phase interface integrates out dependence on one spatial independent variable. The hyperbolic suboperator (of the original parabolic operator) is exposed, and use of its characteristics facilitates formulation of integral equations describing heat and mass transfer in the interfacial plane. Coupling of these integral equations with the locally pertinent algebraic relations describing boundary conditions holding at the two-phase interface permits "zone-of-influence", "zone-of-silence" concepts to produce a solution in the interfacial plane. While extension of the solution off the interfacial plane is conceptually straightforward, it is computationally demanding in realistic cases. However, while the solution is not complete, the most practically important insight is available from solution in the interfacial plane; for instance, the translation of the pyrolysis front in time is available.

The present undertaking seeks to improve the efficiency and the accessibility of the computational implementation of the above-described novel methodology. However, there are two aspects of the present formulation wherein the physics of the process is so idealized that improvement seems highly desirable before portability is addressed. (The matter of modeling turbulent diffusion flames is a broader, long term question whose scope is taken to lie outside the immediate concerns of the present undertaking.) The first aspect to be addressed is the modeling of the mechanism for gasification (and the attendant process of charring); the second aspect is the modeling of the radiative transfer associated with the existence of soot particles in the gas-phase diffusion flame.

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Previously the mechanism for gasification was taken to be sublimation. That is, at downwind portions of the two-phase interface, no interphase mass transfer occurs because the (to be determined) surface temperature lies below the (specified) sublimation temperature; continuity of temperature, and continuity of heat flux (aside from radiative transfer), hold at the interface. Along an upwind portion of the slab, the temperature of the surface is constant at the (specified) sublimation value; aside from radiative contributions, that heat flux from the gas which is not conducted into the interior of the (semi-infinitely thick) slab, serves to furnish the (specified) latent heat of sublimation and thus to meet the endothermic requirement for interphase mass transfer. In fact, the previously discussed separatrix is that special locus along the surface that is at the sublimation temperature but at which no interphase mass transfer occurs. There are two limitations for such a formulation. First, while exceptions such as PMMA may be cited,

the overwhelming preponderance of synthetic and natural polymers used as construction materials does not gasify by sublimation; rather, these polymers form a porous carbonaceous layer (known as a char layer) between the pristine solid in the interior and the gas-solid surface. Second, the solid surface was taken as planar in the sublimation case, despite the fact that the rate of interphase mass transfer is highly variable along the two phase interface from the leading edge to the separatrix. Thus the solid was taken to be capable of shear as required to maintain planarity of the two-phase interface; while such an approximation is conventional within boundary-layer treatment, it is an idealization.

Here the presence of a char layer is to be accounted for within the interpretation that the role of such a layer is of concern primarily in heat-transfer considerations, as opposed to chemical-kinetic considerations.<sup>#</sup> At a postulated char-layer/pristine-solid interface, a sublimation mechanism (at known temperature, with known specific heat of phase transition) effects gasification of a (known) fraction of the polymer into vapor, a (known) fraction of which is exothermically combustible with air at high-enough temperature. This vapor flows through the finite thickness of the porous-char layer to the gas phase; under a Burke-Schumann model no oxygen reaches to the char surface, so no reaction of the fuel vapor within the char, nor of the char surface itself, is possible. (Endothermic reaction at the char surface via reduction of carbon dioxide could be included, but seems nonessential at the outset.) The char-layer/gas-phase interface (at known position) is hotter than the char-layer/pristine-solid interface (at position to be determined), so the role of the char is seen to be that of large "thermal storage". Since the char is taken not to attain a temperature at which the char has no residual strength (such that carbon fragments would spall off into the gas), the char-layer/gas-phase interface is rigorously taken as planar. While such a model introduces a new dependent variable and an associated integral equation, it proves entirely compatible with the previously developed methodology.

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The other physical phenomenon that warrants inclusion is the radiative transfer associated with the presence of particulate matter in the

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<sup>#</sup>Of course, the release of toxic gases owing to thermal degradation of the polymer may also be of prime concern. However, the rates and mechanisms remain largely unknown; might well be intractable in the present context of wind-aided flame spread, even if they were known; and, in any event, probably would be so case-specific that generality of insight from any special material might be nil. It would be interesting to inquire whether the rate of toxic gas release, in complicated multi-dimensional unsteady fire of practical interest, might not be as adequately discussed within the above char-layer model as any finite-rate-process model yet advanced. Such a model must parameterize preferential release of gases, but at least in this manner still could incorporate the phenomenon.

vicinity of the diffusion flame. (Other roles for radiative transfer associated with cooling of the bulk gas as it streams along the length of the slab, and with radiative loss from the hot char-layer surface owing to radiated heat not returned by other surfaces with a finite view factor, are either already incorporated, or else readily added, to the existing formulation.) Because of treatment of the gas-phase in terms of Shvab-Zeldovich passive-scalar functions, accounting for the radiative transfer associated with soot is less readily effected. While the subject is still under development, it is interesting to recall the approach introduced by J. de Ris in his 1967 doctoral thesis at Harvard University on the spread of a diffusion flame against the wind over a solid surface (capable of gasification by sublimation). A fraction of the gas-phase chemical exothermicity is taken to be convected and diffused from the site of the diffusion flame, and a fraction is taken to be radiated away (part of the radiated heat contributing to the energy balance at the two-phase interface). However, utilization of this concept requires that the amount of heat of combustion locally released be known; such information is part of the solution in the problem under examination, and a relatively inaccessible part at that. The amount of fuel vapor being introduced into the gas stream is readily available in the course of solution of the wind-aided problem of interest here; however, fuel vapor may be convected downwind before it reacts, so that the site of mass transfer and the site of chemical exothermicity may be appreciably displaced. Nevertheless, soot formation may be the result of pyrolysis of fuel in the oxygen-free portion of the gas phase, and soot that migrates into the oxygen-containing portion of the gas-phase may be burned up. Thus, the interfacial mass-transfer rate may furnish a basis in terms of which soot radiation is formulated.

In conclusion, the extension of the methodology for wind-aided flame spread to include soot radiation and char-layer enthalpy content is proceeding. Attention is then to be placed on implementation of these improvements in a computer code more accessible to interested users.

#### Reports and Papers

Carrier, G. F., Fendell, F. E., and Feldman, P. S., "Wind-Aided Flame Spread Along a Horizontal Fuel Slab," *Combustion Science and Technology* 23, (1980), 41-78.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: Underwriters Laboratories Inc.

Grant No.: NB80NADA1016

Grant Title: "Investigation of Fire Hazards Associated  
With Installations of Fireplace Inserts  
In Factory-Built and Masonry Fireplaces."

Principal Investigator: Wayne R. Terpstra  
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Fire Protection Department  
Underwriters Laboratories Inc.

Other Professional  
Personnel:

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NBS Scientific Officer: R. D. Peacock

Technical Abstract:

A program is proposed to support NBS efforts related to fireplace inserts. The objective of the program is to investigate potential fire risks associated with the use of fireplace inserts in factory-built and masonry fireplaces. Representative fireplace/fireplace-insert combinations have been identified and an appropriate testing program developed. Fifteen fireplace/fireplace-insert combinations are being tested, and presently recommended practices for installation and use of these devices have been reviewed.

National concerns for energy conservation and development of alternate fuels for domestic uses have lead to increased emphasis on fuel wood and coal for home heating. Products which are designed to produce heat by burning coal and wood are being actively promoted and are finding rapidly increasing markets in the U.S. Among these products is the fireplace insert, which is a radiant-type heater designed to be placed wholly or partially within an existing fireplace. Its purpose is to improve the heating efficiency of the existing fireplace without the need for major structural alterations to the building.

It is estimated that there are more than 20 million fireplaces in U.S. homes which are candidates for installation of fireplace inserts. In view of the large potential market involved, it is essential that safety standards and testing programs for these devices keep pace with the developing technology to prevent the introduction of unreasonable and unforeseen hazards into American homes. Therefore, it is appropriate that the National Bureau of Standards conduct a multi-year program to accelerate the identification and resolution of fire problems associated with fireplace inserts.

The program initiated under the grant is in support of the NBS efforts related to solid fuel burning devices. The objective of the program is to determine and quantify potential fire risks associated with the use of fireplace inserts in fireplaces. The program is being accomplished by identifying representative fireplace/fireplace-insert combinations, developing an appropriate testing program, testing approximately 15 fireplace/fireplace-insert combinations, and reviewing present recommended practices for installation and use of these devices. The program is considering (1) thermal effects, (2) chimney connections, (3) material, construction, and structural aspects, (4) electrical component evaluation, (5) leakage of combustion products, and (6) securement and stability of the fireplace inserts.

The initial work contained a review of the constructional and operating characteristics of fireplaces representative of those presently in use today. Based on this review, generic categories of fireplaces have been identified. A similar effort with respect to fireplace inserts has been conducted at Auburn University under a concurrent grant from NBS.

In concert with representatives of NBS and Auburn University, the information developed by UL and Auburn has been reviewed, and a number of fireplace/fireplace-insert combinations has been selected to represent the generic categories in subsequent tests. For these combinations, a testing program has been developed and carried out to identify and quantify parameters related to fire hazards associated with the fireplace inserts.

Information obtained from the review of fireplace designs, and similar information on fireplace inserts developed by Auburn University has been used to identify fireplace/fireplace-insert combinations for test, and to outline the test program. In this process, existing standards for wood-burning devices have been reviewed for their applicability to fireplace inserts. This has been done in concert with representatives of NBS and Auburn University. The test program will be designed to develop information on approximately a dozen constructional and operational features, including:

- A. Temperatures on the existing fireplace.
- B. Temperatures on adjacent combustible materials.
- C. Temperatures on the fireplace insert and fire chamber walls.
- D. Compatibility of the insert with the fireplace.
- E. Methods of sealing the fireplace opening.
- F. The effects of installation of the insert on air flow and air cooling of the fireplace.
- G. The effects of chimney size and construction on the performance of the insert.
- H. Securement or removal of existing fireplace dampers when installing the insert and connection of the insert to the existing chimney.
- I. Material, construction, and structural integrity of the fireplace insert.
- J. Evaluation of electrical components and controls associated with the warm air handling equipment of fireplace inserts.
- K. Flue-gas temperature and composition, and
- L. Carbon monoxide leakage into the living area.

The test program is being carried out, using 15 combinations of fireplaces and fireplace inserts. The masonry fireplaces of minimum construction in conformance with building code requirements are being used in the program. The fireplace inserts are installed in the fireplaces in accordance with the insert manufacturer's instructions.

A portion of fire tests has been conducted; these have been a fuel source consistent with the methods presently being used for solid-fuel burning appliances under Nationally recognized standards.

The schedule for the project anticipates an August 31, 1981 completion date. The first six months of the investigation were devoted to an extensive research review of masonry fireplace designs and the development of the test program. The remaining nine months encompass the physical testing and analysis of the data developed.

The current status of the project is such that during the first half of the project, work was performed under the first task of the program and included:

- 1) Review of factory-built fireplaces.
- 2) Review of masonry fireplace designs.
- 3) Design of the masonry fireplace test fixture, based on the information from the review.
- 4) Coordination and planning meeting with NBS and Auburn University staff members.

The review of factory-built fireplaces included identifying the design parameters which might be affected by the installation of a fireplace insert into the fireplace. A survey questionnaire for factory-built fireplace manufacturers was developed and distributed.

Using the information from these questionnaires to identify the existing designs of factory built fireplaces along with manufacturer's data and data previously developed, four generic categories were established.

These categories considered such design features as air flow and cooling patterns, insulating materials, chimney sizes, and installation methods.

The review of the masonry fireplace designs included a detailed review of numerous publications, masonry construction handbooks, and all model building codes used in the U.S. This resulted in the development of design drawings of the masonry fireplace test fixture and the associated instrumentation.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: The University of Arkansas at Pine Bluff

Grant No.: NB 81NADA 2015

Grant Title: Fire Safety Problems as Affected by Human Behavior

Principal Investigator: Carolyn R. Gaylord, Ph. D.  
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Other Professional Personnel: None

NBS Scientific Officer: Irwin A. Benjamin

Technical Abstract

Available evidence indicates that loss of property and lives due to fires is higher in the southeastern states than in the U.S. as a whole. Also blacks in this region tend to sustain twice as much loss as whites in the same region. The objective of the research is to identify the psychological and behavioral characteristics of blacks that contribute to or prevent the likelihood of fires, identify the major reasons leading to the differential rates of losses between blacks and whites, and to develop appropriate instruments for studying the factors so identified.

The proposed project will review the literature on psychological attitudes and behaviors which may influence

the likelihood of fires occurring and which may influence the extent of loss due to fires. In addition the proposed project will review educational programs which aim at reducing losses due to fire.

