NBSIR 78-1526

Annual Conference on Fire Research

Clayton Huggett, Editor

Center for Fire Research
National Engineering Laboratory

December 1978

Final Report

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*

Dr. Sidney Harman, *Under Secretary*

Jordan J. Baruch, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

FOREWORD

The size and scope of this compilation for the Center for Fire Research's Second Annual Conference is unusual; the spirit which produced it is unique.

We at NBS are privileged to stand at the crossroads of fire research in the United States. We were originally put there by Congress when we were assigned responsibility for a major extramural research program. That program has at one time or another put us in partnership with most of the nation's premier fire laboratories, and it is a partnership from which we have invariably profited. The aims of this conference are to share among the participants the sense of community and synergy we have experienced.

It is crucial that this goal be achieved. Fire research is challenging and important. There are only enough resources to support the very best efforts of which all of us in the research community are capable. The more we can help one another the more progress we can make.

August 16, 1978

Frederic B. Clarke, Director
Center for Fire Research

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ANNUAL CONFERENCE ON FIRE RESEARCH

September 27-29, 1978

Clayton Huggett, 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 and descriptions of the internal programs of the Center for Fire Research.

Key words: Combustion products; fire hazards; fire modeling; fire research; human behavior in fires.

Final Program

ANNUAL CONFERENCE ON FIRE RESEARCH

Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
September 27, 28, 29, 1978

Wednesday, September 27

8:15 a.m. REGISTRATION, Green Auditorium Lobby

9:15 OPENING SESSION, Green Auditorium
Dr. Clayton Huggett (CFR/NBS)

9:45 FOCUS ON THE FIRE PROBLEM
Chairman - Philip S. Schaenman (NFPCA)

The U.S. Fire Problems and NFIRS - Mr. Schaenman

10:30 COFFEE BREAK, Employee Lounge

11:00 FOCUS ON THE FIRE PROBLEM (continued)

Update on Maryland Fire Casualty Data -
Byron Halpin (JHU/APL)

Plastics Hazards in Residences - James Slater (CFR/NBS)

Project People - Dr. John L. Bryan (U. of MD)

Arson Problem - Dr. Robert Vreeland (U. of NC)

Major Fire Investigations - A. Elwood Willey (NFPA)

12:30 p.m. LUNCH, NBS Cafeteria

1:30 FIRE TESTS
Chairman - William Parker (CFR/NBS)

Development of Fire Tests - Mr. Parker

Fire Growth Experiments - Dr. R. Brady Williamson (U. of Calif.)

Standard Room Fire Tests (w/discussion panel) -
Dr. Williamson - Chairman

3:15 COFFEE BREAK, Employee Lounge

Wednesday, September 27

3:45 p.m. FIRE TESTS (continued)

Air Movement Past Fire Doors - R. Brehenig (UL)

High Temperature Creep in Concrete Structures - Melvin Abrams (PCA)

Insulation Fire Hazards - D. Gross (CFR/NBS)

5:00 ADJOURN

6:00 BARBECUE, Smokey Glen Farm

Thursday, September 28

SIMULTANEOUS TECHNICAL SESSIONS
FIRE TESTS - Green Auditorium (continued from Wednesday)
TOXICOLOGY - Lecture Room A

9:00 a.m. TOXICOLOGY - Lecture Room A
Chairman - Dr. Merritt Birky (CFR/NBS)

Combustion Product Toxicity Data and Its Use - Prof. Yves Alarie (U. of Pittsburgh)

Combustion Model - An Analytical Point of View - Dr. B. Mason Hughes (U. of Utah)

10:15 COFFEE BREAK, Employee Lounge

10:45 TOXICOLOGY (continued)

Effects of Heat Stress on Toxicity - Prof. Zoltan Annau (JHU)

Chronic Health Effects of Exposure to Fire (Firefighters) - Dr. Marshal Levine (JHU)

Treatment of Fire Victims - Dr. Roy Meyers (JHU)

12:00 Discussion

12:30 LUNCH, NBS Cafeteria

9:00 a.m. FIRE TESTS - Green Auditorium

Effect of Retardants on Heat Release Rate - Stanley Martin (SRI)

Rate of Heat Release (w/discussion panel) - Mr. Martin - Chairman

Thursday, September 28

10:15 COFFEE BREAK, Employee Lounge

10:45 a.m. PRODUCT FLAMMABILITY FIRE RESEARCH - James Winger (CFR/NBS)

FURNISHING FLAMMABILITY FIRE RESEARCH
Introduction - Sanford Davis (CFR/NBS)

Mattress Flammability, Small Scale Tests -
Dr. Vytenis Babrauskas (CFR/NBS)

11:45 HUMAN BEHAVIOR IN FIRES
Chairman - Dr. Bernard Levin (CFR/NBS)

Effect and Value of Training Nursing Home Staffs -
Dr. Leonard Bickman (Loyola U. of Chicago)

12:30 p.m. LUNCH, NBS Cafeteria

1:30 HUMAN BEHAVIOR IN FIRES (continued)

Capabilities of Disabled in Fire Drills -
Dr. John Fechter (CCPT)

Characteristics of Alarms - Dr. Harold Wakeley (IITRI)

Arousal from Sleep by Emergency Alarms - V. J. Pezoldt (CCPT)

Commentary - Dr. John Keating (U. of WA)

3:00 COFFEE BREAK, Employee Lounge

3:30 FIRE DETECTION AND CONTROL
Chairman - Edward Budnick (CFR/NBS)

Automatic Sprinklers in Health Care Facilities -
John O'Neill (CFR/NBS)

Reliability Analysis of Smoke Detectors -
H. C. Rickers (RAC, IITRI)

Development of An In Situ Smoke Detector Test Apparatus -
Richard Bukowski (CFR/NBS)

5:15 ADJOURN

Friday, September 29

9:00 a.m. ANALYTICAL APPROACHES TO FIRE PROTECTION
Co-Chairmen - Benjamin Buchbinder (CFR/NBS)
Dr. John Watts (U of MD)

Introduction - Mr. Buchbinder

Using Decision Analysis to Set Fire Policy - Dr. Fred Offensend (SRI)

Decision Analysis Application to Update Furniture Fire Safety - Susan G. Helzer (CFR/NBS)

The Goal Oriented Systems Approach - Dr. Watts

Fire Safety Evaluation System - Harold Nelson (CFR/NBS)

Session Summary - Dr. Watts

12:00 CONFERENCE HIGHLIGHTS - Tom Waterman (IITRI)

CLOSING OF CONFERENCE

12:30 p.m. LUNCH, NBS Cafeteria

1:30 FREE TIME

Informal Discussions
Visits to Laboratories
Visit to Fire Research Information Service
Tour of Fire Research Facility (Building 205)
Tour of Nike Site (Field Test Station)
Tour of NBS

TRANSPORTATION TO AIRPORTS

(Please sign up at the registration desk for tours and transportation to airports.)

PROGRAM FOR INFORMATION AND HAZARD ANALYSIS
FIRE SCIENCE DIVISION
CENTER FOR FIRE RESEARCH

Professional Personnel

Benjamin Buchbinder, Program Chief
Alan Gomberg, Fire Prevention Engineer
Susan Helzer, Mathematician
Nora Jason, Technical Information Specialist
Stefan Leigh, Operations Research Analyst
James Slater, Mathematician

The work carried on in this program is based on two major objectives. The first is to characterize fire hazards by analytical means, both to help establish research priorities and to guide the development of test methods for codes and standards. The second objective is to expand and maintain a technical fire literature collection, to provide technical information services for the Center for Fire Research (CFR) and for the fire community at large, and to provide access to fire loss data for CFR.

Methodology and Data Base Development

In the past our hazard characterization has been basically qualitative, involving the identification and definition of patterns of fire accidents. More and better data were required before meaningful quantitative analysis could be done. The establishment of the National Fire Data System (NFDS) at the National Fire Prevention and Control Administration (NFPCA), and the development of specialized data bases on fabric related fires and plastic fires in our own program, provided us with sufficient data to enable us to use quantitative methods based on operations research technology. The successful pilot decision analysis on upholstered furniture fires spawned a new project area (see Decision Analysis below). Current efforts will provide us with interactive access to NFDS. The quantity and quality of data are continually improving, and new types of data are becoming available. Our future plans under this project include continued application of current operations research techniques, with emphasis on integrating the different types of data from such sources as fire incident reporting, fire growth modeling, large scale testing and economic studies.

PROGRAM FOR CHEMISTRY
FIRE SCIENCE DIVISION
CENTER FOR FIRE RESEARCH

Professional Personnel

Richard G. Gann, Chief
John W. Rowen, Physical Scientist
Gerald D. Mitchell, Research Chemist
Kermit C. Smyth, Research Chemist
W. Gary Mallard, Research Chemist
Michael J. Manka, Chemist
William Earl, Postdoctoral Research Associate

Affiliated

John Hastie, Center for Materials Science

The objectives of the Chemistry Program are:

(1) to provide understanding of the chemical processes which are important in the development and control of unwanted fires: kinetics and thermodynamics of combustion, fuel structure and additive effects on flammability, ignition, flame spread and structure, generation of combustion products, and fire retardance and extinction;

(2) to transmit that knowledge to other fire research groups and to the technical community at large for use in developing fire resistant materials, standard test methods and building design codes.

Current Projects

Spontaneous Ignition

In many instances fires begin or propagate when materials are heated, smolder for a while, and then burst into flame or ignite some other substance. The Bureau of Mines has a similar problem with the ignition of low-grade coals long before they reach their eventual destination. Hence, studies on the self-heating of materials have a dual potential to reduce both fire loss and energy waste. It is our intent to develop a scientifically based susceptibility index for materials prone to spontaneous ignition and to demonstrate the validity of this index as a basis for ranking these materials for fire hazard.

We are using an updated version of an adiabatic furnace pioneered at NBS some 25 years ago, and several samples of ground coal have been studied. The use of coal samples reflects the partial sponsorship of the Bureau of Mines and the relative "cleanliness" of coal samples as compared to, for instance, polyurethanes. To date, we have studied the effects of sample size, particle size, and moisture (absorbed and gaseous) on the tendency to self-heat and the resulting temperature-time behavior. The results show thermal runaway occurring at temperatures as low as 40°C. We are testing applicability of thermal explosion theory and, through it, the derivation of a set of furnace operating conditions relevant to the actual coal mining or storage conditions. Other coal properties, such as heat content, elemental composition and combustion products, are being determined concurrently to establish possible correlations with autoignition hazard.

Polymer Thermostability and Fire Resistance

Several rigid plastics were subjected to a variety of test methods to investigate possible correlations between measurements intended to be indicative of fire behavior and thermal stability. The commercial polymers include PMMA, a polyimidamide, two PVC's (with and without a fire retardant), a polycarbonate, two polyethylenterephthalates (also with and without a fire retardant), and a research phthalocyanine (with and without a fire retardant). The measurements, now completed, are of oxygen index, rate of weight loss (TGA) in air and nitrogen, rate of generation of combustible gases in air and nitrogen, rate of heat release (with and without piloted ignition), and isothermal weight loss. Within the next few months, a factorial analysis will be performed and any performance correlations noted. These will also be related to the chemical structures of the materials.

Flammability of Dielectric Fluids

In a recent action, the Environmental Protection Agency (EPA) banned the use of polychlorinated biphenyls, thus elminating the existing "non-flammable" insulating fluids for transformers and capacitors. We are conducting a study to comprehensively delineate the fluid's properties which determine its fire potential in these uses. The work includes gathering data on past device failures, conducting tests to verify failure mode identification, locating or devising procedures for approximately measuring pertinent fluid properties, determining the effect of thermal and electrical aging on the properties, and constructing a probabilistic model (with the Program for Information and Hazard Analysis) for quantifying fluid property interactions. To date, we have gathered enough information to isolate four transformer failure scenarios involving significant fire hazard potential, prepared a summary of existing test methods and participated in the development of an advanced test scheme, constructed the equipment for the aging studies, and let contracts for assistance with the model construction and actual scale fire testing. During the winter and autumn of 1978, a final report will be prepared, and further work will be continued by the involved industries.

Rate of Heat Release (RHR)

Fortunately, when a component of a room catches fire, it generally does not burn instantaneously to completion. Rather, a gradual involvement occurs, often with far less heat than ΔH_c being released over an extended time interval. Coordinating with the Construction Materials Program, we are involved with two aspects of this phenomena. The first, recently completed, was an assesment of the utility of oxygen depletion by combustion as a quantitative measure of heat release. The study indicates that the technique is applicable to a wide range of materials and yields both instantaneous values for the rate of total (i.e, convective plus radiative) heat release and also an integrated heat release in agreement with theoretical values (for totally consumed fuels). The results are being prepared for publication.

A second project will combine RHR and chemical measurements to elucidate the mechanisms of polymer degradation during flaming combustion. The intent is to allow some degree of predictability for the contribution of components to room fires. This is in the development state, with the criteria for the calorimeter still being considered. Variables likely to be studied, in addition to the structure of the fuel, are irradiance level, air flow, and sample orientation. Analysis of both the gaseous combustion products and polymer residue is planned.

NMR Studies of Combustion of Solids

Jointly with the Center for Materials Science, we are developing a capability in magic angle spinning, high resolution nuclear magnetic resonance of solids. Our intent is to follow the degradation of polymers and phosphorus-containing fire retardants using the ^{13}C and ^{31}P nuclides, respectively. At present, a modular apparatus for the former is operational and the first spectra of _trans_ and _gauche_ polyethylene, a hydrocarbon sludge, and cellulose have been obtained. The electronics for the ^{31}P studies have been constructed also, with the spinner due soon. The initial research plans involve burning a cellulosic fuel, with and without retardant, and analyzing samples from at and about the combustion zone for changes in fuel structure and retardant valence.

Sulfur Smoldering Retardance Mechanisms

According to current statistics, at lease one fourth of all fire deaths result from scenarios which include a non-flaming step. As a result, test methods are being developed to evaluate the smoldering performance of materials, and the need for smoldering inhibitors has been accentuated. Experiments in the Program for Physics and Dynamics have shown that elemental sulfur is an effective smoldering inhibitor, and we are now studying the modes in which it works. Experiments to date have shown that sulfur in cotton batting eases ignitability under radiant flux and decreases the smoldering propagation rate and the smoldering front temperature. In addition, we are looking for sulfur-containing products, such as SO_2, H_2S, S_2 in the vapor phase or bound sulfur in the cotton residue. The concept of activity as a heat sink is also being pursued by comparison with other additives of comparable heat capacity. A report on likely retardance mechanims is in preparation and should lead to ways to maximize the desirable effects and to select similarly-acting alternative additives.

Polymer Volatilization

A powerful method for studying the degradation of polymer-inhibitor systems and the resulting flames is by molecular beam sampling directly into a quadrupole mass spectrometer. Studies have been carried out on retardant systems based on phosphorus, iron, molybdenum, antimony and halogen-containing species. Numerous radicals have been identified, many previously unobserved. Coordinated H-atom optical studies have shown that in different temperature regimes, phosphorus additives can either promote or reduce H atom formation. OH absorption studies are being pursued with the intent of comparing fuel-rich systems where H-atom processes are expected to dominate with fuel-lean systems where OH reactions are prevalent. Concurrently, the OH absorption, vibration and rotational Raman spectra of N_2 and O_2, and Na D-line reversal techniques are being compared as to their accuracy and applicability in measuring flame temperatures. The latter two produced temperature profiles for H_2-O_2-N_2 flames which are in good agreement. However, the Raman-derived profiles are more valuable, as they extend along the whole flame, including the reaction zone region, while the Na D-line method is limited to the post-flame region.

In addition, a new, high pressure sampling mass spectrometer apparatus is under construction. This will enable sampling of diffusion flames, flames at pressures up to 10 atm, and flames containing particulates.

Opto-Galvanic Spectroscopy of Flames

A joint effort within NBS has devised this laser-excitation technique in which atomic and molecular absorptions are detected by changes in flame conductivity rather than by changes in light intensity. The current objective is to explore its application to flame and combustion product analyses. To date, we have detected sodium atoms at the sub ppb level, as well as a number of other atomic species. We have also recently observed absorptions from molecular species of LaO, YO, ScO, SrOH and BaCl, in the process recording previously unreported transitions and some of the best metal oxide spectra ever reported. We now understand the opto-galvanic mechanism reasonably well and flame species temperature measurements are becoming feasible. A major application of this technique, currently in the infant state, is to examine the contribution of flame ionic processes to soot formation.

Associated Grants and Contracts

"Polymer Combustion and Flame Chemistry"
Robert F. Sawyer and Nancy J. Brown, University of California, Berkeley

"Ignition and Fire Spread of Cellulosic Materials"
Fred Shafizadeh, University of Montana

"Flame Suppression by Chemical Inhibitors"
James Chien and Marcel Vanpee, University of Massachusetts

"Polymer Flammability and Flame Inhibition"
Robert Fristrom and Lawrence Hunter, Johns Hopkins University Applied Physics Lab

"Kinetics Investigation of Flame Initiation and Propagation Reactions"
A. Ravishankara and Frank Tully, Georgia Institute of Technology

"Decision Analysis Studies: Transformer Fire Hazard Analysis"
Fred Offensend, SRI International

"NEMA Transformer PCB Replacement Study"
John Motherway, NEMA

PROGRAM FOR PHYSICS AND DYNAMICS
FIRE SCIENCE DIVISION
CENTER FOR FIRE RESEARCH

Professional Personnel

John A. Rockett, Chief
Howard R. Baum, Research Physicist
Margaret Harkleroad, Physicist
Takashi Kashiwagi, Material Engineer
Thomas G. K. Lee, Fire Protection Engineer
Bernard J. McCaffrey, Mechanical Engineer
Robert J. McCarter, Chemical Engineer
George W. Mulholland, Research Chemist
James G. Quintiere, Mechanical Engineer

The Program objectives are:

1. Growth and Spread of Room Fires: To predict the growth and spread of fire in a room or a set of simply interconnected rooms.

2. Mathematical Models: Develop advanced mathematical models for various flow phenomena in fires.

3. Ignition: To identify and quantify the phenomenon related to flaming ignition of solid and liquid fuels.

4. Smoke Characterization: To study smoke formation and to develop techniques for producing well characterized and reproducible aerosols.

5. Smoldering: To identify and quantify the phenomenon related to smoldering combustion of (porous) solid fuels and to devise means of quantifying the smolder tendency of materials.

Growth and Spread of Fire

The objective of this program is to improve predictions of fire behavior in a room. A steady state model which relates the potential for flashover in a room to its combustible contents and thermal and ventilation characteristics has been developed and compared to small scale experimental data. Predictions are qualitatively good; quantitative predictions range from fair to quite good. Data obtained for wood and high density polyurethane foam cribs will be compared with the model after inclusions, now in progress, of the effect of radiation from the crib to its surroundings, of flow entrainment by the crib, and of the effect of the hot vitiated layer sinking below the top of the crib. Transient terms will be added to the model using a simple but accurate heat flow model.

Experimental work begun by McCaffrey and Cox at the Fire Research Station, Borehamwood, England, on the near field entrainment of a diffusion flame will be continued. Results to date suggest significant differences between the measured plume quantities and predictions based on current (far field) models.

Full scale experiments just getting underway will provide more detail for model evaluation especially to check the overall flow prediction, secondary flows around the door (or window) and plume near field effects.

Mathematical Models

The objective of this program is to improve the capability and accuracy of fire models through the application of the most efficient mathematical techniques.

Three relatively separate activities have been pursued.

1. In most fire situations the Reynolds (or Grashof) number is large. This suggests that, as is true in other areas of high Reynolds number fluid flow analysis, an inviscid flow approximation should prove useful. Since, for strongly buoyant flows, the equations are quite non-linear, numerical methods are called for. A careful examination of several numerical schemes has been pursued with numerous cross comparisons with analytic solution of test problems to determine the accuracy and stability of the techniques as applied to this set of equations. When a satisfactory solution algorithm has been developed, the ability of the inviscid analysis to represent practical fire problems will be studied.

2. Containership operations allow below deck storage only of containers carrying no hazardous cargo. However, scheduling economics are strongly affected by the definition of hazardous. It has been proposed to the International Maritime Consulting Organization (IMCO) that the present limitations on below deck storage could be relaxed if forced hold ventilation were provided. To examine this, a procedure for calculating the in-hold flows and combustible vapor concentrations for various ventilation schemes and accident scenarios is being developed.

3. Jointly with the smoke characterization program, aerosol calculations have been developed.

Ignition

The purpose of this program is to identify and document the important phenomenon related to ignition. Work to date has concentrated on radiation assisted ignition - to flaming combustion - of solid and liquid fuels. Additional data on energy absorption by evolved gases in the convective plume above the ignition target has been obtained. The simplying concept of a material dependent characteristic surface temperature for ignition has been found to be satisfactory for PMMA (about 400 °C) but quite poor for red oak (variable from about 400 to 600 °C). Future work will concentrate on other important parameters such as surface orientation, size, pilot type and location.

Smoke Characterization

The objective of this program is to improve the accuracy and capability of smoke characterizing instruments and apply this to improving fire detection and fire analysis.

Techniques developed for generation of controlled, reproducible aerosols of known size distribution have been applied to smoke detector standardization and testing. A prototype portable tester suitable for evaluation of installed smoke detectors has been built and is being field tested. Aerosol generators have been designed for several other special applications related to environmental control.

An analytical model of smoke aging in the buoyant plume above a fire that has been developed. This will form a part of a larger study of detector siting and sensitivity now in progress.

Future work will focus more strongly on the mechanisms of smoke formation and the role of aerosol and particulates in flame radiation.

Smoldering

The objective of this program is to identify and quantify the phenomena related to smoldering combustion of (porous) solid fuels and to devise means of quantifying the smolder tendency of materials. Much of the recent effort has been directed at applied problems.

During the past year the emphasis of this program has shifted from upholstery materials to blown cellulose insulation. It was demonstrated that some flame retarded insulation would smolder readily and, in the presence of a slight draft, could ignite the timbers of a residential attic. A smoldering test for insulation was developed. It was found that the amount of inhibitor needed to pass the proposed smoldering and flaming tests was quite sensitive to the particular cellulose fiber and method of blending the inhibitor with the fiber. This process variability suggests the need for an inexpensive quality control test. Current work is directed at this.

Associated Grants & Contracts

1. "An Investigation of Fire Impingement on a Horizontal Ceiling," G. M. Faeth, Pennsylvania State University.

2. "Fire and Smoke Spread," K. T. Yang, Notre Dame University.

3. "Thermal Radiation of Luminous Flames and Smoke," C. Tien, University of California/Berkeley.

4. "Investigation of Properties of the Combustion Products Generated by Building Fires," B. T. Zinn, Georgia Institute of Technology.

5. "A Proposal to Conduct Experimental Studies on Pyrolysis Aerosols and Fire Detectors," R. Chuan, Brunswick Corporation.

6. "An Experimental Investigation of Flame Spread Over Condensed Combustibles: Gas Phase Interactions," F. Dryer, R. Santoro, Princeton University.

7. "Fire Modeling," P. Pagni, University of California/Berkeley.

8. "Experimental Study of Environmental and Heat Transfer in a Room Fire," E. E. Zukoski, California Institute of Technology.

9. "Studies of Flame Extinction in Relationship to Fire Suppression," F. J. Williams, University of California/San Diego.

10. "The Home Fire Project", H. W. Emmons, Harvard University, R. Friedman, Factory Mutual Research Corporation.

11. "Smoldering Combustion Studies," I. Glassman, Princeton University.

12. "Flame Propagation and Extinction for Solid Fuels," M. Sibulkin, Brown University.

PROGRAM FOR TOXICOLOGY OF COMBUSTION PRODUCTS
FIRE SCIENCE DIVISION
CENTER FOR FIRE RESEARCH

Professional Staff

Merritt Birky, Chief
Maya Paabo, Research Chemist
Barbara Levin, Research Biologist
James Brown, Research Chemist
Susan Womble, Chemist
Dolores Malek, Guest Worker/JHU
Alan Stolte, Student Trainee

The goal of the Program for Toxicology of Combustion Products is to reduce the human loss which results from the inhalation of toxic combustion products of fires. In support of this goal, the program is divided into 4 major activities:

1. the development of a test method for the identification of materials that produce "unusually" toxic combustion products,

2. identification of specific toxic species in a fire environment,

3. identification of materials that contribute to human losses and

4. identification of toxic degradation products of polyvinyl chloride.

Test Method Development

A test method for the identification of materials that produce unusually toxic combustion products has been drafted. The proposed test procedure involves determining the LC_{50} (concentration of products that lead to 50% of animal population being killed) and the EC_{50}. The EC_{50} concentration is based on 50% of the animals losing the avoidance response as determined by the hind-leg flexure paradigm.

The test procedure requires the determination of COHb at the time of incapacitation on 2 of the 6 rats that are exposed during each test. Atmospheric carbon monoxide, oxygen, carbon dioxide and temperature measurements are also required.

After the test procedure was drafted, a group of experts representing various disciplines from industry, academia and government agencies was called together to review and critique the method. This committee has met 5 times and made a number of changes in the procedure. The committee is presently involved in developing an interlaboratory evaluation of the test method.

The purpose of exposing the development of this test method for comment prior to experimental verification was to provide the opportunity for a broader involvement of those interested in toxicity test method development. A second reason was to get the involvement of more experts into this area of fire problems.

Selected Toxicant Analysis

In the NBS toxicity laboratory, certain other toxicants are also measured in the test procedure. For example, environmental levels of HCN and HCl are measured when those materials that produce these toxicants are studied. A rapid gas chromatographic method that utilizes a detector highly specific for N-compounds is used for environmental measurement of HCN. The ion-selective electrode technique is used for monitoring HCl.

When environmental levels of HCN are greater than about 50 ppm, blood cyanide is also determined. The need for this measurement was based on the human fatality study that indicated elevated blood cyanide levels in a significant percentage of the human fire victims. Research is still in progress on a new blood HCN measurement technique to establish its accuracy, reliability and utility.

Material Identification

Analysis of materials involved in fatal fires is being carried out on a regular basis. The major thrust of this activity is the generic classification of these materials by infrared spectroscopy. However, when warranted, x-ray fluorescence can also be used to identify the presence of elements commonly found in fire retardant chemicals in these polymeric systems.

We have developed extensive experience in the identification of polymeric materials and offer this service to a variety of interested parties.

Poly(vinylchloride) Study

Toxicity studies on PVC decomposition indicated that hydrogen chloride did not explain the entire toxicity problem. In addition, various reports implicated phosgene as a possible toxicant during the thermal degradation of PVC. As a result of these factors, a study was undertaken to determine if phosgene is produced during the thermal degradation of PVC.

Three types of experiments were planned:

1. thermally degrading PVC in a small furnace in a chamber,

2. electrical over-loading of wire with PVC insulation in a chamber and

3. electrical arcing between wires coated with PVC.

The first 2 experiments have been performed. Phosgene has been identified in both experiments. Analysis of this data is in progress so as to assess its toxicological significance. The experiment involving an electrical arc has not been completed.

Associated Grants

"Fire Casualty Studies"
Walter Berl, Johns Hopkins University, Applied Physics Laboratory

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

"Evaluation of Toxicity of Combustion Products"
Zoltan Annau, Johns Hopkins University

"Toxicological Evaluation of Material Combustion Products"
G. Hartzell, W. Galster, M. Hughes, University of Utah

"Evaluation of the Combustion Toxicology of Several Polymeric Materials"
J. Wesley Clayton, University of Arizona

PRODUCT FLAMMABILITY PROGRAM
FIRE SAFETY ENGINEERING DIVISION
CENTER FOR FIRE RESEARCH

Professional Staff

James H. Winger, Chief
Emil Braun, Physicist
John Krasny, Textile Technologist
Joseph Loftus, Research Chemist
Richard Peacock, Chemical Engineer
Lee Smith, Physicist
Bill Hibbard, Research Associate
Rita Perkins, Research Associate

The objective of the Program is to develop and apply technology to reduce fire losses associated with the use of products by working through regulatory agencies and voluntary standards and codes.

Mine Fire Safety

The objective is to develop effective test methods, standards, and operating procedures to reduce fire losses in underground coal mines. The accident data have been reviewed and analyzed and fire scenarios developed for several products and systems. The existing fire tests for hydraulic fluids and conveyor belts have been reviewed, and appropriate tests are under development. Review of fire tests for electrical cables has started. Future items to be reviewed include brattice cloth, explosion containment, hoses, intrinsic safety, etc. A recommended procedure and supporting documentation will be prepared for each product area and submitted to the mine Safety and Health Administration.

Fuelwood Fire Safety

The objective is to develop methods and procedures to assume adequate fire safety when wood is used as a fuel in residences and small industries. The literature, model codes, and tests for the fire safety of wood burning appliances have been reviewed, and a report is in preparation. An experimental program will be planned and conducted based on the review. Recommended code changes and test procedures will be provided to the Department of Energy and the model codes organizations.

Textiles

The objective is to reduce fire losses due to the ignition and burning of textile products. A standard for cigarette ignition of upholstered furniture has been recommended to the Consumer Product Safety Commission (CPSC). Technical support is being provided to the CPSC staff as documentation is prepared to support a decision by the CPSC Commissioners.

A new standard for the flammability of general apparel has been recommended to the Consumer Product Safety Commission. Technical support is being provided to the CPSC staff.

A standard for the flammability of flight crew uniforms has been recommended to the Federal Aviation Administration (FAA). Technical support is being provided to the FAA as they prepare a proposed rule.

The capabilities for apparel fabrics to provide some protection from an existing fire is under investigation. Various test concepts and procedures are under evaluation as well as the performance of various fabrics in these procedures.

The effect of small quantities of gasoline on the flammability of different apparel fabrics is under investigation. The amount of wetting, evaporation, and ultimately, the ignition characteristics, are being measured.

Associated Grant

"Flammability and Combustion Behavior of Textiles"
B. Miller, Textile Research Institute

FURNISHINGS FLAMMABILITY PROGRAM
FIRE SAFETY ENGINEERING DIVISION
CENTER FOR FIRE RESEARCH

Professional Personnel

Sanford Davis, Chief
Vytenis Babrauskas, Fire Protection Engineer
David D. Evans, Mechanical Engineer

The primary goals of the Furnishings Flammability Program are to assess the hazards of furnishings and building contents involved in fires and to provide the methodology for predicting these hazards based on small-scale laboratory tests and analytical models. A number of projects are in progress relating to interior furnishing products and their impact on the environment during a fire. As a consequence of the floor covering work over the past years, a similar approach has been evaluated for attic floor insulation, primarily used for retrofit applications. The people movers project relates to past transportation vehicle programs and their kinship to the room fire problems.

1. Institutional Mattress Fire Hazard Test Development

Last year a series of full-scale room burn results were reported for institutional mattresses. These data have served as a basis for developing bench-scale test procedures. The goal for this project is to develop a performance standard based on laboratory test procedures that will provide specifiers the assurance that mattresses exposed to flaming ignition sources will not create intolerable conditions. Bench scale tests being considered include rate of heat release, smoke development, calorific value, flame spread, and ease of ignition.

2. Burn Room Sensitivity Study

Analysis of room burn test data and subsequent design use are often hampered by the lack of closed-form, approximate expressions for the effects of different variables. This problem is especially evident in that time-to-flashover, which is a most important hazard indicator, currently cannot be estimated. A set of approximate functional relationships are needed that would enable time-to-flashover and other fire variables to be predicted, knowing fuel, room, and geometric conditions.

To this end, a series of test burns and numerical simulations will be conducted using a simulated pool fire; a pool fire represents the simplest quantifiable fuel arrangement. The experimental facility for this project has been prepared and the experimental work is under way.

3. Parsons Table Fire Hazard Evaluation

The data from a series of eighteen room fires, each involving a single plastic Parsons table as the only combustible item of furniture, were studied in an effort to assess the hazards of these products and to find correlations between the results from small laboratory and large room fire tests for the different table materials tested. Very good predictions of the total amount of smoke produced by the burning tables were made using smoke chamber measurements of the mass optical density (MOD) for the table materials. A report on the analysis will be available soon.

4. Television Receivers

A study to characterize ignition sources within a television receiver has been initiated. A detailed study of the circuitry of four television receivers has been made to select specific failures that could produce overheating of components and possible ignition of combustibles within the receivers. Auxiliary measurements to characterize the ignition source burner specified in the Underwriters' Laboratory (UL) 1410 standard for television receivers and video products have been performed. The results of this study will help to assess the adequacy of the voluntary standard and determine the need for a mandatory standard.

5. Automated Fixed Guideway Vehicles

The fire safety aspects of mass transportation vehicles used in fixed guideway systems had not been vigorously studied. The purpose of this project is to explore and formulate the fire safety guidelines to be required for automated vehicles used for the movement of people in congested urban areas. The results of this effort are needed to set reasonable requirements on the systems to be deployed in several cities under the Urban Mass Transportation Administration's "Downtown People Mover" (DPM) program. By reviewing existing systems similar to those that are expected to be used in the DPM program, scenarios have been formulated in order to establish the minimum levels of fire safety of the vehicles for several types of DPM systems. In addition to the materials and methods of construction, the interior finish materials, the means of fire detection and suppression, size of vehicles, accessibility, and operational environment are being considered for preparing these fire safety guidelines.

6. Cellulosic Loose Fill Insulation

An interlaboratory program has been conducted to evaluate the reproducibility of the attic floor radiant panel test and the smoldering combustion test which have been required in Federal Standard HH-I-515D for cellulosic insulation. Six independent commercial laboratories and five government laboratories have participated in the evaluation of seven cellulosic thermal insulation materials. This project builds on the information developed in the Construction Materials Program and will provide the necessary back-up information for a mandatory standard recently enacted by Congress for this type of product.

CONSTRUCTION MATERIALS PROGRAM
FIRE SAFETY ENGINEERING DIVISION
CENTER FOR FIRE RESEARCH

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The overall goal of this Program is to improve the probability of preventing the growth and spread of a fire and its combustion products by developing fire test methods and acceptance criteria for construction design and materials.

Fire Test Standards

The objective is to develop laboratory fire test methods for evaluating the potential fire hazards of construction materials. The fire properties of concern are ignitability, heat release rate, flame spread, and smoke. The approach is to participate actively in the American Society for Testing and Materials, National Fire Protection Association, International Standards Organization, Conseil International Du Batiment, and government-wide committees, to develop appropriate fire test methods and standards, to perform testing, analysis and round robin coordination of such tests, to make recommendations for performance standards and test criteria, and to relate building fire standards to actual building fire performance.

A new heat release rate calorimeter has been constructed for research studies on heat release rate. This instrument is capable of measuring the simultaneous heat and mass loss rates of vertical specimens 12 x 12 inches and horizontal specimens 6 x 12 inches at radiant fluxes up to

8 watts per square centimeter. A new flame spread test is being developed for studying lateral flame spread on a vertical surface as a function of the material's surface temperature and of the velocity, temperature and oxygen content of the air flowing across the material surface. A report has been completed on an ease of ignition test by flame impingement. This will be submitted as a standard test for ignitability of interior finish materials. A report has been published on an investigation of the fire environment in the ASTM E-84 Tunnel Test (NBS Technical Note 945, August 1977).

Fire Spread and Growth

The objective is to evaluate the potential for fire spread and growth in various occupancies in terms of the materials of construction, the combustible contents, the building design and the probable ignition sources. The approach consists of (a) developing analytical models of fire growth based on heat and mass balance considerations which take into account the spread of flame over the combustible interior finish materials and their heat release rates, (b) running full-scale fire tests for validation of these models, and (c) conducting reduced scale fire tests, which permit verification of the model for many more combinations of parameters at considerable savings in time and money.

The work includes a cooperative effort between CFR and the National Research Council of Canada on the E-84 Tunnel Test. In order to establish the most realistic method of running and reporting on the tests of cellular plastics, a set of materials with a large range of flame spread was tested in three different configurations in the tunnel, in full-scale and reduced-scale rooms and corners, and in various laboratory fire tests. Data analysis is continuing and a report will be prepared.

Structural Fire Endurance

The objective is to predict the fire endurance of structural building components under typical fire exposure conditions using thermal and structural analysis. The predictions will be verified with full-scale tests. The basic analytical approach is to combine thermal analysis and structural analysis programs which include elasto-plastic material properties, creep in concrete and steel, and local failures. Improved basic data on concrete creep at elevated temperatures is being obtained, as well as experimental data on thermal restraint due to expansion of fire-exposed concrete floors and roofs.

Fire Endurance of Floor Constructions

The objective is to develop a test procedure for evaluating the structural fire resistance of floor assemblies in residences and to recommend rational performance criteria for protected and unprotected load-bearing components. The approach is to conduct full-scale fire tests in a simulated basement recreation room using modern furniture with a typical fire load for that type of room. A series of 16 tests with varying room size, interior finish, and ventilation conditions has been completed. The fire was started with a newspaper placed on a couch with polyurethane cushions. The temperatures, heat fluxes and pressures recorded during those tests will form the basis of the new test procedure. A standard set of conditions has been selected and a series of room fire tests has begun on seven different floor constructions including cases with exposed floor joists. Finally, the time-temperature curve and the pressures will be duplicated in a gas-fired endurance furnace using the same types of floor constructions. An analytical prediction capability for fire growth is being developed along with the experimental testing.

Fire Safety in Mobile Homes

The objective is to document the effect of interior finish materials on fire growth and spread and on the attainment of untenable conditions in mobile homes. A rational basis for regulating these materials will be developed. The approach is to conduct full-scale fire tests on single-wide mobile homes using upholstered chairs and 14 lb. wood cribs as ignition sources in various areas of the mobile home. The chair is a realistic source of ignition which will not lead to full involvement of the mobile home in the absence of combustible interior finish. The wood crib provides a relatively reproducible ignition source of smaller size for comparison of different interior finish materials. Temperatures, heat fluxes, smoke densities, and gas concentrations are monitored throughout the mobile home. The interior finish materials are characterized by their E-84 tunnel rating, heat release rate, time to ignition in the ease of ignition test, and the smoke density in the NBS Smoke Density Chamber.

Reports on testing conducted in the corridor and kitchen areas have already been published. In addition, reports on testing conducted in the living room and bedroom areas, a report on ignition source characterization, and a summary report containing recommendations based on all of the testing conducted for the project, are in preparation. During the next stage of the work an attempt will be made to duplicate the essential features of the full-scale test results using reduced scale modeling. This will then be followed by an attempt to deduce the results by analytical prediction techniques.

Shipboard Fire Research

The objective of this project is to evaluate the potential fire hazard of ship hull insulations and to improve the application of laboratory fire tests for screening compartment lining materials. The approach is to subject the variety of ship 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 maximum temperature in the full size 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 tests, the usefulness of the quarter-scale model as a screening tool can be evaluated. At the same time analytical and experimental studies are used to improve the ability of the quarter-scale model to predict full-scale fire behavior.

Evaluation of Fire Loads in Residences

The objective is to provide fire and live-load data for single-family dwellings and mobile homes in order to provide a basis for establishing standard fire exposures for structural fire endurance tests. The approach involved a survey of fire loads in residences using inventorying techniques. A pilot survey of 359 dwellings (61 attached, 200 detached, 98 mobile homes) was made in the Washington metropolitan area. The assembled data will provide the fire load input to analytical models for fire growth and severity which will generate fire exposure curves for residences and mobile homes. The work has been completed.

Fire Tests of Marine Construction

The objective is to furnish technical data on a flame spread test method under consideration as an international standard on marine construction and to make recommendations for improvements in the test method and its application. Studies are being made of (a) the method of securing and positioning specimens, (b) the incident heat flux distribution, (c) a suitable pilot burner for igniting the sample, and (d) the effect of air cross flow on test variability. Samples of several materials are being tested and the results are being analyzed to evaluate the performance under various modifications of the existing method. The specimen can be run in either a floor, wall or ceiling orientation. Materials run in the room fire tests will also be evaluated with this test method in order to establish its validity.

Fire Criteria for Solar Heating Fluid

The objective is to provide a technical basis for specifying the flammability standards for the heat transfer fluids used in solar heating systems. The approach was to perform fire tests of representative combustible heat transfer fluids in simulated accident scenarios involving floor spills and flowing leaks in a room and to conduct fire tests of spray leaks and of insulation soaked with these fluids. The fluid temperatures at which the fluids begin to flash when they are exposed to a pilot flame, the rates of surface flame spread, and the times to reach complete room fire involvement were compared with the flash points of the fluids, as measured with the Pensky-Martens closed cup test. By performing the above analysis, the suitability of using flash point temperature as an indicator of fire risk was established.