The researchers will become familiar with the programs and data at the National Bureau of Standards and the U.S. Fire administration. A review of current literature will be made to identify psychological and behavioral factors which can cause and/or prevent the likelihood of fires and fire losses. The researchers will also review current educational programs on fire prevention. A list of attitudinal, behavioral, and knowledge factors will be selected for further study with the target population.

The review of the current literature will help to determine the demographic characteristics of the "fire prone" population (e.g. - those involved in fires). This literature review should indicate some factors which seem to increase the frequency of fires and fire losses. For example, it may be important to know the causes of fires, the rural urban occurrences of the fires, the educational and literacy level of the population, the average age of household members, and the average number of children in the household and their ages. Subsequently a survey research instrument will be developed which will include a wide variety of questions related to relevant attitudes, knowledge, and behaviors. After identifying the demographic characteristics of the "fire prone" population, it may be necessary to prepare two survey instruments one for children and one for adults. These instruments will be prepared, pretested with appropriate samples and then revised if necessary. The project directors will develop a research design to study the behaviors and attitudes of the relevant population.

The results from the proposed plan of study will be summarized and presented to the National Bureau of Standards in the form of a major research proposal designed to obtain information on the significant psychological or behavioral factors which lead to extensive fire losses of southerners. The data obtained from such a research program will be valuable in designing educational programs to decrease the losses incurred due to fires.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: University of California, Berkeley

Grant No.: NB 80 NADA 1064

Grant Title: Fire Propagation in Concurrent Flows

Principal Investigator: Professor A.C. Fernandez-Pello  
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NBS Scientific Officer: W.J. Parker

Technical Abstract

A research program has been undertaken to study experimentally and theoretically the process of fire spread in gas flows moving in the direction of fire propagation. The study concentrates on two characteristic modes of fire spread: a) Concurrent wall-ceiling fire spread in free convection and b) fire spread in a concurrent forced flow. Experiments are presently being performed to measure the rate of fire spread over the surface of thick combustible materials as a function of the properties of the material and of the oxidizer gas flow. A theoretical model of the process of concurrent flame spread has been developed. The analysis provides a unified explicit expression for the rate of flame spread in laminar flow configurations that accept a similarity solution. The predicted flame spread rates for these particular flows provide limits for the rates of spread in other non-similar gas flow configurations. This theoretical model will be extended to include radiation and turbulent flow. The experimental observations will be used to define the basic character of the theoretical models and to verify their predictions.

Analysis of Concurrent Modes of Flame Spread: A unified theoretical analysis of several modes of concurrent flame spread has been developed during this past year. The analysis draws on the fact that the different concurrent flame spread configurations have common general characteristics, thus allowing a unified treatment of the problem. The analysis makes use of a laminar boundary layer and flame sheet approximations to describe the gas flow and of an ignition surface temperature to define the flame spread rate. By means of an isothermal wall condition, the gas phase problem is uncoupled from the solid phase and is solved for each case using a similarity solution approach. The deduced heat flux at the fuel surface is used as a boundary condition in the solid phase analysis. The rates of spread of the pyrolysis and flame

fronts are obtained from the solution of the energy equation by imposing the condition that the surface temperature at the pyrolysis front is equal to the vaporization temperature of the fuel. The predicted dependence of the spread rate of the pyrolysis front on time and on the thermodynamic and transport properties of the fuel and oxidizer is

$$V_P = (2n)^{\frac{1-2n}{2n}} \left[ \frac{\lambda_{g\infty} c_P B C F'(0) \phi_w (\Lambda, n)}{(\lambda \rho c)^{\frac{1}{2}} (T_V - T_\infty)} \right]^{\frac{1}{2n}} t^{\frac{1-2n}{2n}}$$

where  $n$  is the similarity exponent,  $B$  is the mass transfer number and  $C$  is related to the Grashoff or Reynolds numbers for free and forced convection, respectively. The present theoretical model will be used as a basis for the development of a numerical analysis of the fire spread process that will include radiation heat transfer and will consider the existence of turbulent flow conditions.

Experimental Measurements of Concurrent Fire Spread: During this reporting period the experimental measurements have been limited to the wall-ceiling configuration in natural convection. The results show that there is a strong interaction between the two walls and that the spread rate is dependent on the scale of the experiment, i.e., the length of the walls. The existence of a ceiling surface retards the generation of the convective flow on the vertical surface, while the existence of a vertical inflow is essential for the development of the ceiling gas flow. Once the gas flow is established, the fire spreads at increasing rates with time over the wall and ceiling. The spread of flames over the ceiling is the result of the combustible being heated by the vertical plume and is initiated well before the vertical pyrolysis front arrives at the ceiling surface. The delay time of initiation of ceiling spread and the rate of acceleration of spread depend on the length of the vertical wall. While a longer wall delays the initiation of ceiling spread, once it is initiated the spread is faster because of longer preheating of the ceiling surface. For the experimental scales tested, both the vertical and ceiling fire spreads appear to correlate with power functions of time. The experiments on the wall-ceiling fire spread will be continued during the next contract period concurrently with the measurements of the fire spread rates in a forced convective gas flow. During the present period, a laboratory scale wind tunnel has been designed and constructed to study the spread of fire as a function of the velocity, oxygen concentration and initial temperature of the gas flow.

#### Reports and Papers

Mao, C.-P. and Fernandez-Pello, A.C., "A Boundary Layer Analysis of a Free Burning Horizontal Fuel Surface" Presented at the 1980 Fall Meeting Eastern Section of the Combustion Institute, Princeton University, Princeton, N.J., October 1980.

Fernandez-Pello, A.C. and Mao, C.-P., "A Unified Analysis of Concurrent Modes of Flame Spread" Accepted for publication in Combustion Science and Technology. Also to be presented at the 20th ASME-AIChE National Heat Transfer Conference, Milwaukee, WI, August 2-5, 1981.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: University of California, Berkeley

Grant No: NB81 NAHA 2038

Grant Title: "Dynamics of Smoke and Inert Tracers Produced in Porous Fuels"

Principal Investigator: Professor Simon L. Goren  
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Berkeley, California 94720

Other Professional Personnel:

NBS Scientific Officer: Dr. Thomas Ohlemiller

Technical Abstract

The objective of this research is to quantify the mass generation rate and the size distribution of smoke aerosols produced by smoldering porous fuels. These variables are to be related to the chemical and physical properties of the fuel and to the combustion conditions. Since temperature, gas velocity and location of pyrolysis change during the course of smoldering, the amount and other characteristics of the emitted smoke also vary with time. Our approach to this dynamic process is a coordinated theoretical and experimental study.

A theory of formation, transport and ageing of smoke within porous fuels will be developed leading to a predictive model for the rate of release and size distribution of smoke produced during smoldering. The model ultimately must combine principles of heterogeneous chemical kinetics, transport phenomena in porous media, and aerosol mechanics. In view of the complexity of smoldering, the model must strike a balance between sophistication and workability. In our initial modeling efforts we will assume that the thickness of the pyrolysis zone is much smaller than the distance the combustion gases travel to reach the fuel's surface. With this assumption, the physical processes of condensation, coagulation and deposition become uncoupled to the chemical processes occurring in the pyrolysis zone. However, the combustion generated heat and condensable species rates of release at the pyrolysis front, and the velocity of smolder propagation, are needed inputs. The model of Dr. Thomas Ohlemiller and coworkers will be adapted to give these inputs by including a kinetic term for condensables generation. The particle-size population balance equation will be solved using reasonable expressions for particle growth rate, coagulation frequency factor, and

deposition rate guided by our concurrent experimental program. Attention will be directed at the possibility of finding self-preserving size distributions, at least under restrictive conditions; this is motivated by the great simplification introduced for self-preserving size distributions and the fact that even when self-preserving conditions are not fulfilled, forcing a self-preserving spectrum often gives reasonable results for less sensitive variables, such as the total number and total volume of the particles.

Time dependent rates of release and size distributions of smoke aerosols produced by smoldering porous fuels will be measured. The fuel will be cellulosic insulation. Initial experiments will be one-dimensional cocurrent or countercurrent smoldering with forced air flow through the fuel. Later experiments will involve more complex geometries such as the buoyant (free convection) plume above a localized ignition source within the porous fuel. The location and velocity of propagation of the pyrolysis front will be inferred from time-temperature signals of thermocouples embedded in the fuel. The smoke production rate will be measured at intervals by weighing the deposit captured on in-line filters. An on-line measure of smoke concentration will be provided by a Sinclair-Phoenix Smoke and Dust Photometer, Model JM-3000-AL. The size distribution of smoke will be measured with a Royco Laser Particle Counter, Model 226 which is capable of counting and sizing particles larger than  $0.12 \mu\text{m}$  in diameter. The maximum particle concentration for which the Royco can be used is about  $1.8 \times 10^9$  particles/ $\text{m}^3$ ; consequently measurement of the expected concentrations may require dilutions of 100 to 10,000 fold of the gases emerging from the fuel's surface. An important part of the research will be the development and characterization of a dilution procedure for concentrated, volatile aerosols. This work will be done in collaboration with Dr. George Mulholland. Both the virgin fuel and the charred remains will be carefully characterized as to porosity, permeability to air flow, and aerosol particle capture efficiency when challenged with dilute test aerosols or externally produced smoke. The fraction of the fuel lost by combustion will be determined from the weight change.

The information to be obtained on time dependent rates of production, size distributions and other properties of smoke aerosols emitted from smoldering porous fuels is important for improved fire detection. A significant fraction of fire related deaths, injuries and property losses are due to fires that originate as slow smoldering combustion of porous fuels. Early and reliable detection of smolder generated smoke could reduce these losses by enabling automated countermeasures. Unfortunately, existing smoke detectors do not adequately discriminate between smokes of different types, so that now there is an unacceptably large percentage of false alarms. The development of more reliable smoke detectors that would respond to specific smoke "signatures" will be enhanced by this research. This research also is important for the development of models for estimation of fire hazards. Smoke reduces visibility, making evacuation or

rescue more difficult. Inhaled smoke may have a debilitating effect by inducing choking and a long term health effect as a carrier of toxic chemicals. Smoke also alters the development of fire by modifying the heat transfer through radiation. All of the effects depend on both the quantity and size of the smoke aerosol. Any modeling of the smoke aerosol in the air spaces must have information on the source term.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: University of California, Berkeley

Grant No.: NB8ONODAL072-Williamson-7/81

Grant Title: INTRALABORATORY EVALUATION OF A STANDARD ROOM FIRE TEST

Principal Investigator: Professor Robert Brady Williamson  
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Other Professional Personnel: Wai-Ching Teresa Ling, Ph.D. Candidate  
Fred L. Mowrer, Graduate Student  
Fred L. Fisher, Development Engineer

NBS Scientific Officer: William J. Parker

Technical Abstract

This research program is an intralaboratory study of a "Standard Room Fire Test" which is currently being created by a working group within the American Society for Testing and Materials (ASTM). Their place of departure is the ASTM E603-77 "Guide for Room Fire Experiments"<sup>1</sup> which discusses the choices available for such parameters as compartment design, ignition source, instrumentation, test procedure, analysis of data, and reporting of results. The current draft of the standard has a propane burner placed in the corner of a 2.4 x 3.7 x 2.4 m (8 x 12 x 8 ft) compartment which has a single door and has been lined on both walls and ceiling with the material to be evaluated. The purpose of the test method is to evaluate the contribution of the specimen to fire growth in the compartment and the potential for flashover. There are measurements of temperature, heat flux, oxygen depletion, and smoke density specified in the draft standard. In addition, visual observations and photographic records are required for each test so that the apparent spread of flame can be established as well as the documentation of other events. It is well known that this kind of test procedure is an effective method for evaluating wall and ceiling finish materials in a preflashover environment. It will also be very useful for validating small-scale tests and predictive models of fire growth.

The use of "intralaboratory" in the title is to draw attention to the process of test method development discussed by Wernimont<sup>2</sup> and in direct contrast to "interlaboratory" studies such as those discussed by Mandel.<sup>3</sup> An intralaboratory study asks the questions:

1. Is there statistical control of the measurement process?

2. Are the measurements performed during the test the most valid for describing the "property" being evaluated?
3. How sensitive is the method to variations of operating conditions?

These and similar questions should normally be answered before the interlaboratory comparisons of a test method are undertaken in which "identical" specimens are tested in different laboratories.

This research program is an extension of the previous research effort described in last year's project summary. There has been a delay in starting the experiments due to changes being made in the smoke hood and the acquisition of instruments to measure oxygen depletion and the concentration of CO in the exhaust gases. A list of the experiments is given in Table I and they are scheduled to be completed by mid-July 1981.

TABLE I  
Room Fire Test Program\*  
University of California, Berkeley

Test No.	Wall Material	Ceiling Material	Comments
1	Glass Fiber Insulation	Glass Fiber Insulation	Conduct 2 experiments to determine the contribution of binder.
2	Gypsum Wallboard	Gypsum Wallboard	Conduct 2 experiments to determine the contribution of paper.
3	Plywood	Glass Fiber Insulation	
4	Plywood	Gypsum Wallboard	See Tests 7 and 8.
5	Glass Fiber Insulation	Plywood	
6	Plywood	Plywood	
7 8	Plywood	Gypsum Wallboard	Two experiments to duplicate Test 4 and also the effects of H <sub>2</sub> O in wood.

\*NOTE: There are a total of 8 tests with multiple experiments on Tests 1 and 2.

The experiments listed in Table I involve three types of wall and ceiling finish materials. Two of them, glass fiber insulation and gypsum wallboard, are non-combustible\* while the third, plywood is combustible. The purpose of these experiments is to develop data for the intralaboratory study and for direct input into the ASTM task group developing the standard test. The particular results of these experiments will provide insight by which to characterize:

- "1. The existence of a definite relationship between the magnitude of the property and the test result; and,
2. The degree of insensitivity of the test results to a) variations in other properties (which may be denoted as 'interfering properties') and, b) variations in environmental conditions." (Page 6 of Ref. 4).

The previous research on these materials shows rapid flashover for situations where plywood was used on the walls.<sup>5</sup> The average temperatures recorded 25 mm (1 in) below the ceiling for five previous experiments are shown in Fig. 1, and the occurrence of flashover is clearly evident for those experiments. The use of multiple temperature plots, as shown in Fig. 1, is a graphic way to demonstrate the difference in the levels of performance between materials, and the sensitivity of the test to the chosen experimental conditions. The sequence of Tests C-167 through C-171 shown in Fig. 1 underscore the important effect the size of the ignition source has on the draft standard. There was no ignition of the plywood ceiling in Test C-167 and it is evident from Fig. 1 that the average temperature 25 mm (1 inch) below the ceiling was essentially the same as in Test C-171 which had gypsum wallboard throughout the compartment. In Test C-168, the plane of the burner was raised from 0.3 m (12 inches) to 0.87 m (34 inches) above the floor which allowed the flames to impinge on the ceiling. This led to ignition of the ceiling after 3 minutes, 43 seconds, with flames emerging from the door, 2 minute, 21 seconds later to signal flashover or full involvement.

The current draft standard increases the ignition source for a standard room fire test to 176 Kw ( $10^4$  BTU/min [Gross]) as compared to the 88 Kw ignition source used in Tests C-167 through C-171. This increase in the ignition source insures that flames will reach the ceiling, simulating a more severe fire scenario. If ceiling materials are to be tested with different wall finishes, it is reasonable that the larger ignition source be used so that the test relates to the more severe condition. This year's experiments, listed in Table I, will aid the ASTM Task Group in making final choices regarding ignition source characteristics; and those experiments proposed for next year will further document ignition source characteristics by using the current 176 Kw ignition source.

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\*Defining this term as the model building codes by ASTM E136<sup>1</sup> and an allowance for the paper facers on the gypsum wallboard.

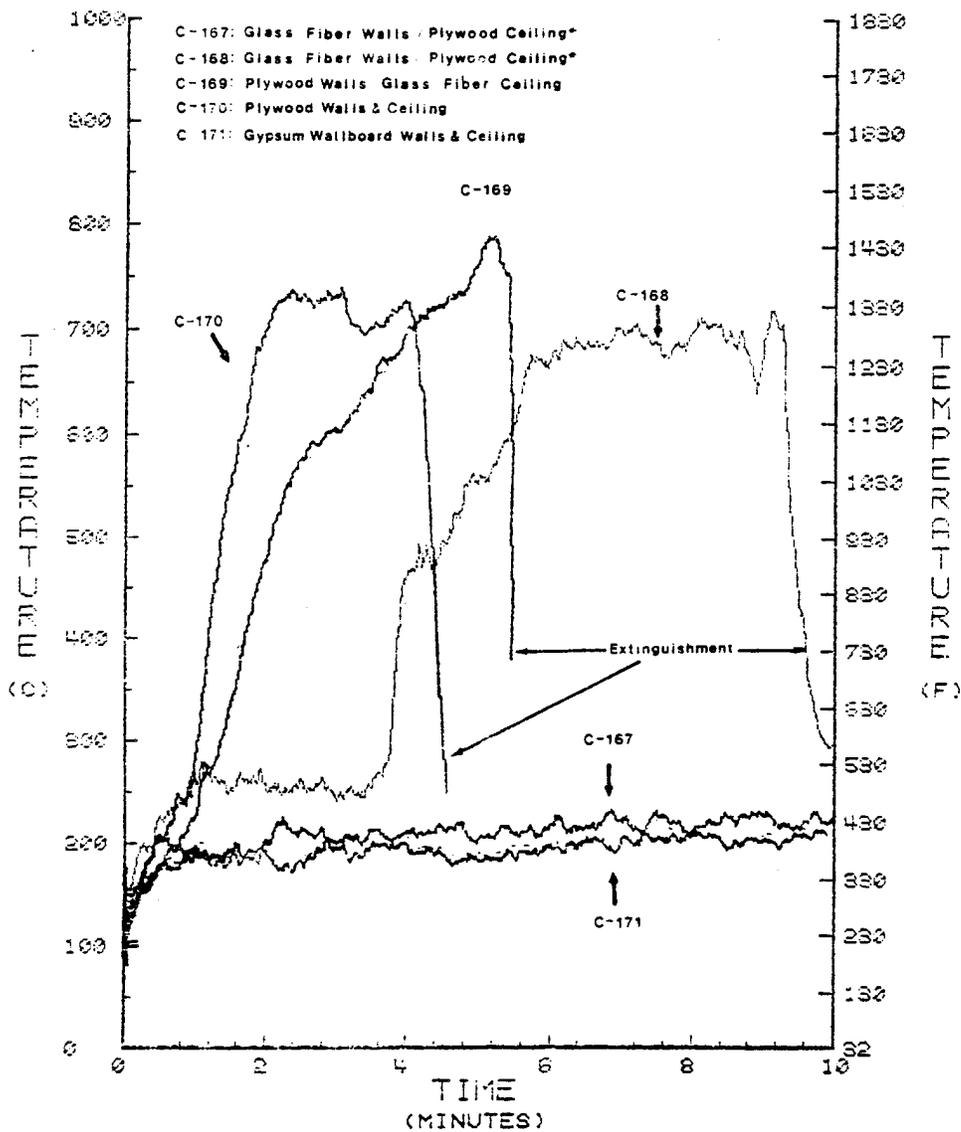


Fig. 1: Average Temperature Recorded 25 mm (1") Below the Ceiling of the Room Test with an 88 Kw (5,000 BTU/min) Methane Burner. Note that the burner was moved in C-168 to that flame impinged on the plywood ceiling

\*Gypsum wallboard was placed in the corner behind the ignition source in C-167 and C-168

### References

1. Annual Book of ASTM Standards, American Society for Testing and Materials, 1916 Race St., Philadelphia, PA.
2. Wernimont, G., "Careful Intralaboratory Study Must Come First," ASTM Standardization News, 6, Dec. 1978, pp. 11-14.
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4. American Society for Testing and Materials, "ASTM Manual for Conducting an Intralaboratory Study of a Test Method," STP 335, Philadelphia, PA 1963.
5. Williamson, R. B., and Fisher, F. L. "Fire Growth Experiments - Toward a Standard Room Fire Test," Presented at the Western States Section, the Combustion Institute, Berkeley, CA, October 1979, Paper No. WSS-79-48.

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CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: University of California, San Diego  
Grant No: NBS Grant G8-9005  
Grant Title: Studies of Flame Extinction in Relationship  
to Fire Suppression

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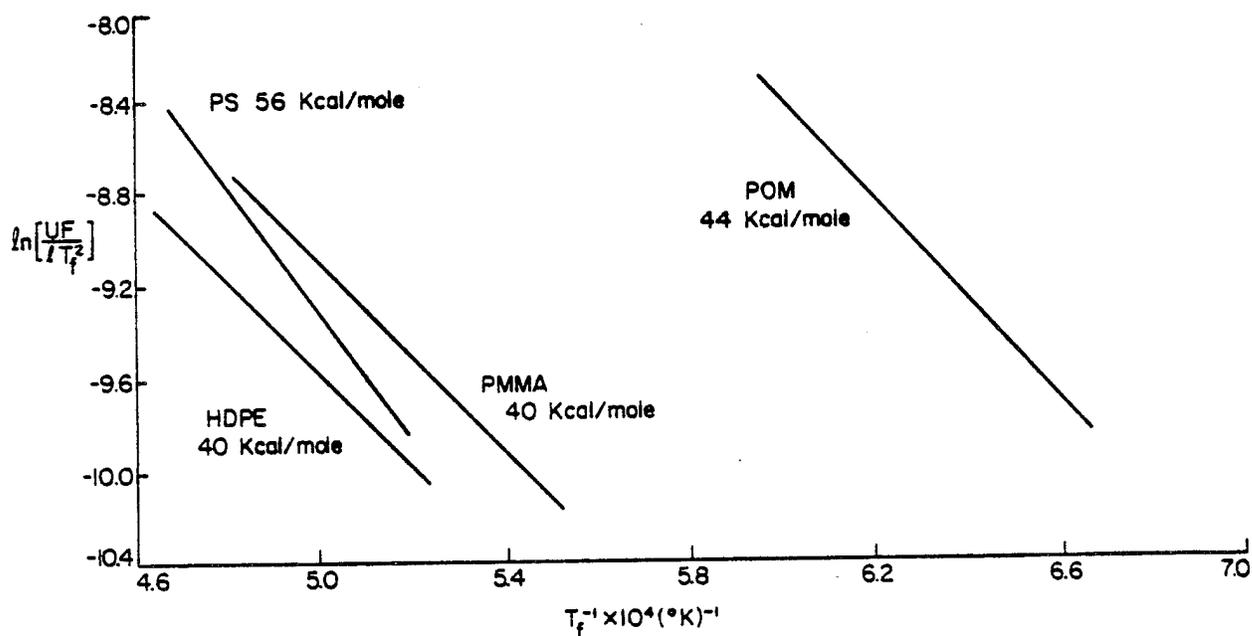
Technical Abstract:

The objective of this work has been to develop an improved understanding of mechanisms of fire suppression by studying flame extinction in the presence of suppressive agents. The main suppressants considered were nitrogen and halons. The principal configurations studied were the downward propagation of premixed flames through quiescent mixtures contained in tubes and the counterflow diffusion flame produced by directing an oxidizing gas stream, containing suppressant, downward onto the burning surface of liquid or solid fuel. Data included concentrations (obtained by sampling and gas chromatographic analysis), temperature profiles (measured with thermocouples), flame shapes, flame speeds, burning rates, and extinction conditions. Results were interpreted on the basis of a critical Damköhler number of extinction. The plan was to apply theory to extract overall chemical kinetic information under conditions near extinction, to attempt to relate such information to chemical kinetic mechanisms underlying suppression, to ascertain differences in the thermal, flow and kinetic aspects of extinction by the different agents, and to develop theoretical descriptions of influences of radiant losses on extinction in the counterflow diffusion flame.

Most of the progress made during the past year concerns studies of counterflow diffusion flames. Work on premixed flames, completed earlier, appeared in the literature. The diffusion-flame studies concerned extinction of flames above polymeric fuels by addition of nitrogen to the oxidizing stream, theory for influence of radiant heat loss on diffusion-flame extinction and experiments on extinction of flames above liquid fuels by addition of  $\text{CF}_3\text{Fr}$  and  $\text{HBr}$  to the oxidizing stream.

Concerning polymers, extinction of flat diffusion flames in the stagnation-point flow above the commercial materials poly (methyl methacrylate), polyoxymethylene, polyethylene and polystyrene was studied. The extinction data were used to obtain overall rate parameters for gas-phase combustion of the fuels. Radiant heat loss from the surfaces of the burning polymers was included in the theory from which these rate parameters were extracted. It was found that such radiation corrections were quite significant for polyethylene and polystyrene. Surface temperatures and surface regression rates were measured to aid in the radiation correction. These results were used in an Arrhenius-type rate expression to obtain overall activation energies for the thermal degradation of these polymers. Activation energies obtained for bulk degradation were 30, 25, 45 and 63 kcal/mole for poly (methyl methacrylate), polyoxymethylene, polyethylene and polystyrene, respectively. Best estimates for effective heats of gasification were found to be 385, 630, 1000 and 475 cal/g for these polymers, in the same order, respectively. Overall activation energies for gas-phase combustion, respectively, were calculated as being  $40 \pm 3$ ,  $44 \pm 5$ ,  $40 - 5$  to  $40 + 20$  and  $56 \pm 10$  kcal/mole. Arrhenius graphs for these last values are shown in the figure, where curves farther to the right correspond to higher gas-phase reactivities.