Fire Hazards of Insulation in Residential Occupancies

The objectives of this project are: 1) to identify and determine the magnitude of the various fire risks associated with the use of particular types of insulation, 2) to recommend, and develop where necessary, the laboratory fire tests needed to characterize insulation materials with respect to these risks and to control their use for insulation retrofit, 3) to provide the necessary data on the fire and thermal properties for generic types of insulation considered for use in basements, wall cavities in attics of buildings, and 4) to recommend acceptance criteria suitable for adoption in the building codes.

A review of the available fire statistics indicated that a serious hazard exists with recessed light fixtures covered with insulation. Though most such fires involved cellulosic insulation, mineral wool and fiber glass insulations have also been involved. Reduced scale model tests, based on the scaling rules developed at NBS, will be run with various insulation materials to verify the important fire scenarios. The models tested will include 1) the simulated basement with exposed insulation, 2) an above grade room with insulation in the wall cavities and in the space above the ceiling, and 3) an attic space with exposed insulation. These tests will determine the effect of the insulation on 1) the maximum fire intensity (as measured by air temperature rise), 2) the time to full involvement of the space, if it occurs, and 3) the rate of production of the smoke and toxic gas. The role of the insulation as a site for flaming and smoldering ignition will be examined in these models. Important findings will be verified by full-scale tests. A radiant panel test for flame spread and a cigarette test for smoldering ignition have been developed for updating the General Services Administration (GSA) standards for thermal insulation. Experiments are being run on the smoldering characteristics of loose fill cellulosic insulation as a function of retardant concentration as a basis for improving the proposed standard test for smoldering. The settling and moisture absorption of the insulation and the leeching of the flame retardant chemicals will be investigated for loose fill insulation.

Associated Grants and Contract(s)

"Fire Growth Experiments - Toward a Standard Room Fire Test"
Robert Brady Williamson, University of California at Berkeley

"Effect of Retardants on the Heat Release Rate of Building Materials"
Stanley B. Martin, Stanford Research Institute

"Short Term Creep Tests at Elevated Temperatures"
Melvin S. Abrams, Portland Cement Association

"Simulation of Realistic Thermal Restraint During Fire Tests of Floor and Roof Assemblies - Phase III-V"
Melvin S. Abrams, Portland Cement Association

"Measurement of Air Flow Around Doors Under Standardized Fire Test Conditions"

Abdur Abbasi, Underwriters Laboratories, Inc.

FIRE DETECTION AND CONTROL SYSTEMS PROGRAM
FIRE SAFETY ENGINEERING DIVISION
CENTER FOR FIRE RESEARCH

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In the event of a fire, certain fire protection systems are relied upon to: 1) alert the occupants prior to the attainment of conditions adverse to human safety, and 2) to actively prohibit or reduce the growth and spread of the fire and combustion products. The overall objective of this Program is to provide research and engineering technology for such systems. To this end the Program is divided into three areas of concentration; automatic fire detection, automatic fire suppression, and smoke control.

Specific aspects such as engineering design, installation, performance and reliability requirements are being studied for these fire protection systems in pursuit of overall design technology and appropriate test methods upon which to judge system capabilities. In addition, the development of design criteria and installation guidelines leading to subsequent reductions in costs plays a key role in the development of this technology.

Automatic Fire Detection

Considerable research is ongoing in this program to identify the key parameters and conditions which must be considered when measuring the performance of detection devices. Extensive full-scale and laboratory testing is being utilized as the basis for the identification process and will be extended to support Program efforts to develop standard tests for measuring detector performance. Current activities also include studies on the arousal potential of state-of-the-art detector alarms and the reliability of detector components and systems. Much of the technology developed in this program is inputed directly to U.S. and international standards groups for automatic detection.

Fire Detection in Health Care Facilities

This project is designed to provide data and ultimately guidance on means of optimizing detection system performance in health care facilities. Full-scale tests have been conducted in a simulated health care environment to provide data on performance of detectors under actual fire conditions. Field data is being collected and analyzed to assess the performance of detection systems currently being used in typical health care facilities. A significant output from this project has been the development of a portable aerosol generator for use as a field tester for installed detectors. A report, NBSIR 78-1480, "An Instrument to Evaluate Installed Smoke Detectors", by T. G. Lee has been published. A prototype is currently being field tested.

Smoke Detector Performance in Mobile Homes

An initial phase of this work, including full-scale detector siting tests in an actual single-wide mobile home, has been completed. A report, NBSIR 76-1016, "Mobile Home Smoke Detector Siting Study", by W. M. Gawin and R. G. Bright has been published. The results of this initial work provided the basis for further experimental work in this area. Additional full-scale testing is now being conducted to examine the effects of key environmental conditions including air movement from both the heating and air conditioning systems and the outside ambient conditions during winter and summer periods.

Test Method Development

The development of a uniform and comparative test method for all types of automatic fire detectors is ongoing. The project is separated into two areas of interest: 1) the development of environmental stress tests, and 2) the development of a full-scale test protocol. The first area is planned for future investigation while the bulk of the emphasis to date and in the near future will be the development of a full-scale fire test protocol. Current test methods have been evaluated and a determination has been made of the most suitable approach to be used in developing the test. A full-scale test facility, based on this approach which is similar to the proposed International Standards Organization (ISO) full-scale test protocol, has been constructed and experiments are being conducted.

Automatic Fire Suppression

A great demand exists for technology advancement for automatic fire suppression systems. Efforts in this area have been directed toward full-scale performance testing under varying conditions and exposure fires. Initial work in this area included an experimental study to develop design criteria for the use of automatic sprinklers for the protection of corridors from fires beginning in adjacent rooms with open doorways for multi-family and care-type facilities. Work has also been done to develop water distribution mapping techniques, factors affecting the geometric distribution of water from sprinklers, statistical parameters of water droplet populations from sprinklers as a function of pressure and deflector design, and the use of sprinklers in health care facilities.

In addition to this long range work, continuous efforts are made to assist in the development of U.S. and international standards for automatic sprinkler systems and components. This work has included analysis of water distribution patterns, K-factor (coefficient related to orifice pressure and flow rate) measurement techniques, and mechanical safety factors applied to sprinkler devices.

Fire Tests of Patient Rooms with Automatic Sprinklers

The objective of this study is to provide engineering design information on health care facilities incorporating automatic sprinklers. The effectiveness of sprinklers is being measured in terms of overall fire control, time available for evacuation, and the maintenance of tenable conditions for patients who cannot be evacuated. Current nationally used fire safety design criteria for health care facilities are being specifically examined from the viewpoints of life safety of the occupants and cost efficiency of system designs.

Phase I tests were conducted between August and November 1977 and a draft report of these tests is currently in NBS review. This phase of the test series developed important information on the movement and concentration of selected combustion gases throughout the test space.

Phase II tests, scheduled for completion in 1978, will examine variations in water flow rates and nozzle pressures of sprinklers. Improved techniques will be utilized to measure smoke movement and concentration in a corridor adjacent to the room of fire origin.

Sprinkler Protection of Open Stairways

The objective of this study is to develop engineering design information for alternative methods of protecting open stairways using sprinkler and spray nozzle systems. This work is designed to refine and update test results dating back to the 1940's which serve as the basis for methods currently used in the National Fire Protection Association (NFPA) sprinkler and life safety codes. A propane burner serves as the energy source and currently is operated at two heat release rates, 5.5 and 13.6M Btu/hr (≈ 1500 and 4000 KW). Performance curves will be developed for these systems to indicate their capacity to inhibit passage of combustion gases into the stairway resulting from the convective heat flow from the burner. In addition, design information for these systems will be developed. Experimental full-scale testing to be conducted in a specially constructed four story facility is scheduled for completion in 1978.

In support of this work a report has been drafted on the State-of-the-Art of Sprinkler and Spray Nozzle Systems for Protection of Openings in Fire Resistive Assemblies, and is in NBS review.

Smoke Control Systems

The smoke control project has been in operation for a number of years. During that time the work has developed along two parallel and now converging directions. Initially work was done with simple computer modeling of smoke movement in buildings. This effort builds upon the work of the National Research Council of Canada and others. At the same time field tests were conducted in actual office, apartment and hospital buildings using sulfur-hexafluoride tracer gas to study the movement of simulated smoke under a variety of mechanical systems and climatic conditions. Included in the field work were several studies of buildings equipped with smoke control systems. In each case the building was evaluated both with and without the smoke control system in operation. This allowed for comparison of the relative effectiveness of the systems compared to a building without any smoke control. More recently, the output from the field survey program has been combined with a sophisticated computer program designed to predict the movement of air in a building as influenced by an air handling system. The result has been the generation of a computer-based design methodology for smoke control.

Work has also been done to compare the results of sulfur-hexafluoride smoke movement studies to actual movement of smoke in dwellings. This work showed substantial correlation between the simulated smoke and real smoke. Future work will involve the development of smoke control methodologies for residential application.

The primary output mechanisms for the results of this research is through additions or changes to various voluntary standards including NFPA and the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standards.

Field Investigations

Field tests have been conducted using the sulfur-hexafluoride (SF_6) tracer gas technique to determine smoke flow patterns in various types of occupancies, including office, apartment and health care facilities. The most recent investigation was conducted in the NIH Clinical Center in Bethesda, MD, in which both winter and summer conditions were tested. The objective of these tests was to gain understanding of smoke flow in buildings under normal operations, and under operation of the smoke control systems. A draft report is in NBS review.

Smoke Movement in Merchant Ships

This project will extend the use of the SF_6 technique to study the smoke flow patterns aboard a merchant marine ship in order to provide recommended guidelines for smoke control in such vessels. The project is currently in the planning stage.

Computer Modeling of Smoke

Two computer programs designed to model smoke movement in buildings have been developed under contract to Integrated Systems Incorporated (ISI). One of the programs, designed to evaluate steady-state conditions, has been verified by field test results. Verification of the unsteady-state model is currently being pursued. 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.

Associated Contracts

"Reliability Modeling of Smoke Detectors"
H. D. Rickers, IIT Research Institute, Reliability Analysis Center, Chicago, IL

"Development of an Air Movement Simulation Program"
John Fothergill, Integrated Systems, Inc., Brunswick, MD

"Continued Development, Testing, Evaluation, and Application of Computer Simulation Technology for Smoke Movement Control"
John Fothergill, Integrated Systems, Inc., Brunswick, MD

PROGRAM FOR DESIGN CONCEPTS
FIRE SAFETY ENGINEERING DIVISION
CENTER FOR FIRE RESEARCH

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Program Objectives

The objectives of the Program are to synthesize and integrate research and technology to develop technically based rational approaches towards 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.

Research Approach

The world of technology and its uses can be divided into three basic elements areas: data, models and use. The work of this Program is formed around these divisions.

Data

Scientific and empirical data are being compiled in the research community. The data ranges from physical properties such as calorific value, density, rate of heat release, and critical radiant flux to empirical values such as detection time, flame spread ratings, and sprinkler discharge capabilities. All of these involve one or more types of basic reproducible tests directed at producing data either for handbook reference or other descriptive literature. Major efforts in this program are directed at producing missing data elements particularly in areas related to detection, automatic extinguishment, and human behavior and capabilities under fire stress.

Models

Models and systems are used by scientists or engineers to explain the inter-relationship of two or more data elements. These can range from simple formulas to complex inter-relationships. The Program has undertaken modeling efforts. Significant success and spillover has been achieved in advancing the interest and activities of the entire scientific fire research community in this area.

Use

"Use systems" are those systems which are now used or can be used to govern and measure the real world. Were the technology and description of the real world perfected to an advanced level of understanding and predictability, the models developed by the scientists and research engineers could fulfill this function. The real world, however, is not that well described or completely understood and the practitioners must produce answers at a rate that demands relatively simple but sufficiently accurate approaches. Various types of use systems, therefore, govern the real world.

Use systems are frequently in the form of codes, standards, and evaluation systems. There is currently no method for a direct crosswalk from scientific data and models to the use system. In each case judgment of how the technological data fits into the real world is involved. In current practice the difficulty in crossing this gap has resulted in the development of existing use systems that ignore technical bases and presume that a parliamentary concensus equates to technical accuracy.

The data and model development activities are directed at producing technologically sound outputs that will be more responsive to the needs of the use systems. Simultaneously the project aims at further reducing this gap by developing use systems that are more accountable to the technological base and receptive to improved data. Professional judgment and concensus will remain a major portion of the developments of use systems for the foreseeable future. Major improvements can, however, be made in the quality and accountability of these judgment and concensus activities. The end result will be both improved approaches that are more readily evaluated and accepted as rational; and a compendium of design measurements and parameters that will permit wider flexibility in the individual designs, with traceable consistency of the technological basis, the performance requirements, and the approaches from jurisdiction to jurisdiction.

MAJOR PROJECT AREAS

Life/Fire Safety Program for Health Care Facilities

The objectives of the Fire/Life Safety Program are to develop technically based rational approaches towards providing safety from fire in health care facilities; and to provide an operating mechanism for using these approachs. The mechanisms are to be usable by those expected to apply them, acceptable to both the federal and nonfederal authorities, and credible in terms of a link to applied engineering and science techniques.

The program is targeted towards the needs of federal agencies, voluntary standards organizations, state and local regulatory authorities, practicing architects and engineers, facility operators and health care providers. The program outputs will include management tools for setting approved fire safety requirements and technical data and design guides for architects, fire protection engineers and others involved in the process of design. Cost-effectiveness will be considered in the development of these management tools. Other project outputs will be recommendations for changes in existing fire safety codes and other regulatory standards as well as advances in the state-of-the-art of applied fire protection engineering and fire technology.

The program is of 5 years duration. Over 3 years of this period have been completed. Some significant accomplishments undertaken under the auspices of this program include:

A. The development of a fire safety evaluation system for grading the equivalency of alternative approaches to fire safety and health care facilities.

B. The funding of the initial development of RFIRES, a fire development model prepared by R. Pape, IIT Research Institute.

C. The funding of several separate studies aimed at the advancement of understanding and use of probabilistic approaches to fire safety systems.

D. The development of a cost comparison model for determining cost effective alternative approaches to fire safety in health care facilities.

E. Development of a simulation model of emergency movement by occupant of buildings during fire exposure.

F. The collection and publication of data and concepts on emergency decisions made by hospital staff personnel and others exposed to fire threat.

G. Participation in and the support of significant test and research activities in detection, extinguishment, and the development of smoke control models and design tools.

A number of intermediate research programs are still underway in this program. The data, however, is now being assembled towards the organization and preparation of a final report. In addition to summarizing the data produced, an attempt will be made to assemble the material in a comprehensive, logical guide for those involved in making fire safety, regulatory, or related design decisions. Future work is visualized as extending the present ongoing research with particular emphasis on the resolution of design problems related to the individual subsystems and elements of health care facilities.

Life/Fire Safety Program (Group Homes for the Developmentally Disabled)

A recent development in the care of the mentally retarded (and other developmentally disabled persons) is to provide their custodial care in small home-like facilities in the community rather than in large remote institutions. Fire/life 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 National Fire Protection Association's (NFPA) Life Safety Code standards for: 1, private homes; 2, boarding houses, and 3, hospitals. Whenever the hospital standards are applied, the cost becomes prohibitive. It is also very difficult to obtain the desired home-like atmosphere and the facility does not blend into the community. The objective of this project is to develop fire/life safety performance criteria for these group homes.

This is a 39 month project starting in July 1977. 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. The fire protection requirements will depend, in part, on the level of capabilities of the residents. The criteria will be developed with the advice of experts throughout the country.

A preliminary version of the system will be developed in the summer and early fall of 1978. Review and testing of the system will start in the fall of 1978 and the system will be modified as needed based on the field tests and the comments of the reviewers.

Means of Egress Study

The objectives are to establish a data base after surveying the existing state-of-the-art, to provide a technical basis for hazard assessment approaches and to determine specific engineering solutions important to yielding emergency escape criteria for means of egress arrangements. The effort includes an assessment of the literature state-of-the-art on the human factors relating to emergency egress in buildings and a review and analysis of the current state of technology theories and test data involved in the growth of fire, controlling factors, and the speed and distribution of effects that interfere with or terminate the ability to escape from fire. Physical experiments will be conducted to evaluate the effectiveness of water spray and/or draft arrangements to protect open stairwells and similar open floor penetrations, along with the development of procedures to determine the smoke restricting capability of various qualities of stairwell doors.

The program is a 2 year study now in its second year. The initial literature analysis of emergency egress has been completed and a report entitled "A Critical Assessment of the Technical Literature on Emergency Egress From Buildings" has been written. Tests are in process on a full size open stairwell test facility at NBS and tests have been initiated in cooperation with Underwriters' Laboratories to evaluate a shroud method (International Standards Organization approach) for using the standard door furnace in a positive mode to determine leakage rate through fire doors during the course of fire exposure.

Significant gathering of the necessary data and classification and sorting of the literature related to fire development and spread has been completed. A preliminary computer sort using state transitions/state condition sorting matrix has been completed. The major remaining effort of the project consists of completing the experimental work and the analysis and organization of the data into a coherent form suitable to assist in the evaluation of the impact of structural and occupancy condition on the risk to occupants.

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 will be designed to evaluate the equivalency of alternative fires safety approaches as compared to the normal requirements of the Department of Housing and Urban Development minimum property standards.

The project is of 18 months duration and has just been initiated. The evaluation system will be based on the relevance of the various elements of building design to the performance objectives of fire safety (e.g.; prevention of ignition, litigation of fire development capability, confinement of fire, detection and extinguishment, and escape and rescue). The objective is a working tool as an alternative to the existing explicit requirements.

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 is scheduled for 1 and 1/2 years' duration and has just been initiated.

Extra-Program Activities

A major portion of the activities of the Program for Design Concepts is conducted by other elements within the Center for Fire Research (CFR), other groups within the National Bureau of Standards, and contractors and grantees external to NBS. These include:

A. Fire Detection and Control Systems Program, CFR

1. "Performance Approaches to Protection of Vertical Openings in Buildings."

2. "The Role of Detectors in Health Care Facilities."

3. "Analysis of Field Performance of Detectors in Health Care Facilities."

4. "Report of Performance of Detectors in Full Scale Tests in Simulated Health Care Facilities."

5. "Analysis of Spray Patterns of Sprinkler Heads."

6. "Analysis of the Impact of Sprinklers in Health Care Facility Bedroom Fires."

7. "Smoke Control Model."

8. "Smoke Control Selection Guide."

9. "Application of Smoke Control Model to Elements of the NIH Clinical Center."

B. Construction Materials and Assemblies Program, CFR.

1. "Performance of Fire Doors as Smoke Barriers."

C. Center for Building Technology, NBS.

1. "Simulation of Human Behavior in Fires, a Computer Model," Fred I. Stahl.

2. "Communication for Fire Safety in Buildings," Aurther Rubin and Robert Glass.

3. "System for Cost Comparison of Fire Safety Alternatives," Robert Chapman.

4. "The Evacuation of Nonambulatory Patients From Hospitals and Nursing Home Fires," John Archea.

D. Center for Consumer Product Technology.

1. "Arousal From Sleep By Emergency Signals," V. Pezoldt and H. Van Cott.

2. "Safe Environments for the Developmentally Disabled," John Fechter.

E. Extramural.

1. "An Evaluation of Planning and Training for Fire Safety and Health Care Facilities," Leonard Bickman, Loyola University of Chicago.

2. "A Review of Behavioral and Physical Characteristics of the Developmentally Disabled," F. Rick Heber, University of Wisconsin.

3. "The Determination of Behavior Response Patterns in Fire Situations-Project People II," John Bryan, University of Maryland.

4. "Life Cycle Cost Benefit Workbook," W. J. Griffith, Dallas Texas.

5. "A Theoretical Rationalization of The Goal Oriented Systems Approach to Building Fire Safety," John Watts, University of Maryland.

6. "Fire Alarms and Response to Alarms in Health Care Facilities," Harold Wakeley, IIT Research Institute.

7. "Development and Evaluation of Local Alarm Systems for Hospitals and Convalescent Homes," John Keating and Elizabeth Loftus, University of Washington.

Ad Hoc Working Group on Mathematical Fire Modeling
Center for Fire Research

Steering Committee - Dr. Robert S. Levine, Chairman

Sub-Committees
- Definition, Coding and Computers - Dr. John Rockett, Chairman
- Synthesis, Models and Scenarios - Dr. Howard Emmons, Chairman
- Sub-Programs - Dr. John DeRis, Chairman

A major goal in the technically oriented fire community is the development of validated mathematical techniques to predict the growth and spread of a fire from laboratory-measurable properties of the fuels and the physical parameters of the fire system. Some of the simpler models are in usable state now, and active research is proceeding on the more intricate, flexible models. When developed, and validated by measurements in full-scale tests, these models should result in design criteria for fire safety where we do not yet have adequate experience (for instance, with broad use of plastic materials), criteria for improved material fire tests, and quantitative methods for achieving a given degree of fire safety in new or refurbished occupancies.

A substantial amount of research knowledge on fire-related subjects is needed for the development of the mathematical models. A significant portion of this research is supported by CFR grants or conducted in-house and is described in other parts of this report. Other important studies are being conducted in a number of academic, industrial, independent, and government laboratories. These studies will contribute to better mathematical models, and the models, in turn, are a mechanism by which this research knowledge can contribute to fire safety.

To achieve a better coordination of the diverse programs which can contribute to the modeling effort, an ad hoc working group has been formed under sponsorship of the Center for Fire Research. Representatives of academic, independent, and industrial laboratories and other government agencies participate in the activities of the working group. Anyone active in the development of mathematical models for fire-related processes is invited to join the working group.

Arson Control Project
Center for Fire Research

Professional Staff

Robert S. Levine - Acting Project Manager for Arson

Associated Staff

Bernard Levin - Research Psychologist
Richard Bright - Senior Research Engineer
Nora Jason - Technical Information Specialist

The objective of this project is to support efforts to attack the arson problem through the development of improved technical information and improved availability of the technical information needed by arson investigators, forensic laboratories, psychiatric therapists, etc.

Major Projects

Psychology of Arson - The purpose of this project is to develop a summary of the technical literature regarding the psychology of arsonists and to relate this literature to the more general psychology literature and to selected behavioral models. The literature on psychology of arson has been surveyed, organized and summarized. A report on this will be available by early 1979. Work has started on relating this literature to the general psychology literature.

Arson Investigator's Handbook - Information that would be useful to an arson investigator is scattered through a number of books and other documents. Some investigators carry a collection of reference documents in the trunk of their car. The purpose of this handbook is to collate this information conveniently. An outline of the desired information, with emphasis on physical and chemical processes, is being prepared.

Associated Grants and Contracts

"Psychology of Arson - Theoretical Analyses with Suggestions for Application," Marcus Waller, University of North Carolina

Large Scale Fire Research Facilities
Center for Fire Research

Professional Staff

D. Gross	-	Supervisor
W. Bailey	-	Supervisory Engineering Technician
S. Steel	-	Physicist (Instrumentation)

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 by 20 ft. in plan 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.

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

This building also contains rooms for specialized calorimeters, small furnaces, and model enclosures. Laboratories are included for holding 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.

NBS Annex

This is a former DOD facility adjacent to the NBS site which is available for special tests. It has a 3 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, and a large laboratory designed for smoke detector testing.

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 6 technicians and an instrumentation specialist is available to support CFR Research Programs. An instrumented van is available for field testing at distant sites.

Institution: Brown University

Grant No: NBS Grant G7-9009

Grant Title: Flame Propagation and Extinction for Solid Fuels

Principal Investigator: Merwin Sibulkin, Division of Engineering, Brown University, Providence, RI 02912 (401) 863-2867

Other Professional Personnel: Anil Kulkarni, graduate student
K. Annamalai, research associate

NBS Scientific Officer: C. Huggett

Project Summary:

The objectives of this program are to advance our understanding of flame propagation and extinction for fuels involved in urban fires. An understanding of the theoretical basis of flame propagation and the ability to make quantitative predictions of flame spread rates should lead to more rational ways of testing the relative flammability of different materials. A more fundamental understanding of extinction mechanisms is desired to enable improved methods of fire suppression to be developed. The program includes both experimental and analytical tasks. Measurements are made with solid fuels of simple geometry in controlled atmospheres of oxygen, nitrogen and extinguishing agents. Burning rate, flame spread velocity and surface temperature are measured for the fuel phase. Flame temperature, location and CO/CO_2 concentration are measured in the gas phase. A parallel theoretical effort is made to determine the causes of extinction for different modes of burning using mathematical models. Different hypotheses as to the controlling physical mechanisms are tested by comparing the predicted conditions for extinction with the measured ones.

Progress Report:

Previous annual reports have described our work on downward burning cylinders. This has been followed by studies of "fully burning" cylinders of PMMA in $O_2/N_2/CF_3Br$ atmospheres. The mass burning rate $\dot{m}$ was measured by hanging the burning cylinders from a beam connected to a balance and recording the system weight as a function of time. As the oxygen concentration in an O_2/N_2 mixture is reduced, there is a slow decrease in burning rate $\dot{m}$. Extinction occurs at an oxygen mass fraction $Y_O = 0.181$ which is well below the value of $Y_O = 0.206$ found for downward burning. Two series of $O_2/N_2/CF_3Br$ mixtures were tested. In series (1) the O_2/N_2 ratio was maintained constant at its atmospheric value $(Y_O/Y_N = 0.233/0.767)$; in series (2) the oxygen concentration was maintained at its atmospheric value $(Y_O = 0.233)$. In series (1), $\dot{m}$ decreased slowly as Y_{CF_3Br} was increased and extinction occurred at $Y_{CF_3Br} = 0.10$; in series (2),

$\dot{m}$ increased slowly as Y_{CF_3Br} was increased and extinction did not occur. A comparison of the results of adding N_2 and CF_3Br to "air" gives the following values of additive concentration at extinction:

downward burning	Y_{N_2}	= 0.11
	Y_{CF_3Br}	= 0.05
fully burning	Y_{N_2}	= 0.22
	Y_{CF_3Br}	= 0.10.

Changes in the measured burning rates were compared with predictions using Spalding's approximate mass transfer equation

$$\dot{m}/A = (h_o/\bar{c}_p)\ell n(1 + B)$$

where for a given fuel B depends upon Y_O and $\bar{c}_p$. Values of the ratio $\dot{m}/\dot{m}$(air) were calculated for the $O_2/N_2/CF_3Br$ mixtures tested. The calculated and experimental values for the fully burning cylinders are in good agreement. However, this simple form of mass transfer theory cannot be used to predict extinction.

In order to investigate the causes of extinction for the fully burning cylinder configuration, a theoretical study of burning on a vertical wall was undertaken. A particular aim of this study was to investigate the influence of radiation from the burning surface on extinction. Boundary layer, similarity solutions were obtained for fuel and gas phase properties corresponding to PMMA burning in O_2/N_2 mixtures. The analysis is based upon the thin flame model (infinite chemical reaction rate). The resulting ordinary differential equations are solved numerically by a finite-difference procedure. In the absence of surface radiation, the burning rate approaches zero as the ambient oxygen mass fraction Y_O approaches zero. When a radiative loss corresponding to the surface conditions of burning PMMA ($T_W = 390°C$, $\varepsilon = 0.9$) is included, the analysis predicts extinction at $Y_O = 0.12$. Since the measured oxygen concentration at extinction is $Y_O = 0.18$, it is concluded that surface radiation is an important contributor to extinction for free burning, solid fuel fires but that other factors must also be involved.

Other factors which could significantly affect extinction are incomplete combustion and finite chemical reaction rate. When the heat of combustion h_c used in the calculations was changed from h_c for CO_2 to h_c for CO, the predicted oxygen concentration at extinction increased from $Y_O = 0.12$ to $Y_O = 0.16$ which is close to the measured value of $Y_O = 0.18$. Boundary layer temperature measurements designed to determine the degree of completeness of combustion have been undertaken but conclusive results have not been attained as yet.

Accomplishments:

The effects of an inert additive N_2 and a chemically active additive CF_3Br on the burning rates and extinction limits of free burning, solid fuel fires have been measured. It has been shown that the effects on burning rate but not on extinction can be correlated by a simple mass transfer theory. Similarity solutions of the boundary layer equations for a burning, vertical wall have been obtained which show that surface radiation significantly affects extinction.

Potential Applications:

This work increases our knowledge of the factors affecting extinction which could lead to the design of improved test methods and to more effective fire suppression techniques.

Future Milestones:

Measurement of extinction limit of fully burning cylinders for a variety of materials. Correlation of extinction limit with surface radiation. Measurement of gas phase temperature and CO/CO_2 profiles to determine the degree of completeness of combustion. Development of a non-similar, boundary layer analysis which includes effects of finite chemical reaction rate and gas phase radiation.

Reports and Papers:

"The dependence of flame propagation on surface heat transfer. II. Upward burning," by M. Sibulkin and J. Kim, Combustion Science and Technology 17, 39 (1977).

"Propagation and extinction of downward burning fires," by M. Sibulkin and M. W. Little, Combustion and Flame 31, 197 (1978).

"An interpretation of the oxygen index test," M. Sibulkin and M. W. Little, Eastern Section Meeting Combustion Institute, Nov. 1977.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Brunswick Corporation
3333 Harbor Blvd.
Costa Mesa, California 92626

Contract No.: NBS Contract EO-A01-78-00-3577

Contract Title: Experimental Studies on Pyrolytic Aerosols and Fire Detectors

Principal Investigator: Dr. Raymond Chuan
Brunswick Corporation
3333 Harbor Blvd.
Costa Mesa, CA 92626
714-546-8030

Other Professional Personnel: Houston D. Chen
Emory Thomas

NBS Scientific Officer: Thomas Lee

Project Summary: Experimental studies of the characteristics of pyrolytically released aerosols under steady-state conditions are being pursued. Sample mass loss, aerosol mass concentration, size distribution and optical opacity will be measured in real-time in a flowing system in which the aerosols generated by a stationary source are convected by a metered air stream past the observation station. The experiments will be performed in Brunswick's Incipient Fire Smoke Chamber under well-controlled and reproducible conditions. These data have contributed toward a better understanding of the aerosol characteristics in the course of proceeding from an incipient state to a runaway fire condition.

The incipient fire aerosol research has been directed toward gaining an improved understanding of the physical mechanism of aerosol generation during the incipient stages of a fire. The knowledge gained herein can be utilized in designing a sensitive, reliable, and false-alarm-free early warning fire detector.

Progress Report: The existing incipient fire smoke chamber (Figure 1) was designed to determine the physical characteristics of pyrolytic aerosols produced under carefully controlled and reproducible laboratory conditions. This chamber simulates a scaled-down room with a closed-loop free-convection arrangement for smoke dispersion. However, to study the basic physics of aerosol genèration under a steady-state

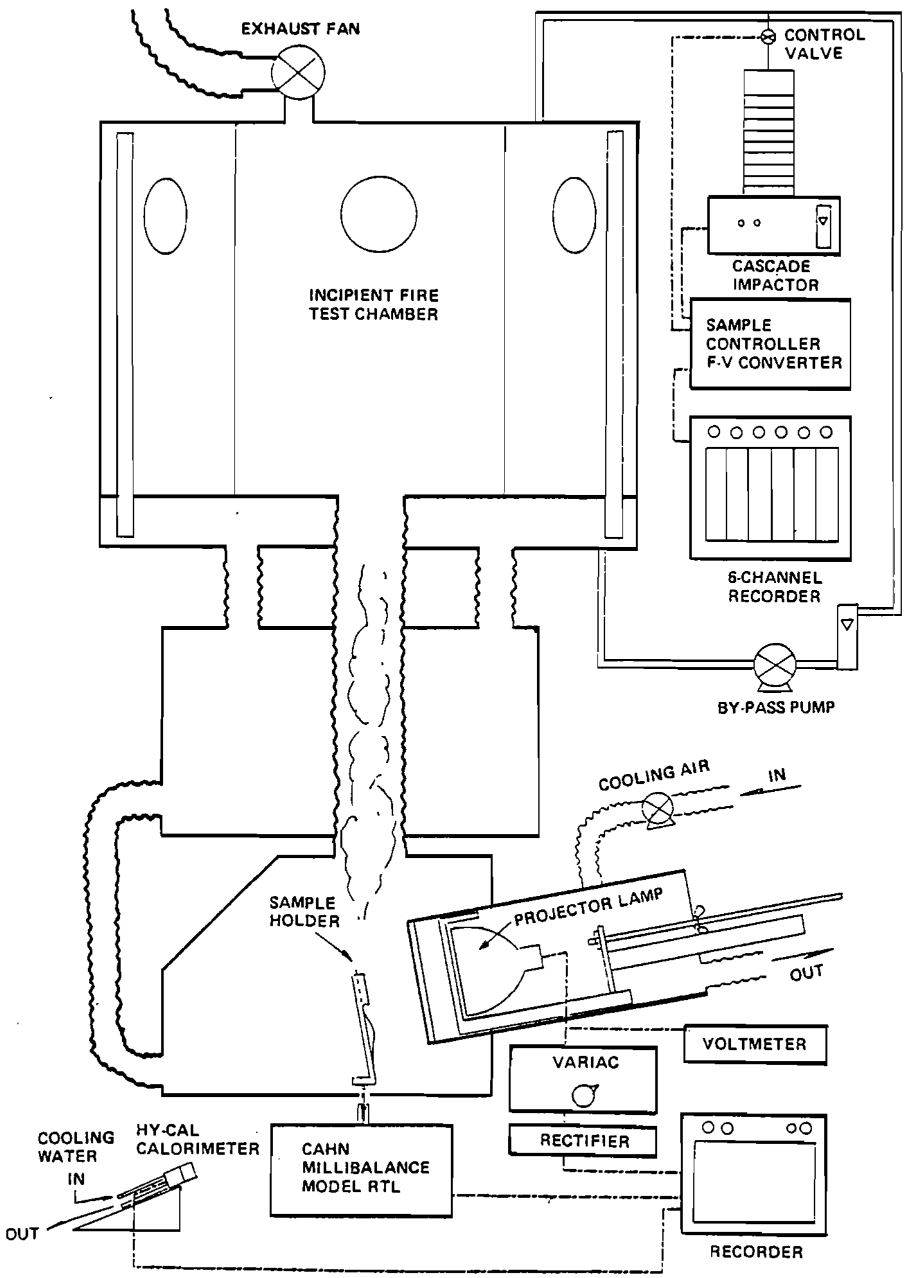

Figure 1. Incipient Fire Test Chamber Schematic

flow-through condition, slight modifications to the existing test facility would be necessary, which will include rearrangement of the test equipment and instrumentation as well as a few minor additions. The schematic flow diagram of the test set-up is presented in Figure 2. The redesign and modification of the test set-up have been completed. The system has been checked out and instrumentation calibrated.

An air diffuser is positioned around the sample holder to provide the primary mixing air for the pyrolytic process. Filtered shop air controlled by a regulator and a flowmeter would provide an airflow from 0 to 24 ℓ/min. from which an initial mixing velocity of up to 20 cm/sec. would result. The plexiglas chamber has been raised and a 3-inch diameter flow tube is added. The smoke would rise, entraining and mixing with the secondary dilution air which is injected into the flow tube by a fan through an ejector tube. The amount of secondary dilution airflow is controlled by a valve and the velocity of the total flow in the flow tube can be varied from 25 to 500 cm/sec., as measured downstream with a hot wire anemometer. A thermocouple is used to monitor the temperature at the same location.

The diluted smoke travels within the tube at a fixed velocity, and will be sampled at fixed intervals by the 10-Stage Cascade Impactor from which the concentration and size distribution data will be derived.

In order to correlate data of this system with the existing NBS data, a transmissometer is installed on the top of the chamber for opacity density measurements. The output is monitored continuously by a recorder.

Accomplishments: The system designed for this program is now in operation. Tests can be performed and data generated. During the closed-loop system testing performed by Brunswick Corporation, an "abundance ratio" has been discovered which exhibits a behavior which can clearly be used as a means of detecting a prelude to a runaway pyrolytic reaction. Brunswick investigators have found that in the early stages of pyrolysis the distribution of generated aerosols is dominated (in mass) by particles less than .3 μm. A distinct shift in distribution towards a larger size takes place as the material approaches a self-sustaining combustion state. If one defines $C_{.8}$ as the mass concentration of particulates near .8 μm and $C_{.1}$ for those near .1 μm, the ratio $C_{.8}/C_{.1}$ which is defined as an "abundance ratio", exhibits a behavior typified in Figure 3. It is seen that the ratio $C_{.8}/C_{.1}$ goes from less than 1 to greater than 1 just as the rate of mass loss begins its precipitous change.

Potential Application: This behavior of the abundance ratio can clearly be used as a means of detecting a prelude to a runaway pyrolytic reaction. Further, by utilizing the abundance ratio, which is dimensionless, as a discriminator, considerations of quantity of combustible material, proximity to the source, ventilation, and dilution are obviated.

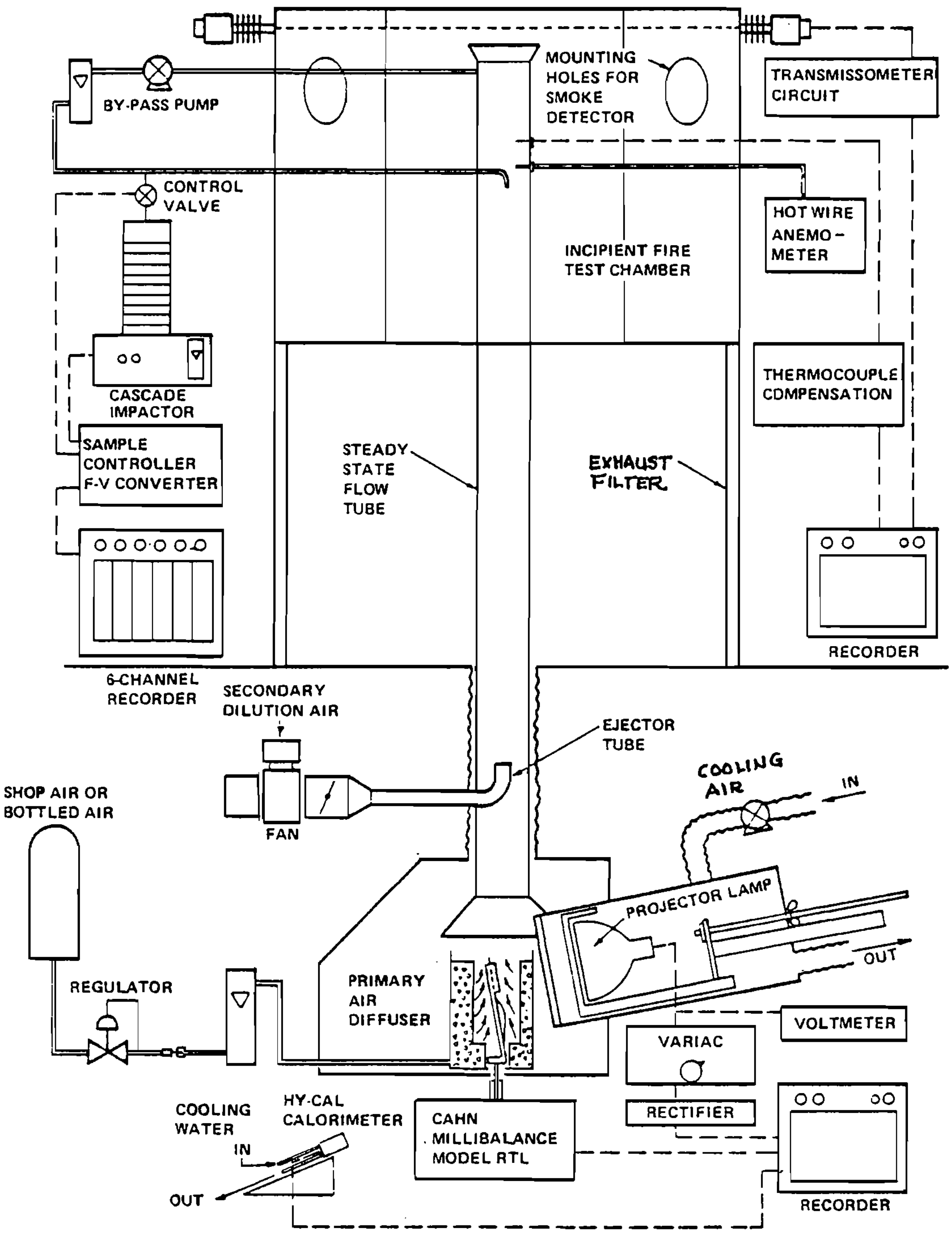

Figure 2. Schematic Diagram of Test Set Up

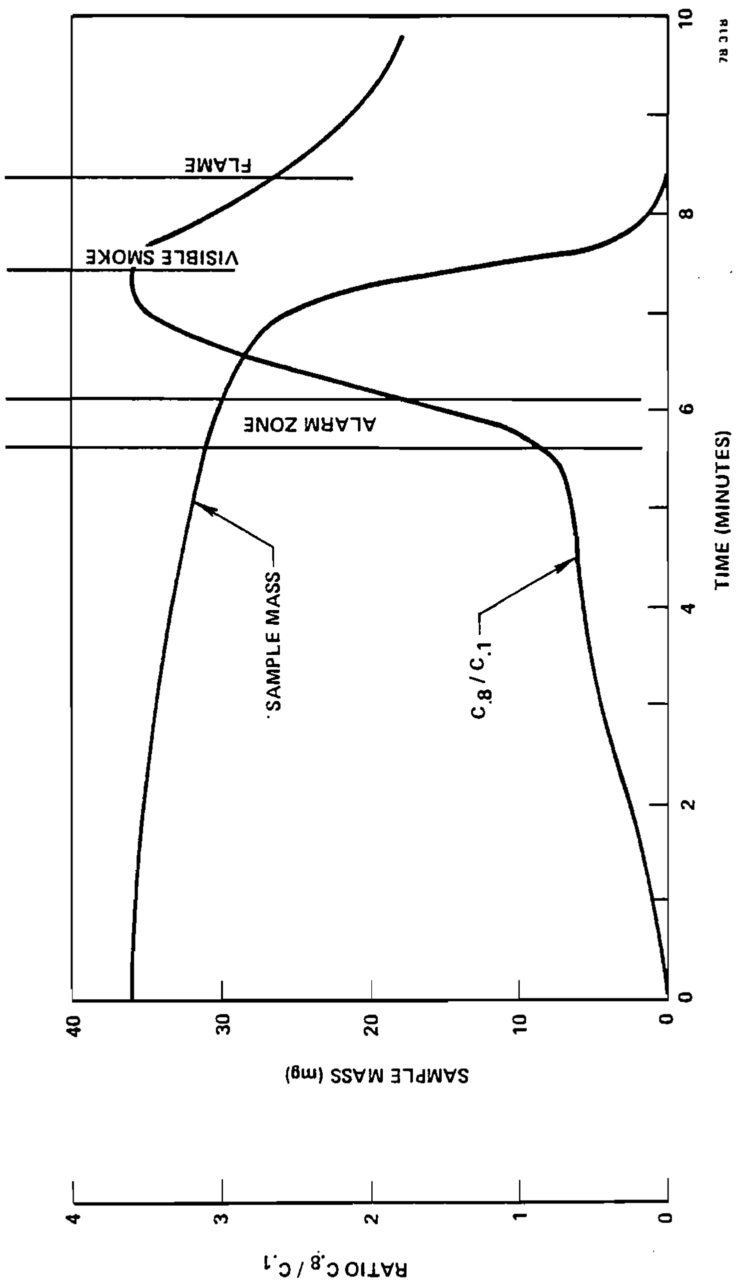

Figure 3. Sample Behavior of Abundance Ratio

Future Milestones:

(1) A matrix of tests shall be performed with irradiance and primary dilution air as variables, and using alpha-cellulose as the reference sample. Concentration, size distribution, optical density, and mass loss rate, responses of fire detectors will be determined.

(2) Selected tests will be performed to show the effect of secondary dilution air on the characteristics of the pyrolytic aerosols.

(3) Selected tests will be performed to show the effect of light source of transmissometer on its performance (i.e. @ λ= 900 nm versus 550 nm).

ANNUAL CONFERENCE ON FIRE RESEARCH
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GAITHERSBURG, MARYLAND

September 27-29, 1978

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 Investigators: E. E. Zukoski
Toshi Kubota
Jet Propulsion Center
California Institute of Technology
Pasadena, California 91125
(213) 795-6811 x1785

Other Professional Personnel: E. N. Tangren, Engineers Degree (June 1978)
W. S. Sargent, Ph. D. Candidate

NBS Scientific Officer: Dr. John Rockett

Project Summary: The flow field produced by a pre-flashover fire within one room and multi-room structures is being investigated in experimental and analytic studies. The experimental studies include the determination of convective heat transfer rates, and the entrainment rates of fire plumes and of jets formed at openings connecting a fire room to other spaces. The analytic work is primarily concerned with the development of simple computer programs which can be used to calculate the spread of products of combustion through a structure.

Our program can be divided into four parts. The largest section concerns the measurement of convective heat transfer to the walls of a half scale room from a fire plume produced by the combustion of natural gas — air fires. Room height is 1.22 meters and fires of 10-20 kw strengths are being studied. The influence of a number of parameters on heat transfer and the flow fields in the room are being considered. These include fire geometry and heat release rate, and the location of the fire with respect to openings of various geometries.

The second program, which started with this Grant, concerns the experimental determination of entrainment rates of a non-Boussenesq fire plume. The entrainment rate is a key element in the modeling scheme and its dependence on fire geometry and heat input rate, and the way it changes with height above the fire will be determined experimentally for a number of typical fires. These two programs constitute three-fourths of the efforts for the current year.

We also are continuing our program of using salt water/water modeling to study certain features of the fire plume and door-flow entrainment regions.

Finally, we are continuing to develop parts of a computer program into which the experimental results of our and other investigators' programs can be incorporated. The aim of this work is to generate a comprehensive computer model of fire spread in a multi-room structure. We are concerned with the development of the portion of this model which deals with the motion of gas within the structure, and the convective heat transfer resulting from this motion.

Progress Report: Convective heat transfer measurements have been made for a number of fire locations, fire heat input rates and opening geometries. The temperature and concentration fields were also measured for these conditions. This data is being analyzed now and a correlation will be developed to represent it.

Preliminary salt water/water modeling for the fire-plume entrainment work has been carried out and the results indicate that the proposed measurement scheme is satisfactory. Construction of the full scale apparatus will be completed early in September, 1978.

The two-room fire model has been extended to include a more general geometry for the opening between the two rooms, the possibility of a counter flow of hot gas between the two rooms as well as a single cold flow, and arbitrarily specified ambient pressures at each opening connecting either room with the outside. Development of a multi-room/-multi-story extension of the program and a subroutine for calculation of convective heat transfer is in progress. Document. of the existing program is available as a Report, see Zukoski and Kubota, below.

Finally, the salt water modeling studies of the fire plume in a room with a single opening to the outside (see Tangren et al., below) and modeling concerned with the measurement of fire-plume entrainment rates in a full scale configuration have been completed. A small effort is being continued to determine entrainment rates of door jets.

Accomplishments: 1) We have clarified the conditions for which the salt water/water modeling technique (Tangren et al., below) can be used. With this technique, the influence on the development of a fire in a room of the location, heat input rate and geometry of the fire, and the geometry of the openings between the room and adjacent spaces have been determined for the limiting case of a small heat input rate. 2) Measurements of convective heat transfer and the flow field produced in a room by a fire have been completed for a number of the configurations in a half scale room. 3) A computer program for a two room configuration has been developed and documented.

Potential Applications: Information derived from this work will be used to develop a better understanding of the pre-flashover stage of a room fire and will be used in the development of a comprehensive computer program which will predict the spreading of combustion products and fire in a multi-room structure.

Future Milestones: Completion of convective heat transfer experimented studies and correlation of results. Measurement of fire-plume and door-jet entrainment rates for a range of parameters.

Reports and Papers:

Zukoski, E. E., "Development of a Stratified Ceiling Layer in the Early Stages of a Closed-Room Fire," accepted for publication in Journal of Fire and Materials.

Zukoski, E. E. and Kubota, T., "A Computer Model for Fluid Dynamic Aspects of a Transient Fire in a Two Room Structure," California Institute of Technology Report, First Edition January 1978, Second Edition June 1978.

Tangren, E. N., Sargent, W. S., Zukoski, E. E., "Hydraulic and Numerical Modeling of Room Fires," California Institute of Technology Report, June 1978.

ANNUAL CONFERENCE ON FIRE RESEARCH
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NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Factory Mutual Research Corporation

Grant No.: NBS Grant G7-0911 (subcontract through Harvard University)

Grant Title: The Home Fire Project

Principal Investigator: R. Friedman
Factory Mutual Research Corporation
Norwood, Massachusetts 02062
617-762-4300 X570

NBS Scientific Officer: J. Rockett

Project Summary: The overall objective of the Home Fire Project, being conducted jointly with Harvard University, is to develop a method for physical or mathematical modeling of the growth of a fire in a residence, and the corresponding movement of the combustion products. Under this grant, the FMRC role has been to carry out certain research tasks to develop needed scientific knowledge for this objective. (Under another contract with the Products Research Committee, FMRC has conducted a series of highly instrumented room-scale burns, with participation of Harvard personnel in experiment planning and in data analysis.)

Two of the tasks under the present grant, concerned with physical modeling, were terminated on May 31, 1978. A third task, a study of radiation from flames and smoke layers, is being continued. A fourth task, radiation from pool fires, is being initiated, as is a fifth task, burning of pool fires in vitiated air.

Progress reports on each of these tasks are presented:

Progress Reports:

Pressure Modeling - R. L. Alpert, task leader

During this program, terminated May 31, 1978, radiance measurements of PMMA wall fires at 1.1 MPa (11 atmospheres) have been used to determine effective flame radiation temperature, flame optical depth and surface temperature by using three separate radiation path lengths. Such measurements are needed whenever elevated pressure, model experiments are performed to verify theoretical models of fire growth. Results show that the effective flame radiation temperature and fuel surface temperature are virtually identical to the normal atmosphere (0.1 MPa) values, while flame absorption coefficient increases as about the 4/3 power of pressure, as suggested by modeling theory. If these trends were to continue at higher pressures, the net radiative flux from the flame to the fuel surface would be pressure-modeled most accurately at about 3 MPa (30 atmospheres). Currently, the results are being applied to the study of the relative magnitudes of upward fire spread rates for a variety of interior finish materials, sponsored by the Federal Aviation Administration.

Atmospheric Pressure Modeling - P. A. Croce, task leader

The recent activity in this task, terminated May 31, 1978, was to test the ability to do quarter-scale modeling of fires spreading over the surface of a centrally ignited horizontal polyurethane slab in an enclosure with: (a) normal doorway; (b) narrow doorway; (c) window only. (The full-scale tests were performed in the series sponsored by the Products Research Committee.) The quarter-scale compartment tests were preceded by free-burn tests, which gave satisfactory correlations, assuming power-law behavior, for both flame spread (2nd power of time) and weight loss (6th power of time) with slabs ranging in size by a factor of four (but with constant thickness). These free-burn results were utilized (as is inherent with this scheme) to select the wall material and thickness for the model enclosure, which was quarter-scaled to the full-scale test enclosure.

Comparison of results of the quarter-scale and full-scale enclosure fires shows qualitatively similar behavior during the transient period being modeled, and reasonable agreement between scaled event-times (sprinkler activation and secondary ignition). Reports are being prepared.

Study of Radiation from Flames and Smoke Layers - G. H. Markstein, task leader

In many fires, energy transfer from the flame to the fuel and the surroundings occurs predominantly by thermal radiation. A portion of this study therefore concentrated on the measurement of radiative properties of fires, with emphasis on characterizing plastics fuels by the radiation of their flames. As an extension of this work that is currently underway, a scanning radiometer has been developed and is being used for determining the spatial distribution of radiative intensity in fires.

Studies of fires within enclosures have established that radiation from the hot smoke layer that accumulates under the ceiling participates significantly in the energy balance within the enclosure. Another portion of this study has therefore dealt with measurements of radiative properties of smoke layers produced by plastics fires. Instruments developed in the course of this work have also been used successfully in full-scale enclosure fire tests.

Measurements on smoke layers produced by PMMA pool fires and polyurethane foam spreading fires showed that for these two fuels about 2.5 percent of the burned fuel is converted into soot. The absorption coefficients for blackbody radiation at 0.94 μm were in good agreement with soot concentrations obtained by sampling and flow rates.

Radiative temperatures and emissivities of plastics fires have yielded soot volume fractions ranging from 0.47×10^{-6} for PMMA to 3×10^{-6} for polystyrene, at a height of 50 mm above the 305 x 305 mm pools.

A scanning narrow-view-angle radiometer has been designed and built. The instrument uses a fast-response pyroelectric sensor, and two mirror-galvanometer scanners to permit two-dimensional scans of fire radiance. In the mode of operation currently used with pool fires, horizontal scans at fixed height above the fuel surface are repeated a sufficient number of times to yield a good average of the radiance distribution. Storage of the fast linear-sweep scan (∿4 ms) with a digital storage oscilloscope and subsequent transfer to a programmable calculator are used for data acquisition.

Initial runs have been performed with a 0.38 m diameter PMMA pool fire. The use of the Abel integral transformation to convert the radiance data into a radial distribution of radiative power is currently being investigated, by comparing results obtained with several alternative distribution functions fitted to the measured radiance data. Among the functions tried thus far, a modified beta distribution seems especially useful, since this distribution can be readily extended to the case of a constant absorption coefficient. Evaluation of scanning data showed that the influence of absorption on the results is appreciable. The volumetric radiative power at the center of the flame, near the flame base, evaluated with an absorption coefficient of $1.3\ m^{-1}$, is about 50 percent larger than the result computed with vanishing absorption coefficient.

An instrument for measuring local flame absorption coefficients is under development. It consists of a water-cooled and nitrogen-purged fiber-optic probe, and corner-cube reflector, using an infrared-emitting diode or laser diode source and a silicon photodiode sensor. The probe and reflector assembly is inserted into the flame for measuring the absorption coefficient with an effective path length of about 0.15 m.

Radiation from Pool Fires - A. T. Modak, task leader

This research program, initiated in June 1978, addresses the problem of "pool" fires on horizontal fuel surfaces.

The degree of flammability of various materials and the spread rates of large turbulent fires are controlled by the radiative heat transfer from the flames. In view of this, the present research program seeks to provide a simple quantitative model for predicting the radiative energy transfer from pool fires. The local radiative properties (i.e., the effective radiation temperatures and absorption-emission coefficients) of the flames of pool fires are measured by means of a Schmidt type of measurement (see paper by Markstein) and are used as input parameters for radiation heat transfer calculations involving detailed geometric integrations over distributed radiating volumes.

For most large fires, flame radiation is dominated by soot radiation. Since the absorption-emission coefficient of soot varies only weakly with wavelength, it may be regarded as being nearly gray. This approximation simplifies flux calculations and experimental measurements of absorption-emission coefficients since they then become independent of pathlength. However, radiation from cooler fire smokes and combustion gases (e.g., CO_2 and H_2O) tends to be considerably less gray. The degree to which nongrayness affects radiation fluxes in fires will be investigated in detail by this research program.

The usefulness of models for predicting flame radiation depends critically on a knowledge of 1) geometric structure and shapes of buoyancy controlled diffusion flames of pool fires, and 2) spatial distributions of temperature and concentrations of molecular species and soot. This research program will provide empirical correlation of flame shapes of pool fires and will develop a nonhomogeneous and nonisothermal radiation model for pool fires to account for the spatial variations of temperature and soot concentrations on the burning rates of fires.

Burning of Pool Fires in Vitiated Air - F. Tamanini, task leader

This research was initiated in June 1978. In enclosure fires, where the supply of fresh air is insufficient to satisfy all the combustion requirements, recirculation occurs and the oxidizing medium is, therefore, preheated and depleted in oxygen content. It is important to determine the effect of these two changes on the flame characteristics, particularly with reference to the radiative properties of the flame and the rate of fuel depletion in the reaction region (incompleteness of combustion). Neither of these two processes is currently understood in the case of buoyancy-controlled turbulent diffusion flames. We are planning to begin by looking at the effect of oxygen depletion on the radiative properties (Schmidt flame temperature and absorption coefficient) of flames from pool fires. Initial tests will be carried out using a 30-cm-diameter level-controlled PMMA pool fire; at a later stage a 38-cm-diameter sintered-metal gas burner, which is currently being designed, will be used with both aliphatic and aromatic hydrocarbons. Concurrently the enclosure used for the tests will be modified to allow for preheating of the air as well as reduction of oxygen concentration. Finally, the question of the burning rate distribution in the fire plume will be addressed by constructing a device to aspirate and quench the fire plume. The analysis of the composition of the products collected by the device when positioned at different distances above the pool will yield a measurement of the unburnt fuel present in the flame at different heights as a function of vitiation of the ambient air. The information sought by this program is expected to be essential to the modeling of enclosure fires.

Accomplishments: The magnitude of the error caused by surface reradiation in pressure-modeling of polymethyl methacrylate has been determined and found to be reasonably small. The atmospheric modeling procedure has been shown to give good results for enclosure burning as long as the free-burning behavior is accurately known and is properly adjusted, and as long as the enclosure walls are properly modeled for thermal response. New instruments to measure fire radiance (two-dimensional scan) and local flame absorption coefficient are being developed. Radiative properties of a number of plastics fires have been measured.

Potential Applications: The two modeling techniques are available for use in appropriate applications. (FMRC is currently using the pressure modeling technique to study upward flame spread on aircraft interior finish materials, and the atmospheric modeling technique to model a corner test for plastic foam wall insulation.) The radiation measurements are being used in the mathematical modeling of room fires. They may be crucial in evaluating relative flammability of various plastics.

Future Milestones: Current radiation studies will be completed and reported, and Schmidt radiation measurements on charring fuels will be undertaken in the current contract year. The pool fire studies of flames on sintered metal burners are being initiated and should be completed by June 1979. The vitiated air facility should be constructed, calibrated, and instrumented by February 1979.

Reports and Papers:

1) Croce, P. A., "Modeling of Vented Enclosure Fires, Part I. Quasi-Steady Wood-Crib Source Fire," FMRC Technical Report, FMRC J.I. 7AOR5.GU, RC 78-T-25, June 1978.

2) Croce, P. A. and Hill, J. P., "Modeling of Vented Enclosure Fires, Part II. Transient, Non-Spreading, Polymethyl Methacrylate Slab Source Fire," in preparation.

3) Croce, P. A., "Modeling of Vented Enclosure Fires, Part III. Transient, Spreading, Polyurethane Slab Source Fire," in preparation.

4) Alpert, R. L., A report on the effect of surface reradiation on pressure modeling is in preparation.

5) Markstein, G. H., "Radiative Properties of Plastics Fires," accepted for presentation at Seventeenth (International) Symposium on Combustion, August 20-25, 1978, University of Leeds, England.

6) Orloff, L., Modak, A. T. and Markstein, G. H., "Radiation from Smoke Layers," accepted for presentation at Seventeenth (International) Symposium on Combustion, August 20-25, 1978, University of Leeds, England.

7) Modak, A. T. and Alpert, R. L., "Influence of Enclosures on Fire Growth: Vol. I. Guide to Test Data." FMRC Report RC77-BT-14, November 1977 (sponsored by Products Research Committee).

8) Modak, A. T. (editor), "Influence of Enclosures on Fire Growth: Vol. II. Analysis." FMRC Report RC78-BT-24, July 1978 (sponsored by Products Research Committee).

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Georgia Institute of Technology

Grant No.: NBS Grant G7-9003

Grant Title: Effect of Ignition Sources and Fire Retardants on Material Ignition

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NBS Scientific Officer: Dr. James Winger

Project Summary: The objectives of the recent program have been (i) to expand previous experiments on ignition time and ignition frequency measurements to thermally thin and thermally thick materials, under broad exposure conditions, varied geometry and various materials, (ii) to determine the effect of flame retardant treatments on the ignition characteristics of materials, and (iii) to modify and extend the modeling analysis for the prediction of ignition time. Measurements have been carried out to provide required data on thermophysical properties, constitutive description of processes, and ignition times. Description of the preignition processes and the prediction of ignition time was formulated and the results compared with measurements.

Progress Report: Thermal radiative properties have been measured both on original and charred samples of cellulosic, thermoplastic and blend materials. The charring was carried out under transient conditions. Thermal conductance measurements were carried out on fabrics and wood samples.

Using heating rates ranging between 20°C/min and 6000°C/min, fire retarded and untreated materials were pyrolyzed in a furnace. The pyrolyzate gases were mixed with air and their minimum self-ignition temperature was determined as a function of concentration at each pyrolysis heating rate. The measurements have indicated that minimum self-ignition temperatures of pyrolyzate-air mixtures are dependent on the heating rate during pyrolysis of the sample material. The ignition temperatures decrease with increasing heating rates. Minimum self-ignition temperatures of pyrolyzate-air mixtures generated at the high heating rates indicate that the ignition temperatures are lower for the flame-retarded material compared to the untreated cotton. The results are shown in Figure 1. Apparent molecular weights of pyrolyzate gases decrease with increasing heating rates during pyrolysis. Molecular weight of pyrolyzate gases generated at the high heating rate from a condensed phase active flame-retarded material is substantially lower than the gases generated from the untreated fabric, for cotton material tested.

Ignition time and ignition frequency measurements under convective heating have been carried out with a microburner ignition source on fire retarded and untreated fabrics. The ignition times were found to be dependent on the heating intensity, the surface structure of the material and the fire retardant treatment. Some representative results are presented in Figures 2 and 3. Fabrics exposed to a non-radical convective heat flux source were found to ignite.

Ignition time measurements on vertical fabric samples under radiative heating were conducted using large samples of fire retarded and untreated fabrics. Figures 4 and 5 show infrared detector responses of two 100% cotton fabrics, one untreated and one flame retarded respectively, exposed to radiant heating. Figure 4 exhibits the onset of self-ignition at the top of the fabric and the arrival of the flame front at the lower point on the fabric. This figure is representative of all untreated fabrics which ignited. The fabrics with the flame-retardment treatment, during the initial stages of the radiative heating period behave in similar manner to the untreated fabrics, pyrolyzing slowly and generating a visible gas at a low rate. However, at some instant, the top exposed portion of the fabric burst into a very vigorous gas generation process which was accompanied simultaneously with the consumption of major portions of the condensed phase at the top of the fabric. This then produced an intense pyrolysis front which propagated downward and as it consumed the major portion of the condensed phase it left behind only a very thin fiber structure of charred material. The pyrolysis front was found to propagate and cover the entire length of the material as long as the radiative exposure was continued. For this group of materials, in spite of the intense level of pyrolysis and large volume of gas generation, no visible flame was observed. Figure 5 shows the initiation of the pyrolysis front and the arrival of this front at the 5 cm point.

A comparison of the behavior of five fabrics under radiative heating is made in Table 1. All the fabrics are 50/50% polyester-cotton blends. Fabrics No. 16 and 25 are untreated and the remainder have received different levels of flame-retardant treatment. As shown in this table the onset of the pyrolysis front occurs at an elapsed time after initial exposure which is considerably shorter than the ignition time of the untreated fabrics.

The modeling analysis developed and used to predict pyrolyzate ignition for forced convective heating of a pyrolyzing solid has shown that ignition times are strongly dependent upon reaction kinetics governing solid decomposition and pyrolyzate generation rates. The predicted ignition times compare favorably with the experimental results. The analytical model which was developed to predict the ignition times of thermally thin fabrics under radiative heating, using the boundary layer ignition criterion, has been improved. Predicted ignition times were within 15% of measured values for high heat flux levels. The principal parameters used in the calculations were ranked in terms of their sensitivity in predicting the ignition time and activation energy was found to be the most critical one.

Accomplishments: Experimental techniques and apparatus have been developed to measure ignition times and ignition frequencies on small and large samples of thermally thin and thermally thick media under time invariant radiative heating. Experimental techniques and apparatus have been developed to measure ignition times and ignition frequencies on thermally thin and thermally thick media at various orientations and under time invariant convective heating. Experimental techniques and apparatus have been developed to pyrolyze materials at heating rates ranging from 20°C/min to an excess of 6000°C/min and to measure the minimum self-ignition temperatures on pyrolyzate-air mixtures as a function of pyrolyzate concentration. Modeling analysis has been developed to describe the ignition process along with the associated pre-ignition stages for thermally thin materials under convective and radiative heating.

Potential Applications: The ignition time and ignition frequency measurements serve to establish critical parameters which effect the ignition process, and procedure and techniques which should be used to assess the relative ease of ignition for thermally thin and thermally thick materials.

The investigations with flame retardant material serve to assess the effect of the treatment and level of treatment on the ignition process.

The investigations on the self-ignition temperatures of pyrolyzate-air mixtures serve to describe the ignition of materials as well as assess conditions which will establish a flashover in a room fire.

Reports and Papers:

P. Durbetaki and C. Thorn-Andersen, "Effect of Heat Flux Level and Exposure Time to a Radiant Heat Source on the Thermal Radiative Properties of Cellulosic and Thermophastic Materials", Proceedings of the Seventh Symposium on Thermophysical Properties, Ared Cezairliyan, Editor, The American Society of Mechanical Engineers, New York, 1977, pp. 324-330.

P. Durbetaki and M. L. Teague, "Fabric Ignition Studies with a Microburner", Proceedings of the Eleventh Annual Meeting, Information Council on Fabric Flammability, Galveston, TX, 1978.

W. J. Tingle, P. Durbetaki and W. C. Tincher, "Self-Ignition of Pyrolyzate-Air Mixtures", Paper No. 78-29, Spring Meeting, Western States Section, The Combustion Institute, University of Colorado, Boulder, CO, 17-18 April 1978.

P. Durbetaki, W. C. Tincher, H. Chang, C. C. Ndubizu, M. L. Teague, V. L. Wolfe, Jr., "Effects of Ignition Sources and Fire Retardants on Material Ignition", Sixth Research Report, NBS Grant No. G7-9003, Fire Hazard and Combustion Research Laboratory, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, 31 March 1978.

P. Durbetaki, W. J. Tingle, W. P. Ryszytiwskyj and W. C. Tincher, "Self-Ignition of Pyrolyzate-Air Mixtures", Fire Research (in press), 1978.

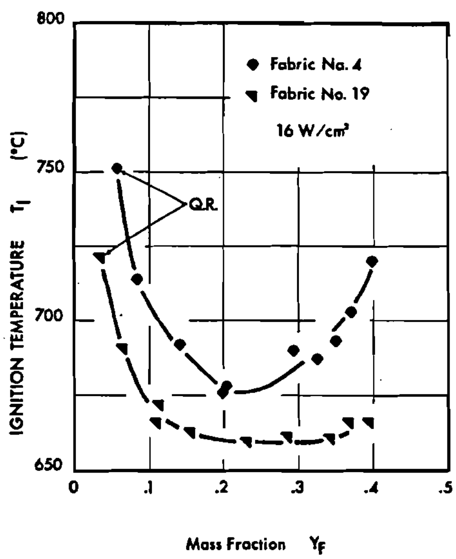

Figure 1. Comparison of Self-Ignition Temperatures of Pyrolyzate Gases Generated from Two 100% Cotton Fabrics, Flame-Retarded Fabric No. 19 and Untreated Fabric No. 4 at a Heating Rate of 16 W/cm^2.

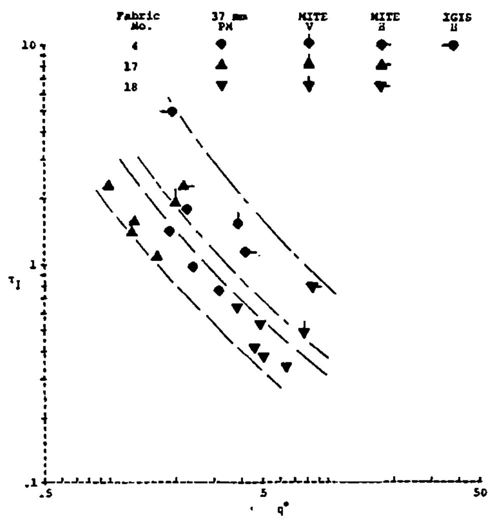

Figure 2. Comparison of Normalized Ignition Times for Three 100% Cotton Fabrics.

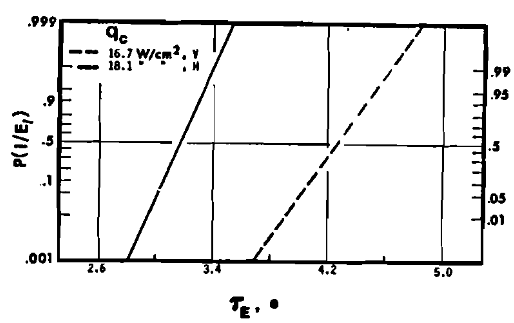

Figure 3. Ignition Probability as a Function of Exposure Time to the Microburner, GIRCFF Fabric No. 4; ----- Vertical Orientation, ——— Horizontal Orientation.

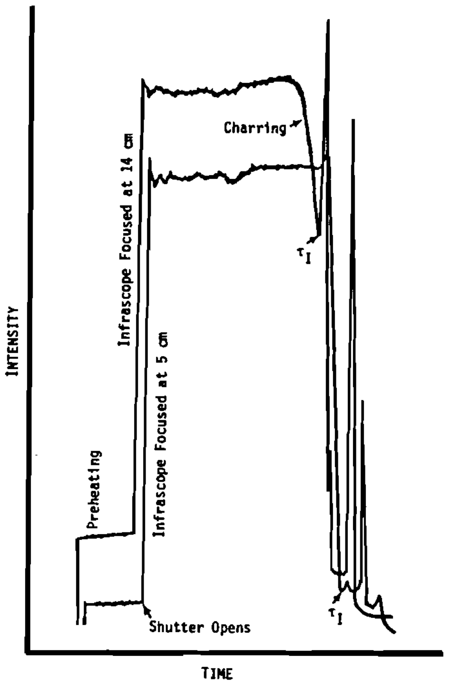

Figure 4. Infrascope Output History Plots Representing Ignition; ETIP Fabric No. 21 (100% Cotton, Untreated) Exposed to an Incident Heat Flux of 9 W/cm².

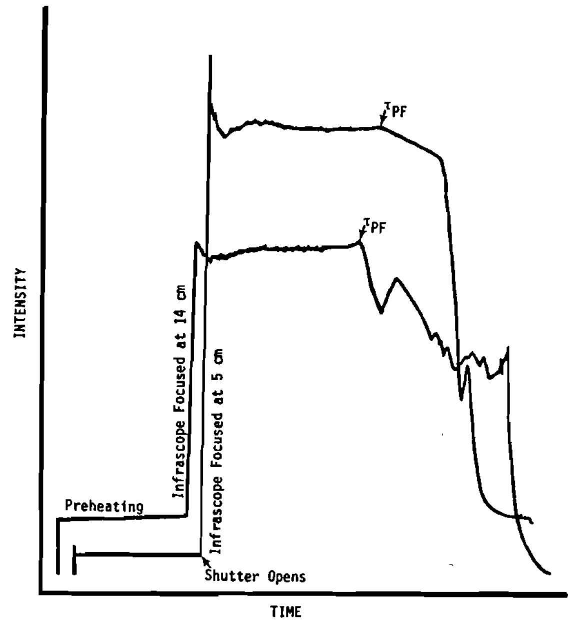

Figure 5. Infrascope Output History Plots Representing a Pyrolysis Front; ETIP Fabric No. 23 (100% Cotton, Flame Retarded) Exposed to an Incident Heat Flux of 6.8 W/cm².

Table 1. Comparison of Ignition Time and Pyrolysis Front Time Measurements Under Radiative Exposure, 50/50% Polyester-Cotton Fabric Samples, Untreated and Flame Retarded

Incident Heat Flux W/cm²	Ignition Time (s)				Pyrolysis Front Time (s)					
	GIRCFF #16		ETIP #25		ETIP #26		ETIP #27		ETIP #28	
	5 cm*	14 cm*	5 cm	14 cm	5 cm	14 cm	5 cm	14 cm	5 cm	14 cm
	τ_I	τ_I	τ_I	τ_I	τ_{PF}	τ_{PF}	τ_{PF}	τ_{PF}	τ_{PF}	τ_{PF}
6.8	98.2	98.0	150.0	149.2	33.0	15.2	27.6	16.1	24.0	15.3
8.6	----	24.8	----	48.6	12.3	10.0	12.0	10.2	11.7	9.6
8.6	----	----	----	----	12.9	10.0	12.5	10.3	----	----
8.6	----	----	----	----	12.9	10.1	----	----	----	----
9.0	----	----	43.5	36.6	----	----	----	----	----	----
9.0	----	----	37.2	35.1	----	----	----	----	----	----
10.8	14.4	12.3	22.5	21.0	8.4	7.1	8.3	7.4	8.4	7.3
13.0	10.0	9.1	----	----	6.4	5.9	6.8	6.1	6.6	6.0
13.0	----	----	14.7	13.7	6.5	5.9	----	----	----	----
15.8	8.8	7.6	11.2	9.8	5.3	4.6	5.3	4.8	5.4	5.0
15.8	----	----	----	----	5.3	4.9	----	----	----	----

*Infrascope focused from bottom edge of sample.

INSTITUTION

School of Aerospace Engineering
Georgia Institute of Technology

NBS GRANT NO.
G8-9003

GRANT TITLE

"Investigation of the Properties of the Combustion Products Generated by Building Fires"

PRINCIPAL INVESTIGATOR

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NBS SCIENTIFIC OFFICER

Dr. George Mulholland

PROJECT SUMMARY

An experimental facility is being used for the determination of the properties of the combustion products generated by burning various building materials. Measurements of particle size distributions and particulate mass concentrations, chemical properties of both particulate and gaseous products, optical densities and mean particle diameters have been obtained under conditions simulating various fire situations. The fire-exposure variables considered are the temperature and composition of the chamber atmosphere, the type of burning (i.e., flaming or non-flaming), the radiant heat flux to the sample, the orientation of the sample, and the amount of ventilation. During the past year this project has been aimed at identifying the physical and chemical processes leading to smoke production, as well as utilizing small-scale test data with related theoretical data to predict the smoking properties of various materials.

The efforts of this research project can be divided into five major categories or tasks. Task A is concerned with determining the effect of substrate polymer structure upon smoke characteristics, while Task B deals with the effect of various additives upon smoke properties. Task C is a cataloging of smoke physical properties data from results obtained on this project through September 30, 1977. The chemical analysis of the smoke particulates is performed under Task D, and the development of a theoretical smoke formation model is Task E.

PROGRESS REPORT

Task A. - Determination of the Effects of Substrate Polymer Structure on Smoke Characteristics.

In this study the following pure materials were tested in the Combustion Products Test Chamber (CPTC) under a radiant flux of a 5 W/cm^2 in the horizontal sample mount: polystyrene, PVC, polypropylene, polyethylene, and polymethyl methacrylate (PMMA). Low temperature tests (25°C) have been completed for both nonflaming and flaming combustion, and high temperature tests (200°C) have been completed for flaming combustion. Data obtained for all tests include the maximum optical density per meter at 458nm (blue) and the volume-surface mean particle diameter at maximum optical density, while the fraction of sample weight loss converted to smoke particulates (Γ) and the mass median diameter were also obtained for low temperature tests.

For low temperature tests, less total smoke by mass is generated under flaming conditions, but peak optical densities tend to be greatest in flaming tests. Also, the smoke particulates are predominantly liquid droplets in nonflaming tests, while the particles generated under flaming conditions are sooty agglomerates. Furthermore, the relative ranking of the smoking tendency of polystyrene, PVC, and polypropylene (according to Γ) were opposite for flaming and nonflaming conditions.

Under flaming conditions, increasing the environmental temperature to 200°C gave a moderate to strong reduction in the peak optical density and a small increase in the mean particle diameter. The data also shows that elevated temperature does not change the relative smoke ranking of these materials according to optical density. Additional optical data taken with the 90°-scattering system for the high temperature flaming tests are consistent with the light scattering properties of sooty or carbonaceous smoke particles, but further analysis of the data will be necessary to determine the complex refractive index of the smoke particles.

Analysis of the above data is underway to correlate the polymer structure with the volatile and particulate pyrolysis products which are known to affect smoke production.

Task B. Determination of the Effect of Additives on Smoke Characteristics.

In this study a series of seven additional PVC formulations and six additional polypropylene formulations containing various additives were tested under flaming conditions in both low temperature (25°C) and high temperature (200°C) environments.

PVC Samples. Low temperature tests of PVC samples showed that the presence of fillers ($Al_2O_3 \cdot 3H_2O$ and $CaCO_3$) reduced smoke production in the flaming case, which agrees with earlier results from nonflaming tests. This is probably due to the reduced concentrations of soot-producing aromatics which have been identified in the pyrolysis products of PVC. Furthermore, both high and low temperature results showed that $CaCO_3$ is much less effective in reducing smoke production than $Al_2O_3 \cdot 3H_2O$. Also, the addition of plasticizer greatly increased the maximum optical density as compared to the pure PVC polymer.

Polypropylene Samples. Polypropylene samples containing fire-retardant additives tended to generate considerably more smoke than the pure polypropylene under flaming conditions in both low and high temperature atmospheres. The only char-former among the polypropylene samples tested yielded a relatively low peak optical density because it generated less total smoke over a longer period of time than the other samples which do not char.

As in the case of the pure polymers discussed under Task A, all of the PVC and polypropylene samples yielded moderate to large reductions in peak optical density and small increases in mean particle diameter when the environmental temperature was raised to 200°C. The relative ranking of the smoking tendency, however, was the same at both low and high temperatures.

A new experimental apparatus has been developed to study the effects of additives upon smoke formation in a polymeric diffusion flame by the controlled, direct injection of additive species into the polymer thermal degradation products. Additive species planned for study include: (i) metallic compounds that are expected to reduce smoke formation and (ii) organic compounds commonly found in polymer pyrolysis products that are expected to enhance smoke formation. Initial tests have demonstrated the feasibility of this apparatus.

Task C. Cataloging of the Smoke Physical Properties Data.

The cataloging of the smoke physical properties data from results obtained through September 30, 1977 has been carried out, and the formal report containing the data has been completed and forwarded to the National Bureau of Standards.

Task D. Chemical Analysis of Smoke Particulates.

Determination of Polynuclear Aromatic Hydrocarbon Content of Polymer Smoke. A simple, accurate separation scheme has been developed for PAH analysis in smoke particulates which has been applied successfully to PAH determination in smoke particulates generated from a number of PVC samples containing various additives. Results indicate that: (1) pure PVC polymer gave nearly identical yields for both flaming and nonflaming mode, (2) a steady increase in total PAH yield was found as heat flux was raised for nonflaming mode, (3) $CaCO_3$ and $Al_2O_3 \cdot 3H_2O$ both reduced PAH yield to nearly zero in flaming mode, but made very little difference in the nonflaming mode. Other polymers tested (i.e., polyethylene, polypropylene, polystyrene, and PMMA) yielded negligible quantities of PAH.

Measurement of Volatile Components Adsorbed onto Smoke Particulates. A new, small thermal degradation chamber has been developed with collection facilities for both vapor and particulate smoke components. This apparatus was designed to determine (with the aid of GC and GC/MS techniques) the presence of vapors adsorbed onto smoke particles and acutely toxic substances such as HCl, HCN and acrolein. A significant number of volatile components have been observed, and detailed identification and quantitation of these compounds is currently underway.

Task E. Development of a Theoretical Smoke Formation Model.

The one-dimensional model developed previously has been used to obtain solutions for the smoldering decomposition with charring of a slab of polymeric material of finite thickness subjected to a known incident heat flux. The material sample is characterized by regions which range from the primary solid decomposition reaction zone to a very porous char structure closest to the sample surface. Calculations of the time-resolved porosity, temperature, pressure, and velocity profiles have been made under the assumption that condensation of the gaseous pyrolysis products did not occur.

The governing equations have now been modified and expanded to investigate the role of heterogeneous and homogeneous condensation in the production of smoke particulates from a burning polymeric material under nonflaming conditions. The system of equations consists of the following: (1) gas phase continuity, (2) condensed phase (particulate) continuity, (3) condensible vapor species continuity, (4) momentum, (5) global energy, (6) solid decomposition, and (7) particle growth. These equations will allow the calculation of the gas phase pressure, gas velocity, gas and solid phase temperature, solid porosity, condensible vapor species mass fraction, condensed phase mass concentration, and mean particle size as functions of space and time. The changes are presently being incorporated in the computer program and calculations will begin during the next quarter.