Concerning extinction theory, an asymptotic analysis was developed for the influence of radiant loss from the flame zone on diffusion-flame



extinction. Matched asymptotic expansions were employed with the large parameters being the temperature sensitivities of the rate of chemical heat generation and of the rate of radiant heat loss. It was found that typically there are zones of radiant loss on one or both sides of the thin reaction zone and that steepening of the temperature gradient within these radiant-loss zones enhances the tendency for extinction of the reaction to occur. Formulas were derived defining critical conditions for flame extinction, including influences of radiant loss. The radiant loss appears in these formulas mainly through the reduction in flame temperature that it produces. The critical condition for extinction remains defined by a balance between the rate of heat generation in the reaction zone and the rate of conductive loss of heat from that thin zone. The ratio of a characteristic time for emission of radiation to a characteristic time for chemical heat release was identified as a Damköhler number based on radiant loss, but this parameter was found to be of questionable significance in diffusion-flame extinction.

Concerning diffusion-flame extinction with bromine-containing suppressants, measurements were made of extinction conditions for heptane with molar ratios of  $\text{CF}_3\text{Br}$  to  $\text{N}_2$  and of  $\text{HBr}$  to  $\text{N}_2$  in the oxidizing stream fixed at 0.01, 0.02, 0.05 and 0.10. Reduction of the data according to the theory based on a one-step reaction showed that the overall reaction rate decreased and the overall activation energy increased as the bromine content increased. Correlation formulas were obtained for these variations. Considerations of chemical kinetic mechanisms indicated that the effectiveness of bromine-containing species in reducing overall rates of heat release occurred in the wings of the reaction zone rather than in the center. These considerations are being pursued further in efforts to better rationalize the extinction observations.

The objective in extracting overall rate parameters was to enable improved estimates of extinction conditions to be obtained in practical situations. In a first approximation, extinction may be said to occur at a critical flame temperature that varies somewhat as conditions are varied. The information developed in this program should help to provide a basis for calculating this variation, thereby improving accuracies of extinction calculations. These results ultimately may afford improvements in techniques for fire suppression, derived from increased understanding of mechanisms of flame extinction, taking into account interactions between chemical kinetics, fluid flow and heat transfer.

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Williams, F. A., "A Review of Flame Extinction," *Fire Safety Journal*, to appear (1981).

Sohrab, S., Liñan, A. and Williams, F. A., "Asymptotic Theory of Diffusion-Flame Extinction with Radiant Loss from the Flame Zone," *Combustion Science and Technology*, submitted (1981).

Sohrab, S. and Williams, F. A., "Extinction of Diffusion Flames Adjacent to Flat Surfaces of Burning Polymers," *Journal of Polymer Science, Polymer Chemistry Edition*, submitted (1981).

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: University of Maryland

Grant No: NB80 NADA 1067

Grant Title: The Determination of Behavior Response Patterns in Fire Situations, Project People II

Principal Investigator: Dr. John L. Bryan, Professor and Chairman  
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Dr. Norman E. Groner, Research Assistant

NBS Scientific Officer: Dr. Bernard Levin

Technical Abstract

The study involves the identification and analysis of the behavior patterns of building occupants in fire situations. Intensive in-depth open-ended interviews were conducted with participants, supplemented with a structured questionnaire. The interviews were conducted up to June, 1980 by the research study personnel at the scene of the fire incident between one to four weeks following the fire incident.

The objectives of this research study were previously established as follows:

1. To analyze the established variables of building occupants in fire situations as these variables have been established and identified in the previous Project People studies primarily concerned with residential occupancies, and the health care occupancies, with some significant exceptions.
2. To attempt the evaluation of models of human behavior in these fire incidents utilizing the premodel development concepts of Archea or Withey, and to validate the conceptual modes of Bickman, Edelman, and McDaniel, the computer model of Stahl, and the egress model of Berlin.
3. To compare the analyzed scenarios, results and data to the current edition of the Life Safety Code, and model building codes.

The 150 staff participants in this study were examined utilizing an open-ended individual interviewing technique. These interviews were conducted by research study personnel from the Department of Fire Protection Engineering, University of Maryland. All study participants have been identified only through the study variables and personal anonymity has been assured.

The computer analysis of the human behavior variables concerned with fire related training, education or the experience possessed by the participants involved in the study population fire incidents has been completed. The observed and documented behavior and actions during the fire incidents relative to the critical incidents of each fire situation and the dynamic interaction between the behavior of the participants with the propagation of the fire and smoke within the building have been examined. The analyses of the behavior response patterns of the participants and the psychological, sociological, educational and related variables influencing the predisposition to the adopted response have been elicited from the study populations and will be utilized in the model development and the model evaluation in the second phase of this study.

Thus, the total interactional context of the individual, the cultural role variables, and temporal sequence and the critical identified parameters of the fire incident will be analyzed as to the modification of the outcome of the fire incident.

Another objective of this research study pertains to the development of a fire safety manual for the board and care home operators. The manual will be developed to include a series of step-by-step decision aids that will establish contributions toward the formulation and implementation of a fire emergency plan suited to the specific needs of the board and care home.

A portion of the fire safety manual specific chapters will be developed providing information and suggestions on important fire safety topics for the board and care home operators.

The manual will be subjected to periodic review during its development by fire safety authorities from the University of Maryland, the National Bureau of Standards and related associated professional organizations. This review will be designed to insure the manual effectively and concisely addresses the critical information areas of estimating the assistance and survival needs of the residents; determining minimal staffing needs to provide reasonable evacuation of protection aids and to minimize the life safety risk; developing realistic and effective fire drill planning and practices; specifying the adequate and practical means of egress from all areas of the home, varying with time and area of fire origin; evaluating the refuge potentials of various areas of the home for residents from the fire generated products of combustion.

Following completion of the fire safety manual in a preliminary form the manual will be field tested by a sample of board and care home

operators to determine the adequacy of the content, the presentation of the subjects, and the applicability of decision aids, and informational topics. The operators will develop or modify fire emergency plans for their facility from the manual and will evaluate the functional efficiency of the plans in cooperation with personnel from the local fire service organization responsible for the public fire protection of the facility.

The manual will receive final development following an examination of the results of the field testing and evaluation, with a comprehensive review by a panel of pertinent experts.

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Bryan, John L., Philip J. DiNenno and James A. Milke, The Determination of Behavior Response in Fire Situations, Project People II. Final Report - Incident Reports, August, 1977 to June 1980. College Park: University of Maryland, Fire Protection Engineering, August 31, 1980.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: University of Maryland

Grant No: NB80-NADA-1011

Grant Title: An Investigation of the Water Quality and Condition of Pipe in Existing Automatic Sprinkler Systems for the Analysis of Design Options with Residential Sprinkler Systems.

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Dr. James E. Alleman  
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University of Maryland  
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Other Professional Personnel: James A. Milke

NBS Scientific Officer: J. O'Neil

Technical Abstract

The objectives of this study are defined as follows:

1. To investigate the potential effect of backflow of sprinkler water into potable water;
2. To investigate the potential severity of the pressure reduction due to tuberculation in pipes in residential sprinkler systems.

The first objective is achieved by physical, chemical and biological analyses of water samples extracted from existing automatic sprinkler systems. The latter objective is accomplished by calculating the Hazen-Williams 'C' coefficient associated with a measured water flow rate and pressure differential along a sprinkler pipe. Specific sprinkler systems and locations for sampling are selected to provide a wide variety of conditions for the project relative to the study parameters of pipe material, age, size and network configuration.

In particular, this study attempts to compare the quality of water in sprinkler system pipes with that from the potable water supply for the building. The detailed analyses allow relevant and significant comparisons to be conducted to potentially assess the necessity for backflow prevention in residential sprinkler systems. Comparison of the calculated Hazen-Williams coefficient with the coefficient associated with new pipe facilitates an approximation of the degree of tuberculation in the pipe. This result provides information to assess

the severity of pressure reduction as a function of time as affected by the turberculation and thus to address the useful life of the pipe.

A total of 57 water quality tests and 19 flow tests have been conducted and analyzed. The project has been extended to perform more detailed analyses of the condition of the pipe.

Reports and Papers:

Milke, James A., "Preliminary Conclusions on the Water Quality and Pipe Conditions of Existing Residential Sprinkler Systems," Presented at the NFPA Fall Meeting, San Diego, California, November 18, 1980.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: The University of Maryland

Grant No.: NB81NADA2035

Grant Title: Theoretical Investigation of Large-Scale Turbulent  
Pool Fires

Principal Investigator: Professor T. M. Shih  
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NBS Scientific Officer: Dr. Bernard McCaffrey

Technical Abstract

The present project is in its initial stage. It is proposed that the large-scale turbulent pool fire be investigated using numerical methods. Prior to investigating the turbulent characteristics of the pool fire, the laminar small-scale "nonradiative" pool fire will be numerically analyzed. It is believed that it is worthwhile to take a conservative attitude simply solving the set of partial differential equations (in the cylindrical coordinates) governing the steady, laminar and "nonradiative" pool fires. Therefore, the turbulence correlations and the radiative-flux term are absent, and the combustion generation terms can be eliminated using the Shvab-Zeldovich formulation. This numerical problem remains nontrivial since, in both radial and axial directions, the pressure gradients exist and the diffusion is of equal strength (elliptic type).

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: The Maryland Institute for Emergency Medical Services  
Systems, University of Maryland

Grant No.: NB80NADA1023

Grant Title: Psychometric Testing and Carbon Monoxide Poisoning

Principal Investigator: Roy A.M. Myers, M.D.  
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Dennis Jones, R.N.  
Jeffrey T. Mitchell, M.S.  
Lawrence Messier, M.S.  
Byron Halpin

NBS Scientific Officer: Merritt Birky, Ph.D.  
Barbara Levin, Ph.D.

Technical Abstracts:

Psychometric Testing and Carbon Monoxide Poisoning

For the past two years, the Maryland Institute for Emergency Medical Services Systems (MIEMSS) has been engaged in studying methods of increasing the accuracy in the diagnosis of acute carbon monoxide poisoning resulting from smoke inhalation. Twenty short psychometric tests were initially investigated and a final group of six tests ultimately decided upon as being the basis of a 20 minute screening test for toxic brain involvement. The traditional tests for diagnosis of carbon monoxide poisoning (blood and alveolar air carbon monoxide levels) were also utilized.

Blood carbon monoxide levels both pre and post treatment with oxygen were noted. The psychometric testing score results both pre and post oxygen treatment were noted and conclusions drawn from the results.

Fifty-nine patients were assessed in detail and 16 then excluded because of other factors interfering with the results. These factors were alcohol intoxication, senility, mental impairment or emotional distress.

The scoring system was based on the number of errors in the six tests. By plotting these errors and times on a graph (Table I) the level of central nervous system impairment was determined. The severity of the impairment was the indication to us as to the optimal treatment of the patient, namely 100% oxygen by face mask or hyperbaric oxygen therapy (Table II).

Of the tests used, the Benton Visual Retention test was the best single predictor of carbon monoxide poisoning and the need for aggressive oxygen therapy.

Psychometric evaluation provided a good correlation of carboxy-hemoglobin levels and the patients' mental impairment. During the summer months we shall be developing normal standards which will then be used as baselines for all future tests. This will then form the basis of our future reports.

#### MINICO Alveolar Air Analyzer

MIEMSS continued to field test the MINICO (developed by Catalyst Research Corporation, CRC) carbon monoxide analyzer until February of 1981. Unfortunately because of non compliance of the volunteers to allow blood withdrawal only 47 breath/blood correlations were obtained. These 47 results showed that the instrument was reading approximately twice as high as it should. The instrument when exposed to temperature extremes, was grossly inaccurate. Excess heat or cold caused inaccuracies. The members of the "Smoke Team" experienced much difficulty with maintenance of zero as well as span calibration during the cold winter months. CRC, after being made aware of these defects, began conducting tests of their own. When the MINICO was stored and/or exposed to an environment of less than 32° Fahrenheit for periods of 30 minutes or longer, the output of the mercurcy oxide batteries decreased by approximately 70%. After exposure to these conditions for two hours, the output dropped to zero. The MINICO was however very accurate when stored and used at constant room temperature.

Radio transmissions from the fire ground affected the MINICO's readings by causing the needle to shift to the right side of the gauge. Distance helped to decrease the problem, but did not eliminate it. The CRC has attempted to correct this problem by inserting a copper shield in the instrument. However, it is still difficult to conduct tests at the scene of a multiple alarm fire because radio transmissions are made almost continuously.