ACCOMPLISHMENTS

(1) Experimental facilities have been enhanced by the addition of (i) a 90^{o}-scattering optical system for determination of the complex refractive index of smoke particles, and (ii) a new Hewlett Packard 5982 EI/CI Mass Spectrometer for identification of compounds extracted from the smoke particulates.

(2) Low temperature nonflaming tests and high and low temperature flaming tests have been completed for pure polystyrene, PVC, polypropylene, polyethylene, and PMMA samples.

(3) Flaming tests (both low and high temperature) have been completed for PVC and polypropylene samples containing various additives.

(4) Cataloging of all physical property measurements obtained in CPTC tests before September 30, 1977 was completed.

(5) An analytical scheme was developed for the quantitation of polynuclear aromatic hydrocarbons (PAH) extracted from PVC samples, and a detailed analysis of PAH from PVC samples of different compositions was provided.

(6) The analytical model of smoke production was extended and expanded to include heterogeneous and homogeneous condensation processes.

POTENTIAL APPLICATIONS

Data obtained in this research program will aid in the evaluation of hazards resulting from smoke produced during building fires. Furthermore, these data can be of use in determining what environmental conditions and material additives most affect smoke production, and thus aid in the development of safer commercial materials. Finally, correlation of measured smoke properties with theoretical predictions will provide detailed information on the mechanisms of smoke production which has not previously been available.

FUTURE MILESTONES

The following milestones have been established for the coming year: (1) High temperature nonflaming tests of the PVC samples will be completed by September 1978, (2) Identification of major components adsorbed onto particulates by October 1978, (3) Computer solutions will be obtained using the smoke formation model with homogeneous and heterogeneous condensation by October 1978, (4) New experimental apparatus for studying the effects of additives upon smoke formation by a polymeric diffusion flame will be operational by December 1978, (5) Polypropylene tests with organic additives to be completed by April 1979, (6) Polypropylene tests with inorganic additives to be completed by August 1979, (7) Chemical analysis of smoke particulates and adsorbed volatiles generated by combustion of polypropylene, polyethylene, polystyrene and PMMA to be completed by October 1979.

REPORTS AND PUBLICATIONS

1. Zinn, B. T., Cassanova, R. A., Bankston, C. P., Powell, E. A., Browner, R. F., and Rhee, J. U., "Investigation of the Properties of the Combustion Products Generated by Building Fires," Final Report of National Bureau of Standards Project No. G7-9001, November 1977.

2. Bankston, C.P., Cassanova, R.A., Powell, E.A., and Zinn, B.T., "Review of Smoke Particulate Properties Data for Burning Natural and Synthetic Materials," Supplemental Report for National Bureau of Standards Project No. G8-9003, May 1978.

3. Powell, E.A., Bankston, C.P., Cassanova, R.A., and Zinn, B. T., "Effect of Environmental Temperature Upon the Physical Characteristics of the Smoke Produced by Burning Wood and PVC Samples," presented at the Combustion Institute Meeting (Eastern Section) on Chemical and Physical Processes in Combustion, East Hartford, Connecticut, November 10-11, 1977 (Submitted for publication).

4. Liao, J.C., and Browner, R. F., "Determination of Polynuclear Aromatic Hydrocarbons in Poly-(Vinyl Chloride) Smoke Particulates by HPLC and GC/MS, Analytical Chemistry, submitted for publication.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Harvard University

Grant No.: NBS Grant G7-9011

Grant Title: The Home Fire Project

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NBS Scientific Officer: John Rockett

Project Summary: The principal thrust of the Harvard portion of the Home Fire Project which is carried out jointly with the Factory Mutual Research Corp. is the development of a Mathematical Model of Fire Development. During the past year, advances have been pursued on three fronts:

(1) The numerical analysis technique has been generalized and made more flexible and more stable.
(2) The subroutines which describe the various component phenomena have been improved and new subroutines have been devised to cover more of the relevant phenomena.
(3) Several component problems - fire spread, growth and extinguishment have been studied to provide basic data for the Math Model.

Progress Reports: The Mathematical Model - H. Mitler, H. Emmons & L. Trefethen

A number of attempts have been made over the last fifty years or so to make a mathematical "model" of the burning of a room. A good historical review of the efforts - theoretical and experimental - up to 1975 can be found in Babrauskas and Williamson, for a fully-involved compartment fire with a single vent.

In 1973, a joint effort at understanding the progress of compartment fires in the pre-flashover phase was started at Harvard University and Factory Mutual Research Corp. as the Home Fire Project. One of our principal tasks was the mathematical modeling of such a fire. (Similar efforts were started at about the same time by R. Pape at IITRI and by

C. MacArthur at the University of Dayton, as well as by T. Tanaka in Japan).

Full-scale test fires were carried out at FMRC in 1973, 1974, 1975 . There was considerable success in understanding these, but it was still at a rather rudimentary level, neither very general nor flexible. Out of this experience a more general calculation was set up. This consists of a main program with many subroutines, each subroutine describing one physical process (or one set of processes). This modular approach allows for a great deal of flexibility: not all physical processes may need to be described for certain low accuracy purposes, for example. Any process can be described in as much detail as desired.

The model being developed at Harvard had taken shape by June 1, 1977 though still in fairly simple form: it was almost, but not quite, ready to predict the progress of some new test fires that were run in June and July 1977 at the FMRC facility (sponsored by the PRC).

In the year since then, a substantial amount of progress has been made; the extent subroutines were standarized and their "bugs" removed, and several new physical subroutines were developed. There were numerical instabilities and other difficulties inherent in the (Jacobi) technique of successive substitution theretofore used in the solution of the equations. These were overcome by making it possible for the computer to move from one numerical method to another. Two new algorithms, which we refer to as Newton and Newton-fast have been added. Still others can be added as desired in the future.

A start was made at extending the calculations to handle an arbitrary number of rooms, vents, fires, etc. (This is done by an elaborate indexing procedure).

Predictions (and some post-dictions) were made for the 1977 test fires. A description of the program and a partial analysis of the results of the comparison between calculation and experiment was published. Agreement between theory and experiment was improved, and extended over more variables. Since then some half-dozen physical subroutines have been modified to remove some unsuspected bugs, have parameters changed to conform with better data, and be made internally more consistent. Another half-dozen or so new subroutines (mostly radiation) have been written and incorporated into the program. As of June 1, 1978, not all were yet incorporated, but there was evident improvement of overall results with the promise of further improvement in the near future. (All of this is still for the single room with a single vent, single fire, and single target object). Several sensitivity studies were carried out. These indicated that one of the principal parameters affecting the result of the calculation is the entrainment coefficient, α. This study also showed that the fire ought to be most strongly affected by the level of the base of the fire: the higher it is, the smaller can the maximum fire be.

Finally, one of our aims is to have our program universally usable, and (conversely) able to accept subroutines written by others. To these ends, we have sent our program to the NBS to run, and (after some rewriting by them) it runs on their 1108 computer and 732 mini-computer.

Also, a radiation subroutine written by A. Modak at FMRC was easily incorporated into our program.

Thus the current status of the program is satisfactory, and we continue to make progress at roughly the expected rate.

The Effect of External Radiation on Ignition and Fire Spread - T.M.Shih & R. Land

The objective of this task is to investigate the characteristics of a horizontal fire under the influence of external radiation. Emphasis has been placed on measurements of the flame spread rate, $\dot{r}(t)$; the mass pyrolysis rate, $\dot{m}_p(t)$, and the mass burning rate $\dot{m}_b(t)$.

The apparatus includes: (a) four radiant heaters providing total wattage of 11,000w and a nearly uniform incident radiant flux of $0.29\ w/cm^2 \pm .01\ w/cm^2$ on the fuel surface (b) an electronic weighing device for $\dot{m}_p$ measurements with linearity 0 to 4Kg and sensitivity of better than 1g, and (c) an exhausting system capable of withdrawing flows of 250 gm/sec and with a test section for velocity, temperature and species measurements.

The thermal diffusivities and the thermal conductivities of the foams used as fuel were obtained by measuring the temperature histories in the foams exposed to a constant radiant flux. The heat of reaction was measured with the oxygen bomb calorimeter.

It was relatively easy to measure $\dot{r}(t)$ and $\dot{m}_p(t)$ using photography and the weighing transducer. More than ten burns of 50 cm square polyurethane foam buns were conducted inside a 3m cubical test enclosure with and without external radiation, $\dot{q}_e''$. These two parameters increase significantly as $\dot{q}_e''$ is increased. For a 40% retarded PU foam, $r(t)$ and m_p increase by 100% and 400% respectively with $\dot{q}_e'' = 0.29 w/cm^2$ at $t = 100$ sec. It was also unexpectedly found that, at a given flame spread radius, $\dot{m}_p$ under external radiation is smaller than that without external radiation. The reason lies in the fact that the external radiation heats the bun surface and causes the radius to enlarge much more rapidly than the corresponding percentage increase in pyrolysis rate. For steady-state acetone pool fires, $\dot{m}_p$ remains unchanged under $\dot{q}_e'' \leq 0.29\ w/cm^2$. This suggests that an external radiation of $0.29\ w/cm^2$ is small in comparison with the flame radiative feedback.

Much effort has been directed to the measurement of $\dot{m}_b$ defined herein as the rate of complete fuel combustion. Thus $\dot{m}_b$ is equal to the ratio of the total chemical energy evolved, $\dot{q}_t$, to the heat of reaction ΔH_r measured with a calorimeter. Both the energy balance method and the oxygen depletion method are being developed.

The Theory of Laminar Boundary Layer Burning with Radiation-J. Backovsky

A numerical parametric study has been done for radiation effects in forced and free convection, laminar boundary layer burning of (vertical) fuel surfaces - with the further restrictions that the flow-field be steady-state and two-dimensional. The backbone of this approach is the similarity analyses by H.W. Emmons and J. deRis on forced and free convection burning, resp. Flame, surface, and external radiation are included through redefinition of variables, some parameters, and boundary conditions. The values of local burning rate at the flame is key to this approach, and has been computed.

The parameters which were varied presently include:

(a) those arising from the solution with no radiation: B, the mass transfer number, in forced convection; B,τ (the ratio of thermal enthalpy above ambient-fluid enthalpy to the latent heat of fuel), and stoichiometric coefficient r (mass of fuel material burnt per unit mass of air), in free convection.
(b) those arising from the necessity of taking into account the actual fuel consumption at the flame in order to calculate the flame radiation: τ and r for forced convection. These are needed to obtain fuel consumption whether radiation is included or not.
(c) those directly indicating the amount of radiation or the radiative properties: χ, the ratio of the heat radiated per unit area of the flame to the combustion energy liberated in the same area a, surface absorptivity; A, the dimensionless group indicating the net of wall radiative losses and externally applied radiation.

The effects of the above parameters on the following aspects of burning have been obtained: fuel pyrolysis rate, fuel consumption rate, flame temperature, max. fluid velocity (free conv.), air entrainment rate, etc. The mass transfer no. B was again the major parameter indicating the vigor of pyrolysis, which is linked strongly with all other aspects of the flow-field. It was found, however, that there is a critical B (for given τ,r,χ,a,A) below which the theory with no flame radiation overestimates the pyrolysis rate, i.e., below which the cooling of the flame by flame radiation is not sufficiently offset by a lesser conductive heat requirement at the fuel surface. Above the critical B the flame radiation significantly increases the pyrolysis rate.

Extinguishment by Water -(R. Land) It was shown in previous work that moisture in air does not change the burning rate of charcoal. Fine water drops in small amounts (2%) in air increases the burning rate up to 30%. Larger drops (2mm) studied this year extinguish an area of about 50 sq. m.m. which re-ignites in from 5 to 30 seconds. A reliable dropper has not yet been devised. This experiment has been temporarily discontinued because of lack of research funding.

Accomplishments: The 8 experimental fires have been predicted with fair accuracy and new sub-programs have been devised to more accurately describe the physics. The design, construction and calibration of the test equipment to study the effect of external radiation on fire spread is complete except for exhaust gas composition measurement. The effect of radiation on boundary layer burning can be extensively understood using available similarity solutions.

Potential Applications: The Math. Model already provides priorities on needed fire research and will have wide applicability to small scale fire tests, fire codes, arson investigation, etc. if it can be completed to the degree that now appears hopeful. Since radiation is a major heat transfer process in fires, the radiation studies are essential to the

Math Model.

Future Milestones: The theoretical study of boundary layer combustion will be completed in the year ahead. The Math Model will be further developed through additional subroutines and will be made more flexible by a new subscripting plan. The apparatus for the measurement of the effect of external radiation on fire spread will be completed by the end of the summer and needed fire data should be measured thereafter.

Reports and Papers:

1) Emmons, H. W. "A Scientist Looks at the Future of Fire Research", Fire Chief Magazine, Jan. 1978. Vol. 22, No. 1

2) Emmons, H.W., Mitler, H. & Trefethen, L.N. "Computer Fire Code III" Harvard, Home Fire Technical Report No. 25, Jan. 1978

3) Emmons, H.W. "Using Technology to Resolve Issues Associated with the Built Environment", 3rd Annual Conf. NFPCA, Oct. 1977

4) Emmons, H.W. "The Home Fire Viewed as a Scientific System" Soc. Fire Protection Engrs. Oct. 1977

5) Emmons, H. W. "Fire" (in press) 8th Nat. Congress Applied Mechanics UCLA, June, 1978.

6) Emmons, H.W. "The Prediction of Building Fires", 17th Int. Symposium on Combustion, Leeds, England, 1978 (in press)

7) Land, R. "Aspects of Polymeric Materials, Proc. Nat. Symp. Fire Safety, Amer. Chem. Soc. 1977 (Home Fire Project)

8) Land, R. "Home Fires" Man and Molecules, syndicated 15 min. Radio Program, Amer. Chem. Soc. 1977 (#863)

9) Land, R. "Test Burns of Mattress and Bedclothes" Harvard Univ. HFP Tr-24-1977

10) Land, R. "1975 Bedroom Fire Test" 10 min. Color, Sound, Film, produced in assoc. with Harvard Univ. Video Serv. OIT, 1978

11) Land, R. "Flame Shape Observations" in Factory Mutual Research Corp. Report on 1977 Full Scale Test series, PRC (in preparation).

12) Min, K. "Catalytic Sensor for the Measurement of Heat of Combustion of Smoke", Harvard, Home Fire Project Tech. Report #23, Aug.1977

13) Bhagat, P. M. "Effects of Water on Wood Charcoal Combustion" Harvard, Home Fire Project, Tech. Report #22, Aug. 1977

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Contract No.: NBS 711510-1

Contract Title: Reliability Modeling of Residential Smoke Detectors.

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Project Summary: The critical nature of the applications of residential smoke detectors, in safeguarding human life and property, emphasizes the importance of the reliability of these devices. The residential smoke detectors, which are relatively inexpensive, must be essentially maintenance free over long periods of time and are required to reliably provide an early warning upon incidence of smoke and/or fire even when exposed to a multitude of environmental conditions. Therefore, it is essential that a reliability prediction methodology must accurately assess the consequences of the design, application and environmental influences upon the ability of the components and circuits employed in smoke detectors to perform their intended functions, even after many years in service.

The methodology which can be employed in the reliability assessment of residential smoke detector designs is being developed. The reliability model development utilizes reliability experiences of smoke detectors and other electronic systems in residential environments and incorporates the most current innovative reliability evaluation techniques. The methodology developed will provide the various techniques required for the identification of critical components, comparative evaluation of design alternatives, screening/test program development and will offer flexibility to accommodate future smoke detector design trends.

Progress Report: Traditional reliability assessment methodology determines system reliability figures from failure rate estimates for each of the individual components employed therein. A number of formal prediction procedures based on theoretical and statistical concepts may be employed in the calculation of component failure rates. These methods differ primarily in the level of detail and in the data from which the prediction models were derived. To determine which technique is most appropriate for residential smoke detectors or how existing techniques could be modified, the attributes of the currently available smoke detectors and future design trends were investigated. A data collection program was initiated to acquire smoke detector design information, component procurement practices, component quality and inspection techniques and field experiences from each of the major smoke detector manufacturers. In addition, the manufacturers of components employed in smoke detectors and manufacturers of other equipments employed in residential applications were contacted for similar information.

The information obtained in the data collection activities are being utilized as the basis for testing currently available reliability assessment techniques and the development of new methodology. The development of prediction models for the various components employed in residential smoke detectors is presently underway. These models are assuming forms similar to existing reliability models with parameter modifications to adequately reflect the impact of various smoke detector application characteristics on the component reliability.

Smoke detector reliability assessment also involves the determination of component criticality. Information pertaining to computerized Fault Tree and FMECA programs has been documented and reviewed to evaluate their applicability to smoke detector circuits. A comparative analysis has been performed indicating the advantages, disadvantages and requirements associated with each of the techniques. A manual Fault Tree/FMECA technique is presently being developed which will provide a standard procedure and all necessary supporting information to perform a comprehensive system reliability evaluation.

Accomplishments: A survey of the residential smoke detector manufacturers has been completed. This activity has been instrumental in the identification of current smoke detector designs, future trends and design philosophies, as well as the reliability experiences with the components employed in smoke detectors.

An analysis of computerized Fault Tree and FMECA evaluation techniques has been completed. The investigation provided a review of the computer code abstracts, code efficiencies and applicability to residential smoke detector systems for each of the analysis techniques.

Significant progress has been made in the development of reliability prediction models for the various smoke detector components. Discussions with the manufacturers have provided insight to the impact of various factors upon component and system reliability. These factors are being reflected in a quantitative fashion in the prediction models.

Potential Applications: A comprehensive reliability assessment technique dedicated specifically to residential smoke detectors would serve as an indispensable design tool for the smoke detector manufacturer and would provide the basis for performing a comparative analysis of various smoke detectors. This information, employed during the design stages, would facilitate the identification of components or design techniques which contribute to detector non-reliability and would indicate how these conditions could be minimized. In addition this information can be utilized to establish an industry-standard reliability program.

Future Milestones: The culmination of this program will be a reliability prediction handbook for residential smoke detectors. This handbook will contain all information which is required to completely assess the reliability of residential smoke detectors. Some of the major items contained in this document will include: reliability prediction models for all components, failure mode/indicator distributions for all components, procedure for manual Fault Tree/FMECA system evaluation technique, and a discussion of screening/test techniques which may be employed in the identification and removal of various types of component failures.

Reports and Papers:

Rickers, H.C., Flint, S.J. and Nicholls, D.B. "Reliability Modeling of Smoke Detectors."

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: The Johns Hopkins University, School of Hygiene and Public Health

Grant No.: G8-9001

Grant Title: Evaluation of Toxicity of Combustion Products

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Project Summary: The great majority of fire victims die of the inhalation of toxic gases rather than actual burns. The purpose of this project was to develop a sensitive animal behavioral model of the effects of the primary gases of combustion as well as the effects of combustion products. Using rats as subjects we have shown that a dose dependent alteration in the ongoing rate of behavior can be produced by 30 minute exposures to carbon monoxide. The behavior consists of a continuous avoidance schedule where animals have to press a lever every 20 seconds to avoid getting an electric shock. Increasing the CO levels decreases the rate of responding and increases the number of shocks received by the animals. The added stress of increased ambient temperatures greatly enhances the behavioral disruption, suggesting that the interaction between the toxicity of CO and temperature may be complex.

Progress Report: During the initial phase of the evaluation of toxic combustion products we have adopted a simple animal behavioral model in order to determine the effects of brief exposure to CO and elevated temperatures. Since the purpose of the experiments was to evaluate toxic effects on ongoing unrestrained behavior, whole body exposures were used in these experiments.

Twelve adult male Long-Evans rats, weighing 500-550 grams, served as subjects. They were individually housed in a controlled temperature and humidity room with a 12 hour light/dark cycle.

Each of four plexiglass avoidance chambers (20.5 x 12.5 x 21 cm) was equipped with a stainless steel grid floor and a lever connected to a microswitch mounted on the end wall. A digital computer connected to these chambers controlled the avoidance schedule and recorded the number of shocks and responses. Gas exposures were carried out under dynamic conditions with a continuous air flow of 5 liters per minute blown through a port in the top of each 5.4 liter chamber. A gas mixer with an electronically controlled microvalve (Brooks Instruments) provided precise mixtures of carbon monoxide. Chamber CO concentrations were monitored with an infrared gas analyzer (Beckman Instruments) at five minute intervals in each chamber. Concentration gradients had a rise and evacuation time to steady state of 5 minutes and were maintained within 10% of the desired level. Each chamber was placed inside a fibreboard enclosure (60 x 60 x 60 cm) equipped with a simple heater, fan, and thermostat to increase chamber temperatures. Chamber temperature was monitored continuously and maintained within 1^{o} of the desired level.

The avoidance schedule delivered brief electric shocks (0.5 sec, 2 ma) to the grid floor every 5 seconds unless the subject pressed the lever. Each response postponed the next shock by 30 seconds. Each session lasted 105 minutes with a 15 minute warm-up period from which the data were discarded followed by three 30 minute segments. The number of responses/minute, shocks/minute, and interresponse times between 2-40 seconds were printed out every 30 minutes for each chamber. Subjects were run 6 days/week with few exceptions.

Experiment I: Effects of Thirty Minute Exposure to Carbon Monoxide

Eight rats (SA 10, 11, 14, 15, 18, 19, 20 and 22) served as subjects. After their performance had become stable and reliable across daily sessions, they were exposed during the first 30 minute segment of a session to a range of concentrations of CO between 1000 and 2000 ppm in an ascending and descending order. Subjects were exposed to each concentration twice with at least 48 hours between exposures.

Results:

Carbon monoxide produced significant decreases in response rate and increases in shock frequency during the last half of the 30 minute exposures with good recovery by 30 minutes after the exposure. The effect of the CO could be seen most readily as an increase in the number of shocks delivered in the late minutes of the exposure and the minutes immediately following. While subjects differed in their sensitivity to CO, there was a significant increase in overall shock rate at 1300 ppm.

Paired statistical comparisons were made using the Wilcoxin

Matched-Pairs Signed Ranks Test (one-tailed). Control means were calculated from 10 sessions and exposure means from the mean of 2 determinations for each subject. Overall rates were based upon the 30 minute exposures and the 30 minutes immediately following. There was a concentration dependent decrease in response rate and increase in shock rate that peaked between 25-30 minutes, i.e. the last 5 minutes of the exposure although significant changes were evident as early as 10-15 minutes at 2000 ppm. In general, effects on response rate were seen at lower concentrations while effects on shock rate, when present, occurred earlier and were more pronounced. Shocks rates rose to 30 shocks/5 minutes at the peak effect of the highest concentration with the theoretical maximum for this time period being 60 shocks, indicating that the baseline could reveal much greater impairment.

Carboxyhemoglobin levels, taken at the end of the 30 minute exposure from cannulated non-performing rats were between 45-60%. These values are in general agreement with the literature for these exposure levels.

<u>Experiment 2: Effects of Environmental Temperature and Carbon Monoxide Temperature Combinations</u>

A simple heater, fan, and thermostat circuit allowed us to produce steady state (±1°C) chamber temperatures up to 40°C. On temperature control days, subjects were exposed to a constant temperature for the first 75 minutes of the session. For CO and temperature combination sessions, exposure to temperature preceeded onset of CO by 15 minutes and continued at least 30 minutes beyond the 30 minute gas exposure.

<u>Results</u>:

Subject 23 died following the second exposure to 1666 ppm at 36°C and Subject 25 died immediately following a 30 minute exposure to 40°C. All subjects showed a significant increase in shock rate at 1666 ppm at 24°C. Only one subject, SA 26, showed an effect at 32°C without CO, and this subject also showed an enhanced response to CO at 32°C. The other 3 subjects showed no significant response to 32°C. Both subjects exposed to 36°C showed a significant increase in shock rate throughout the session. All 3 subjects exposed to CO at 36°C showed an enhanced effect, with two subjects (23 and 25) showing a dramatic increase in the number of shocks taken.

Exposure to 36°C alone produced decreases in response rate and increases in shock rate that remained steady throughout the course of the exposure. This is in contrast to the effects of CO, where the effect increased sharply with duration of exposure. For SA 24, the 1666 ppm exposure at 36° produced a larger peak effect on shock rate with a much earlier onset of action with significant increases in shock rate between 5-10 minutes and decreases in response rate between 5-10 min. For the same exposure, SA 25 showed significant shock rate increases almost immediately with response rate changes lagging behind by about

15 minutes. Carboxyhemoglobin levels ($\bar{x}$ = 59.8±2.9) taken after 30 minutes at 1666 ppm and 36^{o} were not different from levels found at 32^{o} and 24^{o} at 1666 ppm ($\bar{x}$ = 56.4±2.6, 58.4±3.1, respectively). Further carboxyhemoglobin determinations at 15 minutes into the session along with body temperature measurements as an indication of metabolic state of the subject will further help characterize the physiological correlates of these effects.

Accomplishments: Our results to date indicate that the behavioral paradigm we have chosen is a sensitive indicator of the effects of CO and CO temperature interactions. The CO temperature interaction experiments also show that the animals become far more sensitive to the effects of CO at higher temperatures than at room temperature and that the effects of CO can be observed almost immediately after the CO is administered. The possibility of a synergistic effect arises from the data of animals 23 and 25 which showed an extreme deterioration in performance at 36^{o}C and 1666 ppm CO. These combinations of CO and temperature are not extremes, in fact, the CO concentrations are low when compared to CO concentrations observed in the pyrolysis of synthetic polymers where the CO concentration can exceed 5000 ppm.

Potential Applications: In order to determine the hazards encountered by human fire victims a sensitive behavioral model has to be developed. Current assessment of the toxicity of combustion products relies largely on either incapacitation, (loss of consciousness) or lethality of animals. These behavioral endpoints are not sensitive enough to predict real potential hazards to future fire victims and therefore, will have to be supplanted by animals models that help us determine the relative toxicity of materials as they affect purposeful ongoing behavior.

Future Milestones: Since during real fire situations people are exposed to a mixture of combustion products, our plan is to continue this work by exposing animals in a behavioral situation to mixtures of pure gases, at different ambient temperatures as well as mixtures of combustion products obtained by pyrolising more than one polymer at a time. With this more complex approach, using more than one behavioral technique, we hope to define the hazards of accidental fires more closely.

Reports and Papers:

The Joint Meeting of ASPET/SOT, University of Houston, Texas, August, 1978.

Institution: The Johns Hopkins University/Applied Physics Laboratory

Grant Title: Fire Problems Program

NBS Grant No.: G7-9016

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Overall Project Summary: The two principal objectives of the APL-directed Fire Problems Program, supported since 1970 by the National Science Foundation (IRPOS and RANN) or more recently by the Center for Fire Research of the National Bureau of Standards (1974) and by the National Fire Prevention and Control Administration (1975) are:

1. To quantify the medical and biochemical effects of fires on humans,

2. To investigate the physical and chemical principles of the ignition and extinction of polymers.

These topics are reported on separately as subtasks.

I. FIRE CASUALTIES STUDY

Project Summary: The objective of the program is to obtain reliable in-depth information about people exposed to fire atmospheres. The two project areas are:

A. The Fire Fatalities Project is an on-going program initiated in 1971 under the RANN Program and transferred to NBS in 1974. Case studies are made of exposures to fire atmospheres resulting in respiratory system insult. The study is limited to fatalities occurring less than 6 hours after the fire event. This eliminates most cases in which burns are the predominant cause of death.

B. Prototype "Smoke Inhalation Treatment" extension of the casualties studies was organized. A working arrangement involving the Maryland Institute of Emergency Medical Services was brought to fruition.

*Part-time.

Progress Report:

A. Fire Fatalities Project: This project consists of four major sub-efforts that involve cooperation among APL, the State Medical Examiner, the State Fire Marshal and local fire department jurisdictions. The four tasks are: (1) Case Histories, (2) Cyanide Study, (3) Heart Study in Fire Victims, and (4) Expert Assistance in Special Fire Cases.

(1) Case Histories: During the one-year period July 1, 1977 - June 30, 1978 there were 78 fatalities. This brings the total case load for the program to 580. The victims died within 6 hours after the fire and autopsies were performed with a detailed evaluation of the coronary system. A review of the circumstances at the fire scene is also included.

The fatalities during the year occurred in 69 fires with 64 of them in a residence. For the time period there were 1.1 deaths per fire.

"Smoking" was considered to be the cause of the fire in 53% of the residential cases. The human involvement was quite apparent in the overall fire problem, from ignition to casualty. Alcohol played a significant role in the majority of the "smoking"-caused fires. Other drugs played a very minor role.

Carbon monoxide poisoning was considered to be the primary cause of death in approximately one-half of the fatalities. Pre-existing heart disease in combination with carbon monoxide has been implicated in another 30% of the cases (see heart study). In approximately 10% of the cases, the cause of death cannot be ascertained.

A larger fraction of the residences in which the fatal fires occurred contained more man-made polymeric materials in furnishings than in the first years of the study. The polymers are found in all classes of furnishings for the homes as well as in clothing and building materials.

(2) Cyanide Study: A study has been underway to investigate factors in the analysis and interpretation of cyanide intake so that its role could be evaluated. A gas chromatograph with electron capture detector is used to determine blood cyanide levels.

From January 1, 1975 through March 1978, blood cyanide measurements were made on 257 cases. The distribution of the measured blood cyanide levels for the 257 cases shows that 34% of the victims had a normal level (considered to be 0.25 μg/ml of blood or less). Thirty-one percent of the cases had levels considered to be in the possibly or probably toxic ranges. The range of measured values are 0.0 to 4.3 μg/ml.

In those fires where primarily cellulosic materials were involved, normal levels of blood cyanide were found. When synthetic materials were involved that could have produced cyanide during the fire, raised levels of blood cyanide were measured in the victims.

There is no direct evidence as yet that cyanide was either the incapacitating or lethal agent in the fatalities studied. In general, a high level of blood cyanide is accompanied by a high level of blood carboxyhemoglobin. However, in a number of instances fatalities were observed in which the combined CO/HCN intake was large - even though the separate intakes were insufficient to cause death.

(3) Heart Study: This study was initiated to explore the relationship between pre-existing heart disease and blood carbon monoxide levels inasfar as lethality is concerned. Persons with pre-existing heart disease would be expected to survive for a shorter period of time in a CO contaminated atmosphere than healthy individuals. This premise is based on the assumption that heart disease jeopardizes the myocardial oxygen supply in a normal atmosphere and that relatively low levels of carboxyhemoglobin are sufficient to produce fatal heart attacks.

A measurable and quantifiable parameter of pre-existing heart disease is the degree of coronary stenosis. In addition, it is the most important and prevalent form of heart disease.

The study includes those individuals who die in a "typical" house fire while eliminating flash fires, automobile collision fires, immolations, etc.

Using a scoring system based on the amount of stenosis and the distance from the heart that the stenosis occurs, the relationship between blood carbon monoxide level and coronary artery stenosis can be examined. It is believed that high stenosis scores lead to a low carbon monoxide tolerance. However, in the presence of high alcohol intake prior to exposure to the fire atmosphere, a higher tolerance to carbon monoxide is manifested.

(4) Expert Assistance: In the past year the Fire Casualty team has aided in providing the investigations of the multicasualty Tennessee and Connecticut prison fires as well as the Cinema Follies fire in Washington, D.C.

B. "Smoke Inhalation Treatment" Extension: For some time the Johns Hopkins University Applied Physics Laboratory (JHU/APL) Fire Casualty Program has been attempting to secure a close working relationship with hospital emergency rooms treating "smoke inhalation" victims. Such a working relationship has now been provided and made functional with the availability of the Hyperbaric Medical Treatment team headed by Dr. R. A. M. Myers at the Maryland Institute of Emergency Medical Services (MIEMS) and the Director of MIEMS, Dr. R. A. Cowley. The team is part of the Shock Trauma Center at the University of Maryland Hospital within the MIEMS framework. The hyperbaric medicine facilities of the Shock Trauma Center of MIEMS will function as a "smoke inhalation center" treating serious cases of exposure to the toxic environment of fires. It will also make available data on 'serious' fire smoke injuries.

This program will permit correlation of the survivor data with the fatal fire data since fires will be covered in which both survivors and fatalities result. Fire Departments that have already committed themselves to the program are Baltimore City, Baltimore, Anne Arundel and Prince George's Counties. Howard County has also expressed an interest and will probably be participating by mid-summer of 1978.

Treatment protocols and data formats have been established. The criteria to be used for selection of patients are specifically stated in letters to the fire departments. These criteria are being used as guidelines by the participating fire departments. The basic symptomatic criteria are:

a. All unconscious patients will be transported to the Smoke Inhalation Center unless other criteria such as age, burns, etc., suggest that the patients should go to other special treatment centers.

b. Patients who are combative and incoherent or do not easily follow verbal commands will also be taken to the Smoke Inhalation Center, with the above exceptions noted.

Accomplishments: The framework of cooperation of the Fire Fatalities Studies is functioning smoothly. The special study areas such as heart and cyanide analyses are providing interesting results and procedures. The foundations for expanded effort in the treatment and studying the relationship of "smoke inhalation" survivors and fatalities have been established.

Potential Applications: Knowledge of the physical and medical causes and complications resulting in fire casualties can be used to suggest the direction for care of patients who are "overcome", designs of "fire safe" materials for use in residences, building design, and the need for more intense public education and effective detection and warning devices.

Future Milestones: Fires which have significant interest to the fire community will be included in the study. These will include special materials fires and fires in which a number of people are treated as "Smoke Inhalation" casualties as well as fires in which fire detection or suppression systems have been involved.

Reports and Papers:

1. Halpin, B.M., et al., Proceedings of the 8th Annual Conference on Toxicology, Dec. 1977, "Toxicological Aspects of a Fire Fatality Study".

2. Berl, W.G., Halpin, B.M., "An Analysis of Fatalities Caused by Fires", paper given at CIB W14 13th meeting in Copenhagen, Denmark, 29 May - 2nd June 1978.

II. COMBUSTION RESEARCH

II-A. Polymer Flammability

Project Summary: Our objective is an improved understanding of polymer combustion in terms of basic physical and chemical processes. We carried out an in situ study of the chemistry of a polymer flame by a low pressure moving wire technique (MWT). This study demonstrates the kind of information obtainable and the reproducibility of the results. The MWT functions well with charring polymers, complementing the opposed flow diffusion flame method.

Progress Report: Precision analysis of polymer combustion chemistry is favored by a steady state experiment. This requires moving the polymer in laboratory coordinates so that the flame remains stationary. In the opposed flow diffusion flame technique, the motion of the polymer is opposed to the flow of O_2. However, the steady regression of a charring polymer is controlled by the char that is formed since the char must be completely consumed before the polymer can be advanced. The regression rate must be zero if inert additives are present.

These limitations are avoided by a transverse motion. In the MWT, the polymer is coated on a supporting metal or glass core. The wire is drawn in the direction of its axis across the wake of an O_2-rich flame. The polymer flame is quenched where the wire leaves the wake. Burned polymer is continuously replaced.

Reduced pressure expands the polymer flame and makes it easier to probe the pyrolysate gases. Over the past year, we extended the MWT to reduced pressures. As a demonstration of the technique, we measured the structure of a polyvinyl chloride flame at reduced pressure (0.1 atm = 10 kNm^{-2}). The polymer was commercially coated on a fiber glass yarn, 0.2 mm in diameter. Samples were taken by a quartz microprobe and the higher molecular weight species were analyzed on a quadrupole mass spectrometer. The material evolving from the burning polymer was estimated to be 0.4% benzene and $\simeq$14% pentene isomers. Butene isomers and lower molecular weight species accounted for the remainder. The total mass flux from the burning surface was 0.17 kg $m^{-2}s^{-1}$ and the surface temperature at ignition was 660K.

Composition and temperature profiles were steady and reproducible. The polymer flame front was the surface of a cylinder, coaxial with the yarn, and opening slightly in the downstream direction at a distance of 4 to 5 mm (40 yarn radii) from the yarn. Composition and temperature profiles were also rotationally symmetric. Radial gradients dominated longitudinal and angular gradients. The hydrocarbons were confined to within 2 mm of the surface. The O_2 concentration (22% in the burner wake) dropped to 0 inside the polymer flame front where the CO_2 and H_2O levels showed increases.

Accomplishments: We developed a low pressure MWT for studying polymer combustion. We demonstrated by a detailed study of polyvinyl chloride that the MWT provides a means to identify the flammable gases which evolve under flaming conditions and to study the structure of the polymer flame.

Potential Applications: The MWT functions well with charring polymers, complementing the opposed flow diffusion flame method. The MWT is capable of clarifying the mode of action of inhibiting additives in polymers.

Future Milestones: Ignition in the MWT is highly reproducible due to the use of an O_2-rich burner flame. Ignition of a range of polymers will be studied in such a flame. The MWT has also led us to begin a theoretical study of flame propagation over polymer coated wires, with a goal of clarifying the role of longitudinal heat conduction in a metal core.

Reports

1. H. Schacke, L. W. Hunter, C. Grunfelder and R. M. Fristrom, "Combustion of Poly (vinyl chloride) Studied by the Moving Wire Technique", Sixteenth Symposium (International) on Combustion (The Combustion Institute, 1977).

2. L. W. Hunter and S. Favin, "Steady State Temperature Distribution in a Solid Cylinder Moving in the Direction of its Axis through a Cross-Flow of Hot Gas", J. Heat Transfer 99, 668 (1977).

3. L. W. Hunter and C. Grunfelder, "Heat Transfer Measurements in the Moving Wire Technique for Studying Polymer Flammability", submitted to Comb. Flame.

4. L. W. Hunter, H. Hoshall, C. Grunfelder and R. M. Fristrom, "Moving Thermocouple Measurements of Heat Transfer in Hot Gases", submitted to 10th Materials Research Symposium at NBS.

5. L. W. Hunter, C. Grunfelder, C. H. Hoshall and R. M. Fristrom, "Combustion of Polyvinyl Chloride Studied by a Low Pressure Moving Wire Technique", submitted to Comb. Flame.

II-B. Inhibition Chemistry

Project Summary: The objective of the inhibition chemistry studies has been to develop an understanding of the chemical inhibition of flames so that predictions could be made of the effect of an inhibitor based on its flame chemistry. This would have the two-fold value of suggesting promising candidates for inhibition and extinction and provide an upper limit for the effectiveness of such processes. In this work we have collaborated with the University of California, Berkeley; the University of Louvain la Neuve and the University of Göttingen.

The initial work (Ref. 1) proposed an inhibition index Φ, a dimensionless parameter which normalizes the fractional change in burning velocity with the ratio of inlet oxygen to inhibitor concentration.

$$\Phi = \frac{V - V_I}{V} \frac{O_2}{I}$$

Φ = inhibition index (dimensionless)

V = velocity (cm/sec)

I = inhibitor concentration

By identifying the dominant inhibition reactions with scavenging and cyclic recombination induced by halogen atoms, it was possible to show that this addition of new paths for radical destruction has the effect of increasing the temperature of the radical production zone.

To handle flame problems with complex chemistry, we have developed a simple zonal flame model which yields algebraic solutions. This allows realistic chemistry to be introduced while still allowing economical computations. It has been successfully applied to the hydrogen-oxygen flame (Ref. 2) and an HCl inhibited hydrogen-oxygen flame (Ref. 3).

Further study indicated that inhibition effectiveness appeared to be an additive function of the atomic constitution of inhibitors (Ref. 4). Using the zonal model, we were able to develop an algebraic relation between the inhibition index and the rates of several three body recombinations (H + Cl + M; H + Br + M and H + I + M) and to demonstrate the reasons for apparent additivity of inhibitor effect and to explain the observed deviations with changes of pressure and flame temperature in terms of changing reaction zone temperature and kinetic mechanisms. The theory allowed quantitative correlation of most of the inhibition measurements found in the literature (for CHX compounds) with these three rates and this simple model.

To supplement these studies and provide parameters, we have developed a new technique for measuring reactions at flame temperatures and applied it to several scavenger reactions (Ref. 5) and demonstrated the agreement with accepted methods (Ref. 6). The kinetics of several inhibition reactions have been studied by the discharge flow - ESR technique and by the atomic fluorescence method (Ref. 6). The struction of a low pressure inhibited flame was studied (Ref. 7).

A study of the structure of some low pressure hydrogen-oxygen flames was made in collaboration with the University of California, Berkeley and the University of Göttingen, Germany (Ref. 8).

Seven survey papers have been prepared (Refs. 9-15).

Progress Report: During 1978 six papers were prepared and/or published (Refs. 3, 4, 8, 10, 15, and 16).

Future Milestones: A summary paper on progress in the field of inhibition and extinction is planned.

We hope to explore a new theory connecting halogen extinction phenomena and basic kinetics.

Experimentally, we plan to explore the potential of the point source technique, and the gradient tube methods as measures of extinction.

Reports

1. Fristrom, R.M., and Sawyer, R., "Flame Inhibition Chemistry", AGARD 84, (1971).

2. Brown, N.J., Fristrom, R.M. and Sawyer, R., "A Simple Premixed Flame Model with Application to H_2 + Air Flames", Comb. and Flame 23, 269 (1974).

3. Brown, N.J., and Fristrom, R.M., "A Two Zone Model of Flame Propagation Applied to H_2 + Air Flames and HCl Inhibited Flames", accepted by Fire and Materials (1978).

4. Fristrom, R.M., "An Interpretation of the Inhibition of HCO Flames by HCX Compounds", to be presented at the 17th Symposium on Combustion, Leeds (1978).

5. Hart, L., Grunfelder, C. and Fristrom, R.M., "The Point Source Technique Using Upstream Sampling for Rate Constant Determination in Flame Gases", Comb. and Flame 23, 109 (1974).

6. Westenberg, A.A. and DeHaas, N., "Rate of H + CH_3X Reactions", J. Chem. Phys. 62, 3321 (1975).

7. Hunter, L.W., Grunfelder, C. and Fristrom, R.M., "The Effect of CF_3Br on a CO-H_2-O_2-Ar Diffusion Flame", Halogenated Fire Suppressants, Ed. R. Gans, ACS Symposium, Spring (1975) p. 234.

8. Brown, N.J., Eberius, K.H., Fristrom, R.M., Hoyermann, K.H. and Wagner, H. Gg., "Low Pressure Hydrogen/Oxygen Flame Studies", accepted Combustion and Flame (1978).

9. Fristrom, R.M., "Flames as Catalytic System" (in German) Katalyse, Ed. Hauffe, pp. 1-32, Walter de Gruyter, Berlin, (1976).

10. Fristrom, R.M., "Flames as Chemical Reactors" in Flames as Reactions in Flow, I. Sorgato, ed., Consiglio Nazionale delle Richerche, Roma, p. 89 (1975).

11. Fristrom, R.M., "Probe Measurements in Laminar Combustion Systems", Project Squid Workshop on Combustion Measurements, Academic Press, p. 289 (1975), also Fire Res. Abs. and Rev. 16 1 (1974).

12. Fristrom, R.M., "Flame Sampling for Mass Spectrometry", Int. J. of Mass Spec. and Ion Phys. 16, 15 (1975).

13. Fristrom, R.M., "Sampling and Analysis of Fire Atmospheres", ASTM 614 Fire Standards and Safety, A. F. Robertson, ed., ASTM-NBS Philadelphia, Pa. (1976).

14. Westenberg, A.A. and DeHaas, N., "A Flash Photolysis-Resonance Fluorescence Study of the $O+C_2H_2$ and $O+C_2H_3Cl$ Reactions", J. Chem. Phys. 66 4900 (1977).

15. Fristrom, R.M., "The Problems, Language, and Scientific Basis of Flammability Testing", to be published in the Fire Safety Panel Conference, IEEE Transactions, September 26-29, 1977.

16. Fristrom, R.M., "Polymer Combustion" to be published in the Proceedings of the 1977 Conference on Electrical Insulation and Dielectric Phenomena, sponsored by the National Academy of Sciences/ National Research Council, Albany, N.Y., 20 October 1977.

Institution:

The Johns Hopkins University, School of Hygiene and Public Health, Baltimore, Maryland.

Grant Number:

NBS Grant G7-9025

Grant Title:

(Project Smoke) Fire Problems Research and Synthesis - 1977-78.

Principal Investigator:

Marshal S. Levine, M.D., MPH, Department of Environmental Health Sciences, Johns Hopkins University, School of Hygiene and Public Health, Baltimore, Maryland (301) 955-3295.

NBS Scientific Officer:

Dr. Merritt Birky

Project Summary:

A series of investigations entitled "Project Smoke" have been carried out in conjunction with the Johns Hopkins University Applied Physics Laboratory Fire Problems Research and Synthesis program. The objective of Project Smoke has been to determine the health effects of exposure to the fire atmosphere in both civilians and professional firefighters. We have investigated the health outcome of inadvertent exposures of civilian casualties trapped in fires, as well as the acute and chronic effects experienced by professional firefighters who are repeatedly exposed to the fire atmosphere during their routine activities.

a) Levels of Acute Exposure - We have demonstrated the presence of elevated blood carboxyhemoglobin levels in firefighters who considered themselves healthy and capable of continuing their activities. Elevations of carboxyhemoglobin levels above controls were seen in sixty percent of non-smoking firefighters and were present in all smoking categories. Less frequent elevations of hydrogen cyanide were also found in all smoking categories. The levels of exposure as measured by blood carboxyhemoglobins did not relate to the firefighters' subjective evaluation of the type of exposure he was receiving. There was no relationship to the quality of smoke nor to the time of exposure. Therefore, we feel that the firefighter cannot determine his own exposure status by using common subjective measures of the quality of the fire he is fighting.

b) Civilian Casualties - We have investigated civilian casualties from building fires in the city of Baltimore and have found that the majority of fatalities were due to carbon monoxide intoxication rather than burns themselves, although burns account for more hospital days of treatment. Approximately one in seven of the fire victims in our sample had a fatal outcome.

c) Protective Effect of Breathing Apparatus - We have found that while continuous use of compressed air breathing apparatus protects firefighters from exposure to toxic gases and lack of use does not offer protection, intermittent use of the mask seems to offer little advantage over non use. This may be due to the inability of the firefighter to subjectively determine the level of exposure he is receiving at any particular time, thus encouraging him to remove his mask at inappropriate times.

Progress Report:

An investigation of the chronic effects of repeated short term exposures to the fire atmosphere has been undertaken by obtaining pulmonary function studies and electrocardiograms from firefighters. Pulmonary function tests have been analyzed to determine both obstructive and restrictive defects in pulmonary function. Results were then compared with published standards for normals as well as with a group of neighborhood controls identified through another study. Attempts have been made to relate changes in pulmonary function to subjective measures such as the number of times a firefighter has been hospitalized for smoke inhalation, the number of times he has taken oxygen on the fire ground, the number of times he brought up black sputum for prolonged periods of time, and the number of times he felt overcome on the fire ground. Objective measures of exposure included the number of fires fought, the type of company (engine, truck, or administrative and years on the service).

Computer programs have been developed which allow multiple regression comparisons of these various factors and the different measures of lung function.

Accomplishments:

Project smoke has been able to add to the understanding of the health effects of both occupational and accidental exposures to the fire atmosphere. We are developing a broad understanding of the immediate subtle effects of exposure as well as the cumulative effects of repeated short term exposures over the working life time of firefighters. And finally, we have investigated causes of death in both firefighters and civilian casualties.

Progress is being made toward understanding the nature of compromised pulmonary function occurring in firefighters and the relationship of these defects to various measures of exposure to the fire atmosphere. It appears that firefighters develop restrictive defects in their total lung capacity as compared to controls. Relating these observed defects to exact measures of toxic exposures in the fire atmosphere has been difficult due to the unanticipated nature of building fires as well as the difficulty of measuring the exact quality and quantity of exposures received.

Presentations have been made to members of the Baltimore Fire Department which have included the results of acute exposures and particularly the variable protection afforded by intermittent use of the face mask. This resulted in strengthening of already existing regulations and increased understanding and compliance on the part of the men.

Potential Applications:

The ultimate goal of investigation of the health effects of exposures to the fire atmosphere is the control of those exposures and the prevention of the disease and disability which results. A more thorough knowledge of the exact mechanisms and nature of diseases developed will allow us to improve control procedures as well as to identify those tests which best identify early pulmonary compromise.

Future Milestones:

Previously collected data pertaining to cardiovascular risk factors (EKG, BP, medical histories) requires analysis. Findings of both pulmonary and cardiac defects will be published in the scientific literature and then disseminated to the user community.

Reports and Papers:

Levine, M.S., Radford, E.P. Occupational Exposures to Cyanide in Baltimore Firefighters. J. Occ. Med. 20(1): 53-56. January, 1978.

Levine, M.S., Radford, E.P. Fire Victims. Medical Outcomes and Demographic Characteristics. Am. J. Pub. Health. 67(11): 1077-1080, November, 1977.

Hohman, B., Levine, M.S. Medical Monitoring of Toxic Exposures in the Fire Atmosphere. Submitted to Amer. J. Nursing.

Levine, M.S. Medical Monitoring and Habits of Mask Use. To be submitted to Amer. Ind. Hyg. J.

Levine, M.S., Hohman, B. The Use of the Face Mask and Protection from the Fire Atmosphere. Accepted for publication in Fire Journal.

ANNUAL CONFERENCE ON FIRE RESEARCH
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GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Loyola University of Chicago

Grant No.: NBS Grant-6-9015

Grant Title: An Assessment of Planning and Training for Fire Safety in Health Care Facilities

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NBS Scientific Officer: B. Levin

Project Summary: A quasi-experimental design was used to study the effect of fire emergency training on nursing home staff's knowledge and behavior. Six nursing homes in a Chicago suburb were divided into two groups -- first and second phase homes. First phase homes received training during the study. Second phase homes also received training, but only after the study was completed. These homes served as a comparison group. After reviewing a number of emergency plans and guidelines, the researchers developed a general, one hour training lecture in consultation with the fire department. The full training session consisted of this lecture, delivered by the city's head of the fire prevention and control, and a short (approximately 10 minutes long) slide and cassette presentation developed by the National Bureau of

Standards.

The nursing home staff's knowledge of appropriate fire emergency procedures was assessed using a questionnaire which was developed and pilot-tested by the researchers. The questions were based primarily on the training lecture. The questionnaire was administered to staff on all shifts in all six homes, both pre- and post-training in the first phase homes. Trained graduate and undergraduate students observed the behavior of residents and staff on the fire floor and near the main administrative area of the nursing home. Observers used mini-cassette recorders to record their observations. In addition a video camera directed towards the nurses' station, was positioned some distance from the station and recorded activity over a significant portion of the fire floor.

This project represents the first attempt (known to the researchers) to assess both knowledge and behavior of nursing home staff as it relates to fire emergencies. Secondly, it provides an evaluation of the effectiveness of a fire emergency training session developed by the researchers.

Progress Report: The data collection stage has been completed. The total number of respondents who completed pre-training questionnaires was 252. One to two weeks after questionnaires were completed in each home, fire drills were observed. First phase homes then received the training session about six weeks after the drill observation. The post-training questionnaire was administered in each nursing home approximately one week after training. One hundred ninety-nine staff members completed post-training questionnaires (112 of these staff members completed pre-training questionnaires). A second drill was observed approximately one week after all post-training questionnaires were administered. Second phase homes received training four weeks after this drill observation. To summarize:

Training in second phase homes															x
Post-training drill observation in all homes											x				
Post-training questionnaire in all homes									xxx						
Training in first phase homes								xxx							
Pre-training drill observation in all homes		xxx													
Pre-training questionnaire in all homes	x														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

No. of respondents	
112	Completed both pre- and post-training questionnaires
140	Completed only pre-training questionnaire
87	Completed only post-training questionnaire
339	Total number of completed questionnaires

Accomplishments: A number of specific accomplishments have been achieved. A multiple choice and true and false format survey was developed which can be used to determine the nursing home staff's knowledge of appropriate behavior in fires. In addition, an observational procedure has been developed which can be utilized to measure staff performance during a fire drill. This development is seen as a significant move towards nursing home accountability in terms of fire emergency preparedness. Whereas, H.E.W. requires 12 fire drills during a year's time, no mention is made of the evaluation of these drills. The researchers have developed a technique which can be used to provide the needed evaluation. In addition, a simple checklist evaluation form is being developed which would allow administrator's to assess their own drills (see "Future Milestones").

The emergency plans of the six participating nursing homes have been reviewed with administrators. Revisions have been completed which have made these plans more clear and comprehensive. In most cases this has meant complete rewriting of the fire emergency procedures.

A fire emergency training lecture was developed which, with only minor changes to accommodate differences among nursing homes, can be used in any nursing facility as an introductory lecture. An analysis of respondents' recall of the lecture will provide direction as to what aspects of the lecture need to be emphasized or otherwise altered (see "Future Milestones").

A final accomplishment to date has been the establishment of the computer data file. Analysis of the data has been initiated.

Potential Applications: Currently there are few regulations concerning the preparedness of nursing home staff members for fire emergencies. According to H.E.W. emergency plans must exist and fire drills must be conducted. However, there are no standards against which to judge either plans on drills. In addition, there is no provision for assessing the staff's knowledge of plans or drills.

The researchers' training lecture and model emergency plan based on the lecture -- provides a first attempt at providing the needed standards. The effectiveness of the training is being assessed, and modifications will be ascertained. In addition, the knowledge and behavior of staff members can be determined using the researchers' survey and fire drill evaluation procedure. In this manner, administrators can be assured that they are maintaining the highest level of fire emergency preparedness and they can be confident that should a fire occur, it will be dealt with efficiently and with minimal loss of lives and property.

Future Milestones: The major analysis of the data has only recently begun. There are two types of data to be analyzed. One is the responses to the survey. This material has been computerized and initial analyses have begun. The second type of information to be analyzed is the fire drill observational data. The assessment of this behavioral data is a complicated procedure and the researchers' efforts represent a unique attempt. Therefore, the researchers' are currently developing a number of possible evaluation procedures which might prove useful with this data. Future work in this area will help determine the most appropriate technique of assessment.

Both types of data -- survey and observational -- will be used to study the effect of the training session. Changes in knowledge or behavior after training in first phase nursing homes should provide an indication of the success of the training. In addition, responses to particular survey questions will demonstrate which portions of the training were easily learned and which were not. This in turn will provide information needed to improve the training material.

The data collected from the nursing homes will serve another purpose as well. It will provide baseline information of the general preparedness of nursing homes. The information should be of interest to administrators of other health care facilities.

In conjunction with the assessment of the drill observation, a simple form which can be used by administrators of nursing homes to evaluate their own fire drills is being developed. In this manner, employees can receive feedback on their performance, and further instructions when necessary.

There are two further analyses to be completed. One will serve as a reliability check on data collected previously using the Primary Source Interview (Edelman, Herz, & Bickman, 1978).* The check is on the ability of staff members to recall their behavior during a fire a number of weeks after the drill occurred. This check will provide an indication of the accuracy of responses of individuals who have been involved in simulated and real fire situations. The other analysis concerns the slide and cassette presentation which was developed by NBS and used in training. Staff responses to a short set of questions

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*Edelman, P., Herz, E., & Bickman, L. Manuscript to be published in a book concerning fire and human behavior edited by Dr. David Canter in England, in June, 1978.

concerning the usefulness of the presentation will be analyzed.

Reports and Papers:

Bickman, L., Edelman, P., and McDaniel, M. "A Model of Human Behavior in a Fire Emergency" (Manuscript to be published in a book concerning fire and human behavior edited by Dr. David Canter in England, June, 1978).

Edelman, P., Herz, E., and Bickman, L. "Applications of 'A Model of Human Behavior in a Fire Emergency' to the Analysis of a Nursing Home Fire" (Manuscript to be published in a book concerning fire and human behavior edited by Dr. David Canter in England, June, 1978).

Herz, E., Edelman, P., and Bickman, L. "Fire Emergency Training: Its Impact on the Knowledge and Behavior of Nursing Home Staff" (Manuscript to be published in a book concerning fire and human behavior edited by Dr. David Canter in England, June, 1978.

McDaniel, M.A., Bickman, L., Edelman, P., and Herz, E. "Attitudes Concerning Fire Preparedness: A Survey and Reverse Records Check" (Manuscript to be published in a book concerning fire and human behavior edited by Dr. David Canter in England, June, 1978).

ANNUAL CONFERENCE ON FIRE RESEARCH
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GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Loyola University of Chicago

Grant No.:

Grant Title: Behavioral Analysis of the Life Safety Code

Principal Investigator: Dr. Leonard Bickman, Director
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Other Professional Personnel: Mr. David Rivers

NBS Scientific Officer: B. Levin

Project Summary: The Life Safety Code, NFPA Standard No. 101, is one of many model codes that is used by various government agencies to establish minimum requirements for building fire safety. The Code is based on engineering and technical knowledge in the field of fire safety. However, behavioral and psychological perspectives were generally lacking in the development of the Code.

Within each provision of the Code there may be assumptions made concerning human behavior. The proposed research project will analyze the Code, citing relevant research findings that either support or contradict the provisions. The final product will be a behavioral and psychological analysis of the Life Safety Code by provision. This analysis will include an overview of the Code summarizing inherent themes reflecting assumptions of human behavior in a fire situation.

Institution: Lawrence Berkeley Laboratory, University of California Berkeley

Grant No.: 812464

Grant Title: Fire Growth Experiments - Toward a Standard Room Fire Test

Principal Investigator: Professor Robert Brady Williamson
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Other Professional Personnel: David Van Volkinburg, graduate student
Wai-Ching Teresa Ling, graduate student
Fred Fisher (Development Engineer - UCB)

NBS Scientific Officer: William Parker

Project Summary: A series of six room fire experiments are to be conducted in an 8x12 foot test compartment with the following lining materials on all walls and ceilings:

Test No.	WALL	CEILING
1	Gypsum Wallboard	Gypsum Wallboard
2	Glass Fiber Insulation	Glass Fiber Insulation
3	Plywood	Glass Fiber Insulation
4	Plywood	Gypsum Wallboard
5	Glass Fiber Insulation	Plywood
6	Plywood	Plywood

The ignition source for these experiments will be a gas burner in the corner with 4.9 CFM of CH_4. There will be measurements of (i) the oxygen depletion in the exhaust gases leaving the room, (ii) the average upper air temperature in the room, (iii) the pressure and temperature profile from floor to ceiling in the center of the room, (iv) the surface temperature at the center of the ceiling and on a wall above the ignition source, (v) heat fluxes at several locations and (vi) the vertical temperature profile at the door.

Progress Report: This project only started at the end of June, so as this summary is being written, the experiments are in the initial stage.

Potential Applications: The data gathered in these experiments will be useful to verify the deterministic models of fire growth, as well as support the development of a standard room fire test.

Reports and Papers:

"Toward a Standard Ignition Source," by David Van Volkinburg, R.B. Williamson, Fred L. Fisher and Harry Hasegawa. Paper to be presented to Western States Section of the Combustion Institute at the 1978 Fall Meeting, Laguna Beach, California.

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GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Lawrence Berkeley Laboratory, University of California Berkeley

Grant No.: 809252

Grant Title: Fire Modeling

Principal Investigator: Professor Patrick J. Pagni
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Other Professional Personnel: Dr. Tein-Mo Shih (now Assistant Professor, University of Maryland)
Dr. Reza Toossi (now Postdoctoral Research Engineer, Lawrence Berkeley Laboratory)
Charles M. Kinoshita, Ph.D. Candidate
Steven Bard, Ph.D. Candidate
Richard A. Beier, Ph.D. Candidate
Arthur Ortega, M.S. Candidate
David Wang (now at California State Air Resources Board)
Kevork Kayayan (now at Barry Controls Corp.)

NBS Scientific Officer: Dr. Howard Baum

Project Summary: 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 studies and theoretical analyses attempt to provide bases for eventual development of test methods and predictive capabilities for meaningful evaluation of the real fire hazard of specific materials and configurations. This work is divided into three broad categories: (1) extensions and applications of excess pyrolyzate concepts, (2) soot volume fractions in diffusion flames, (3) flat flame burner designs and experiments.

Progress Report:

1. Excess Pyrolyzate: Several papers have been published describing the effects of fuel which is not consumed locally in the flame that produced it [1,2,3,4,5]. In preparation for applying this concept to compartment fires, the well-defined, steady, two-dimensional, laminar, opposed flow, diffusion flame was considered [6]. Predictions of flame heights and excess pyrolyzate have been obtained for axisymmetric and two dimensional geometries. Agreement within ten percent with preliminary flame height experiments using PMMA in an OFDF apparatus previously described by Sawyer and co-workers has been obtained. The problem of a fuel jet impinging on a noncombustible plate with an oxidizing ambience has also been considered. Order of magnitude extention of laminar flame heights due to this impingement is predicted. In addition, experimental flame heights for PMMA were measured over a wide range of ambient oxygen concentrations in a forced flow apparatus. Agreement with predictions within twenty percent is obtained.

2. Soot Volume Fractions: Experimental values of the volume fraction of small turbulent diffusion flames occupied by combustion generated carbon particulate are listed in Table I for some of the common fuels tested.

Table I. Sample Soot Volume Fractions

Fuel	Polystyrene (Foam)	Polystyrene (Solid)	Polyurethane (Foam)	PMMA (Solid)	Acetone (Liquid)
$f_v x 10^6$	4.7	4.6	0.80	0.31	0.18

Since scattering appears to be important for flames with volume fractions greater than 3×10^{-7}, a multiwave length technique was required to determine accurate soot volume fractions. Measurement of the attenuation at several wavelengths of monochromatic laser beams passing through a flame determines, in addition to f_v, approximate detailed size distributions of the carbon particles within the flame [7]. Calculations of flame radiation back to polyurethane fuel in a pool fire geometry yields good agreement with experimental mass burning rates [8].

3. Flat Flame Burner: The detailed temperature and velocity field around a cooling coil embedded in a porous plug burner have been predicted assuming a low Reynolds number media. The results indicate that the maximum extension of the coil wake beyond the front stagnation point is 5 coil diameters and that as the distance between coils decreases, the length of the coil wake also decreases to a limit of approximately two diameters. The governing nondimensional groups have been identified and the character of the solution over their full range has been examined. Flat flame burners have been designed and built based on these results [9].

Other studies of flame spread in opposed flow, excess pyrolyzate in compartments and heat and mass transfer in wet concrete are in preparation [10].

Accomplishments: Successful comparison between excess pyrolyzate and flame height predictions and laboratory data have been obtained in a wide variety of systems. The effects of physical and chemical parameters on flame height have been clearly delineated. A technique for measuring the volume fraction of soot in flames in situ has been developed and data on f_v and detailed size distributions of combustion generated carbon particles have been obtained for several common solid, foam and liquid fuels. Temperature and velocity fields within water cooled flat flame burners have been predicted and apparata are available designed according to these analyses.

Potential Applications: Flame radiation is now 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 developed here. Criteria to be included in ranking material hazard may develop from our studies of excess pyrolyzate. In addition, similar analyses may have utility as sub-program components in compartment fire prediction models under development elsewhere. The flat flame burner described here is now in use in several laboratories and will permit useful comparisons of detailed flame structure experiments.

Future Milestones: Further applications of excess pyrolyzate calculations in systems with both external and flame generated radiation, vitiated ambience and feedback from compartment configurations are under development. Experiments are continuing to obtain data on flame lengths for comparison with predictions. The multiwavelength laser technique for in situ measurments carbon particulates in flames will be refined to give more accurate particle size distributions for a wide variety of fuels. The effects of flame scale and the variation of the size distribution in space and time will be explored.

Reports and Papers:

1. T.M. Shih and P.J. Pagni, "Excess Pyrolyzate", Sixteenth Symposium (Int'l) on Combustion, The Combustion Institute, 1329-1343, 1976.

2. T.M. Shih and P.J. Pagni, "Laminar Mixed-Mode, Forced and Free, Diffusion Flames", Journal of Heat Transfer, 100, 253-259, 1978.

3. T.M. Shih and P.J. Pagni, "Analytic Incorporation of Probability Density Functions in Turbulent Flames", International Journal of Heat and Mass Transfer, 21, 821-824, 1978.

4. T.M. Shih and P.J. Pagni, "Excess Pyrolyzate in Turbulent Wake Flames", submitted to Combustion and Flame.

5. T.M. Shih and P.J. Pagni, "Parametric Expansion Method for Two-Point Boundary Value Problems", in preparation.

6. C.M. Kinoshita and P.J. Pagni, "Excess Pyrolyzate in Opposed Flow Diffusion Flames", in preparation.

7. P.J. Pagni and S. Bard, "Particulate Volume Fractions in Diffusion Flames" accepted for publication in the Proceedings of the Seventeenth Symposium (Int'l) on Combustion.

8. S. Bard, K.H. Clow and P.J. Pagni, "Combustion of Cellular Urethane" Combustion Science and Technology, in press.

9. R. Toossi, "Physical and Chemical Properties of Combustion Generated Soot", Report LBL-7820, Lawrence Berkeley Laboratory, University of California, Berkeley, May 1978.

10. M.S. Sahota and P.J. Pagni, "Heat and Mass Transfer in Porous Media Subject to Fires", submitted to the International Journal of Heat and Mass Transfer.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Lawrence Berkeley Laboratory, Berkeley

Grant No.: NBS Contract 805180

Grant Title: Polymer Combustion and Flame Chemistry

Principal Investigators: Professor Robert F. Sawyer
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Dr. Nancy J. Brown
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Other Professional Personnel: William J. Pitz, Ph.D. Candidate

NBS Scientific Officer: Dr. R.G. Gann

Project Summary: Polymer combustion, flame inhibition, and flame chemistry are being investigated experimentally and theoretically. Fundamental characteristics of polymer combustion (extinction limits, burning rates, mass transfer numbers and flame structure) are being measured with the objective of relating basic chemical and physical polymer properties to flammability. The flame inhibition studies have been directed toward gaining an improved understanding of inhibition mechanisms which prevail in different combustion environments.

Progress Report: Establishing the conditions under which halogens are effective or ineffective inhibitors will give insight into the mechanism of their behavior. Thus, extinction data have been obtained under the conditions of oxidizer inhibitor addition and fuel inhibitor addition in the opposed flow diffusion flame. Extinction measurements reveal the effect of inhibitors on chemical reaction rate and provide a gage for inhibitor effectiveness. Data have been acquired for polyethylene (PE) and poly (vinyl chloride) (PVC) in N_2/O_2 mixtures (Figure 1). These data were compared to extinction measurements of polyethylene with $N_2/O_2/HC\ell$ mixtures (Figure 2). PVC differs chemically from PE only by a substitution of a chlorine atom for a hydrogen atom in the monomer. With the inclusion of this halogen atom, PVC may be thought of as an inhibited PE and therefore well suited for a comparative study.

A numerical boundary layer model was developed to elucidate the

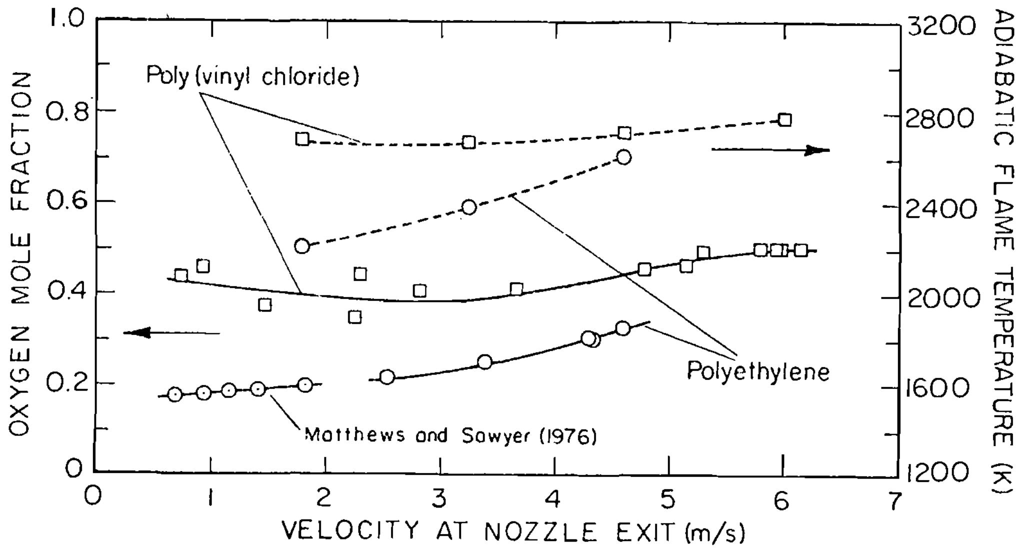

Figure 1. Extinction curves and adiabatic flame temperatures for PVC and PE with N_2/O_2 mixtures.

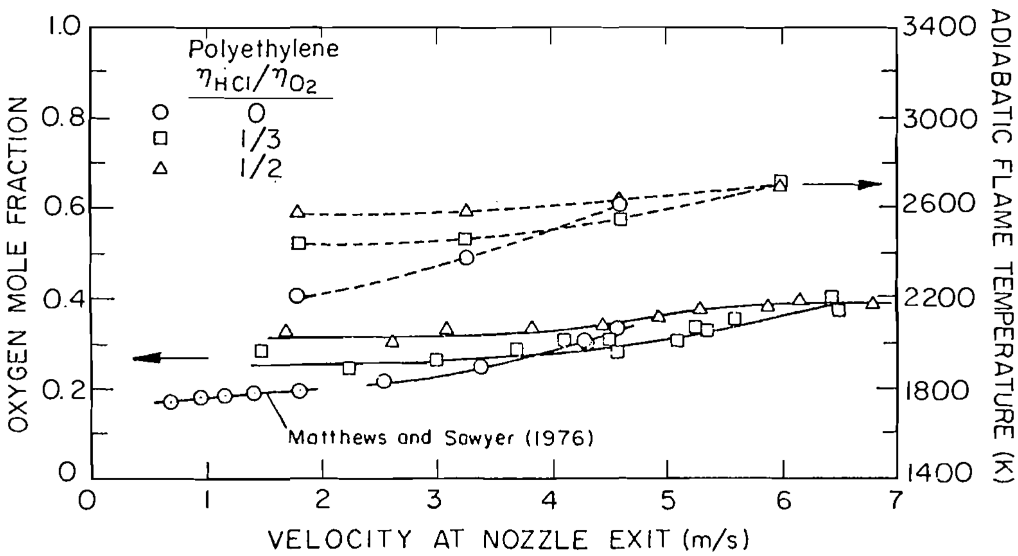

Figure 2. Effect on extinction curves and adiabatic flame temperature of further HCl addition.

analysis of extinction measurements in the opposed flow configuration. This model relates kinetic parameters to various extinction data and may indicate the influence of inhibitors on overall kinetics. Additionally, the model provides profiles of temperature, velocity, and composition across the flame.

Perfectly stirred reactor calculations of $H_2/O_2/Ar$ mixtures with the following variables: 1) inhibitor type, 2) inhibitor concentration, 3) equivalence ratio, 4) hydrogen oxidation mechanism, 5) pressure, and 6) reaction rate variation, were analyzed. The perfectly stirred reactor equations were solved for a series of residence times and the corresponding compositions and temperatures between the blowout condition and thermodynamic equilibrium were obtained. An inhibition parameter to characterize inhibition in a perfectly stirred reactor was defined.

Accomplishments: Hydrogen chloride (HCℓ) was found to be a relatively ineffective inhibitor when added to the oxidizer side of the diffusion flame in comparison to chlorine being added to the fuel side as PVC. Impurities in the commercial PVC and PE may have an effect on the extinction data. A numerical boundary layer model was devised which is useful for determining the effects of inhibition kinetics on extinction.

The blowout parameters: residence times, temperature, composition, reaction rates and heat release rates were especially sensitive to inhibitor type and concentration in the perfectly stirred reactor calculations. Radical concentrations were also found to be sensitive to the variables considered. Two physical inhibitors, Ar and N_2 and two chemical inhibitors, HCℓ and HBr, were investigated. In comparing the two physical inhibitors with HBr the following trends were noted.

Argon and nitrogen acted as physical inhibitors producing lower temperatures at blowout and increased residence times. Hydrogen bromide behaved like nitrogen for the artificial case of no hydrogen bromide kinetics. Hydrogen bromide addition resulted in increased oxygen consumption, increased blowout temperatures, increased residence times and reduced radical pool fractions. The inhibition parameter employed to provide some indication of inhibition effectiveness was a more reasonable choice to characterize argon and nitrogen inhibition but exhibited large variations with composition for hydrogen bromide inhibition. Using the inhibition parameter as an indicator of inhibitor effectiveness revealed that hydrogen bromide was found to be more effective at high pressures than low, for a H_2/O_2 mechanism which includes HO_2 reactions than one that does not, and for rich over stoichiometric and lean flames. The effectiveness of hydrogen bromide resulted in a complex trade-off between reaction exothermicity and radical scavenging ability. A comparison between the mechanisms of HBr and HCℓ inhibition is presently underway.

Potential Applications: Extinction data and their interpretation should provide a clearer understanding of the mechanism of flame inhibition from which a judicial use thereof would result in a reduction in polymer flammability. An improved understanding of flame inhibition will have useful applications in the development of flame retarded materials and in fire suppression methods. The work also applies to the development and understanding of unambiguous test procedures.

Future Milestones: Species composition data will be obtained to provide a more fundamental basis for determining the mechanism of halogen inhibition in polymers. Inhibition of moist CO mixtures will be modelled using the perfectly stirred reactor formalism. Computational studies of inhibited mixtures in plug flow will be undertaken.

Reports and Papers:

Brown, N.J. and Schefer, R.W., "A Computational Study of Physical and Chemical Flame Inhibitors," Western States Section/The Combustion Institute, Paper No. 78-43, 1978; also Lawrence Berkeley Laboratory Report LBL-6899.

Pitz, W.J. and Sawyer, R.F., "Inhibition Effects on Extinction of Polymer Burning," Western States Section/The Combustion Institute, Paper No. 78-32; also Lawrence Berkeley Laboratory Report LBL-6898.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Lawrence Berkeley Laboratory, University of California Berkeley

Grant No.: 809253

Grant Title: Thermal Radiation of Luminous Flames and Smoke

Principal Investigator: Professor Chang-Lin Tien
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Other Professional Personnel: W.W. Yuen (now Assistant Professor UC-Santa Barbara)
L.C. Chow (now Engineer at General Electric)
G.L. Hubbard
G.S. Shiralkar
T.W. Tong

NBS Scientific Officer: Dr. Takashi Kashiwagi

Project Summary: The overall goal of this Thermal Radiation of Luminous Flames and Smoke project is to establish a simple physical framework for complex fire radiation calculations. The basic research approach is based on developing approximate formulations by systematically analysing and experimenting the fundamental aspects of the problem. Considerable progress has been made in developing simple realistic calculation schemes for fire radiation. The following three studies are presently under consideration: (1) Measurements of flame and smoke radiation for burning polymeric materials (2) Further analytical development for flame and smoke radiation and (3) Computation of fire radiation and plume convection in an enclosure. These studies are being carried out with special emphasis on developing simple, realistic calculation schemes for application to actual complex situations.

Progress Report: Infrared transmittance of flames produced by burning cellular plastics has been measured by the monochromatic apparatus used by Buckius and Tien in earlier studies. It has been found that the spectral radiative properties of polystyrene foam flames and liquified polystyrene foam flames are the same. The spectral extinction coefficient for foam polystyrene, however, does not follow the inverse variation with wavelength as opposed to that of solid polystyrene reported previously by Buckius and Tien. This means that for polystyrene foam flames, the soot particle size parameter is comparable to or larger than one, hence the full Mie theory must be used and scattering cannot be neglected in making radiative heat transfer calculations. More studies on this important finding are being persued.

For facilitating analytical calculation of flame and smoke radiation utilizing the gray assumption, a scheme has been established for calculating the infrared mean (i.e., gray) absorption coefficient for luminous flames and smoke (Hubbard and Tien, 1978). The Planck and Rosseland mean coefficients are functions of temperature, the volume fraction of soot and the partial pressures of CO_2 and H_2O, and are presented in the convenient graphical form. This represents a significant extension of the earlier work on the use of the Milne-Eddington absorption coefficient for pure soot systems (Felske and Tien, 1977). Progress has been also made in achieving simple approximate solution for radiation in one-dimensional, non-planar geometries (Yuen and Tien, 1978).

Investigation on computation schemes for convection in an enclosure is being carried out. Four differencing schemes for elliptic-type convection equations have been carefully examined and their respective strengths and limitations are indicated (Chow and Tien, 1978).

Accomplishments: Effective methods of calculation have been developed for the total emissivity and the mean (or gray) absorption coefficient of luminous flames and smoke. Results have been conveniently tabulated or graphically presented. Infrared radiation measurements show that soot particles in polystyrene foam flames are much larger than those in solid polystyrene flames, and scattering contributions must be considered in polystyrene foam flames.

Potential Applications: Radiation of flames and smoke is an important concern in all practical fire problems such as fire detection, ignition, spread, plume convection, and modeling. Radiation assumes an even more prominent role in fires in an enclosure such as in urban housing fires because of the restrictions. Emissivity and mean absorption coefficient calculations developed in this study have already been used by other groups in their related studies and calculations. The finding on the difference in radiation characteristics of solid and foam polystyrene flames has considerable practical implications.

Future Milestones: Further measurements and data interpretation for flame radiation from burning cellular polymeric materials. Development of analytical techniques in calculating radiation from flames of complex geometries and with scattering contributions. Development of a computational analysis for flame and smoke plume spread in a confined system, including convection, combustion and radiation.

Reports and Papers:

Felske, J.D., and Tien, C.L., "The Use of the Milne-Eddington Absorption Coefficient for Radiative Heat Transfer in Combustion Systems," Journal of Heat Transfer, 99, 458-465 (1977); also Fire Research Group, University of California, Berkeley, Report UCB FRG 77-13.

Hubbard, G.L., and Tien, C.L., "Infrared Mean Absorption Coefficients of Luminous Flames and Smoke," Journal of Heat Transfer, 100, 235-239 (1978).

Chow, L.C., and Tien, C.L., "An Examination of Four Differencing Schemes for some Elliptic-Type Convection Equations," Numerical Heat Transfer, 1, 87-100 (1978).

Yuen, W.W., and Tien, C.L., "Approximate Solutions of Radiative Transfer in One-Dimensional Non-Planar Systems," Journal of Quantitative Spectroscopy and Radiative Transfer, 19, 533-549 (1978).

Institution: National Fire Protection Association, Boston, MA

Contract No.: DOC AO-A01-78-001004

Contract Title: Investigation and Analysis of major fires

Principal Investigators: James K. Lathrop, Fire Analysis Specialist and Project Manager
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Other Professional Personnel: A. Elwood Willey, Director, Fire Information and Systems Division
John A. Sharry, Life Safety Specialist
Wilbur Walls, Flammable Gases Specialist
Robert Benedetti, Chemical Specialist
Joseph Redden, Director, Public Protection Division

NBS Scientific Officer: R. L. P. Custer

Project Summary: Under a cost-sharing contract between the National Fire Protection Association, National Bureau of Standards and National Fire Prevention and Control Administration, 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, recreation of 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 backgrounds, 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.

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.

Progress Report: Since the signing of this present contract in March 1978, two incidents have been investigated and reports submitted to NFPCA and NBS. The first incident was a train derailment in Sidney, Nebraska where a tank car of white phosphorous exploded. In the second incident 4 fire fighters were killed during a fire in an apartment house in Syracuse, NY.

The NFPA investigation of the train derailment pointed out several safety and command problems in the handling of hazardous materials accidents by the fire service. The cause of the tank car explosion, a rare incident with this material, is being probed by National Transportation Safety Board specialists. This probe is being monitored by NFPA as it is important to fully understand the hazard and to disseminate information to the fire service.

The Syracuse, NY fire started out as a routine fire in a converted wood-frame apartment house. Tragedy struck when four fire fighters equipped with state of the art protective equipment and breathing apparatus became trapped and died of CO poisoning. An in-depth investigation was made into the spread of fire in the structure, the role of a partial sprinkler system, the role of the fire fighters' protective equipment, and fire ground operations and communications.

Accomplishments: This contract is the fourth in a series of NFPA/NBS fire investigation contracts since 1972. The two most recent contracts have also involved the NFPCA - with funding shared between the two agencies and NFPA in a cooperative effort. Since the original contract, 56 incidents have been investigated and reports prepared.

Following submittal of contract reports to NFPCA/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.

In 1977, the most important investigation concerned the Beverly Hills Supper Club fire May 28, 1977 which killed 165 persons. Under the Fire Investigation Contract, the NFPA launched an intensive study of the fire involving five specialists over a five-month period. The report covers the factors related to the fire origin and spread and factors responsible for the large loss of life. An in-depth analysis of the means of egress system is included, and the report provides important human behavior base-line data. A fire development and spread analysis conducted by NBS staff is included in the report. This is the most extensive study of a multiple-death fire conducted in recent times and the report should be a valuable addition to the literature.