The clinical presentation of the smoke victim at times created a problem in the use of the MINICO. Victims could present with confusion, incoherence, uncooperativeness and combativeness, or unconsciousness. It was difficult to obtain full cooperation from this type of patient and this made instrument usage difficult. Those victims who presented with shortness of breath had difficulty with breath holding and blowing up the balloon which offers a great deal of resistance.

C O SCREENING PROFILE

TABLE I

6									
5	0	140							
4	1	124	15	4	16				5
3	2	108	25	3	21				4
2	3	92	35	2	26				3
CEREBRAL DYSFUNCTION RANGE									
Borderline Range									
1	4	90	40	1	31				2
NORMAL									
0	5	88	45	0	36				1
	6	72	55		41				0
	7	56	65		46				
	8		75						
Test I Gen. Orient.	Test 2 Dig. Span	Test 3 Trails B.	Test 4 Dig. Sym.	Test 5 Aphasia	Test 6 Bl. Design	DIVE INDEX (# in. Dysf. Ran			

TABLE II

PATIENT		COHB		BENTON VISUAL		BLOCK DESIGN		TRAILS TIME		CALCULATIONS		TREATMENT Hyperbaric Oxygen Therapy (HBO) or Oxygen (O <sub>2</sub> )
SEX	AGE	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	
M	21	35	0	16	13	4	6	45	-	5	7	HBO
M	43	34	2	-	-	-	-	60	75	-	-	HBO
M	39	28	2	3	18	5	6	90	64	6	7	HBO
M	24	26.7	1.3	3	10	6	6	90	60	3	5	HBO
M	32	23	0	2	8	-	-	110	140	1	3	HBO
M	33	21	2.3	12	10	5	4	120	60	7	8	O <sub>2</sub> , 4 hrs. - HBO aborted
M	42	16.7	0	10	18	5	6	110	120	5	4	HBO
M	31	16.7	9.7	14	-	5	-	60	-	8	-	O <sub>2</sub> , 4 hrs.
M	27	13	1.8	18	-	6	-	80	90	3	-	O <sub>2</sub> , 4 hrs.
M	38	14.3	2.2	-	-	5	-	90	-	7	-	O <sub>2</sub> , 4 hrs.
F	33	10.5	7.4	10	-	3	-	90	-	8	-	O <sub>2</sub> , 2 hrs.
M	37	9.6	0	14	-	5	-	70	-	8	-	O <sub>2</sub> , 1 1/2 hrs.
M	32	9.4	0	18	-	6	-	72	-	8	-	O <sub>2</sub> , 2 hrs.
F	31	3.5	3.5	16	-	5	-	42	-	3	-	- screening
M	25	3.5	0	8	10	5	4	120	140	3	3	O <sub>2</sub> , 1 hr.
M	33	3.4	0	14	-	6	-	60	-	6	-	O <sub>2</sub> , 4 hrs.
M	24	8	0	4	2	1	3	40	90	1	3	O <sub>2</sub> , 3 hrs.
F	60	9	5.6	14	8	5	4	60	90	5	5	O <sub>2</sub> , 4 hrs.
M	42	6	0	6	6	5	6	90	70	6	8	O <sub>2</sub> , 4 hrs.
F	27	5	0	12	-	5	-	58	-	8	-	O <sub>2</sub> , 4 hrs.
F	43	5	0	14	-	4	-	90	-	7	-	O <sub>2</sub> , 4 hrs.
M	19	3	0	18	-	5	-	45	-	5	-	O <sub>2</sub> , 4 hrs.
M	21	5	0	16	-	6	-	55	-	5	-	O <sub>2</sub> , 4 hrs.
F	44	5.7	0	20	-	-	-	90	-	8	-	O <sub>2</sub> , 4 hrs.
F	25	5	0	-	-	-	-	100	-	3	-	O <sub>2</sub> , 2 hrs.
M	23	5	0	12	-	4	-	85	-	7	-	O <sub>2</sub> , 2 hrs.
M	25	5	0	3	-	-	-	95	-	8	-	O <sub>2</sub> , 2 hrs.
F	19	5	0	12	-	6	-	50	-	6	-	O <sub>2</sub> , 4 hrs.
M	20	5	0	16	-	6	-	75	-	-	-	O <sub>2</sub> , 4 hrs.
M	24	5	0	16	-	6	-	90	-	8	-	O <sub>2</sub> , 4 hrs.
M	22	5	0	14	-	-	-	31	-	6	-	O <sub>2</sub> , 2 hrs.
M	41	4.3	0	18	-	6	-	75	-	6	-	O <sub>2</sub> , 4 hrs.
F	22	3.6	0	10	16	5	5	130	100	5	3	O <sub>2</sub> , 1 hr.
M	19	2.4	0	14	-	5	-	90	-	6	-	O <sub>2</sub> , 4 hrs.
F	22	1.9	0	20	-	5	-	60	-	-	-	O <sub>2</sub> , 2 hrs.
M	31	1	0	2	8	1	3	120	149	7	3	HBO
M	25	0	0	12	-	5	-	45	-	7	-	O <sub>2</sub> , 4 hrs.
M	20	0	0	12	-	5	-	90	-	5	-	O <sub>2</sub> , 4 hrs.
F	37	0	-	6	-	2	-	110	-	5	-	O <sub>2</sub>
M	25	0	-	13	-	6	-	36	-	3	-	O <sub>2</sub> , 4 hrs.
M	27	0	-	16	-	-	-	73	-	8	-	O <sub>2</sub> , 1 1/2 hrs.
M	52	0	-	20	-	6	-	130	-	3	-	O <sub>2</sub> , 2 hrs.
M	22	0	-	18	-	6	-	72	-	8	-	O <sub>2</sub> , 2 hrs.

KEY

Pre = Pre treatment testing

Post = Post treatment testing

CRC concluded that the MINICO Model 250 could not be modified to correct the existing problems and recommended the use of a second generation MINICO. This is the Model 1000 which has the capability of measuring up to 1000 parts per million of carbon monoxide. It is powered by a 9 volt battery which is unaffected by extreme changes in temperature. This particular model also provides a digital readout of parts per million of carbon monoxide thereby eliminating guesswork in the readout. The new model will be tested in the 1981/82 "smoke season" and it is hoped that this will provide us with an accurate means of field triage of smoke inhalation victims.

#### Unconscious Carbon Monoxide Victim with Zero Carboxyhemoglobin Level

The case histories of six patients have been studied where the circumstantial evidence for carbon monoxide poisoning is overwhelming. The first blood samples taken from these victims however revealed a zero carboxyhemoglobin level. It is believed that excessive time delays between presentation and sampling resulted in these low levels. The clinical presentation of unconsciousness remained until hyperbaric treatment had been undertaken.

Three of the four victims were from automobile misadventures with carbon monoxide leakage from faulty exhaust systems entering into the driver/passenger area. The fourth victim suffered from carbon monoxide as a result of a faulty heating system and two members of the family involved with this patient, died with very high carbon monoxide levels. Two victims were involved in faulty heating system in a warehouse. All six victims were comatose on admission to hospital, requiring varying degrees of cardiorespiratory support. Four patients recovered consciousness completely following their second hyperbaric oxygen treatment. Two patients regained full consciousness 48 hours later. It is suggested that the carbon monoxide was acting as a central nervous system toxic agent. With liberation from the tissues, the normal CNS status returned. Psychometric testing of one of the victims at one year post accident surprisingly revealed diffuse central nervous system abnormalities which were not evident to the family in general history and examination.

A detailed description of the cases has been accepted for publication in the Journal of American Medical Association (JAMA).

#### Carboxyhemoglobin Falloff From Scene to MIEMSS

The smoke inhalation protocol is provided to field personnel to serve as a guideline for referral. As part of the protocol the EMT/CRT in the field is to withdraw 5 millimeters of venous blood for later carboxyhemoglobin analysis. He then treats the patient with the highest concentration of oxygen possible. The venous blood sample accompanies the victim to MIEMSS. Upon arrival at MIEMSS the victim is resuscitated appropriately and concurrently a second blood sample is obtained for carboxyhemoglobin analysis. A comparison is then made as

to the carboxyhemoglobin level at the scene and at MIEMSS. The duration of time between sampling is estimated based on reports from the ambulance and inpatient records. By knowing the initial carboxyhemoglobin level, a greater appreciation of the original insult is obtained. The expected half-life elimination according to Peterson and Stewart<sup>1</sup> is 320 minutes at 1 atmosphere absolute (ATA) breathing room air, 80 minutes at 1 ATA breathing 100% oxygen and 23 minutes at 3 ATA breathing 100% oxygen. Pace, Strajman and Walker<sup>2</sup>, 45 minutes breathing 100% oxygen at 1 ATA as the half-life.

The results of the half-life elimination in these 14 patients indicate a 57.76 minute half-life on an oxygen breathing system of approximately 60%. This work will be repeated in detail in this coming year.

#### Reports and Papers

Myers, R.A.M., Mitchell, J.T., Messier, L.D., and Cowley, R A.: Psychometric Evaluation in Carbon Monoxide Poisoning. Submitted to JAMA June, 1981.

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Myers, R.A.M. and Jones, D.W.: Carboxyhemoglobin Falloff from Scene to Hospital. Abstract. Long Beach, California, June 8-10, 1981.

Myers, R.A.M. and Jones, D.W.: Field Evaluation of the MINICO Carbon Monoxide Analyzer. Abstract. Long Beach, California, June 8-10, 1981.

Myers, R.A.M. and Baker, T.L.: Eight Years of Hyperbaric Oxygen Therapy in the United States of America. Abstract. Long Beach, California, June, 1980.

Myers, R.A.M. and Snyder, S.K.: The Unconscious Victim of Carbon Monoxide Poisoning with Zero Carboxyhemoglobin Level. Abstract. Long Beach, California, June 8-10, 1981. Accepted for publication to JAMA.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

INSTITUTION: University of Massachusetts

GRANT NO.: NBS Grant DA0001

GRANT TITLE: Waking Effectiveness of Household Smoke Alarm Detector  
Devices

PRINCIPAL INVESTIGATOR: Dr. E. Harris Nober, Professor  
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NBS SCIENTIFIC OFFICER: Richard W. Bukowski

TECHNICAL ABSTRACT

This is the second year of a three-year research project designed to determine the waking effectiveness of household smoke detector alarms.

The first year was geared to obtain base-line data. First-year results demonstrated that household smoke detector alarms generally provided the required minimum of 85 dBA within a 10 foot radius and that the primary peak energy concentration occurred at 4000 Hz with a secondary peak at 2000 Hz. Data from reverberant and anechoic chambers revealed similar distributions of energy output.

Subject waking latencies were obtained at 85, 70 and 55 dBA to correspond with the maximum unobstructed alarm output, ear-pillow level bedroom door open and ear-pillow level bedroom door closed, respectively. Alarms were activated during sleep in a "quiet" mode, with an air conditioner noise present and during waking while watching a video-taped movie. Results indicated that subjects were generally awakened by the alarms at all three intensity levels within one minute, although the 55 dBA group had problems with the air conditioner noise masking overlay. A pre- and post-alarm questionnaire also provided pertinent additional data about attitudes and performance.

The objective for the second (current) year was to enlarge the baseline data of waking effectiveness, but in this instance the actual smoke detectors were installed in the household dwellings. Actually, two household smoke detectors were installed in each of 40 households. One was an AC unit wired so it could be activated remotely by an RF signal at a predetermined date. The second unit was battery-operated

and would activate if a fire actually occurred during the experimental waiting period; therefore, subjects were advised to evacuate accordingly. The detector units were stationed in the dwellings from 4 weeks to 13 weeks prior to activation. Subjects were not aware of the activation date nor the targeted time of night, i.e., between 1 a.m. and 5 a.m. Experimental variables included type of household dwelling construction, households with children vs. households without children, male vs. female, and adults vs. children.

Responses to the alarm activation included turning on a light when awakened and evacuation of all household occupants present that night regardless of the relationship to the household. Subjects were requested to assume there was a fire and exit with the upmost dispatch. A stopwatch was used to obtain the evacuation latency for each subject (interval from the instant the alarm was activated to the instant the subject stepped outside the predesignated exit door). The contact representative from each household also completed pre- and post-alarm questionnaires.

Preliminary results of the evacuation latency raw data (not yet treated statistically) were as follows:

Type of Dwelling	Apartment	House	Apartment	House	Houses & Apartments
Type of Family	with children*	with children*	without children*	without children*	total experimental pop.
Average Evacuation Time (sec.)	46.7 sec.	49.7 sec.	49.9 sec.	47.6 sec.	48.5 sec.

\*Children are considered to be 11 years of age or younger.

Hence, it appears from these preliminary unanalyzed raw data that households can be evacuated within a minute from when an alarm is activated in the middle of the night when occupants are asleep.