Among the more notable incident investigations are:

- o Rault Center, High-Rise, New Orleans, LA, November 29, 1972, 6 killed
- o Baptist Towers Housing for the Elderly, Atlanta, GA, November 30, 1972, 10 killed

- Upstairs Lounge, New Orleans, LA, June 24, 1973, 32 killed
- LP Gas Tank Car BLEVE, Kingman, AZ, July 5, 1973, 13 killed
- Conflagration, Chelsea, MA, October 14, 1973
- Joelma High-Rise, Sao Paulo, Brazil, February 1, 1974, 179 killed
- Gulliver's Discotheque, Port Chester, NY, June 30, 1974, 24 killed
- Sac-Osage Hospital, Osceola, MO, December 3, 1974, 8 killed
- Telephone Exchange, New York, NY, February 27, 1975
- Refinery, Philadelphia, PA, August 17, 1975, 8 fire fighters killed
- Night Club Fire, New York, NY, December 18, 1975, 7 killed
- Wincrest Nursing Home, Chicago, IL, January 30, 1976, 24 killed
- Cermak Nursing Home, Cicero, IL, February 4, 1976, 8 killed
- Social Club, New York, NY, October 24, 1976, 25 killed
- Beverly Hills Supper Club, Southgate, KY, May 28, 1977, 165 killed

Potential Applications: The information gained from in-depth investigation and analysis of fire incidents has many uses both in the field and in the research environment.

Reports contain commentary on the performance of fire detection and extinguishing equipment, building assemblies and system 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: Fires are investigated on an ad hoc basis.

Reports and Papers:

Best, Richard L., Investigation Report, "Union Pacific Railroad Train Derailment, White Phosphorous Tank Car Explosion, Brownson (near Sidney), Nebraska, April 2, 1978".

Demers, David P., Investigation Report, "Four Fire Fighter Fatalities, 701 University Avenue, Syracuse, New York, April 9, 1978".

The above reports are scheduled for publication by NFPA this Fall. The following are samples of publications from previous fire investigation contracts.

Best, Richard L., "Tragedy In Kentucky," Fire Journal, Jan., 1978, NFPA.

Best, Richard L., "Disaster at Beverly Hills," Fire Command, Jan., 1978, NFPA.

Best, Richard L., "Three Die in Single Family Dwelling Fire," Fire Journal, Sept., 1977, NFPA.

Best, Richard L., "Motor Lodge Fire," Fire Journal, July, 1977, NFPA.

Best, Richard L., "Social Club Fire," Fire Journal, May, 1977, NFPA.

Best, Richard L., "Propane Gas Explosion," Fire Journal, March, 1977, NFPA.

Lathrop, James K., "Two Die in Fire in Retirement Home," Fire Journal, Nov., 1977, NFPA.

Lathrop, James K., "Buildings Design, 300 Fire Fighters Save Los Angeles High-Rise Office Building," Fire Journal, Sept., 1977, NFPA.

Lathrop, James K., "Five Dead in Mobile Home Fire," Fire Journal, July, 1977, NFPA.

Lathrop, James K., "Five Die in Fraternity House Fire," Fire Journal, May, 1977, NFPA.

Lathrop, James K., "Nine Dead in Apartment House Fire," Fire Journal, March, 1977, NFPA.

"Train BLEVE Causes Five-Alarm Structural Fire," Fire Command, Sept., 1977, NFPA.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

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
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The Pennsylvania State University
214 M.E. Bldg.
University Park, PA 16802

Other Professional Personnel: T. Ahmad, Ph.D. Candidate
H-Z. You, Ph.D. Candidate

NBS Scientific Officer: H. Baum

Project Summary: The interaction between turbulent flames and surfaces is being investigated in order to provide more complete understanding of unwanted fires within structures. The results of the study have application to the modeling of fires in structures, the design of fire detectors, and a better understanding of the fire resistance and fire spread properties of materials.

Two configurations have been considered, a fire spreading up a wall and a fire impinging on a horizontal ceiling. The study emphasizes experimental results, although integral models are constructed for the processes in order to provide a rational method for correlating the data. Measurements are made of flame position and length; convective and radiative heat fluxes to the wall; radiative heat fluxes to the ambiance; and profiles of mean quantities in the flow (velocity, temperature and species concentrations). The energy transport measurements are useful as direct input to comprehensive fire models. The flow structure measurements provide valuable information on the thermal environment of fire detectors and fire control agents (sprinklers, etc.) in the presence of fires, as well as information on flame structure which is required to determine the radiation characteristics of fires and to understand the production of toxic materials by fires.

Progress Report: Measurements were completed for turbulent fires on a vertical surface, and the results have been correlated using integral models. These results have been reported. A simple correlation was found which provides a unified method of estimating the burning rate of the surface for both laminar and turbulent flow. The data base includes both present measurements and earlier results in the literature. The correlation includes various fuel types and ambient conditions, and a wide range of radiative heat fluxes from the flame to the surface. Correlations were also found for the convective heat flux at the wall, as a function of position in the plume region above the zone of active pyrolysis; for the length of the flame; and for temperature and velocity profiles within the plume.

One wall fire condition was thoroughly documented. Profiles of mean velocity, temperature and species concentration were obtained at the end of the pyrolysis zone, within the combusting portion of the plume, at the flame tip and in the noncombusting portion of the plume. Radiative heat fluxes to the wall and the ambience, and convective heat fluxes to the wall were also measured. Qualitatively, the structure of the flame is similar to a turbulent diffusion flame although influences of wall mass transfer in the pyrolysis zone, and the cooled unburned wall in the plume region were observed. A striking feature of the flow involves the presence of relatively large concentrations of carbon monoxide in the noncombusting portion of the plume. The production of this toxic material appears to be related to the quenching effect of the wall, although a quantitative description of the process has not been constructed as yet. Since the experimental conditions are well defined, and the measurements are comprehensive, these results will be useful for developing more complete models of the chemistry, hydrodynamics and radiative properties of unwanted fires.

Current experimental work is considering fire impingement on a horizontal ceiling. Both unconfined and confined ceilings are being examined. Soot-free fuels have been tested, therefore, convective processes are emphasized.

In order to define the combusting region, measurements were completed of flame length along the ceiling for various flame strengths, fuel types and degrees of confinement. A simple correlation of the flame length along the ceiling has been found in terms of the flame height under unconfined conditions. In general, the radial spread is about 70% of the distance that the flame would rise above the ceiling position, if the ceiling were not present. Some effects of source size and degree of confinement (including a ceiling layer extending completely to the floor) were noted, but these are clearly higher order phenomena. Unconfined flame heights were found to be in good agreement with Steward's[1] correlation, which completes the information required for flame spread predictions.

The stagnation point on the ceiling, which is the position directly over the center of the fire, receives the maximum heat flux when the flame height is less than or equal to the ceiling height. A simple

[1] Steward, F.R., Comb. Sci. and Tech. 2, 203 (1970).

expression has been found to estimate this quantity for unconfined ceilings by combining results for the plume and the stagnation point boundary layer. Moving in the radial direction, the heat flux remains relatively constant for distances up to 20% of the ceiling height, and then declines in a manner which approximates Alpert's[2] model of ceiling heat transfer rates.

Current work is considering the more complex problems of ceiling heat transfer rates in the presence of a hot ceiling layer, and under conditions where the flame spreads along the ceiling. Not surprisingly, the measurements indicate that the unconfined ceiling correlations, developed for the case where the fire does not spread along the ceiling, are no longer adequate. In the absence of flame, the heat flux to the ceiling is increased by the presence of a ceiling layer. However, when the flame spreads large distances along the ceiling, the stagnation point heat transfer rate decreases. This behavior results when the cooler gases in the core of the plume impinge at the stagnation point.

Modeling the effects of confinement and flame spread along the ceiling will require extension of the theory. Measurements of temperature profiles within the flow are currently in progress to support the new modeling effort.

Accomplishments: Measurements of burning rates, heat fluxes and profiles of mean velocity, temperature and species concentrations were completed for turbulent fires on upright surfaces. Integral models have been successfully employed to provide simple algebraic expressions for estimating a number of fire properties (burning rate, wall heat fluxes, temperatures and velocities).

Measurements of ceiling heat fluxes and flame spread distance along a ceiling have been completed for fires impinging on both unconfined and confined ceilings. A simple correlation has been found for estimating the extent of the flaming region along the ceiling for both unconfined and confined ceilings. Formulas have also been developed for determining ceiling heat fluxes for unconfined ceilings, when the flame height is less than or equal to the ceiling height.

These measurements have provided a more complete picture of the structure of flames impinging on surfaces. The results have highlighted a potential problem, namely the production of toxic gases by impingement as a result of flame quenching due to the presence of a cool surface. A complete understanding of these processes will require more sophisticated models than those developed during the current investigation. The experimental results should provide valuable

[2] Alpert, R.L., Technical Report No. 22357-2, Factory Mutual Research Corp., Norwood, MA, 1974.

information required to validate more advanced models.

Potential Applications: Comprehensive models of fires within structures are currently being developed in order to provide a means of reducing the need for full scale fire tests, or at least providing a better understanding of the results of such tests. The present correlations of flame shapes, heat fluxes, etc., have been formulated so that they can be adapted for use in comprehensive fire models with little difficulty. The present results are also directly applicable for estimating the environment of fire detectors, sprinklers, etc., since these devices are normally located on or near surfaces. Information on the structure of fires near surfaces also improves the understanding of a number of standard fire tests.

In the longer term, enhanced computational abilities and continued development of turbulent combustion models will eventually allow the development of detailed models of the chemical and physical processes within turbulent unwanted fires. The present work has substantially expanded the data base available to validate such models.

Future Milestones: Additional measurements of ceiling heat fluxes will be completed, concentrating on cases where the flame extends along the ceiling and a hot ceiling layer is present due to confinement. Algebraic expressions for correlating this data will also be developed.

A more complete picture of the flow structure when a flame impinges on a ceiling will be developed. This will involve measurements of profiles of mean velocity, temperature and species concentrations within the plume, the ceiling jet and the ceiling layer. In particular, the concentration measurements should provide needed information on the radiative properties of the flow and the generation of toxic materials.

Reports and Papers:

Liburdy, J.A. and Faeth, G.M., "Fire Induced Plumes Along a Vertical Wall: Part I. The Turbulent Weakly Buoyant Region," The Pennsylvania State University, 1977.

Ahmad, T., Groff, E.G. and Faeth, G.M., "Fire Induced Plumes Along a Vertical Wall: Part II. The Laminar Combustion Region," The Pennsylvania State University, 1977.

Ahmad, T. and Faeth, G.M., "Fire Induced Plumes Along a Vertical Wall: Part III. The Turbulent Combustion Region," The Pennsylvania State University, 1978.

Ahmad, T. and Faeth, G.M., "An Investigation of the Laminar Overfire Region along Upright Surfaces," Trans. ASME, Series C., J. Heat Transfer Vol. 100, 112-119, 1978.

Liburdy, J.A. and Faeth, G.M., "Heat Transfer and Mean Structure of a Turbulent Thermal Plume Along a Vertical Isothermal Wall," Trans. ASME, Series C, J. Heat Transfer, Vol. 100, 177-183, 1978.

Ahmad, T. and Faeth, G.M., "Combustion in Turbulent Fire Plumes on a Vertical Wall," 1977 Technical Meeting, Eastern Section of the Combustion Institute, 1977.

Groff, E.G. and Faeth, G.M., "Laminar Combustion of Vertical Free-Standing Fuel Surfaces," Combustion and Flame, Vol. 32, 139-150, 1978.

Liburdy, J.A., Groff, E.G. and Faeth, G.M., "Structure of a Turbulent Thermal Plume Rising Along an Isothermal Wall," ASME Paper No. 78-HT-24, 1978.

Ahmad, T. and Faeth, G.M., "Turbulent Wall Fires," Seventeenth Symposium (International) on Combustion, Leeds, England, 1978.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Portland Cement Association

Grant No.:

Grant Title: Fire Tests of Reinforced Concrete Beams

Principal Investigator: Melvin S. Abrams, Manager
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312-966-6200

Other Professional Personnel: Dr. William Gene Corley
Dr. Tung Dju Lin

NBS Scientific Officer: Lionel Issen

Project Summary: The provision of fire resistance and reserve load-carrying capacity for reinforced concrete structural members exposed to severe fires is a particularly important engineering problem, as losses due to fire in the U.S. exceed those resulting from other extreme environmental factors which are normally considered in design. In the U.S., fire ratings for structural components have traditionally been measured by endurance or temperature rise in structural components subjected to a standard ASTM E119 fire test. When used to develop design criteria, these tests can be a very costly tool to employ on a large scale and, moreover, do not provide a basis for extrapolating to situations not covered by the limited test data. Furthermore, the ASTM E119 time temperature curve represents only one type of fire exposure.

In recognition of these factors, analytical procedures are being developed and refined at the National Bureau of Standards, the University of California at Berkeley, and elsewhere which show promise in predicting structural behavior under severe fires. These procedures enable the effects of various material parameters on thermal and structural response to be studied without resorting to expensive laboratory testing. They also make it feasible to consider alternate fire curves (time temperature histories) for design besides ASTM E119, and make it possible for the designer to consider fire explicitly as another limit state. Ultimately, this should lead to cost savings in certain structures and result in more uniform reliability for all structures.

With the increasing reliance placed on computer modeling, it is essential that the computer programs being developed be validated using experimental data; only in this way can they be used with confidence. Laboratory data can then be used to check and in some cases improve the analysis rather than to develop design aids, per se. It is generally agreed that while computer analyses offer hope in resolving the difficult problems associated with analyzing structural behavior under fire, the analyses have of yet been insufficiently validated to warrent their use in design. The work proposed herein will materially assist in this important validation phase; it will not only provide credibility to the analyses but also might suggest areas where they should be modified.

Validation of the computer models of the behavior of reinforced concrete structures under fire will be accomplished by conducting a series of six fire endurance tests of reinforced concrete beams in which:

1. Temperature distributions on the beam cross sections as well as beam distortions and deflections will be measured as functions of reinforcement cover, fire environment, and beam size.

2. Test results will be compared with calculations performed at NBS/CBT for the same beams.

These tests are to be conducted on full-scale beams representative of service conditions, and will provide valuable support to NBS in its efforts to develop computer thermal and structural analyses.

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: Professor I. Glassman, Dr. F.L. Dryer, and Dr. R.J. Santoro
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NBS Scientific Officer: Dr. T. Kashiwaghi

Project Summary: An experimental program has been undertaken to study the heat transfer mechanisms controlling the process of flame spreading over solid materials under different flame spread configurations. Efforts are particularly concentrated in the resolution of the importance of naturally induced or forced gas flows on the flame spread process. A laser doppler velocimeter facility is used to measure gas flow velocities and thermocouple probing and laser interferometry to measure the temperature fields. The measured gas velocity and temperature fields are used to construct energy balances to determine the relative importance of the different modes of heat transfer affecting the flame spread process.

Progress Report: A study of the downward propagation of flames over a combustible solid for flames propagating under naturally induced and forced air flows has been completed. A similar study for the horizontal mode of flame propagation is currently underway.

For downward flame spread in natural convection, the objective was to determine the dominant mode of heat transfer from the flame to the unignited fuel ahead of the flame. The heat transfer parameters ahead of the flame (gas phase velocity and temperature and solid phase temperature) were measured for flames spreading over PMMA cylinders of two extreme thicknesses (2" and 1/6" in diameter). The measured velocity and temperature fields were used to construct energy balances along control volumes in the gas and solid phases ahead of the flame. The results showed that the dominant mode of heat transfer is heat conduction through the solid for thick fuels and that as the fuel thickness decreases heat conduction through the gas is of increased importance. Particularly interesting was the observation that convective effects due to the entrainment of air by the flame plume play an important role in the ability of the heat to be conducted through the gas from the flame. The induced air flow moves in the direction opposing flame propagation and a substantial amount of the energy conducted through the gas from the flame goes into heating the incoming air flow.

In the forced convection case, the objective was to determine the influence of an opposed gas flow on the flame spread rate. Rates of flame spread for the downward propagation of flames over vertical cylinders of PMMA of 2.54, 0.64, and 0.16 cms in diameter were measured in an opposed forced air flow with free stream velocities ranging from 2 to 70 cm/sec. It was found that for all fuel thicknesses, the flame spread rate is independent of the opposed flow if the velocity of the flow is smaller than that induced by natural convection by the flame. For larger flow velocities, the spread rate decreases as the velocity of the opposed flow increases. It was also found that profiles of surface temperature ahead of the flame present similar characteristics with the profiles remaining unchanged for low opposed flow velocities and becoming steeper with the temperature gradients near the flame front increasing as the opposed flow velocity increases. A simplified theoretical model was developed to account for the effect of an external opposed flow on the flame spread process. It is shown in the model that the principal effect of the opposed gas flow is to decrease the thickness of the thermal boundary layer which in its turn decreases the residence time, resulting in an inverse power functional dependence between the spread rate and the magnitude of the external flow velocity.

The study of the horizontal propagation of flames in a natural convective environment is currently being pursued. This case is complicated by the fact that buoyancy forces are normal to the fuel surface. The flame induced gas flow follows a pattern similar to that of a flow past an oblique corner and a recirculation or stagnation region could be generated ahead of the flame. In addition the flame shape favors the transfer of heat by radiation from the flame to the unignited fuel. Measurements of the gas flow pattern, radiant flex at the fuel surface, gas and solid phase temperatures ahead of the flame are in progress. The results will be used in energy balance in the gas and solid phases to determine the relative importance of the different pathways of heat transfer.

Accomplishments: The results of the completed work, coupled with previous research in different geometries, thickness and fuels, resolve the present discrepancies on the dominant mode of heat transfer for downward flame spread. It can be concluded that for this mode of flame propagation the dominant mode of heat transfer is a function of the thickness of the fuel, with heat conduction through the solid being dominant for thick fuels and heat conduction through the gas becoming of increased importance as the thickness of the fuel decreases. It can also be concluded that when a forced flow of air opposes flame propagation, the flame spread rate decreases as the opposed air velocity increases, once the effect of the opposed flow is dominant on the spread process.

Potential Applications: Determination of the controlling mechanisms in the spread of fire along the surface of a solid fuel will provide a better understanding of the process of fire propagation and will help to develop models capable of predicting rates of spread. The information would be helpful in developing flammability ratings for materials and in calculating the time to flashover of rooms. An improved understanding of the effect of an opposed forced flow on the fire spread process is of importance in the study of the propagation of fire in corridors and forests where strong opposed air currents are generated by either heat released by the core of the fire or by prevailing winds.

Future Milestones: Measurements of the heat transfer parameters in horizontal flame spread will be completed and analyzed. Qualitative information will be obtained on the influence of an opposed flow in horizontal flame spread. The qualitative results will be compared with the results of downward flame spread to determine whether the flame spread configuration affects the results already obtained. Measurements will be initiated on the gas phase flow field parameters induced by an axisymmetric fire propagating horizontally over a solid surface.

Reports and Papers:

Santoro, R.J., Fernandez-Pello, A.C. and Glassman, I. (1978), "Two-Dimensional LDV Measurements of Flows Induced by Flames Propagating Over Condensed Fuels", Presented at the CLEOS 78-IEEE/OSA Conference, February 6-9, San Diego, California.

Santoro, R.J., Fernandez-Pello, A.C., Dryer, F.L. and Glassman, I. (1978), "An Application of a Two-Component Laser Doppler Velocimeter to the Measurement of Flows Induced by Flames Propagating Over Condensed Fuels", Accepted for publication in Applied Optics.

Santoro, R.J. (1978), "A Laser Doppler Velocimeter for Measurement of Flows Induced by Flames Propagating Over Condensed Fuels", Aerospace and Mechanical Science Report #1361, Princeton University.

Fernandez-Pello, A.C., Ray, S.R., and Glassman, I. (1978), "Downward Flame Spread in an Opposed Forced Flow", Accepted for publication in Combustion Science and Technology. Also presented at the 1978 Spring Meeting of the Western States Section of the Combustion Institute, April 17-18, University of Colorado, Boulder.

Santoro, R.J., Fernandez-Pello, A.C., Dryer, F.L., and Glassman, I. (1978), "Laser Doppler Velocimetry as Applied to the Study of Flame Spread Over Condensed Phase Materials", presented at the Third International Workshop on Laser Velocimetry, July 11-13, Purdue University, West Lafayette, Indiana.

Fernandez-Pello, A.C. and Santoro, R.J. (1978), "On the Dominant Mode of Heat Transfer in Downward Flame Spread", accepted for presentation at the Seventeenth Symposium (International) on Combustion, The Combustion Institute, August 20-25, University of Leeds, England.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Princeton University, Princeton, NJ

Grant No.: NBS Grant 4-9026

Grant Title: Smoldering Combustion Studies

Principal Investigators:

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Mr. D. A. Lucca, Graduate Student

NBS Scientific Officer: Dr. J. Rockett

Project Summary: The initiation and propagation of smoldering combustion in solid organic fuels, as well as its transition to flaming, are being investigated. The fuel of primary interest at present is loose-fill cellulosic insulation, both with and without known retardants.

Smolder initiation is being studied by means of a simple hot plate apparatus that closely simulates one-dimensional behavior; this permits correlation and extrapolation of the data by means of established thermal ignition theory. The data so obtained are being studied as a possible basis for a smolder tendency rating.

Smolder propagation is being examined first in the limiting cases of simple geometry (1-D forward smolder and 1-D reverse smolder) to assess the impact of configuration on smolder propagation rate and major gaseous products (vs air flow rate and retardant loading). The investigation will then focus on the role of gas phase reactions in smolder and the transition to flaming (vs retardant loading in 1-D and 2-D configurations).

The kinetics and thermochemistry of the thermal and oxidative degradation of retarded and unretarded loose-fill cellulosic insulation are also being investigated. These studies will give an insight into the mechanism and overall chemistry involved in the smolder process.

Progress Report: The problem of smolder initiation in a cellulosic insulation material resembles the ignition of a pre-mixed reactive medium which has been extensively treated by thermal ignition theory. The case of a finite layer of a material in contact with a hot wall on one surface and convective cooling on the other has been studied in the literature; the results provide a potentially useful basis for analyzing the smolder potential in such applications as attic insulation in contact with electric light fixtures. This situation is approximately simulated by means of a layer of insulation placed on a temperature-controlled hot plate. The material can either have an essentially non-reactive steady-state (if the layer is thin enough or the plate temperature low enough or the convective losses large enough) or it can ignite to smolder and be consumed. Experimentally, one finds the maximum plate temperature, as a function of layer thickness (fixed convective losses), which just permits the non-reactive steady state. This temperature function is characteristic of the insulation material (for a fixed configuration) and can be used to predict behavior in other thicknesses and also to deduce effective ignition kinetic parameters. It also provides a potential basis for rating the relative smolder tendencies of different insulation formulations though the most proper means for utilizing this information is still under study. This procedure has been applied to two commercial cellulosic insulation materials and it reveals substantial differences in behavior. Studies of the alteration in this minimum smolder initiation behavior as a function of retardant loading (e.g., borates) are now under way. These studies are intended to quantify the impact of retardants and, together with the work described below, to help clarify how they achieve this impact.

Smolder propagation subsequent to initiation is dependent on the relative direction of movement of the air flow with respect to the wave. Two limiting cases are under examination first: (1) smolder wave moving in same direction as air flow, i.e., forward smolder; (2) smolder wave moving against the air flow, i.e., reverse smolder. The latter case has been most extensively investigated by us, both experimentally and theoretically. Reverse smolder propagates as a relatively thin reaction wave (few cm) which is far from stoichiometric, yields total O_2 consumption, and moves at a rate heavily dependent on heat transfer processes. Forward smolder propagates as a thick reaction wave (few tens of centimeters at same air flow rate), which again yields total O_2 consumption but moves at a rate dictated by the stoichiometry of charred fuel oxidation. More quantitative comparisons of smolder velocity behavior, temperature, and major gas concentration profiles (vs air flow rate) are currently being made experimentally. These should substantially enhance our understanding of the mechanisms of smolder propagation in porous fuels.

Thermal analysis (TG & DSC) studies performed in conjunction with small-scale smolder tests are providing insights into the relationships of thermochemical and kinetic parameters to the smolder process of loose-fill cellulosic insulation. Thermal analysis gives the heats, kinetics, and possible mechanistic rate law involved in the oxidative and pyrolytic processes. Combining TG and DSC data furnishes a quantity we call the specific heat release rate (dq/dw) which measures the progress of heat evolution as a function of conversion. The small-scale smolder test on the same materials was carried out in a 6 x 6 x 6" screen box filled with insulation into which is placed a temperature programmable 75 watt heater rod. This test can provide comparative data on smolder tendency more quickly than the hot plate test above.

These studies indicate that the overall heats of oxidation are similar whether the retardant added is aluminum sulfate, borax, or boric acid. The heats of oxidation of retarded insulations tend to be lower initially than untreated insulation, but not sufficiently low to preclude smolder. These retardants, however, do have a significant effect on the mechanism and kinetics of this heat release process. Boric acid tends to retard the oxidation step while borax changes the mechanism resulting in a catalysis of oxidation. The retarding effect of boric acid can be overcome by conducting the smolder tests at higher temperatures.

Compounding this smolder problem of loose-fill insulation is the tendency of this combustion mode to make the transition to flaming. Current thought on this incompletely characterized transition seems to favor ignition of fuel-rich pyrolysis vapors from the front of the smolder wave by "hot spots" on the advanced part of char oxidation. Of the important hydrocarbons expected from the pyrolysis of cellulose (i.e., methane, ethylene, ethane, and propylene), we have found propylene to be particularly oxidizable in the 500 - 700^{o}C range. Carbon monoxide is also an important product in the oxidation and pyrolysis of cellulose but its rate of oxidation in the 600^{o}C region is not significant. Cellulose also produces a host of oxygenated species (aldehydes, ketones,ethers) whose competitive role in the transition to flaming is unknown and serves only to make the whole process more complex.

Accomplishments: The work on smolder initiation should lead in the near future to a potentially useful basis for assessing smolder tencency in cellulosic insulations.

Our understanding of the underlying processes of smoldering combustion has increased greatly over the state of knowledge only a few years ago. Models for initiation and propagation of smolder are now available and able to shed substantial light on how smoldering might be controlled.

Potential Applications: A knowledge of smolder initiation and propagation mechanisms coupled with a knowledge of how retardants affect these mechanisms are clearly of benefit in the attempt to produce materials with minimal smolder tendency and attendant life hazard.

Future Milestones: Specific configurations of multi-dimensional smolder propagation (simulating insulation in an attic) will be examined experimentally to assess whether new elements of behavior are implicit in non-parallel air/smolder wave travel.

The role of gas phase reactions in smolder and the transition of smolder to flaming will be examined together with the influence of retardants on these processes. The effective oxidation kinetics of pyrolysis products will be measured in separate experiments to provide a simplified kinetic description for modeling purposes.

Reports and Papers:

F. E. Rogers, T. J. Ohlemiller, A. Kurtz, and M. Summerfield, "Studies of the Smoldering Combustion of Flexible Polyurethane Cushioning Materials," Fire & Flammability, Vol. 9, January 1978, pp. 5-13.

F. E. Rogers and T. J. Ohlemiller, "Minimizing Smolder Tendency in Flexible Polyurethanes," to be published in Journal of Consumer Product Flammability.

T. J. Ohlemiller and F. E. Rogers, "A Survey of Several Factors Influencing Smoldering Combustion in Flexible and Rigid Polymer Foams," submitted to Journal of Fire and Flammability.

T. J. Ohlemiller, J. Bellan, and F. E. Rogers, "A Model of Smoldering Combustion Applied to Flexible Polyurethane Foams," submitted to Combustion and Flame.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Stanford Research Institute

Contract No.: 8-3559

Contract Title: The Effect of Fire Retardants on the Heat Release Rate of Building Materials

Principal Investigator: Stanley B. Martin, Manager
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Other Professional Personnel: Dr. Sharon K. Brauman
Mr. Robert G. McKee
Mr. Walter H. Johnson

NBS Scientific Officer: William J. Parker

Project Summary: The goal of this project is to establish a relationship between the heat release rate of cellulose and the increase in char production due to the addition of flame retardants. Water released in the char forming process dilutes the volatile pyrolysis products and thus lowers their effective heat of combustion. The char layer then acts as an insulating barrier reducing the heat flow to the reaction zone thus lowering the pyrolysis rate. The relative importance of these two effects will be investigated on this project.

We will restrict our attention to cellulose for the purpose of demonstrating the validity of the approach when it is applied to a well characterized, much studied, and hence, relatively well understood, char-producing, natural polymer. Both untreated and fire-retardant-treated specimens will be employed, the selection of fire retardants being made, in consultation with the CFR Technical Monitor, to reveal differences between practically important classes of retardants. Examples include borax-boric acid, ammonium phosphate, potassium oxalate, and zinc chloride.

Instrumented specimens approximating semi-infinite thickness will be exposed to three or more flux levels in the SRI rate of heat release (HRR) calorimeter. Continuous records of heat release with time will be acquired from which peak rates and selected time-averaged rates will be determined. Detailed temperature profiles during exposure will be measured to sufficient depths to provide gradients in virgin as well as charred material throughout the entire period of exposure.

We will attempt to measure also the specimen weight loss with time during exposure in the calorimeter. If we find, however, that the cost of the modifications needed to achieve this are prohibitive, we will then resort to a separate set of measurements of weight loss with time.

Several measurements of the resulting char will be made to provide information about (1) yields (and the dependence of yield on retardant choice), (2) chemical composition (specifically the relative amounts of C, H, and O), (3) physical properties (mainly the density from which heat conduction properties may be inferred), and (4) thermochemical measurements of residual heats of combustion. The measurement techniques will include, but are not necessarily limited to; visual gauging of char depth, microtome sampling of the char layer with depth to provide samples for chemical analysis (CHO only) and, when coupled with weight loss information, to provide an estimate of char density, optical densitometry of radioautographs of thin sections to provide an independent measure of char density with depth, and bomb calorimetry of char residues. Effects of varying retardant concentrations will not be measured. We have previously shown (see: A. E. Lipska and S. B. Martin, The Effect of Flame Retardants on Thermal Degradation of α-Cellulose in Nitrogen, SRI Project PYU-8150 (OCD Work Unit 2531C) August 1971) that the linear increase in char yield with retardant concentration predicted by theory applies approximately up to concentrations of about 2×10^{-4} mols of retardant per gram of cellulose, at which concentration the char yield has reached approximately 2/3 of its asymptotic value. Therefore, we will arbitrarily choose some fixed level of retardant concentration in the range of 1×10^{-4} to 3×10^{-4} mol/g as a consistent basis for intercomparing retardants. For a retardant having a molecular weight in the range of 100 to 200, a retardant concentration of 2×10^{-4} mol/g amounts to an add-on weight of 2 to 4 percent.

The data will be evaluated to ascertain the relative importance in the char forming process of (1) reduction in available heat through retention of unburned carbon in the char, on the one hand, and (2) the insulating character of char layers as an impediment to heat conduction into the undecomposed cellulosic substrate and a consequent slowing down of the burning process, on the other.

Since the work has just begun, there is no progress to be reported at this time.

Publications:

Martin, S.B., "Characterization of the Stanford Research Institute Large-Scale Heat-Release-Rate Calorimeter," NBS-G CR 76-54, October 1975.

Institution: SRI International

Contract No.: E0-A01-78-00-3569

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

Principal Investigator: Dr. Fred L. Offensend
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Other Professional Personnel: Mrs. Ellen B. Leaf
Mr. Scott M. Olmsted

NBS Scientific Officer: Mr. Benjamin Buchbinder

Project Summary: The purpose of this project is to test the utility of decision analysis in carrying out fire hazard analysis. The project is being conducted jointly with the Program for Information and Hazard Analysis of the Center for Fire Research. The project is focusing on the problem of upholstered furniture fire safety. Three basic strategies for addressing this problem are being evaluated: 1) do nothing, 2) proposed upholstered furniture ignition standard currently under study by the Consumer Product Safety Commission, and 3) federally required smoke detectors in all residences.

The alternatives are being evaluated on the basis total expected cost plus loss. A probabilistic model has been developed to assess the losses occurring under each alternative. The model addresses such factors as source and type of ignition, time of discovery, and flame extent. Economic analyses have also been performed to determine the total annual cost of each alternative. The analysis is carried out over time to give a time varying description of the costs and losses under each alternative.

Progress Report: The analysis of the upholstered furniture problem is nearly complete. Several presentations of preliminary results have been made to various governmental and interest groups. The results have been revised reflecting new information brought to light during these reviews, and a final documentation of results is now in preparation. We expect the report to be ready in late 1978.

Work is also underway in structuring a decision analytic approach to other problems of fire safety, including mobile home fire safety and electric transformer fluids fire safety. Our experience on the upholstered furniture fire safety problem and initial discussions in these other areas indicated that decision analysis is a powerful tool for systematically analyzing policy decisions in fire safety. The methodology provides for an explicit identification of the alternatives, uncertainties, outcome measures, and value assignments. It provides a logical structure for reviewing the consequences of the different strategies and a common vehicle for experts to test the importance of their differences. Through sensitivity analysis and value of information calculations the methodology also provides a rationale and direction for further basic fire research studies.

Accomplishments: Loss and cost models have been developed and computerized. Full-scale evaluations have been made of threee basic intervention strategies.

Potential Applications: Whereas the specific cost and loss models cannot be applied without modification to other problems of fire safety we expect that the decision analytic approach will become a major tool in the analysis of fire protection strategies.

Future Milestones: A final report summarizing the upholstered furniture analysis should be issued in late 1978.

Reports and Papers:

Buchbinder, B., Helzer, S. G., and Offensend, F. L., "Preliminary Report on Evaluating Alternatives for Reducing Upholstered Furniture Fire Losses," November, 1977. Available from Center for Fire Research (NBSIR 77-1381).

Institution: SRI International

Contract No.: 3103-6329-38008

Contract Title: Cost Effectiveness Study of Regional Fire Fighting Units

Principal Investigator: Dr. Fred L. Offensend
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Other Professional Personnel: Mr. Raymond S. Alger
Mr. Stanley B. Martin
Dr. Peter C. McNamee
Dr. Kenneth R. Oppenheimer

Department of Commerce Technical Representatives: Mr. William Bovis
Mr. Frank Steiner

Project Summary: The purpose of this project is to carry out an evaluation of alternative intervention strategies for reducing marine fire losses. The project is being sponsored jointly by National Fire Prevention and Control Administration, Maritime Administration, and National Bureau of Standards. Over a dozen different alternatives are being evaluated ranging from various training programs to programs requiring fixed hardware such as carbon dioxide systems in the engine room. The alternatives are being evaluated on the basis of cost plus loss. The project has drawn heavily on the decision analysis and fire science capabilities of SRI. Considerable expertise has also been utilized from the marine community.

Progress Report: Probabilistic models have been developed to assess the costs and losses occurring under each intervention strategy. Data for the model were obtained from historical statistics as well as expert judgment. The models have been computerized and an evaluation of alternatives has been carried out. Documentation of final project results should be available in autumn, 1978.

Accomplishments: Probabilistic models have been developed to assess the costs and losses occurring under each alternative. Previously unavailable expert judgments have been obtained characterizing the technical performance of each alternative. Whereas initially there was much disagreement on the performance of the different alternatives, the structure of our analytical models has allowed the experts to identify their differences. In most cases we found that the differences were the result of different assumptions on the type of fire under consideration, and once we precisely defined the fire conditions, the experts were able to resolve their differences.

Potential Applications: The project has provided a structured approach for evaluating a previously controversial fire protection decision. The probabilistic models do not eliminate uncertainty, but they do show the implications of existing levels of uncertainty. Even under conditions of uncertainty, we often find that many alternatives are clearly superior to others, and that many alternatives can be eliminated from the decision problem without resolving the uncertainty. The underlying approach of using decision analytic methods in conjunction with fire technology expertise provides a rational means for evaluating fire protection strategy under conditions of uncertainty.

Future Milestones: A final report will be issued in autumn, 1978.

ANNUAL CONFERENCE ON FIRE RESEARCH
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NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Textile Research Institute, Princeton, N.J.

Project Title: Flammability and Combustion Behavior of Textiles

Principal Investigator: Dr. Bernard Miller
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Other Professional Personnel: Dr. J. R. Martin
Charles H. Meiser, Jr.
Rudolph Turner
William W. Leoniy

NBS Scientific Officer: John Krasny

Progress Report: During the past year this project has been mainly concerned with the use of convection calorimetry to investigate the influence of various chemical and physical parameters on the burning behavior of textile materials. The Convection Calorimeter, developed at TRI, is a device which is capable of producing a continuous record of the rate at which heat is emitted from a substance burning under natural convection without the need to specify the location and nature of any target for the heat.

Three major aspects of this work have been: 1) the burning of oil-treated fabrics, 2) the effect of disperse dyes on the flammability behavior of polyester fabric, and 3) the influence of porous and nonporous substrates placed in close contact with burning fabrics.

Accomplishments: It has been shown that the presence of adsorbed oils on fabrics can increase the amount of heat emitted by burning fabrics, in some cases approaching the maximum possible heat output. The study of dyed polyester fabrics has revealed that nearly all dyes used for this purpose make the fabric more easily ignitable and certain classes of dyes cause increased heat output. The study of porous and nonporous substrates has led to a method for separating the extinguishing effects of inert heat sinks and vapor transport barriers.

Reports and Papers:

Miller, B., Martin, J.R. and Meiser, C.H., Jr., "Design, Calibration, and Use of a Convective Air Flow Dynamic Calorimeter," Thermochimica Acta, Vol. 20, 253-61 (September 1977).

Martin, J.R. and Miller, B., "Effect of Calcium Salts on the Flammability Behavior of Fabrics," Textile Chemist & Colorist, Vol. 9, 20-24 (December 1977).

Miller, B. and Meiser, C.H., Jr., "Heat Emission from Burning Fabrics; Potential Harm Ranking," Textile Res. J., Vol. 48, 238-43 (1978).

Institution: Underwriters Laboratories Inc.

Grant No.: G8-9010

Grant Title: Measurement Of Air Flow Around Doors Under Standardized Fire Test Conditions

Principal Investigator: Robert M. Berhinig
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Other Professional Personnel: G. T. Castino
Managing Engineer
Fire Protection Department

NBS Scientific Officer: Lionel Issen

Project Summary: Using standardized fire test methods, data will be developed for the evaluation of the leakage of smoke around the peripheries of four types of fire doors under conditions of high temperature.

The test method to be used is entitled "Smoke Control Door and Shutter Assemblies-High Temperature Tests," proposed by the International Organization for Standardization (ISO-DP5925).

To develop data, five fire tests will be conducted on four separate door assemblies mounted in brick walls. The door size will be 3 ft by 7 ft. The door types will include:

A) Hollow Metal Type, Stiffener Design, No Glass

B) Hollow Metal Type, Stiffener Design, 100 sq in. Vision Light

C) Hollow Metal Type, Stiffener Design, 1200 sq in. Vision Light and

D) Wood Covered Composite Type, No Glass.

The fifth door assembly will include the same door type as described in A. This assembly will be used for calibration purposes.

The fire tests will be conducted using the method of ASTM E152 and UL10(B), with three exceptions. The pressure in the furnace chamber will follow the criteria specified in ISO-DP5925 and the doors will be mounted so that the normal direction of swing is away from the furnace. The hose stream portion of the ASTM E152, UL10(B), method will not be utilized.

Accomplishments: A calibration test was conducted on June 13, 1978, and observed by Mr. L. Issen and Mr. L. Cooper of NBS.

The performance of the furnace, door assembly, collection hood and data recording instrumentation performed satisfactorily during the initial 40 minutes of the test. At approximately the 40 minute mark, the positive furnace pressure was increased to approximately 25 Pa at the request of the NBS representatives. As the furnace pressure was increased, air leakage developed along the seams of the collection hood and the test was therefore terminated.

Upon conclusion of the test, the following items were reviewed with an intent to improve the data development possible during future tests:

A) An improved synchronization method for the opening and closing cycles of the purge doors on the collection hood should be designed.

B) An electronic means should be provided to record the opening and closing of the purge doors.

C) Additional light should be provided inside the collection hood to enable better visible observations of the door assembly during the test.

D) The data developed during the test should be transmitted directly to magnetic tape.