#### REPORTS AND PAPERS

Nober, E. Harris, Charles C. Johnson, Henry B. Peirce, Arnold D. Well and Charles E. Clifton, "Waking effectiveness of household smoke detectors," Poster session, American Speech-Language-Hearing Association, Annual Convention, Detroit, Michigan, November 21-24, 1980

Nober, E. Harris, "Human Behavior in Fire/Waking Effectiveness," National Fire Protection Association, Annual Meeting, Dallas, Texas, May 18, 1981.

Nober, E. Harris, Henry Peirce and Arnold Well, "Acoustic Spectral Characteristics of Household Smoke Detector Alarms," Fire Journal, May, 1981.

Nober, E. Harris, Henry Peirce and Arnold Well, "Waking Effectiveness of Household Smoke and Fire Detection Devices," Fire Journal, July, 1981.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: The University of Michigan

Grant No.: NBS Grant NB8ONADA1054

Grant Title: Degradation of Mechanical Properties of Wood During Fire

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A.C. Loos, Ph.D. candidate  
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NBS Scientific Officer: W. Parker

Technical Abstract:

The objective of this investigation is to evaluate the decrease in mechanical properties of wood and wood assemblies exposed to fire. In order to achieve this objective tests are being performed measuring the thermal response as well as changes in the mechanical properties of wood exposed to flames or to a radiant heat source. In conjunction with the tests a model is also being developed for describing the behavior of wood exposed to high temperature environments.

The first series of tests was performed with redwood. Specimens were exposed to flames and the mass (weight) loss of the specimens and the decrease in ultimate tensile strength parallel to the grain were measured. A correlation was established between the change in tensile strength and the mass loss.

Following the preliminary tests with redwood, tests were conducted measuring the thermal and mechanical responses of southern pine exposed to high temperatures. The southern pine specimens were placed in a temperature controlled oven and the weight (mass) losses of the specimens and the centerline temperatures were recorded as a function of time. The oven temperatures were 200, 400, 600, and 800C. The specimens were 4 inches long and 1 inch wide. Specimens of different thicknesses were used, the thicknesses being 1/4 inch, 1/2 inch, 3/4 inch and 1 inch. Ten specimens were used at each condition. Accordingly, a total of 160 specimens were used in these tests. The weight loss and the thermocouple data were compared to the results of the analytical model. Good agreement was found between the data and the results of the model, lending confidence to the model.

Tensile, compression, and shear specimens were also placed in the oven at 400, 600, and 800C. The specimens were kept in the oven for a predetermined length of time. The strengths and the moduli in the directions both parallel and normal to the grain were then measured at room temperature. Attempts are now being made to establish correlations between the measured mechanical properties and other parameters such as mass loss, char layer thickness, and temperature distribution inside the wood.

In addition to the testing, an analytical model is being developed to simulate the response of wood to fire exposure. The specific goal in constructing the model is to describe changes in the thermal and mechanical properties and, most importantly, to predict the time of failure. The model is based on the law of conservation of energy, with the chemical reactions being represented by a single step Arrhenius bulk reaction. On the basis of this model a computer code was developed which provides the following parameters as a function of exposure time: a) temperature distribution inside the wood, b) mass loss as a function of position, and c) thickness of the char layer. The computer code can be applied to both one-directional (slab) and two-dimensional (rectangular cross-section) geometries. As noted above, the results generated by the model were found to be in good agreement with data.

At the present time the strength and modulus data together with the von Mises failure criterion for anisotropic materials are being incorporated into the model. The resulting computer code will yield a) the changes in strengths and in moduli as a function of exposure time, and b) the time of failure. The times of failure predicted by the model will be compared to data generated using thick (2 in by 2 in) specimens. Work is now in progress measuring the strengths and the moduli at elevated temperatures, without allowing the material to cool to room temperature after the high temperature exposure. In these tests the load will be applied and data will be taken while the specimens are at elevated temperatures.

#### Reports and Papers

1. Pering, G.A., and Springer, G.S., "Decrease in Tensile Strength and in Mass of Burning Wood," Fire Technology, 16, 245 (1980).

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: University of Montana

Grant No: NBS Grant G8-9011

Grant Title: Ignition and Fire Spread of Cellulosic Materials

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NBS Scientific Officer: Dr. William Earl

Technical Abstract

Objectives

The objectives of this project are to investigate the chemical mechanism and kinetics of smoldering combustion and to determine the effects of inorganic additives in order to provide a chemical description of the processes involved in ignition and fire spread in cellulosic materials.

Experimental Approach

It has been shown that smoldering combustion of cellulosic materials involves (a) pyrolysis of the substrate to provide a highly reactive pyrophoric char, (b) chemisorption of oxygen on the fresh char, and (c) gasification of the char from sites containing chemisorbed oxygen, resulting in the creation of new active sites.

The pyrolysis and chemisorption have already been investigated and experimental work has been focused on various additives, in order to show how they could affect the above reactions and ultimately inhibit or enhance the smoldering process. This investigation was carried out by determining the effect of various additives on the char properties, including yield, surface area and free spin concentration; the kinetics of oxygen chemisorption; and gasification, including kinetics of CO and CO<sub>2</sub> production and the rate of heat release which provides the driving force for propagation of the smoldering.

Results

A series of chars was prepared by pyrolyzing cellulosic fabric

treated with different additives at 550°C. Table I shows (1) the effect of these additives on the char yield; (2) char surface areas determined by CO<sub>2</sub> adsorption at room temperature; (3) relative unpaired spin concentration determined by ESR spectroscopy; (4) Elovich kinetic parameters for oxygen chemisorption; (5) gasification rate constants, calculated for 750°C from Arrhenius kinetic parameters determined by isothermal gasification experiments; and (6) the rate of heat release, calculated from the heats of formation of CO and CO<sub>2</sub>. It is apparent from these data that pre-pyrolysis addition of inorganics has very little effect on the surface areas of the chars, all of which fall between 300 and 400 m<sup>2</sup>/g. On the other hand, the unpaired spin concentration varies widely between treatments and correlates very well with the pre-exponential Elovich kinetic parameter, *a*, which indicates the reactivity of the char towards oxygen according to the equation:

$$dq/dt = a \exp(-bq)$$

where *q* is the amount chemisorbed and *a* and *b* are constants.

These data in turn correlate with the rates of gasification and the rates of heat release which provide the driving force for propagation of smoldering.

Furthermore, as shown in Figure 1, the unpaired spin concentration in chars formed at 550°C correlates very well with the rate of CO<sub>2</sub> production calculated at either 500° or 750°C. Since the heat of CO<sub>2</sub> formation is considerably larger than that for CO formation ( $\Delta H_f^{500} = -88.5$  kcal/mole for CO<sub>2</sub>, as compared to  $\Delta H_f^{500} = -22.9$  kcal/mole for CO formation), this correlation is significant in terms of the predominance of CO<sub>2</sub> formation in determining heat release and propagation of smoldering combustion.

These data demonstrate the effect of the additive in altering the course of the pyrolysis reactions and the resulting reactivity of the char. Further effects could also be expected to occur through catalysis of the solid phase combustion reactions by processes such as oxygen transfer, which has been demonstrated for a wide variety of inorganic materials in the combustion reactions of coal and graphite. Similarly, additives such as the phosphate or borates could inhibit the combustion reactions by competing with oxygen for active sites or by coating the surface with a glassy residue.

In order to determine the extent of these modes of inhibition or catalysis, chars prepared from untreated cellulose were ground with additives, heated to about 300°C in H<sub>2</sub>, cooled under N<sub>2</sub> to 207°C, and then exposed to O<sub>2</sub>; then the reactivity of the chars toward oxygen chemisorption was determined. The results are summarized in Table II. The data from Elovich kinetic parameters are similar for all additive treatments, indicating that the effect of the additives on the combustion reactions is much less important than their effect on the pyrolysis reactions, which gives rise to a wide range of chemical

functionality and reactivity. However, the extent of the solid phase catalysis may depend on the reaction of the additive with carbon during pyrolysis; thus further work is required to demonstrate conclusively the nature and extent of this mode of catalysis or inhibition.

The effect of sulfur is more complex and harder to determine because it evaporated during the pyrolysis process. Exposure of the char to a stream of sulfur vapor indicates that it may adsorb on char and interfere with free spin concentration to produce an inhibitory effect. The transition metals which could catalyze the oxygen transfer are also being investigated.

### Conclusions

Prepyrolysis addition of inorganic materials to cellulose can, depending on the additive, result in either inhibition or enhancement of the subsequent combustion reactions. These additives have very little effect on the surface areas of the char, but dramatically affect the chemical functionality or "active surface area", particularly the unpaired spin concentration. This in turn correlates well with the rates of both oxygen chemisorption and gasification reactions, suggesting that free radical sites play a critical role in controlling the combustion behavior of cellulosic chars. Catalysis by oxygen transfer or other mechanisms does not appear to be a significant factor.

### Reports and Papers

1. Bradbury, A.G.W. and F. Shafizadeh, "The Role of Oxygen Chemisorption in Low Temperature Ignition of Cellulose", Combustion and Flame, 37, 85, (1980).
2. Bradbury, A.G.W. and F. Shafizadeh, "Chemisorption of Oxygen on Cellulosic Char", Carbon, 18, 109 (1980).
3. Shafizadeh, F., A.G.W. Bradbury, W.F. DeGroot and T.W. Aanerud, "The Role of Inorganic Additives in the Combustion of Cellulose", submitted to Industrial and Engineering Chemistry/Product Research and Development.
4. Shafizadeh, F., A.G.W. Bradbury, and W.F. DeGroot, "Formation and Reactivity of Cellulosic Chars", presented at Western States Section/ The Combustion Institute, Pullman, Washington, April 13-14, 1981.
5. Shafizadeh, F., "Introduction to Pyrolysis of Biomass", Proceedings, Specialist Workshop on Fast Pyrolysis of Biomass, SERI/CP-622-1096. Copper Mountain, Colorado, Oct. 19-22, 1980.
6. Shafizadeh, F., "Chemistry of Pyrolysis and Combustion of Wood", International Conference on Residential Solid Fuels, Oregon Graduate Center, Portland, Oregon, June 1-4, 1981.

Table I. Properties and reactivity of chars from untreated and additive-treated cellulose (HTT 550°C).

Additive	Char Yield	Surface Area	Relative Unpaired Spin Concentration	Rate of Gasification (kCO <sub>2</sub> +kCO)/750°C	Elovich Kinetic Parameters		Rate of Heat Release (750°C) (kcal/mole/min)
					a	b	
NaCl	13.3%	359±81 (m <sup>2</sup> /g)	2.05	1.29 min <sup>-1</sup>	1.31±0.41	2.96±0.04	-83.5
Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	33.3%	371±13	1.23	1.24 min <sup>-1</sup>	1.26±0.28	3.59±0.39	-64.3
Untreated	5.7%	352±49	1.00	1.04 min <sup>-1</sup>	0.87±0.19	2.20±0.14	-54.2
(NH <sub>4</sub> ) <sub>2</sub> HPO <sub>4</sub>	21.8%	324±21	0.41	0.74 min <sup>-1</sup>	0.38±0.09	1.76±0.08	-27.3
H <sub>3</sub> BO <sub>3</sub>	18.7%	351±50	0.58	0.61 min <sup>-1</sup>	0.41±0.06	2.34±0.11	-27.5

\* Chemisorption of O<sub>2</sub> at 230°C

Table II. Elovich kinetic parameters for oxygen chemisorption at 207° for chars ground with inorganic additives (approximately 10% of additive).

Additive	Elovich Kinetic Parameters	
	<u>a</u>	<u>b</u>
NaCl	0.22±0.05	2.29±0.20
Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	0.30±0.07	2.48±0.03
Untreated	0.32±0.06	2.13±0.04
(NH <sub>4</sub> ) <sub>2</sub> HPO <sub>4</sub>	0.35±0.01	2.00±0.04
H <sub>3</sub> BO <sub>3</sub>	0.20±0.02	2.06±0.01

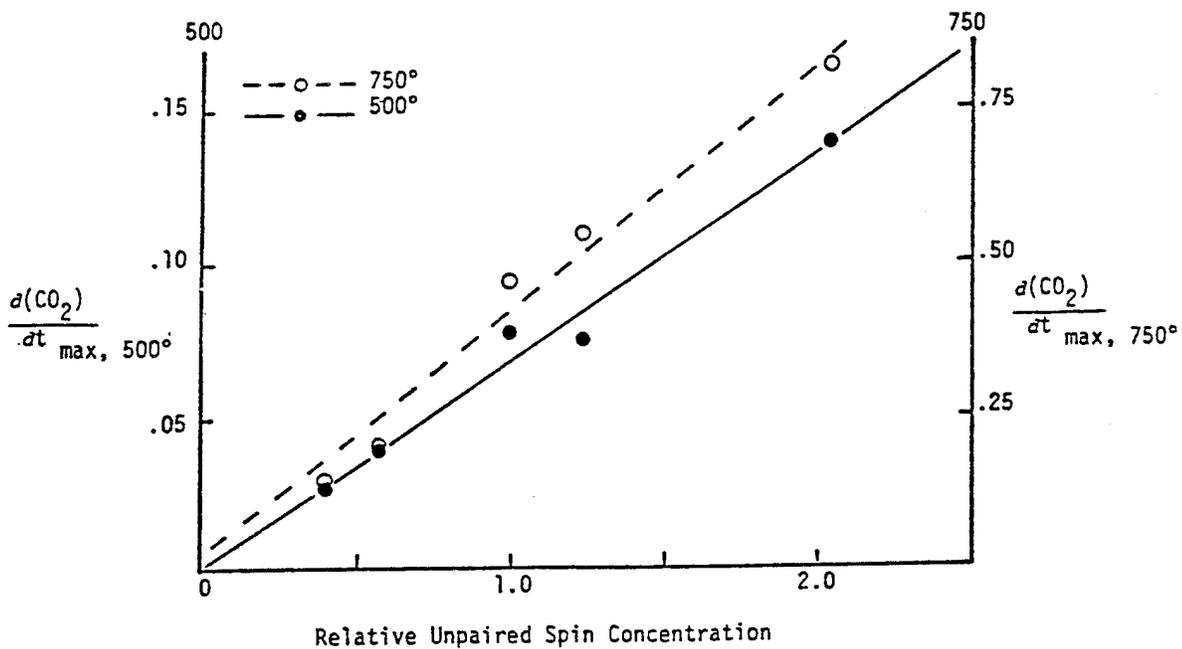


Fig. 1. Correlation between maximum rate of CO<sub>2</sub> production at 500° and 750°C and unpaired spin concentration in chars prepared from treated cellulose fabric samples (HTT 550°C).

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

Institution: The University of Notre Dame

Grant No.: NBS Grant NB81NADA2000

Grant Title: Computer Modeling of Aircraft Cabin Fire Phenomena

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NBS Scientific Officer: Dr. Walter Jones

Technical Abstract:

The overall objective of this study is to simulate the aircraft cabin fire phenomena by means of a differential field model computer code UNDSAFE for the purpose of better understanding the dynamics of fire and smoke spread in aircraft cabins. Various scenarios relative to the fire source, seating arrangement, and venting in a designated aircraft cabin form the base for the present study. The following is a listing of progress that has been made during the current grant period.

1. UNDSAFE Code Modification

The original UNDSAFE computer code was developed for fire and smoke spread in essentially empty two-dimensional compartments with venting. The unique requirement for the aircraft cabin problem with the presence of seats on the floor of the cabin dictated some modifications of the basic code. This effort has been carried out and the computer code is now fully operational to deal with the detailed two-dimensional cabin geometry. Two seat configurations can now be accommodated: solid seats reaching all the way to the floor and seats with an opening between the seat bottom and the floor. In addition, to make the code more useful, smoke movement based on species convection and diffusion has been incorporated to allow for the simultaneous computations of the flow, temperature, and smoke concentration fields. The smoke concentration results can now be used to compare with light transmission data in experimental measurements.

## 2. Numerical Simulation of NASA/FAA/UDRI Cabin Fire Test

A series of cabin mock-up fire tests was conducted at the NASA Johnson Space Center to produce test data useful to verify the DACFIR zone model developed at the University of Dayton Research Institute under the FAA sponsorship. Test 3-B has been specifically chosen as a base for comparison with the results of the numerical simulation study. The test phenomena are three-dimensional, and to simulate them with a two-dimensional code requires adjustments of simulation parameters. In view of the large number of parameters involved, any reasonable simplification is desirable. While the UNDSAFE code, modified for the aircraft cabin geometry, is fully capable of handling ceiling heat losses and unsteady fuel weight loss rates at the burner, we have chosen to limit the comparisons of the numerical results with the experimental data at the 60 second point from the initiation of the fire, so that the ceiling heat loss can be neglected and the fuel weight loss rate can be taken to be a constant. By doing so, this simulation study can be simplified to concentrate on more important parameters such as the heat load, the fire shape, the doorway height, and the level of turbulence in the test cabin.

The simulated aircraft cabin consists of a long compartment with two doorways at the two end walls and a heat source on the floor at the mid section. Altogether 27 simulation runs have been carried out on the computer for a variety of the simulation parameters mentioned above. No attempt has been made to achieve a perfect agreement between the numerical results and the experimental data, particularly in view of several uncertainties in the experimental measurements. The specific objective here is to demonstrate that the two-dimensional UNDSAFE code is capable of predicting the overall trends in the gas dynamic, temperature and smoke behaviors in the cabin as a result of the fire on the floor, and that ranges of the various two-dimensional geometrical and thermal loading parameters, which have a realistic correspondence to the real phenomena, can be determined. A second objective here is also to demonstrate the sensitivity of each of the parameters so that the more important effects for the overall cabin fire can be delineated.

Computer runs to determine the two-dimensional equivalence of the test phenomena show that the heat load is to be increased about 50%, while the door height is to be reduced approximately 30%. Even more important is the shape of the simulated volumetric heat source. In order to achieve reasonably close temperature distributions in the cabin, the simulated fire source should have a simulated flame height about 3 times that of the fire base. This is in line with what may be expected in a real fire.

The corresponding sensitivity studies show several interesting results. The fire strength primarily affects only the temperature level in the upper levels of the cabin, while the lengthwise temperature variation remains essentially unaffected. The energy strength distribution within the fire shape is found closely related to the distribution of layers of heat gases. The effect of the soffit height at the doorways is essentially limited to the region close to the doorway, which is the same

region where three-dimensional behaviors predominate. The effect of turbulence levels on the temperature field is essentially in regions away from the fire source. Higher levels of turbulent viscosity implies higher degrees of mixing, and consequently the whole cabin enclosure is involved in both momentum and energy transfer at an earlier time after the fire initiation. As a result, the doorways will make their presence felt also at an earlier time for higher turbulence levels.

### 3. Numerical Simulation of Aircraft Cabin with Seats

Early in the present study, it has become apparent that when seats are present in the cabin and fire is initiated close to these seats, there is a high probability that the seat surface temperature may exceed the ignition temperature so that additional heat may be added to the flow in the cabin. To accommodate such a scenario, the UNDSAFE code has been further modified to allow for additional heat generation when any surface element of the seats reaches a prescribed temperature level.

This simulation study treats a section of a typical wide-body aircraft cabin with six rows of high-back seats. The cabin front has a doorway and the cabin rear has a window or opening. The ceiling loses heat to the environment by convection. Six simulation runs have been carried out on the computer until steady state conditions are achieved. They deal with two different fire scenarios. In one, the fire in the form of a volumetric heat source is initiated between the third and fourth rows of seats, and a smoke source is also added at the same location. In the other scenario, a simulated fire with a flame height approximately three times of the fire base and a flame strength distribution similar to that of the preceding study is located between the doorway and the first row of seats. For each of the two fire scenarios, three computer runs have been carried out for the following three seat configurations: no seats, solid seats reaching the floor, and seats with opening above the floor. The case of no seats is chosen to simulate the condition along the center isle of a wide-body commercial airliner.

Results of the calculations may be briefly discussed as follows: The regions between any two rows of seats, other than that where the fire source is located, are relatively stagnant, and the smoke penetration into these regions from the hot ceiling layer is greatly impeded by the presence of seat backs. This is particularly the case for solid seats reaching the floor, and suggests the merit of having high seat backs to discourage smoke penetration into the passenger seat area. On the other hand, the temperatures in the fire region are much higher for the case of solid seats as compared to that of seats with open bottom. In the latter situation, the low temperature gas feeds along the cabin floor into the seating areas to reduce the temperature there. It is not surprising to find that for the case of solid seats, the seat surface starts to burn much earlier than that of the open seat case.

In the fire scenario where the fire is located in front of the first row of seats, a strong cross flow along the cabin length results from the unimpeded buoyancy due to the free standing fire close to the doorway.

This strong shear flow carries and deposits the smoke throughout the cabin, except in a small region close to the rear opening above the floor, and the seats do not appear to provide as good a protection from smoke as that in the other fire scenario.

4. Pressure Distribution Around an Intact Fuselage Immersed in the Flame of a Burning Pool of Spilled Fuel

The objective of this specific task is to determine the pressure distribution around a circular cylinder (fuselage) as a function of the prevailing wind and the turbulence field near the ground, location and strength of the fire, and the elevation of the cylinder. The modification of the two-dimensional UNDSAFE code to accommodate a cylinder situated horizontally above the ground with a heat source (fire) of width twice the cylinder diameter adjacent to the cylinder has just been initiated. During the current grant period, preliminary computer runs will be carried out to assure the efficiency, stability and accuracy of the calculations by the modified UNDSAFE code.

Fire hazard is an inherent scenario in survivable post-crash accidents for aircrafts, and it is generally recognized that loss of life can be reduced where fire and smoke spread phenomena in such aircraft cabin are better understood and can be adequately predicted in advance. Research efforts in the area of mathematical fire modeling as applied to the cabin fire phenomena specifically addresses this problem by the development of fire models such as zone models and field models. The present study deals with a specific field model for the aircraft cabin fire problem.

Reports and Papers

1. Satoh, K., Lloyd, J. R. and Yang, K. T., "Turbulent Buoyant Flows and Smoke Layers in a 2-D Rectangular Compartment with Vertical Vents," Paper presented at the 1980 Fall Technical Meeting of the Eastern Section of the Combustion Institute.
2. Satoh, K., Yang, K. T., and Lloyd, J. R., "Ventilation and Smoke Layer Thickness Through a Doorway of a Cubic Enclosure with a Central Volumetric Heat Source," Paper presented at the 1980 Fall Technical Meeting of the Eastern Section of the Combustion Institute.

CENTER FOR FIRE RESEARCH  
NATIONAL BUREAU OF STANDARDS

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Pittsburgh, PA 15261

Grant No.: NB79NADA0009

Grant Title: Toxicity of Plastic Combustion Products

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NBS Scientific Officer: M.M. Birky, Ph.D.

Technical Abstract

The toxicity of smoke emitted from polymers, synthetic or natural, is being investigated using a variety of animal models. We have developed models which permit evaluation of the effect of the smoke for specific effects relevant to a fire situation. These animal models detect the following effects of smoke:

1. Sensory Irritation: how irritating to the eyes, nose and throat the smoke is and how this can impede escape.
2. Pulmonary irritation: how irritating the smoke is to the lung and possible acute lethality from this effect.
3. Asphyxiation: how the smoke can induce this effect which will obviously prevent escape from fire.
4. Acute lethality: how the smoke can kill within a specified period of time.

We are now involved in two main areas:

1. Development of a method which can be used for evaluation of pulmonary irritation due to smoke inhalation and evaluation of recovery, if any, of pulmonary function following exposure.
2. Evaluation of recovery following exposure to CO or HCN and what kind of treatment is most effective as well as evaluating whether or not there is a residual effect from such exposures.

During the last year, we have proposed a toxicological classification for smoke from polymers as presented in figure 1. In this approach, Douglas fir was set as a standard and all other materials compared to it. We asked the questions how much polymer is needed to cause 50% mortality within a planned 30 minutes of exposure and how long does it take to produce this 50% mortality in comparison to Douglas Fir. From figure 1 a variety of polymers can be compared for the amount required and the time required. Also both amount and time can be combined to arrive at 4 classifications, A, B, C and D. This approach seems to be a reasonable one for rapid evaluation of polymers and comparison to Douglas Fir. Obviously reference materials other than Douglas Fir can be used when desirable.

#### Reports and Papers (this year)

Alarie, Y. and Anderson, R.C. Toxicologic classification of thermal decomposition products of synthetic and natural polymers. Toxicology and Applied Pharmacology. 57: 181-188, 1981

Alarie, Y., Anderson, R.C., Stock, M.F., Dombroske, R.L., Keller, L.W., Hayduk, L.W. and Park, R.E. Toxicity of thermal decomposition products an attempt to correlate results obtained in small scale with large scale tests. Journal of Combustion Toxicology 8, 58-68, 1981.

Alarie, Y. Toxicology evaluation of airborne chemical irritants and allergens using respiratory reflex reactions. In: Symposium on Inhalation Toxicology and Technology. B.K.J. Leong, Editor, Ann Arbor Science Publishers. Should be in press next September/October.

Alarie, Y. and Anderson, R.C. Toxicologic classification of decomposition products of synthetic and natural polymers. The Toxicologist, Volume I, page 8, Abstract. Presented at the Annual Meeting of the Society of Toxicology, San Diego, CA, March, 1981.