Since the June 13, 1978 test, a new collection hood has been fabricated. This hood includes 16 MSG steel skin in lieu of 0.060 in. thick aluminum and all joints between the skin and the hood frame have been continuously welded. The opening and closing cycles of the purge doors have been synchronized with the addition of an electric solenoid valve and timer to control air flow into a pneumatic operator. The opening and closing cycles of the purge doors have been connected electronically to the data logger by means of a micro switch.

For the subsequent tests, all data inputed to the data logger will be immediately recorded on magnetic tape. The installation of the magnetic tape recording instrumentation is expected to be completed by September 29.

In addition to the above items, the representatives from NBS suggested the test method be revised as follows:

A) The furnace pressure be increased to approximately 125 Pa from the 10 $\pm$ 5 Pa specified in ISO-DP5925.

B) The purge door cycle of the collection hood be revised to 3 min of opening and 2 min of closing from 4 min of opening and 1 min of closing as specified in ISO-DP5925.

To resolve these two items,a meeting has been scheduled for August 16 at NBS. The next fire test should be conducted by October 6. Based upon the anticipated mutual agreements to be commenced during the August 16 meeting and the satisfactory operation of the magnetic tape recording instrumentation.

Potential Applications: The test results may be used for the development of a Standardized Test Method to Determine Air Leakage Through Fire Doors and Frames. The data may also be used to calculate the volume of air and combustion gases during standardized fire conditions that may flow through openings between fire doors and door frames from the fire to non-fire side.

Future Milestones: It is anticipated that the five fire tests will be completed by October 27, 1978. The data developed during each test will immediately be forwarded to the NBS. The data will be on magnetic tape. The Report of the investigation will be delivered to NBS by December 15, 1978.

Reports and Papers: None.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: University of Arizona

Grant. No.: G8-9016

Grant Title: Evaluation of the Combustion Toxicology of Several Polymeric Materials

Principal Investigator: Dr. J. Wesley Clayton
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NBS Scientific Officer: Merritt Birky

Project Summary: The purpose of this research will be to evaluate the combustion toxicity of nine types of polymeric materials (including Douglas fir).

The field of combustion toxicology, or more precisely stated, the inhalation toxicology of combustion products, is in developmental stages. Thus, the parameters for evaluating toxicity have not yet been firmly established in a systematic way. It may even be extremely difficult, if not impossible, to arrive at a "standard" test procedure because of the complexities which inhere in this special area of inhalation toxicology.

Accordingly, round-robin investigations need to be conducted in order to assess toxicity and identify polymers which yield products of unusual toxicity. In this project we propose to determine the acute inhalation toxicities of the designated samples and to assess the relative toxicities from the data which emerge from the experiments.

Samples will be subjected to flaming and smoldering conditions. The latter is defined as the maximum temperature at which auto-ignition is not initiated (i.e., ca. 15°C below auto-ignition point). The former is defined as that temperature at which auto-ignition does occur (≥800°C). These conditions may be modified to conform to other combustion questions. For example, fixed temperatures such as has been used to determine an "ALT".

Combustion of Douglas fir and rats exposed to its combustion products will provide the basis for evaluation of the toxicity of the other samples.

Exposure Chamber Characteristics/Operation

- Chamber type: Head-only exposure, "static" conditions, i.e., combustion products generated as close as possible to animal compartment

- Operation: Rapid rise in the concentration of combustion products. Prior check of O_2 drop, temperature rise, products concentration.

- Temperature: $\leq$35°C inside chamber during exposure. Recorded during exposure. Initial chamber temperature 22 $\pm$ 1°C.

- Construction: Lucite, stainless steel, Potts-type heater, Ref. J. Combustion Toxicol., 4:114 (1977).

- Duration of exposure: Maximum 30 minutes, unless otherwise required.

- Chamber oxygen concentration $\geq$18% (vol.)

- Chamber volume: 60 liters

Analysis of Chamber Contents

- Oxygen, carbon monoxide, carbon dioxide analyzed at 3-5 minutes frequency.

- Chamber temperature and humidity

- Other potential combustion products, e.g., HCl, HCN analyzed as required by polymer type

Biological Parameters

- Animals: male rats, initial weight - 250 to 350 grams. Observed for health indices for one week prior to exposure. Necropsy pre-exposure of enough rats to assure freedom from significant respiratory disease and suitability for exposure.

- Six rats per exposure. Record body weight before and immediately after exposure and for two weeks thereafter prior to necropsy. Mortality data, Dose response, Miller-Tainter method.

- Gross observations within chamber for toxic responses

- Leg flexion system for evaluation of time to incapacitation, conducted during exposure

- Behavioral: pupillary reflex, righting reflex, pain response, respiration characteristics (rapid, deep, abdominal, etc.), open field test, posture lachrymation, chromorhinorhea. Conducted post-exposure and compared with control observations and leg flexion data.

Institution: University of California, Berkeley

Grant No.: G7-9006

Grant Title: Fire Growth and Testing Section in "Fire Safety in Urban Housing"

Principal Investigator: Professor Robert Brady Williamson
Department of Civil Engineering
University of California
Berkeley, California, 94720 415-642-5308

Other Professional Personnel: David Van Volkinburg, graduate student; Wai-Ching Teresa Ling, graduate student; Harry Hasegawa (now at Lawrence Livermore Laboratory); Bob Draemel (now at General Electric, San Jose); Fred Fisher, Asst. Development Engineer.

NBS Scientific Officer: Daniel Gross

Project Summary: This grant covers two areas of fire research: 1) fire growth experiments and 2) post-flashover fire tests. The objective of the first area has been to establish methods for evaluating the contribution of room furnishings and finishing materials to fire development. The objective of the second area has been to more clearly define the relationship between requirements for post-flashover fire endurance and the fire resistance of building components.

An event logic analysis has been applied in both areas and a state transition model has been developed which extends from pre-fire conditions through full involvement in the room of origin. Fault tree analysis has been coupled to the state transition model for those events

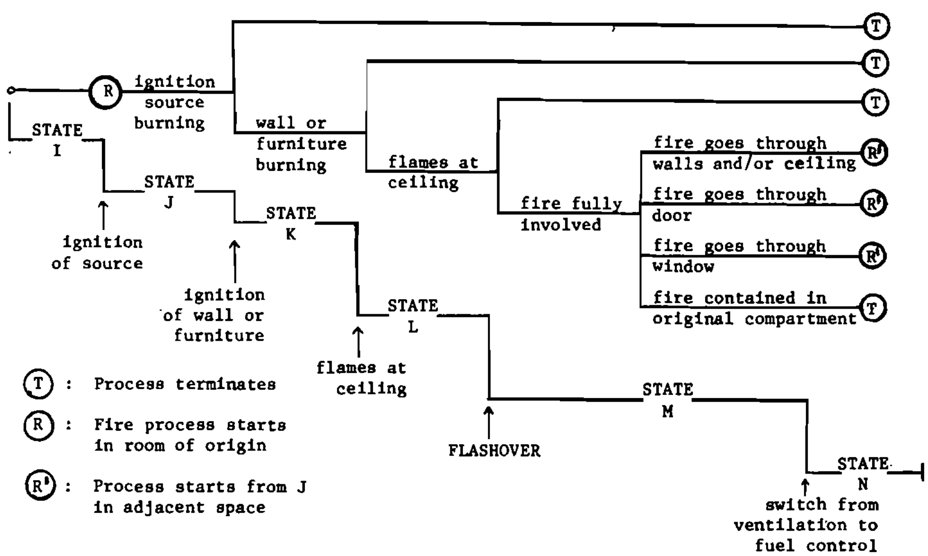

Figure 1. State Transition Model for Room of Origin.

which are intrinsically stochastic or cannot be reliably predicted by deterministic means.

A modular experimental compartment has been constructed to facilitate full-scale room fire growth experiments. A number of ignition sources have been evaluated and a series of trash bag sources that are uniform, realistic, reproducible and fast-acting have been developed.

Progress Report: The state transition model for fire growth is shown in Figure 1. The events shown there are not necessarily the only events which could be chosen, but, as previously reported (1), they represent observable phenomena that are useful in quantifying full-scale fire tests. The histograms and cumulative distribution functions (CDF's) for the observed state durations can be directly utilized as probabilities of the end event for tested materials (1).

One of the special features of the state transition model in Figure 1 is that it spans the entire duration of fire in the room of origin, and subsequently, in adjacent spaces, the fire growth process starts from a new state J where the flames emerging from the room of origin can be considered the ignition source. This is schematically represented by the symbol (R') in Figure 1.

The events which mark the beginning and end of the states shown in Figure 1 can be considered as the top event in a fault tree. The goal of fault tree construction is to model the system conditions that can cause the undesired event at the top of the tree. When fault trees are constructed for the fire protection system of a whole building, they are quite large and complex; but when they are applied to the limited number of state transition events, they can be relatively simple and the very important time factor is automatically taken into account. An example of one fault tree is shown in Figure 2 where the ignition event is the top event and the three principal sources of real fire ignitions are limited to ignition through an "or" gate.

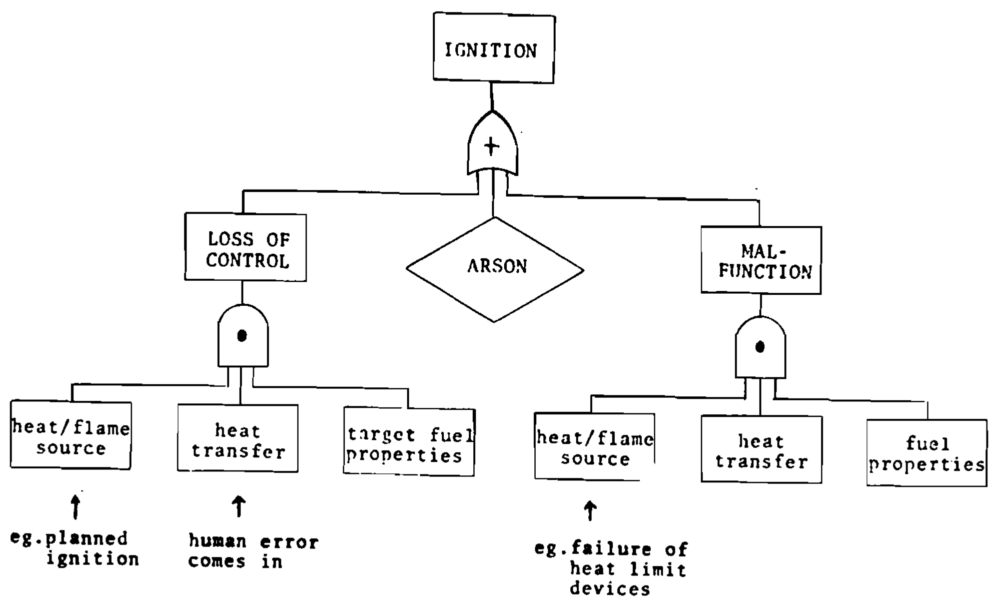

Figure 2. A Simple Form of the Fault Tree for Original Ignition Process

The arson event is shown as undeveloped while the "loss of control" and "equipment malfunction" are further developed through the logic of the NFPA "decision" tree (2). Each of the events in the fire growth model can be treated in a similar manner, as shown in the final report of this project (3). If a deterministic prediction can be substituted for the fault tree, then the top event can be subjected to calculation like the failure of a column. An example of this is developed for the switch from ventilation to fuel control in a fully developed fire. (Those aspects of the research dealing with room fire experiment will be discussed in the following summary).

Accomplishments: The event logic approach has been proven a valuable way to analyze full-scale fire tests and to quantify their results. This has been extended to develop a correlation between laboratory scale fire tests and actual fire conditions as represented by full-scale experiments (3).

Potential Applications: The use of old fire tests to evaluate new materials, products or systems must be confirmed by full-scale fire tests. The event logic, state transition and fault tree approaches can facilitate this comparison. We would be most willing to help anyone in this endeavor.

Reference List

(1) Williamson, R.B., "Fire Performance Under Full-Scale Test Conditions -A State Transition Model," 16th. Symposium (International) on Combustion, pp. 1357-1371, The Combustion Institute, 1976.
(2) Roux, H.J., NFPA Technical Committee Reports, 1B, 1370, 1974.
(3) Williamson, R.B., "Fire Growth and Testing", UCB FRG Report 78-2.

Reports and Papers:

1. "Post-Flashover Compartment Fires: Basis of a Theoretical Model," by V. Babrauskas and R.B. Williamson, Fire and Materials, Vol. 2, 1978, pp. 39-53; UCB FRG 77-14.

2. "The Historical Basis of Fire Resistance Testing, Part I," by V. Babrauskas and R.B. Williamson, Fire Technology, Vol. 14, 1978, p 184-194, UCB FRG 77-16.

3. "The Historical Basis of Fire Resistance Testing, Part II," by V. Babrauskas and R.B. Williamson. To be published in Fire Technology, November, 1978.

4. "Temperature Measurement in Fire Test Furnaces," by V. Babrauskas and R.B. Williamson, Fire Technology, August 1978, p. 226-238. UCB FRG 78-1.

5. "Fire Growth and Testing," by R.B. Williamson. UCB FRG 78-2.

6. "Application of Fault Tree Analysis to Ignition of Fire," by Teresa Ling and R.B. Williamson. Paper to be presented to Western States Section of the Combustion Institute at the 1978 Fall Meeting, Laguna Beach, California.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: University of California, San Diego

NBS Grant No.: G8-9005

Grant Title: Studies of Flame Extinction in Relationship to Fire Suppresion

Principal Investigator: Professor Forman A. Williams
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Other Professional Personnel: T. Mitani (Graduate Student)
K. Seshadri (Graduate Student)
Paul Clavin (Visiting Professor)
Alvin S. Gordon (Adjunct Professor)

NBS Scientific Officer: T. Kashiwagi

Project Summary: The objective of this work is to develop an improved understanding of mechanisms of fire suppresion by studying flame extinction in the presence of suppressive agents. Main suppressants considered are nitrogen, halons and powders. Principal configurations studied are the counterflow diffusion flame produced by directing an oxidizing gas stream, containing suppressant, downward onto the burning surface of liquid or solid fuel, and the downward propagation of premixed flames through quiescent mixtures contained in tubes. Data include concentrations (obtained by sampling and gas chromatographic analysis), temperature profiles (measured with thermocouples), flame shapes, flame speeds and extinction conditions. Results are interpreted on the basis of theory which specifies a critical Damkohler number for extinction. Plan is to apply the theory to extract overall chemical kinetic information under conditions near extinction, to attempt to relate such information to chemical kinetic mechanisms underlying suppresion, to ascertain differences in the thermal, flow and kinetic aspects of extinction by the different agents and to consider theoretical prediction of suppression under nonideal conditions. For the premixed flames, cellular structure occurs, and considerable theoretical development is needed for describing properly the cellular structures and their influence on extinction conditions.

Progress Report: Although approval to begin work on the present grant was first received in May, 1978, the work in many respects represents a continuation of research performed under an NSF grant that terminated in February, 1978. Therefore previously unreported progress made under the NSF grant is included as part of this report, and up-dated information on reports and papers produced under the previous grant is included.

In continuing investigations of diffusion-flame extinction, fuels studied were methanol, heptane and wood, and suppressants considered were water and nitrogen. The configuration studied was the counterflow diffusion flame produced by directing an oxidizing gas stream, containing the suppressant, downward onto the burning surface of a condensed fuel. Data included concentration profiles (obtained by sampling and gas chromatographic analysis), temperature profiles (measured with thermocouples) and extinction conditions (in terms of suppressant content and flow rate of oxidizer). Overall rate parameters for the gas-phase combustion of these fuels were obtained through evaluation of a critical Damkohler number for extinction. The influence of water on flame extinction was observed to be thermal, and it was found that the extinction mechanisms for gas-phase diffusion flames above cellulosic fuels are similar to those observed for liquid fuels.

Some progress has been made in developing improved instrumentation for investigation of the diffusion-flame combustion. Through a separate equipment grant, a dye laser was acquired for the purpose of measuring OH concentration profiles in the diffusion flame by the method of resonance florescence. Such a concentration profile for a radical species may usefully supplement previously measured profiles of concentrations of major stable species, to enable the chemical kinetics of the diffusion flame to be understood more thoroughly. The dye laser is being tested and aligned in the laboratory to make the desired measurements. Also acquired with aid of separate funds was an optical multichannel analyzer, to be used to study spectra in the diffusion flame. This equipment is beginning to be set up, first for the purpose of establishing whether the yellow-orange emissions observed when CF_3Br is added arise from carbon continuum or bromine lines.

Studies of downward propagation of premixed flames of hydrogen-oxygen-nitrogen mixtures in open tubes have progressed appreciably. Improved data were taken on flame speeds and on effects of CF_3Br addition on flame propagation. Also more thorough photographs of cellular structures, of their dependence on mixture ratio and of their time-dependent behavior were taken. Theoretical studies of kinetic mechanisms established a drastic cutoff in reaction rate at temperatures below 1000^oK, casting doubt on the utility of a simple, one-step reaction model with a constant overall activation energy. Nevertheless, the theoretical implications of such a model on cellular structures were pursued further. Special attention was given to study of two-reactant systems with different Lewis numbers for each reactant. Results obtained previously for propagation speeds of planar flames in such systems were clarified, and the stability of planar flames in such systems was studied, resulting in formulas, which remain to be checked, for influences of differing Lewis numbers on stability boundaries. In addition, some theoretical work on nonlinear stability analysis, on steady curved flames and on estimations of flame-temperature changes associated with curvature, was performed. These studies, still in progress, are directed toward obtaining improved understanding of limit phenomena in premixed systems.

Accomplishments: Accomplishments of the previous grant, not previously listed, are demonstrations that extinction measurements for methanol, heptane and wood are consistent with the hypothesis that water influences flame extinction by a thermal mechanism, and indications that extinction mechanisms for gas-phase diffusion-flames above cellulosic fuels are similar to those for liquid fuels. In the present grant, further clarification has been achieved of the methods whereby cellular-flame structures influence the near-limit and extinction behavior of downwardly propagating premixed flames in tubes.

Potential Applications: Long-term applications of these results consist mainly in possible improvemenst 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. The work affords the possibility of extracting basic information on both the fluid mechanics and the chemical kinetics of combustion near extinction, which may be useful in analyzing extinctions under widely different conditions of burning and of suppressive action.

Future Milestones: Many tasks remain to be done in this project. Concerning premixed flames, measurements of percent of fuel unburnt as a function of increasing dilution will be made, measurements of effects of chemical suppressants on flame speeds and extinction will be made, and theories of cellular flames in relationship to extinction phenomena will be pursued further. Concerning diffusion flames, extinction conditions and temperature and concentration profiles will be measured for polymers other than polymethylmethacrylate, extinction tests will be made with chemical suppressants other than CF_3Br, influences of CF_3Br on solid fuels will be investigated, profiles of OH in the diffusion flame will be measured by use of a dye laser, theories of diffusion-flame extinction accounting for differences in molecular weights will be investigated, and theoretical analyses of chemical kinetic influences of chemical suppressants will be pursued.

Reports and Papers:

Seshadri, K. and Williams, F. A., "Laminar Flow between Parallel Plates with Injection of a Reactant at High Reynolds Number," International Journal of Heat and Mass Transfer, 21, 251-253 (1978).

Bregeon, B., Gordon, A. S. and Williams, F. A., "Near-Limit Downward Propagation of Hydrogen and Methane Flames in Oxygen Nitrogen Mixtures," Combustion and Flame, to appear, 1978.

Seshadri, K. and Williams, F. A., "Structure and Extinction of Counterflow Diffusion-Flames above Condensed Fuels: Comparison between Polymethylmethacrylate and its Liquid Monomer, both Burning in Nitrogen-Air Mixtures," Journal of Polymer Science, to appear, 1978.

Seshadri, K. "Structure and Extinction of Laminar Diffusion Flames above Condensed Fuels with Water and Nitrogen," Combustion and Flame, to appear, 1978.

Seshadri, K., "Studies of Flame Extinction," Ph.D. Thesis, University of California, San Deigo, 1977.

Institution: University of Maryland, College Park

Grant No. NBS Grant 7-9014

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

Principal Investigator: Dr. John L. Bryan, Professor and Chairman
Department of Fire Protection Engineering
University of Maryland
College Park, Maryland 20742
(301) 454-2424

Other Professional Personnel: Mr. Philip J. DiNenno, Research Assistant

NBS Scientific Officer: Dr. Bernard Levin

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

The study population is currently limited to health care and educational occupancies, with other significant occupancy fires within the following criteria for the selection of fire incidents: 1. Any known nursing home or hospital fire in the State of Maryland that involved staff procedural action, the evacuation of one or more rooms, the operation of a fire extinguisher, or the occurrence of any personnel injuries. 2. Any known school fire that involved the evacuation of the students, and procedural extinguishment action by the public fire department. 3. Any known fire in a business, residential, mercantile or public assembly occupancy that involved the evacuation of more than 200 occupants.

Progress Report: The detailed information from the interviews and the questionnaires is studied to determine the behavior response patterns of the participants, and the psychological, sociological, educational, and physical variables influencing the predisposition to the adopted response. Thus, the total interactional context of the individual, the functional population, the time variables, the parameters of the fire incident, and the physical environment of the structure in relation to detection, alarm, protection and evacuation variables is being studied. The study has obtained data on minor or successful fires, in which the fire incident was successfully controlled by personnel without the assistance of the public fire department. The behavior response patterns from the fire incidents of the non-threatening type are being compared with the fire incidents which were perceived to be threatening to the extent the assistance of the public fire department was requested by the occupants.

A total of fourteen fire incidents were under study and analysis as of July 1, 1978, with a reporting rate of six fire incidents per month having been obtained in June of 1978. The mapping procedures with the graphical illustration developed by Lerup have been applied to these studies.

Potential Applications: The mapping and graphical illustrations with the temporal sequence analysis developed from the previous study by Lerup, would appear to be applicable to fire study reports from both governmental and private organizations. The determined behavioral response patterns should be of interest to personnel involved in the establishment of specifications and procedures relative to egress facilities, signing requirements, lighting standards, alarm requirements, and exit aids in buildings.

Future Milestones: The analysis of the critical features of the behavioral response patterns between the successful or minor fire incidents, and the unsuccessful fire incidents, requiring public fire department assistance will be conducted. The indicated sociological, psychological, and personal relationship influence between patients and staff in the health care occupancy fire incidents will be studied.

Reports and Papers:

Bryan, John L. and Philip J. DiNenno, An Examination and Analysis of the Dynamics of the Human Behavior in the Fire Incident at St. Joseph's Hospital, Philadelphia, Pa. on August 10, 1977. College Park: University of Maryland, Fire Protection Engineering, May 31, 1978.

Bryan, John L. and Philip J. DiNenno, An Examination and Analysis of the Dynamics of the Human Behavior in the Fire Incident at the Kensington Gardens Nursing Home on January 1, 1978. College Park: University of Maryland, Fire Protection Engineering, June 30, 1978.

Bryan, John L. and Philip J. DiNenno, An Examination and Analysis of the Dynamics of the Human Behavior in the Fire Incident at the Manor Care, Hyattsville Nursing Home on January 10, 1978. College Park: University of Maryland, Fire Protection Engineering, June 30, 1978.

Institution: University of Maryland

Grant No.: NBS Grant-G7-9007

Grant Title: A Theoretical Rationalization of the Goal Oriented Systems Approach to Building Fire Safety

Principal Investigator: Jack Watts
Department of Fire Protection Engineering
University of Maryland
College Park, Maryland 20742
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NBS Scientific Officer: Harold E. Nelson

Project Summary: The Goal Oriented Systems Approach to Building Fire Safety developed by the U.S. General Services Administration is presently the only probabilistic methodology for fire protection evaluation in use in the United States. This project describes and analyzes the GSA approach and formulates a more scientific procedure by synthesizing GSA concepts with additional probability theory. Discussion of systems analysis and modeling concepts emphasizes the need for probabilistic considerations of fire safety. The revised model simplifies data requirements through parameter estimation techniques. The new approach is consistant with the GSA model for several example cases. Facility for sensitivity analysis of alternative fire protection strategies is a demonstrated advantage of the new methodology.

Status: This project is completed. The final report has been submitted and is undergoing an outside technical review.

Reports:

Watts, Jack, The Goal Oriented Systems Approach, NBS-GCR-77-103, National Bureau of Standards, Washington, D.C.(July 12, 1977).

Watts, Jack, A Theoretical Rationalization of a Goal-Oriented Systems Approach to Building Fire Safety, Final Report on NBS Grant No. 7-9007, Department of Fire Protection Engineering, University of Maryland, College Park (February 28, 1978).

Institution: University of Massachusetts, Amherst

Grant No: NBS Grant G7-9010

Grant Title: Flame Suppression by Chemical Inhibitors

Principal Investigators:

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University of Massachusetts
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Marcel Vanpee
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University of Massachusetts
Amherst, MA 01003
Tel. (413) 545-0593

Other Professional Personnel:

Joseph K.Y. Kiang
Ph.D. Candidate

P.P. Shirodkar
Ph.D. Candidate

B. McNamara
B.S. Candidate

NBS Scientific Officer: W. Gary Mallard

Project Summary: Experimental studies of polymer combustion and flame inhibition were pursued in two distinct aspects. Polymer combustion is preceded by thermal and oxidative analysis of polymer to liberate volatile combustible fragments which is followed by highly exothermic combustion processes of the flame. Flame retardant can be affected by (a) inhibition of the crackup processes or by (b) poisoning of flame. State of art flame retardants are compounds containing Cl, Br, Sb and P. These elements are of relatively low efficiency thus requiring from 20 to 40 weight percent of additive to achieve adequate level of flame retardancy.

The research at the University of Massachusetts has been directed toward a thorough understanding of the mechanism and kinetics of thermal and oxidative pyrolysis of major polymers and determination of the intrinsic efficiencies of elements other than those mentioned above to inhibit the breakdown of polymers and suppression of flame propagation.

Progress Report: A. Poly (propylene) was chosen as the first large volume polymer to study the solid phase processes. The experiments were conducted with the UMass "Interfaced Pyrolysis Gas Chromotographic Peak Identification System." Milligram samples of the polymer were introduced into the MP-3 Multipurpose thermal analyzer and heated to the desired temperature for a predetermined length of time in a rapid stream (25 ml sec) of either He, air or O_2. The volatile products were trapped, GC separated and peaks on line identified with a MC-2 mass chromatograph (for molecular weight) a Norcon 201 rapid scan vapor phase IR spectrophotometer, a CDS1200 functional group analyzer and a Perkin-Elmer-Hitachi mass spectrometer.

Pyrolysis in He produces predominately olefins and dienes all of which can be accounted for by a simple mechanism of random chain scission followed by hydrogen migrations. Rate constants and activation energies were determined from 388 to 438°C to give

$$k = 1.13 \times 10^{-22} \exp(56{,}000/RT)\ \mathrm{sec}^{-1}$$ for atactic poly (propylene)

and

$$k = 5.52 \times 10^{-21} \exp(51{,}000/RT)\ \mathrm{sec}^{-1}$$ for isotactic poly (propylene)

Oxidative pyrolysis in air produces predominately ketones and aldehydes though some saturated and unsaturated products were also obtained especially at slow air flows indicating oxygen starvation. The carbonyl products can be accounted for by a reaction mechanism involving random chain scission followed by peroxidation, hydrogen abstraction to form hydroperoxide, decomposition of the hydroperoxide and C-C bond scission accompanied by H or CH_3 transfer. Rate constants and activation energies were determined from 240° to 289°C to give

$$k = 1.0 \times 10^{-10} \exp(17{,}000/RT)\ \mathrm{sec}^{-1}$$ for atactic poly (propylene)

and

$$k = 1.0 \times 10^{-9} \exp(15{,}000/RT)\ \mathrm{sec}^{-1}$$ for isotactic poly (propylene)

Chromium was the first element of choice to evaluate its inhibition activity. Cr is chemically reacted and incorporated on poly (propylene) to a content of 0.4 wt. percent. This material was found to have a self-ignition temperature about 150°C higher than that of uninhibited polymer and a limiting oxygen index of 28 as compared to 17.8 for uninhibited polymer. It was pyrolyzed in He and air as above. For the former, the presence of Cr was found not to affect significantly either the rate or product distribution of thermal pyrolysis. Very marked effect of Cr was seen for oxidatic pyrolysis. The activation energy was increased to 35 k cal mole^{-1}, and the formation of all products were suppressed. In addition, there was formed a char amounting to about 5% of the polymer.

B. The relative effectiveness of a variety of metallic compounds as flame inhibitors were investigated.

The metallic compound was first dissolved in ethanol. The solution was then atomized into a fine fog by means of a Sonicore atomizing nozzle. The mixture of the fog and an oxidizer gas, consisting of oxygen and nitrogen, was directed downwards on a liquid fuel pool. On ignition, a flat laminar flame was obtained in the space between the gas duct and the liquid pool.

The oxygen mass (or mole) fraction in the oxidizer gas at flame extinction was measured as a function of oxidizer velocity. The effectiveness of an additive salt was measured in terms of the change in oxygen mass (or mole) fraction per unit of additive mass (or mole) fraction in the oxidizer stream.

The metal compounds studies were: Acetylacetonates of Li, Na, Pb, Fe, Cr, Co, and Mn; chlorides of Mg, Ni, Li and C, $Fe(CO)_5$, $Pb(C_2H_3O_2)_4$, $LiC_2H_3O_2$ and NaOH. All these compounds were soluble in commercial grade ethanol, which was selected as the fuel.

On a mole basis, lead tetracetate and acetylacetonate of Mn, Co, Fe, and Cr were found to be effective flame inhibitors. While on the mass basis, the alkali (Na, Li) acetylacetonates were found to be very effective flame inhibitors.

The metal-ligand bond was significant effects on the flame inhibition capacity of metallic compounds. The weaker the bond, the better the chance of releasing the active species in the flame, consequently, the more effective the metallic compound is as flame inhibitor.

Accomplishments: A. A detailed thermoanalytical technique has been developed to study reactions of polymer solids which must occur prior to and during its combustion. Mechanisms were elucidated for these reactions for polypropylene and rate constants and activation energies determined. Chromium was found to be extremely effective in inhibiting oxidative pyrolysis of poly (propylene).

B. The opposed jet liquid fuel burner provides a sensitive measure of flame inhibition effectiveness in the form of oxygen mass fraction (or mole fraction) and the extinction velocity of the oxidizer gas stream. The method is quite versatile, and has no limitations with regard to the physical state of the additive. Above all, it gives an easy means to test the inhibition capacity of metal compounds by dissolving them in suitable solvents.

Potential Applications: The ultimate solution to inhibit polymer combustion is to discover new and synergistic systems which are effective when present at very low amounts. This will have the benefit of not affecting the material properties of the polymer and reduce the level of toxic products which may evolve on combustion. On the most basic aspect, this investigation will determine the intrinsic efficiency of various elements in frame retardation of polymer.

Future Milestones: Poly (isoprene) will be the next polymer for this investigation. With this polymer we will be able to chemically bound many elements to it whereas the Etard reaction used in the poly (propylene) work is applicable only to the incorporation of chromium.

Reports and Papers:

Vanpee, M. and Shirodkar, P.P., "A Study of Flame Inhibition by Metal Compounds," 17th Symposium (International) on Combustion, Leeds, England (1978).

Chien, J.C.W. and Kiang, J.K.Y., "Pyrolysis of Polypropylene," Advance in Chem. (in press).

Institution: University of Massachusetts

Grant (or Contract) No:

Grant (or Contract) Title: Waking Effectiveness of Household Smoke Alarm Detector Devices

Principle Investigator: E. Harris Nober
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Other Professional Personnel:

Henry Peirce, Research Associate; Arnold Well, Research Associate; Charles Clifton, Research Associate, Additional Research Associate, Technician Research Assistant to be selected.

NBS Scientific Officer:

Project Summary:

There are three major goals, each with specific objectives. Goal I is to assess the intensity-frequency spectral composition of the smoke and fire alert acoustic signals relative to distance from the source (Experiment A). One objective is to determine the overall dBA output level of the acoustic signals for the 10 top selling units in the U.S. Measures would be taken 10 feet from the source in an area of minimal attenuation, at head location in the bedroom with bedroom door open and then with door closed to determine wall and door attenuation. A second objective is to determine the decibel output levels for these units at nine octave bands with central frequencies 63, 125, 250, 500, 1000, 2000, 4000, 8000, 16000 Hz, respectively.

Goal II is to determine and quantify sleep-waking dynamics as a function of the smoke and fire alert signal and extraneous environmental noise background in a young college age population (Experiment B) and different family constellations and households (Experiment C). An objective for Experiment B is to determine the waking-time latencies that occur from the electronically programmed signal-on presentation to the subject initiated signal-off activity. Variables include three intensity levels (55, 70, 85 dBA), extraneous noise, hours during the night and day of the week. Other objectives for Experiment B include determining the best subject response protocol, pilot test a questionnaire that will provide pertinent complementary data and assess the efficiency of the current alarm signals to be employed in Experiment C. The objective for Experiment C is to field test current household alarm detector units in a variety of household settings and conditions. A profile of behavior for individuals and the household constellation should be developed based on objective latency measures and questionnaire obtained data.

Goal III will explore, determine and test the most efficacious acoustic warning signal-auditory response combinations in a survey of different household sleeping conditions. Hence, one objective will be to determine and test for the most effective temporal acoustic patterns to elicit maximum acoustic arousal, i.e., continuous vs intermittant (Experiment D). Also, the most effective alarm spectral characteristics will be ascertained relative to different populations.

Progress Report:

Since the study has not yet commenced, there is no progress to report. The only data available relative to this study are some of the original pilot data that measured the intensities of several household smoke alert units in nine octave frequency bands. The data showed the major energy was concentrated between 500-4000 Hz inclusive. In still another pilot study, several alarm units were measured in several sample households using three locations, the hallway where the unit was installed, the bedroom with the door open and the bedroom with the door closed. The mean intensity values in dBA were 87, 71, and 56 dBA respectively for the three positions; ranges rarely exceeded plus or minus five decibels. Hence, if a room air conditioner, radio or TV were playing at 65-70 dB, there could be a formidable masking effect on the auditory perception of the alarm signal, particularly if the subject is sleeping.

Accomplishments: None to report.

Potential Applications:

The data from the latency component and from the questionnaire should collectively provide an index and a profile of expected behavior to the current alarm signals used in household detector units. Data should reveal stress reactions of individuals and families when suddenly awakened during the night from sleep. Different types of living conditions will be simulated in programmed experimental groups. Toward the end of the program different alarm signals and modes of presentation will be explored. A separate project will assess the effects of structured fire drills at home on a regulated basis. Application is pertinent for determining the best type of acoustic signal to be used in home alarm units and best placement in the home. There is also relevant applicability to the current programs being implemented by local fire departments throughout the country.

Future Milestones:

Organize and implement the program.

Reports and Papers: None to report.

Institution: University of Montana, Missoula, MT

Grant No.: NBS Grant G8-9011

Grant Title: Ignition and Fire Spread of Cellulosic Materials

Principal Investigator: Professor Fred Shafizadeh
Wood Chemistry Laboratory
University of Montana
Missoula, MT 59812
406-243-6212

Other Professional Personnel: Dr. Allan G. W. Bradbury
Thomas T. Stevenson

NBS Scientific Officer: Dr. Richard Gann

Project Summary: The current objective of this project is to investigate the factors which could affect the process of smoldering combustion of cellulosic materials, including lower temperature pyrolysis and the effect of inorganic materials and flame retardants, in order to provide a chemical description of the process and define the mechanism of its suppression.

Progress Report: In contrast to flaming combustion of the cellulosic materials which is propagated by the gas phase combustion of the pyrolysis products, the smoldering combustion of these materials propagate by oxidation of the solid substrates possibly before or after charring.

The kinetics and mechanism of the pyrolysis of cellulose, at temperatures up to 340°C, in air, nitrogen or vacuum was investigated in order to determine the possibility of oxidation before charring and the rate of the thermal degradation. The results indicated that at temperatures below 300°C, thermal degradation of cellulose in air involves several oxidation reactions including production of hydroperoxide, carbonyl and carboxyl groups. These reactions which involve an initiation period are very slow and at temperatures above 300°C are overtaken by pyrolytic reactions which have a much higher activation energy. Consequently, the thermal decomposition becomes non-oxidative in character. Furthermore, it was found that the smoke generated by smoldering combustion of cotton fabric has almost the same composition as the pyrolysis products under nitrogen. These data point out the significance of the char oxidation as the driving force for propagation of the smoldering combustion. They also indicate that pure cellulose should have a much higher tendency for flaming than smoldering combustion because of the rapid production of combustible volatiles at temperatures above 300°C, unless the char production is catalyzed by inorganic impurities or additives (see Figure 1).

It has also been shown already that the activation energy of pyrolysis could be lowered, the evolution of combustible volatiles could be suppressed, the heat of combustion of the volatiles could be reduced, and production of char could be increased with the addition of flame retardants and inorganic additives, all which are expected to promote the smoldering process. However, investigation of a series of cellulosic substrates treated with various flame retardants and inorganic additives confirmed the fact that some flame retardants reduce while others enhance the tendency for smoldering combustion. Attempted correlations between the tendency for smoldering and other combustion-related characteristics, including heat release, charring, thermal analysis and development of free radicals (ESR) indicated that the process is controlled by complex interrelated factors including composition of the substrates, inorganic additives, rates of oxidation and heat flux and last but perhaps most significant, the reactivity and combustibility of char.

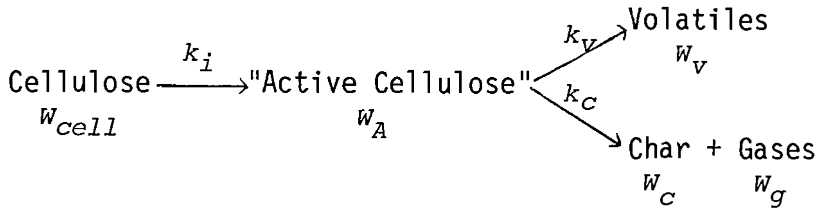
Carbon oxidation has been extensively investigated, but the mechanism of the reactions involved are barely understood. According to the current concepts (see Figure 2) oxidation takes place at the active sites on the surface of the carbonaceous materials. Originally oxygen is adsorbed on the active sites (C*). The adsorbed oxygen ($C(O_2)*$) then dissociates to provide a mixture of mobile surface oxides ($C(O)_m$) and stable oxide species (C=O). The mobile surface oxides then react to provide carbon monoxide and/or carbon dioxide and regenerate new active sites which propagate the oxidation process. The stable oxide species apparently play a minor role by decomposing slowly to provide carbon dioxide and carbon monoxide.

This theory explains the role of some metal catalysts in promoting the smoldering process by helping dissociation of the adsorbed molecular oxygen. It also explains prevention of glowing and smoldering combustion by ammonium phosphates, boric acid and sulfur which could interact with the active sites.

In support of this theory it was found that the char produced by low temperature pyrolysis of cellulosic materials is much more reactive than graphite and other forms of pure carbon, generally investigated. Furthermore, this reactivity is inversely related to the temperature of pyrolysis and charring.

Accomplishments: The kinetics and mechanism of the pyrolysis of cellulose at temperatures up to 340° in air, nitrogen and vacuum have been determined. The results indicate that at temperatures below 300°C thermal degradation in air involves formation of hydroperoxide, carbonyl and carboxyl groups, dehydration, scission of the polymeric chain and ultimately, production of char, carbon dioxide and carbon monoxide. These reactions proceed slowly and are accompanied by an induction period.

At temperatures above 300°C transglycosylation reactions take over and the induction period and the difference between pyrolysis in air and nitrogen gradually disappear. Kinetics of the pyrolysis under reduced pressure could be expressed by the following three reaction model.



where

$$\frac{-d(W_{cell})}{dt} = k_i[W_{cell}]$$

$$\frac{d(W_A)}{dt} = k_i[W_{cell}] - (k_v + k_c)[W_A]$$

$$\frac{d(W_c)}{dt} = 0.35k_c[W_A]$$

For pyrolysis of pure cellulose under vacuum it has been found that the rate constants k_i, k_v, and k_c in the above model could be expressed by $k_i = 1.7 \times 10^{21}e^{-(\frac{58,000}{RT})}$ min^{-1}, $k_v = 1.9 \times 10^{16}e^{-(\frac{47,300}{RT})}$ min^{-1} and $k_c = 7.9 \times 10^{11}e^{-(\frac{36,600}{RT})}$ min^{-1} respectively.