Figure 1

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The method employs a two-step procedure where the witness provides an uninterrupted narrative account of his/her actions during the fire. During this part of the interview the interviewer only attempts to keep the person focused on the fire he/she has witnessed, and refrains from asking any questions pertinent to the account. The purpose of this relatively unstructured narration is to allow the witness to re-create the fire in his/her own terms, without any threat to his/her credibility, nor the insertion of questions which may minimize or truncate important aspects of the witness account.

When the first narration is completed, the interviewer then obtains a second account of the incident, but this time forcing the witness to adopt a predetermined structure. The structure breaks the narrative account down into a continuous sequence of discrete actions, from the first awareness of the fire to the final actions taken by the witness in relation to the fire. The interviewer aids the witness in creating a statement about each discrete action he/she took during the fire incident.

Each statement describing a discrete action is composed of four elements: 1) a situational or cognitive cue which elicited a behavioral response from the witness, 2) a behavioral response to that cue, 3) using what instrument (if any was used), and 4) a reason why such an action was taken. The third component, instrument used, was added to the structure of the interview for the current phase of the project to satisfy a problem identified during the previous phase of research. It has been seldom used, but when used, provides interesting insight into the behavioral episode.

An example of one such discrete action would be the following: 1) I saw smoke seeping from under the apartment door, 2) so I opened the door, 3) with my pass key, 4) to see if there was a fire.

The advantages of such behavioral sequencing are several: 1) The witness is closely tied to the actual behaviors he/she emitted during the fire, and is not allowed to insert irrelevant, distracting information into the account; 2) The sequence of behaviors can be easily charted, and patterns of similar behavior detected as responses to fire, which in turn lend themselves to further analysis relative to demographics, type of fire, extent of fire, etc.; 3) Lacunae in sequences can be determined during the interview, and additional probing about such holes (potentially critical incidences) in the account can be conducted by the interviewer; 4) Potentially this technique can be employed by on-line fire investigators which would both overcome the critical problem of delay between incident and recounting of the incident, as well as facilitate establishment of an adequate volume of standardized witness accounts to allow generalization about behaviors during fires.

The technique is currently being tested in the field, while parameters related to the interviewing process are being examined in the laboratory. When relevant, laboratory findings will be incorporated into the technique for field validation during actual interview situations.

Phase one of this project was completed in winter, 1980, with the theoretical development of the technique and the conduction of pilot interviews with witnesses to thirty residential fires within Seattle.

Phase two of this project will be completed in summer of 1981. It has consisted of forty-five structured interviews of witnesses to thirty-seven fires in Seattle. Data is currently being analyzed, but initial examination indicates that the behavioral sequence interview method has proven itself effective in lending itself to analysis which will allow generalization about fire behaviors, once an adequate sample is obtained.

In addition to the interviews conducted by our own staff in Seattle, the principal investigators conducted a day-long workshop with thirty supervisors and investigators of the Houston, Texas Arson Bureau

in fall, 1980. In spring, 1981, the written accounts of witnesses questioned by investigators from the Houston Arson Bureau were reviewed, and twenty of fifty-seven reviewed were selected as meeting the criteria for selection into a sub-sample of the current study. These cases contained some testimony from approximately 90 witnesses, many of whose accounts are not amenable to our preferred mode of analysis (a problem largely due to the fact that arson investigation, and not personal behaviors, was the focus of the interview).

Analysis proceeds on these data, and those accounts which do focus on human behavior indicate that the behavior sequence interview method and analysis can be adapted for use by on-line fire investigators. Such use would greatly facilitate establishment of an adequate data pool of standardized accounts to help direct subsequent investigations into the behaviors of people in fire. A second workshop is now being planned for the summer of 1981 with Seattle and Puget Sound fire departments, and a subsequent data collection of on-line interviews is planned for the fall, 1981.

Finally, concurrently with the field interviews, laboratory studies are being conducted which probe variables which potentially impact a witness account of the fire incident. The first of these studies examined differences in recall between fire investigators and a university student population when exposed to an involving film of a hospital fire. Fire investigators scored better than students on technical aspects, e.g., the number of fire hoses used, but less well on items which questioned events which would not typically be expected to occur, e.g. elevator door blocked by a cart. This supports the importance of the role of expectancies in the reconstruction of accounts about the familiar.

The second study in this series examined the role of time delay between exposure to the event and recall of specific aspects of the fire, and supported the importance of time as a hindrance to correct recall. A second hypothesis was tested which predicted that re-creating the context of the fire event may facilitate accurate recall. This hypothesis was not supported.

Our plans for the next six months include:

- 1) Extensive analysis of the data gathered from the first wave of interviews from the Seattle sample.
- 2) Extensive analysis of those accounts from the Houston sample which are amenable to our behavioral sequence method.
- 3) Conduct further laboratory studies, especially focusing on aspects of affect and memory.
- 4) Conduct a workshop for Puget Area Fire Department Investigators, and review interview accounts conducted after fire department personnel exposure to the behavioral sequence method.
- 5) Conduct a second wave of interviews with an extended Puget Sound sample, incorporating modifications suggested by the laboratory investigations in the interview format (especially aware of the time delay).

- 6) Complete final analysis of this interview technique for fire witnesses, and assess its applicability as a research instrument, suitable for use by on-line fire personnel.

Articles and Papers: (1980-1981)

- 1) Keating, J.P. and Loftus, E.F. The Logic of Fire Escape. Psychology Today, 1981, 15 (no. 6), 14-19.
- 2) Keating, J.P. and Loftus, E.F. and Manber, M. Emergency Evacuation During Fires: Psychological Considerations. In R.F.Kidd and M.J. Saks (Eds.) Advances in Applied Social Psychology (Vol II). Hillsdale, N.J.: Erlbaum, in press.
- 3) Keating, J.P., Groner, N., and Loftus, E.F. Addressing Emergency Egress Problems in High-Rise and Hospital Settings. Western Psychological Association, Honolulu, 1980.
- 4) Keating, J.P. The Myth of Panic. Invited speech, U.S. Fire Administration sixth annual conference, San Francisco, 1981.
- 5) Keating, J.P. and Loftus, E.F. Human Behavior in Fire: Finding Out What Really Occurred. National Fire Protection Association eighty-fifth annual meeting, Dallas, 1981.

APPENDIX A

AGENDA

FIFTH ANNUAL CONFERENCE ON FIRE RESEARCH

CENTER FOR FIRE RESEARCH  
NATIONAL ENGINEERING LABORATORY  
NATIONAL BUREAU OF STANDARDS  
August 19, 20, 21, 1981

Tuesday, August 18

7:00 p.m. Registration and Informal Reception  
Ramada Inn, Rockville, Maryland

Wednesday, August 19

8:15 a.m. Registration, Green Auditorium Lobby  
9:00 a.m. Opening Remarks, Green Auditorium  
9:10 a.m. Welcome - Dr. F. Clarke, Director, CFR/NBS

Session I. Large-Scale Modeling

9:15 a.m. Session Chairman (Overview) - Dr. J. Rockett, CFR/NBS  
9:30 a.m. Modeling of Aircraft Cabin Fires (FAA) - Dr. R. Alpert, Factory  
Mutual Research Corporation  
9:45 a.m. Modeling of Aircraft Cabin Fires (FAA) - Professor H. Emmons,  
Harvard University  
10:00 a.m. Modeling of Aircraft Cabin Fires (FAA) - Professor M. Kanury  
University of Notre Dame  
10:15 a.m. Discussion on Aircraft Models  
10:20 a.m. Coffee Break, Employee Lounge  
10:45 a.m. Expository Talk - Modeling Wildland Fires - R. Rothermel, Forest  
Service, U. S. Department of Agriculture  
11:45 a.m. Multi-Room and Multi-Story Modeling - Dr. T. Tanaka, NBS Guest  
Worker, Japan, Building Research Institute  
12:05 p.m. Validation of Fire Models - Dr. W. Jones, CFR/NBS  
12:25 p.m. Modeling of Available Egress Time from Buildings - Dr. L. Cooper,  
CFR/NBS  
12:45 p.m. Lunch, NBS Cafeteria  
2:00 p.m. Home Fire Project (Last Five Years) - Professor H. Emmons, Harvard  
University  
2:50 p.m. Heat Transfer in Room Fires - Professor E. Zukoski, California  
Institute of Technology  
3:10 p.m. Fire Modeling - Professor P. Pagni, University of California at  
Berkeley  
3:30 p.m. Coffee Break, Employee Lounge  
4:00 p.m. Fuel Parameters - Dr. A. Tewarson, Factory Mutual Research  
Corporation

Session I. Large-Scale Modeling (Continued)

- 4:20 p.m. Theoretical Investigation of Large-Scale Pool Fires -  
Professor T. Shih, University of Maryland
- 4:30 p.m. Scale Modeling - Professor M. Kanury, University of Notre Dame
- 4:40 p.m. CFR Policy Issues Over the Next Few Years - Dr. F. Clarke,  
Director, Center for Fire Research
- 5:00 p.m. Discussion
- 5:15 p.m. Adjourn
- 6:15-9:00 p.m. Barbeque and Volleyball Game at Smokey Glen

Thursday, August 20

Session II. Pyrolysis

- 9:00 a.m. Session Chairman (Overview) - Dr. R. Gann, CFR/NBS
- 9:15 a.m. Expository Talk - Mechanistic Basis of Polymer Flammability -  
Professor R. Barker, Clemson University
- 10:15 a.m. Degradation of Wood - Professor G. Springer, University of Michigan
- 10:35 a.m. Coffee Break, Employee Lounge
- 11:00 a.m. Polymer Degradation - Dr. S. Brauman, SRI International
- 11:20 a.m. Reactions in Substrate - Professor M. Drews, Clemson University
- 11:40 a.m. Ignition and Fire Spread (Last Five Years) - Professor F. Shafizadeh,  
University of Montana
- 12:20 p.m. Smoldering - Dr. T. Ohlemiller, CFR/NBS
- 12:40 p.m. Ignition - Dr. T. Kashiwagi, CFR/NBS
- 1:00 p.m. Lunch, NBS Cafeteria

Session III. Soot/Smoke/Radiation

- 2:00 p.m. Expository Talk - Flame Radiation - Professor C. Tien, University of  
California at Berkeley
- 3:00 p.m. Session Chairman (Overview) - Professor P. Pagni, University of  
California at Berkeley
- 3:15 p.m. Soot Nucleation - Dr. H. Calcote, AeroChem Research Laboratories, Inc.
- 3:35 p.m. Coffee Break, Employee Lounge
- 4:10 p.m. Soot - Dr. H. Miller, NRC Postdoctoral Fellow, CFR/NBS
- 4:30 p.m. Smolder Smoke - Dr. T. Ohlemiller, CFR/NBS
- 4:50 p.m. Smoke and Inert Tracers Produced in Porous Fuels - Professor S. Goren,  
University of California at Berkeley
- 5:00 p.m. Discussion
- 5:15 p.m. Adjourn
- 6:30-9:00 p.m. Wine and Cheese Buffet/Reception at Gabriel's

Friday, August 21

Session IV. Flame Spread, Burning Rate and Extinction

- 9:00 a.m. Session Chairman (Overview) - Dr. J. Quintiere, CFR/NBS
- 9:15 a.m. Wind Aided Flame Spread - Dr. F. Fendell, TRW Systems

Session IV. Flame Spread, Burning Rate and Extinction (Continued)

- 9:35 a.m. Flame Impingement on Ceilings - Professor G. Faeth, Pennsylvania State University
- 9:55 a.m. Fire Propagation in Concurrent Flows - Professor A. Fernandez-Pello, University of California at Berkeley
- 10:15 a.m. Flame Extinction in Relationship to Fire Suppression - Dr. S. Sohrab, University of California at San Diego
- 10:35 a.m. Coffee Break, Employee Lounge
- 11:05 a.m. Burning and Extinction (Last Five Years) - Professor M. Sibulkin, Brown University
- 11:50 a.m. Wall Flame Spread - K. Steckler, CFR/NBS
- 12:10 p.m. Flame Spread and Spread Limits - Professor J. T'ien, Case Western Reserve University
- 12:30 p.m. Fire Spread Over Solids - Professor I. Glassman, Princeton University
- 12:50 p.m. Closing Remarks - Dr. R. Levine, Chief, Fire Research Resources Division, CFR/NBS
- 1:00 p.m. Adjourn
- — — — —

Ad Hoc Group - Administration Building, Lecture Room A

- 2:00-5:00 p.m. Ad Hoc Fire Modeling Workshop on Burning Rate and Flame Spread - Dr. J. Quintiere, Chairman

APPENDIX B

FIFTH ANNUAL CONFERENCE ON FIRE RESEARCH

Center for Fire Research  
National Engineering Laboratory  
National Bureau of Standards  
August 19, 20, 21, 1981

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