Investigation of smoldering combustion has lead to a chemical description of this process emphasizing the reactivity and combustibility of the char as a critical factor and indicating the mechanism of its control by inorganic additives.

Potential Applications: Reducing the risks and hazards of smoldering combustion by development of safer cellulosic insulation and batting and better applications and standards.

Future Milestones: 1. Further correlation of the smoldering process with the reactivity and combustibility of the char.

2. Investigation of the adsorption properties and reactivity of the char as a possible approach for inhibition of the smoldering combustion.

3. The effect of inorganic additives and pyrolysis products of cellulose on combustion of the char and inhibition of smoldering.

Reports and Papers:

Shafizadeh, F. and Bradbury, A. G. W., "Thermal Degradation of Cellulose in Air and Nitrogen at Low Temperatures," *J. Appl. Polym. Sci.*, in press.

Bradbury, A. G. W., Sakai, Y. and Shafizadeh, F., "A Kinetic Model for Pyrolysis of Cellulose," submitted to *J. Appl. Polym. Sci.*

Shafizadeh, F. and Bradbury, A. G. W., "Smoldering Combustion of Cellulosic Materials," submitted to *J. Fire/Flamm.*

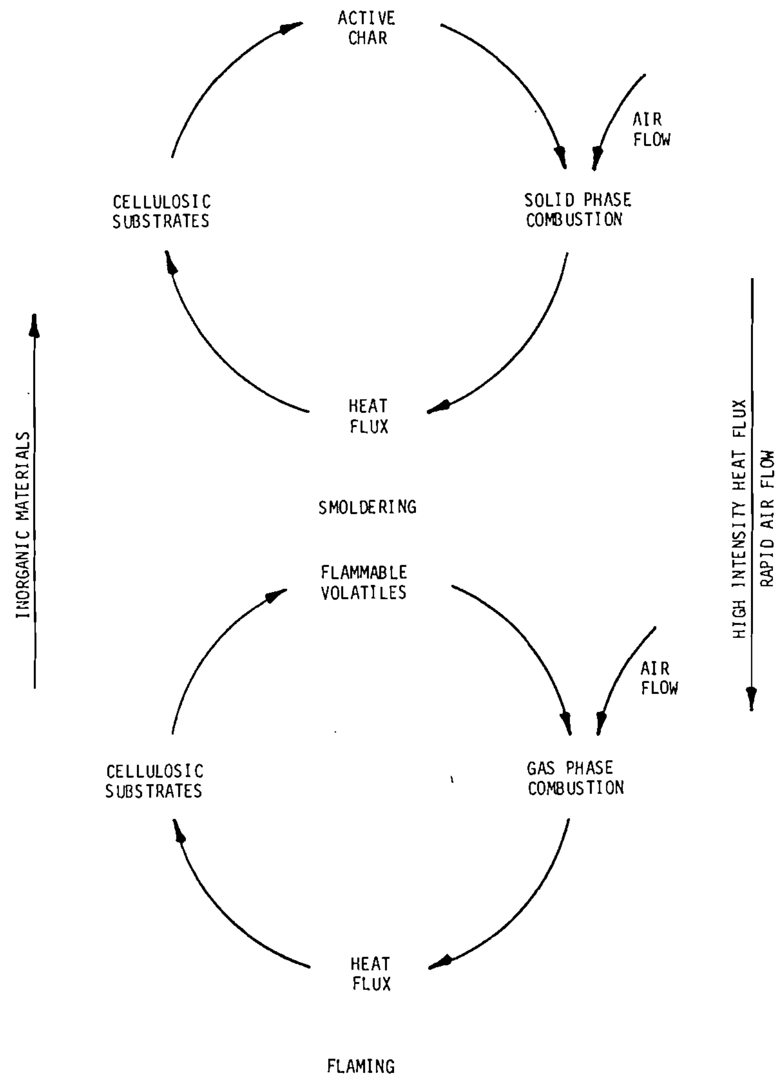


Figure 1

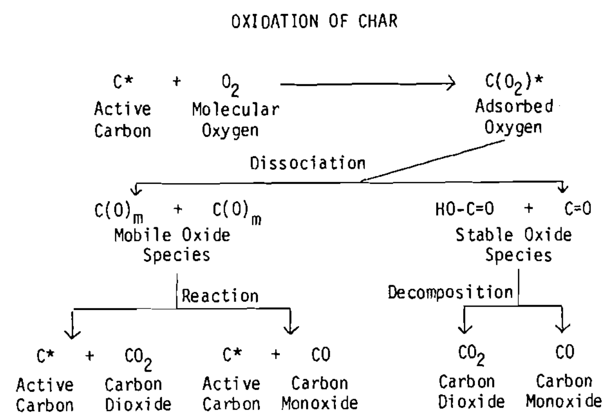


Figure 2

Institution: University of North Carolina

Grant No.: NBS Grant-G7-9021

Grant Title: The Psychology of Arson: Theoretical Analyses with Suggestions for Application

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Other Professional Personnel:
Dr. Robert G. Vreeland, Research Associate and Project Director
Dr. E. Earl Baughman, Associate in Personality Theory

NBS Scientific Officer: Dr. Bernard Levin

Project Summary: Our major purpose is to gain some systematic knowledge about the psychology of arson: the type of person likely to set a fire and the circumstances surrounding the firesetting act. The first year of the current project has been concerned with systematically organizing and reviewing what is known about firesetting. Our information has come from the literature, from meetings and conferences, and from personal contact with researchers, clinicians, and investigators.

The second year of the project will be concerned with interpreting what is known about firesetting in a context of psychological theory. The most important objectives are an improvement of existing classification schemes, an evaluation of the potential contributions of various personality and behavior theories to our understanding of firesetting, and specific suggestions for the application of our findings in the clinical treatment and management of firesetting. Where gaps in our knowledge exist (as they certainly will), we plan to make testable hypotheses and to suggest the types of data likely to be relevant to those hypotheses.

Progress Report: Thus far, our analysis has concentrated on common factors which appear to be characteristic of a wide range of types of firesetters. The traditional psychoanalytic view has emphasized the sexual roots of firesetting, and a great deal of attention has been paid to the relationship between firesetting and sexual problems. However, in our review we have found firesetters' problems to be considerably more extensive. Among adult firesetters of all types (arson-for-profit excluded), marital, occupational, and drinking problems, as well as other criminal activity, have been prevalent. Children and adolescents who set fires have also shown other types of problem behavior such as running away from home, truancy, stealing, general hyperkinesis, and aggression. The "typical" firesetter in many ways appears to be similar to other criminals and delinquents. One major difference, however, has been the general finding that arsonists commit more offenses against property (firesetting excluded) and fewer offenses against the person than do other types of criminals. The extent to which these findings apply to arson-for-profit firesetters is open to question, since we know very little about this type of firesetter.

Accomplishments: Taken together, the findings we have reviewed thus far have led us to emphasize a model of firesetting behavior in which firesetters are viewed as deficient in the skills, particularly social skills, necessary to obtain rewards from the environment in an appropriate manner. Having failed to gain sufficient control over his environment through appropriate interpersonal skills, the individual may turn to interpersonally less direct means for gaining a great deal of control over his environment, firesetting being one such way. A recent paper (Vreeland & Levin, 1978) explains this view in greater detail.

Potential Applications: An understanding of the psychological factors involved in firesetting should aid in the clinical treatment and management of firesetting behavior as well as in the identification of potentially serious firesetters. Current findings suggest that for many firesetters, programs to develop self-confidence and interpersonal and vocational skills would be important components of treatment.

Future Milestones: While we have thus far concentrated mainly on factors common to most groups of firesetters, there are also important differences. Our review of the literature (first year's report) will detail these differences. The development of a functional classification system and the interpretation of different types of firesetting within the framework of current psychological theory may aid in suggesting optimal treatment and case management strategies for different types of firesetters.

Reports and Papers:

Vreeland, R. G., & Levin, B. Psychological aspects of firesetting. In D. Canter (Ed.), Behavior in fires. New York: John Wiley, in press.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: University of Notre Dame

Grant No.: NBS Grant G7-9002

Grant Title: Fire and Smoke Spread

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D. W. Meyers, Undergraduate Assistant

Project Summary: The purpose of this research is to develop a three dimensional computer code for describing the physical movement of fire and smoke in enclosures such as rooms, compartments and corridors. The long-term goal is the development of the numerical code, UNDSAFE, which is capable of predicting the real fire and smoke spread behavior in an enclosure as a function of geometry and materials content. It can be used to study a wide variety of real life problems associated with enclosure fires such as the motion of hot gases, temperature build-up and distribution of products of combustion, ventilation of fire through windows and doorways, radiation from walls, soot and hot gases, and interactions among multiple fire plumes as well as between plumes and ceilings, walls and corners.

This numerical code is based on a finite difference representation of a set of two or three dimensional first-principle differential field equations for unsteady turbulent recirculating flows, including effects

of strong buoyancy, compressibility, combustion, multiple species, and wall, soot and gaseous radiation. The mathematical modeling of turbulence, radiation and combustion is based on phenomenological and physical principles, and the validity is established by comparison of the numerical calculations with experimental studies carried out at the University of Notre Dame and at the Center for Fire Research of the National Bureau of Standards. The complexity of the real fire and smoke spread phenomena dictates a step-by-step approach of developing the three dimensional numerical model to insure that at each step the model is self-consistent physically and correct in terms of known results.

This project was originally initiated under NSF RANN Grant GI-37191, and has since been continued under Grants ATA73-07749A01, AEN-73-07749-A02 and NBS G7-9002.

Progress Report:

1. Computer Code Development - Progress has been made on both the two and three dimensional versions of UNDSAFE. During this past year a technical memorandum was issued outlining the efforts which have gone on in previous years to establish the accuracy convergence, and stability of the UNDSAFE code. Both the parabolic and elliptic two dimensional codes are discussed in the memorandum. Development of the three dimensional UNDSAFE code based on the mass, momentum and energy conservation equations together with a k, ε, g turbulence model has been progressing. The computation algorithm includes three dimensional calculations using primitive physical variables, variable mesh, fully explicit to fully implicit calculations allowed and a pressure correction scheme based on Newton-Raphson's rule which was developed at Los Alamos Laboratory for the SOLA-ICE program.

2. Turbulence Modeling - A technical report describing the development of the algebraic model for recirculating turbulent flow with strong buoyancy has been issued. Basic concepts behind this model are introduced and discussed. Comparisons are made for the constant eddy - viscosity model and the mixing length model. As mentioned in the previous section a differential field model employing three transport equations for the turbulent kinetic energy, the dissipation function and the mean-square temperature fluctuation is being developed to be used with the 3-D code. This formulation includes appropriate algebraic formulae for the Reynolds stresses and the components of turbulent heat flux.

3. Radiation Modeling - A technical report on the one-dimensional model including soot, gas and surface radiation has been written and distributed. The report presents a detailed description of the model which is currently employed in the UNDSAFE code. Interactions between gas and soot radiation are accounted for as well as the effect of overlapping bands in the gaseous radiation. Samples of the results of calculations for three limiting cases, including no radiation in the calculation, surface and heavy soot only in the calculation and surface and gas radiation only in the calculation are presented to demonstrate

the model. Work has continued on the two dimensional model. A single square enclosure is being considered with the top two walls adiabatic and the two side walls at different temperatures. Surface radiation is being considered first before including the effects of gas radiation.

4. UNDSAFE II - The draft copy of the UNDSAFE II report has been completed for some time. It treats the same basic room configuration as that of UNDSAFE I, except that the full algebraic turbulence model and one-dimensional radiation model for wall, soot and gaseous radiation have now been incorporated. Furthermore, the numerical computations can now be extended into the region outside the doorway so that the flow and temperature behaviors outside the doorway can be clearly discerned. The formal issuance of UNDSAFE II in the form of a technical report has been delayed pending the public distribution of two technical reports, one for the radiation modeling and the other for the algebraic turbulence model, since many of the details in UNDSAFE II depend directly on formulations given in these two modeling reports. These two modeling reports have now been formally issued (TR - 79002-78-1 and TR-79002-78-2), and the technical report on UNDSAFE II will shortly follow.

5. Cinematics - In the area of cinematics two developments have taken place. First, streamline or temperature contour plots are available in addition to velocity vector plots on any black and white movie. Second, a short (2200 frames) color movie has been completed with color coding of temperature distribution in the enclosure as well as velocity vector superposition to indicate the flow field. Further, color movies will be produced in the near future using updated versions of UNDSAFE which include multiple sources, radiation, etc.

6. Experimental Studies - Two experimental facilities are currently being employed. The fire wind tunnel is being used to study Richardson number effects on turbulence. In this study a velocity profile and a temperature profile are specified at the entrance to the main test section and the development of the velocity and temperature fields downstream are monitored. Hot wire anemometers and thermocouples are being employed. In the enclosure-corridor facility an exhaustive flow visualization study was made on the four layer behavior observed at NBS and in the UNDSAFE calculations. A technical memorandum has been written outlining these visualization studies. Also in the enclosure-corridor facility measurement of flow velocity field are being made using LDA techniques. The preliminary studies use the back scattering mode of operation with the smoke from the visualization being used as the seed particles. This technique appears to be the only reliable velocity measuring technique to measure the low velocity natural convection driven profiles of the hostile fire environments.

7. ASTM E-84 Tunnel Test Analysis - We have just completed a careful study of the impressive analysis of the tunnel problem performed by Carrier, Fendell and Feldman. Our parabolic code is currently being applied to the tunnel problem. This treatment employs a volumetric heat source to simulate the gas flame and includes the effects of radiation.

We expect to obtain solutions this summer suitable for comparison with both Parker's experimental measurements and Carrier's analytical solutions.

8. Interacting Plume Studies - Initial results of this study which have been discussed at earlier meetings have formed the basis for a more complete study of the behavior of two-dimensional line plumes in the presence of upper and lower confining surfaces. The transient and steady state behavior are being examined for various plume separation widths, elevations off the lower floor and ceiling heights. Development of the relevant dimensionless coordinates to rationally correlate these results are in progress.

Accomplishments: During the past year considerable progress has been made toward the development of UNDSAFE, a computer code designed to predict the spread of fire and smoke in single and multiple enclosures. The two-dimensional code has been developed to the point where it can handle unsteady recirculating flows with turbulence, full compressibility, strong buoyancy, combustion and radiation from surfaces, smoke and products of combustion as well as a wide variety of enclosure configurations. A three-dimensional code has been written and is currently being debugged. This will enable the study of most any room configuration including windows and doors. The three-dimensional code has been written to include the differential field equation turbulence models.

Considerable data was obtained with the experimental facilities. Studies of the four layer flow behavior have led to better understanding of this phenomenon. Techniques for obtaining data on the effects of buoyancy on turbulence have been established and the LDA system has begun to provide some accurate flow velocity measurements in the enclosure facility.

Potential Applications: Once the three dimensional UNDSAFE code, including such physical models as turbulence, radiation, combustion etc, is complete, many applications are apparent. In the case of the fire hazard testing of materials, applications can be found in the design and data interpretation of such tests as the tunnel tests, radiant panel tests, corner tests, etc. The code can also be used in support of large scale fire tests in rooms, corridors, buildings, aircraft and mines. Applications can also be found in architectural design for structural integrity in fires, for establishing escape routes in buildings, for evaluating compartmentalization for fire containment in buildings and aircraft, etc. It should also be clearly pointed out that the code, along with the cinematics capability, would be a vital simulation tool for evaluating fire detection programs and for training fire fighting personnel show the importance of various physical effects on the spread of fire and smoke in rooms and corridors.

Future Milestones:

1. Evaluation of three-dimensional UNDSAFE.
2. Development of two-dimensional radiation model.
3. Comparison of UNDSAFE predictions to LDA velocity data.
4. Complete analysis of E-84 tunnel using parabolic UNDSAFE.
5. Development of combustion model.
6. Development of ignition and spread model.
7. Utilization and implementation.

Reports, Papers, and Memoranda:

1. V. K. Liu and J. R. Lloyd, "One-Dimensional Radiation Model for surfaces and Non-Homogeneous Gases and Soot," Technical Report TR-79002-78-1, Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, March 6, 1978, 98 pp.

2. V. W. Nee and V. K. Liu, "An Algebraic Turbulence Model for Buoyant Recirculating Flow," Technical Report TR-79002-78-2, Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, May 12, 1978, 107 pp.

3. V. W. Nee, "Turbulence Modeling," Technical Memorandum, Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, March 8, 1978, 5 pp.

4. J. R. Lloyd and K. T. Yang, "Accuracy, Convergence and Stability of UNDSAFE," Technical Memorandum, Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, May 2, 1978, 18 pp.

5. D. Meyers and J. R. Lloyd, "Flow Visualizations of the Four Layer Corridor Flow Phenomenon," Technical Memorandum, Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, June 30, 1978, 54 pp.

6. K. T. Yang and V. K. Liu, "UNDSAFE II - A Computer Code for Buoyant Turbulent Flow in an Enclosure with Thermal Radiation," Technical Report TR-79002-78-3, Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana, July 15, 1978.

Institution: University of Pittsburgh

Grant No.: NBS Grant 5-9005

Grant Title: Toxicity of Plastic Combustion Products

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L. Kane, Ph.D.
J. Dierdorf, M.S.
A. Burton, M.S.
H. Lucia, M.D.
C. Volz, M.S. Candidate

NBS Scientific Officer: M. M. Birky

Project Summary: Objectives- (1) To develop broadly applicable indices for the evaluation of toxicity resulting from inhalation of thermal decomposition products. (2) To develop a single test system which will facilitate economical, efficient study of these indices of toxicity. (3) To develop guidelines which will allow incorporation of toxicity data into a hazard index which could then be used for meaningful discriminations between materials.

Progress Report: A test system has been devised to provide logical, reliable, and realistic procedures for decomposition of samples and exposure of animals to thermal decomposition products.

In the development of endpoints, it is not possible to measure every toxic effect, however, it is possible to evaluate the spectrum of common physiological pathways which can be predicted to demonstrate toxic symptoms resulting from inhaltion of noxious or toxic materials.

The common physiological pathways which have been chosen are: 1) Sensory irritation, 2) Physiological stress, 3) Cellular oxygen defficiency, 4) Narcosis, 5) Motor excitation, 6) Acute lung damage, 7) Death.

Great progress has been made in the quantitation of these endpoints. A wide range of materials has been obtained for the purpose of testing both the physical system and the toxicological endpoints.

Accomplishments:

1. The single test system has been devised.
2. The sensory irritation endpoint is completed and published.
3. The physiological stress index has been developed and published.
4. The methods for LC_{50} determinations and comparative ranking of materials have been worked out and published.
5. The first attempt at Hazard Index has been published.

Potential Applications: Toxicity measurements will be appropriately used by manufacturers during the research phase of material development in order to evaluate basic formulations and permutations thereof. Hazard evaluations will ultimately supply guidance in the final choice of materials to be used for any given function.

Future Milestones: The unfinished toxic endpoints are:

1. Cellular oxygen defficiency
2. Narcosis
3. Motor excitation
4. Acute lung damage.

These will be quantitated and evaluated using known toxic chemicals as well as thermal decomposition products of materials in our sample bank.

The concept of the hazard analysis will be further developed.

Reports and Papers:

Anderson, R.C., Alarie, Y. Screening Procedure to Recognize Supertoxic Decomposition Products from Polymeric Materials Under Thermal Stress. Journal of Combustion Toxicology, 1978, 5, 54-63.

Anderson, R.C., Stock, M., Alarie, Y. Toxicologic Evaluation of Thermal Decomposition Products of Synthetic Cellular Materials, Part I. Journal of Combustion Toxicology, 1978, 5.

Anderson, R.C., Alarie, Y. Approaches to the Evaluation of the Toxicity of Decomposition Products of Polymeric Materials Under Thermal Stress, Journal of Combustion Toxicology, 1978, 5.

Lucia, H., Burton, A., Anderson, R.C., Alarie, Y. Renal Damage in Mice Following Exposure to the Pyrolysis Products of Polytetrafluoroethylene. Journal of Combustion Toxicology, 1978, 5.

Anderson, R.C., Dierdorf, J., Stock, M., Matijak, M., Sawin, R., and Alarie, Y. Use of Experimental Materials to Assess the Ability of Toxicological Testing Schemes in Rating the Hazards of Polymeric Materials Under Thermal Stress. Fire and Materials, 1978.

Anderson, R.C, Alarie, Y. An Attempt to Translate Toxicity of Polymer Thermal Decomposition Products into a Toxicological Hazard Index and Discussion on the Approaches Selected. Submitted, 1978.

Barrow, C.S., Lucia, H., Alarie, Y. A Comparison of the Acute Inhalation Toxicity of Hydrogen Chloride Versus the Thermal Decomposition Products of Polyvinylchloride. Submitted, 1978.

Barrow, C.S., Alarie, Y. and Stock, M.F. Sensory Irritation Evoked by the Thermal Decomposition Products of Plasticized Poly(vinyl chloride). Fire and Materials, 1978, 1, 147-153.

Barrow, C.S., Alarie, Y., Stock, M.F. Sensory Irritation and Incapacitation Evoked by Thermal Decomposition Products of Polymers and Comparisons with Known Sensory Irritants. Archives of Environmental Health, March/April 1978, 79-88.

Barrow, C.S., Lucia, H., Stock, M.F., Alarie, Y. Development of Methodologies to Assess the Relative Hazards from Thermal Decomposition Products of Polymeric Materials. In press.

Lucia, H., Barrow, C.S., Stock, M.F., Alarie, Y. A Semi-Quantitative Method for Assessing Anatomic Damage Sustained by the Upper Respiratory Tract of the Laboratory Mouse, Mus Musculis. Journal of Combustion Toxicology, 4, 1977, 472-486.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Flammability Research Center, University of Utah, Salt Lake City, Utah

Grant No.: NBS Grant-G8-9012

Grant Title: Toxicological Evaluation of Material Combustion Products: A. Biological investigation supporting development of methods for evaluating combustion toxicology.

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Other Professional Personnel: Gordon E. Hartzell, Director Flammability Programs
David G. Farrar, Industrial Research Associate, ICI Ltd., U.K.
Thomas L. Blank, Chief Technician

NBS Scientific Officer: Dr. Merritt Birky

Project Summary: Physiological investigations leading to the establishment of an animal model system capable of predicting human toxicological involvement with combustion products are being conducted. Life-threatening components in the fire scenario are being considered separately and in combination to determine the appropriateness and sensitivity of the rat model system. Toxicity found in combustion products are also being quantitated and causality is being sought in comparisons with identifiable components in combustion atmospheres. It is postulated that a failure to establish causality considering involvement with the ubiquitous combustion products will implicate the presence of a

unique toxic insult. This assessment of toxicity provides a firm basis for further considering the risk involved, providing the potency is sufficiently high and animal response is comparable to the anticipated involvement in man.

Progress Report: A. Physiological considerations of life-threatening components of fire. Homogenous mixtures of four gases for considering the toxicity of different atmospheres and physiological complications of heat stress were generated in a Rochester-style dynamic exposure system. Atmospheric composition could be adequately regulated with flow meter proportioning of compressed gases mixed in opposing flows at the top of the chamber for these experiments. A wide range of heat stress (40-60°C) could also be considered by heating the humidified compressed air flow. Exposures to the rats' head region were conducted and the indicators of toxicity used in our material combustion product evaluation were observed. The amounts of heat, increased carbon dioxide, low oxygen and cyanide producing a loss of conditioned avoidance (incapacitation) distortions in arterial blood gas status and lethality were established. Incapacitation and lethal amounts of heat, carbon dioxide, and oxygen were found sufficiently different from those encountered in our 60-liter chamber to be considered minimally involved in any observed toxicity. Arterial blood gas status, however, indicated probable additive effects in apparent increased ventilation and suspected increases in inhalation of toxic gases occurred with small amounts of heat, carbon dioxide and oxygen depletion.

Sensitivity of the rat to hydrogen cyanide gas was also established with this dynamic system. Atmospheric levels sufficient to produce incapacitation and death were determined and correlated with arterial blood concentrations of cyanide and respiratory gas status. In thirty minutes or less, 80 and 150 ppm of cyanide were found to be incapacitating and lethal, respectively. Added to our earlier considerations of sensitivities to carbon monoxide, causalities associated with both cyanide and carbon monoxide can now be recognized.

B. Materials Testing. The combustion product toxicity of three materials were evaluated following our suggested approach. These observations included determining the amount of material combusted in flaming and nonflaming conditions producing 50% incapacitation and death, and implicating the probable cause of the toxicity in observations of the levels of arterial blood gases and concentrations of toxic gases in the exposure atmosphere. Attempts were also made to compare this more elaborate toxic evaluation with the method proposed at the National Bureau of Standards.

Phenolic foam, urea formaldehyde foam, and polyvinyl chloride materials were evaluated following our approach to the assessment of combustion toxicity. The nominal dose-related incapacitating lethal effects of these polymers are compared to those of other materials in Table 1. As is frequently the case, each of these

Table 1

COMPARISON OF COMBUSTION PRODUCT TOXICITY OF UREA FORMALDEHYDE AND PHENOLIC FOAM WITH RESULTS FROM OTHER MATERIALS

	Incapacitating Effects (EC_{50})		Temperature
	Flaming	Nonflaming	(°C)
Urea Formaldehyde Foam	7.4±0.9	0.7± .1	850 / 830
Phenolic Foam	2.0	1.5	750 / 730
Polyvinyl Chloride - plasticized	7.1	3.4	540 / 500
Douglas Fir*	13.3±3.3	5.0±1.1	490 / 465
Rigid Polyurethane*	5.3±1.0	9.6±3.0	570 / 540
Flexible Polyurethane*	8.1±1.4	4.2±0.9	430 / 400
Polystyrene Foam*	15.3±3.3	27.0±3.1	540 / 480

	Lethal Effects (LD_{50})		Temperature
	Flaming	Nonflaming	(°C)
Urea Formaldehyde Foam	11.2±0.8	1.2± 0.1	850 / 830
Phenolic Foam	8.4±1.1	5.9± 1.1	750 / 730
Polyvinyl Chloride - plasticized	40.0	21.0	540 / 500
Douglas Fir*	24.5±4.5	19.0± 3.4	490 / 465
Rigid Polyurethane*	16.9±3.3	55.0±14.2	570 / 540
Flexible Polyurethane*	43.2±3.4	14.3± 2.4	430 / 400
Polystyrene Foam*	29.0±4.9	66.0±13.0	540 / 480

* data from PRC Interim Report of September 1977.

materials is unique in the expressed combustion toxicity which should be considered along with the relative potencies seen in this table. Arterial blood gases and calculated atmospheric concentrations at the point of incapacitation and death implicate cyanide as the causitive agent from urea formaldehyde, carbon monoxide from phenolic foam, and involvement of neither gas in the toxicity from polyvinyl chloride. Considering the potency of the two foams are similar, it becomes important to establish the causitive agent involved to make a more meaningful evaluation of the toxicity. Polyvinyl chloride presents yet another type of toxicity which appears in "dose"-related loss of body weight and lethality occurring after the exposure. However, the relative potency of combustion products from this polymer are low in comparison with other tested material in Table 1. Thus, it seems inappropriate to consider only the relative potency of a material without some consideration of the expressed toxicity and the causative agent involved. Knowing this, conditions favoring production of the poison during combustion might be avoided in new formulations or applications of the polymer. Treatment of fire victims could also be improved with a better appreciation of the complexity of the combustion toxicity.

Accomplishments: A dynamic system suitable for considering individual toxic components in the combustion mixture has been constructed. The incapacitating and lethal effects of heat stress, increased carbon monoxide, decreased oxygen and cyanide gas have been observed and quantitated. Comparison of these data with conditions during the testing of material combustion product toxicity established the appropriateness and possible limitations of our 60-liter chamber. Additional comparison of sensitivity to carbon monoxide and cyanide with conditions at the time of incapacitation and death identified the primary involvement of these poisons in combustion products of two materials.

Potential Applications: These experimental observations provide some basic information useful in the development of a meaningful test of combustion toxicity. Considerations of tolerance to heat, oxygen depletion, and carbon dioxide build-up should be used in constructing a combustion chamber. Sensitivities and signs of involvement with toxic gases provide a means of identifying their role in small-scale tests and could possibly be applied in fire victims leading to improved treatment.

Future Milestones: Experience with materials testing suggests pulmonary complications are involved in both immediate and late expressions of combustion toxicity. Exposures to hydrochloric acid and acrolein fumes will be made and appropriate pulmonary function tests evaluated as indicators of this involvement.

Combinations of toxic gases and heat will be examined to establish additive, synergistic, or independent interrelationships. In particular toxicity of carbon monoxide and cyanide will be explored. Additional observations will also be made on the effects of heat on carbon monoxide intoxication.

Several additional materials will also be evaluated to further establish our approach to testing combustion toxicity and support development of the protocol at the National Bureau of Standards.

Reports and Papers:

G. E. Hartzell and W. A. Galster, "The Role of Asphyxia in the Investigation of Animal Responses to Fire Combustion Products," *Eighth Conference on Environmental Toxicology,* Dayton, Ohio, October 4, 1977 (in press).

D. G. Farrar, T. L. Blank and W. A. Galster, "Toxicity of the Combustion Products of a Phenolic and a Urea Formaldehyde Foam," 7th International Congress of Pharmacology, July 1978, Paris, France.

ANNUAL CONFERENCE ON FIRE RESEARCH
CENTER FOR FIRE RESEARCH
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND

September 27-29, 1978

Institution: Flammability Research Center, University of Utah, Salt Lake City, Utah

Grant No.: NBS Grant-G8-9012

Grant Title: Toxicological Evaluation of Material Combustion Products: B. Development of blood-HCN analysis techniques and measurement of degradation product profiles in the degradation of polymeric materials.

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Project Summary: Analytical techniques are being developed and continuously applied in support of combustion toxicology studies being conducted at the Flammability Research Center (FRC). These techniques range from the development of new methods for the micro-analysis of blood-cyanide levels to the analysis of both time and temperature profiles in the generation of thermal degradation

products. The blood-HCN analysis technique is currently being used to study the incorporation of HCN in the blood of the Long-Evans rats exposed to cyanide-containing atmospheres. The real-time analyses of degradation products are carried out in order to assess the levels of toxicants present during animal exposures and to understand the rates of production of these toxicants during the exposure. Temperature profile studies allow estimates to be made of the degradation conditions which produce a maximum hazard.

Progress Report:

Analytical Methodology for the Determination of HCN in Tissues. In order to use the hind leg flexion response and lethality data to characterize the toxicity of degradation products from the combustion of materials, experiments have been conducted to understand these end points where only single toxicants are present. In support of these experiments, which will be discussed in more detail in a separate section, levels of HCN must not only be monitored in the atmospheres which the animals are breathing, but also in their tissues. The first tissue of prime importance in this study is blood.

The technique involves a modification of the method of Valentour[1] which converts cyanide present in blood to cyanogen chloride followed by gas chromatographic separation and electron capture detection. This method is particularly useful in that cyanide levels in very small amounts of blood (200 μl) can be detected making the technique applicable to small animal exposure studies. Table 1 shows the

Table 1

A COMPARISON OF THE EXTRACTABLE CYANIDE IN BLOOD WITH THE EXTRACTABLE CYANIDE IN SALINE SOLUTION

VACUTAINER METHOD

Concentration of Cyanide	Extracted Blood Cyanide: Raw Response Ratios	Extracted Blood Cyanide: Blank Corrected Ratios	Extracted Saline Solution Cyanide: Raw Response Ratios	Percent Extracted
. Blank	26.77 ± 2.42	-	0.00	
0.1 μg/ml	29.90 ± 1.24	3.13 ± 2.72	5.28 ± 0.10	59.3 ± 51.5
1.0 μg/ml	56.80 ± 2.94	30.03 ± 3.81	38.95 ± 0.36	77.1 ± 9.8
10.0 μg/ml	353.79 ± 12.00	327.30 ± 12.24	435.76 ± 11.50	75.0 ± 3.4

CONWAY DIFFUSION METHOD

Concentration of Cyanide	Extracted Blood Cyanide: Raw Response Rations	Extracted Blood Cyanide: Blank Corrected Ratios	Extracted Saline Solution Cyanide: Raw Response Ratios	Percent Extracted
Blank	8.50 ± 0.43	-	0.00	-
0.1 μg/ml	18.61 ± 0.44	10.11 ± 0.62	21.7 ± 0.31	46.6 ± 2.9
1.0 μg/ml	134.57 ± 10.16	126.07 ± 10.17	257.0 ± 6.28	49.1 ± 4.1
10.0 μg/ml	1456.30 ± 81.90	1447.80 ± 81.90	2303.0 ± 59.73	62.8 ± 3.9

results obtained using this technique for the analysis of cyanide from whole blood. Lower detection limits of 0.1 μg/ml are possible.

Problems encountered in this technique are in the relatively large blank response for unspiked whole blood and the tedious work-up procedure required in the cyanogen chloride derivatization. Thus a second method is being evaluated which converts cyanide to hydrogen cyanide in the head space over blood followed by gas chromatographic separation and alkali flame ionization detection of the HCN. Initial investigations using this technique show this to be a most promising way of analyzing for blood cyanide.

Determination of Time and Temperature Profiles for Toxic Gas Evolution. In order to understand the production profiles of compounds as a function of degradation time and temperature, the FRC has developed several techniques to monitor various compounds in the combustion of materials. This present progress report will outline recent studies which have been conducted in which methods have been developed for the analysis of low levels of HCN and HCl in complex degradation product matrices, along with direct interfacing of the animal exposure chamber to the FRC mass spectrometer/computer instrumentation.

Chromatographic Analysis of Combustion Atmospheres. The atmosphereic hydrogen cyanide produced during the combustion of polymeric materials has been analyzed by gas chromatography with alkali flame ionization detection. Daily calibration of the system is achieved using compressed gas standards which are in turn cali-brated against an HCN permeation device. This secondary calibration is necessary since the compressed gas standards can decay rapidly with time.

In addition to the analysis of atmospheric HCN, a new technique was used to monitor atmospheric HCl levels resulting from the combustion of polyvinyl chloride (PVC). The technique involves the aspiration of a small amount of the chamber atmosphere into a sampling valve which in turn is connected to an electrolytic conductivity detector. Analysis times range from thirty seconds to one minute depending on the amount of HCl present in the chamber. Calibration is again achieved using the permeation device. Compressed gas standards are totally unusable since the highly reactive HCl mixtures decay very rapidly with time.

A summary of the analytical methodologies used for the analysis of various toxicants resulting from the thermal degradation of polymeric materials is given in Table 2. Included in this table are the experimental conditions, detection limits and standardization procedures used in the analysis of the various toxicants.

Table 2.

ANALYTICAL METHODS AND CONDITIONS FOR THE MONITORING OF EXPOSURE CHAMBERS

ANALYSIS	INSTRUMENT	DETECTION PRINCIPLE	CONDITIONS	CALIBRANTS	ANALYSIS TIME	ANALYSIS RANGE	ACCURACY
CO_2 / H_2O	Gow-Mac 550 Gas Chromatograph	Thermal Conductivity (Hot Wire)	2-foot Porapak Q @ 70°C	Analyzed Compressed Gas Standard	3 minutes	400 ppm - 10% / 0.1% - 10%	5%
O_2 / CO	Gow-Mac 10-470 Thermistor Cell	Thermal Conductivity (Thermistor)	1-foot Molecular Sieve 5A Column @ 70°C	Analyzed Compressed Gas Standard	3 minutes	10% - 22% / 500 ppm - 1%	5%
Ethanal / Propenal	Gow-Mac 750 Gas Chromatograph	Flame Ionization	8-foot 10% Carbowax 20M Column @ 60°C	Compressed 400 ppm Butane in Nitrogen (Secondary Standard)	< 5 minutes†	10 ppm - 1% / 1 ppm - 1000 ppm	10%
Toluene Diisocyanate (TDI)	Hewlett-Packard 7620 Gas Chromatograph	Flame Ionization	3-foot 3% OV-17 Column @ 170°C	TDI Standards in Hexane	< 5 minutes†	1 ppm - 100 ppm	10%
HCN	Gow-Mac 750 Gas Chromatograph	Alkali Flame Ionization	4-foot Porapak Q Column @ 150°C	HCN Permeation Device and Compressed Gas Standards	< 5 minutes	1 ppm - 400 ppm	5%
Total Volatile Hydrocarbons	Keithley 610A Electrometer	Flame Ionization	Direct Inlet	Compressed 1% Butane in Nitrogen Standard	30 seconds	100 ppm - 1% (as butane)	15%
HCl	Tracor 700 Conductivity Detector	Solution Electrolyte Conductivity	50% Water-50% Isopropanol Electrolyte	HCl Permeation Device	1 minute	10 ppm - 1%	10%

Mass Spectrometric Analysis of Combustion Atmospheres. The variation in toxic products produced by a material during thermal decomposition was evaluated by analyzing their combustion atmospheres at various degradation temperatures. Approximately 2.5 g of either Douglas fir or polystyrene were combusted in a 60-liter chamber at temperatures of 420°, 460°, 550°C and approximately 3 liters of the combustion atmosphere was drawn through a Porapak Q filled trap cooled to 0°C. The adsorbed species were thermally desorbed into a GC/MS/computer system for the qualitative and quantitative analysis of the combustion products. Figure 1 is an example of the computer

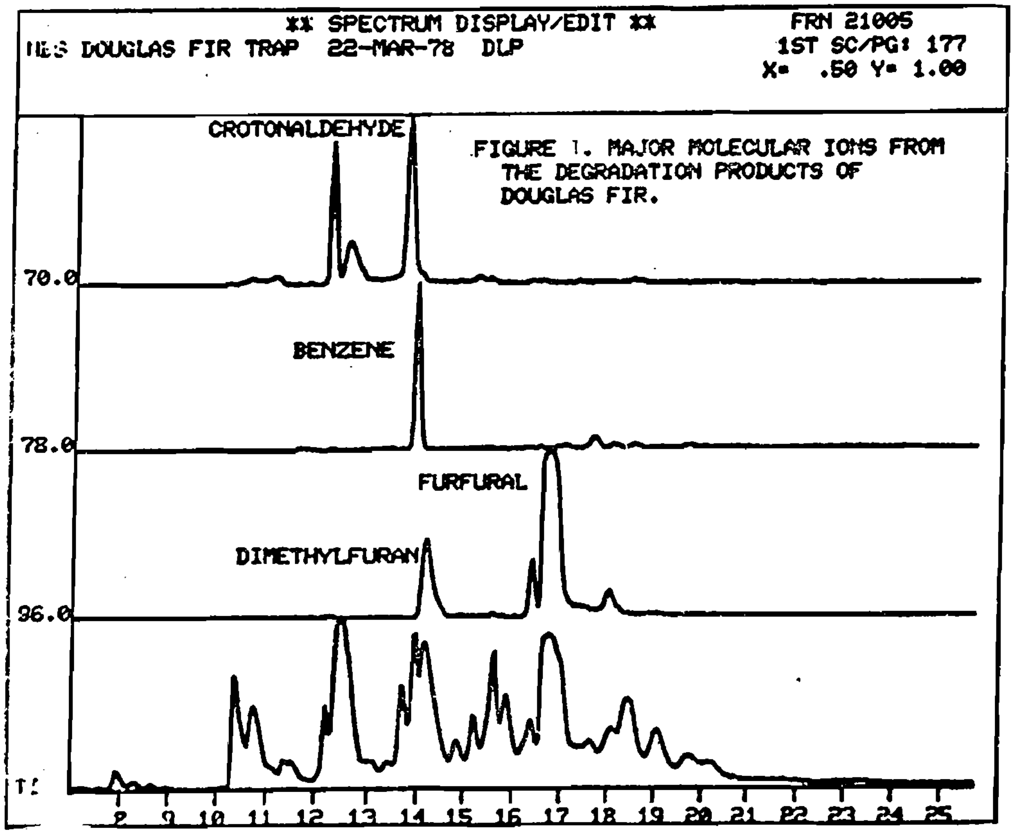

FIGURE 1. MAJOR MOLECULAR IONS FROM THE DEGRADATION PRODUCTS OF DOUGLAS FIR.

display from the analysis of the combustion products of Douglas fir. The combustion of polystyrene produces styrene as the major organic product (greater than 90%) with smaller amounts of toluene and benzene.

Once the degradation products have been determined for the combustion of a material, these compounds can in turn then be studied as a function of time by using the same mass spectrometric data acquisition system while sampling the combustion atmosphere directly. The 60-liter animal exposure chamber was interfaced to the mass spectrometer system using the glass jet separator. Figure 2 shows

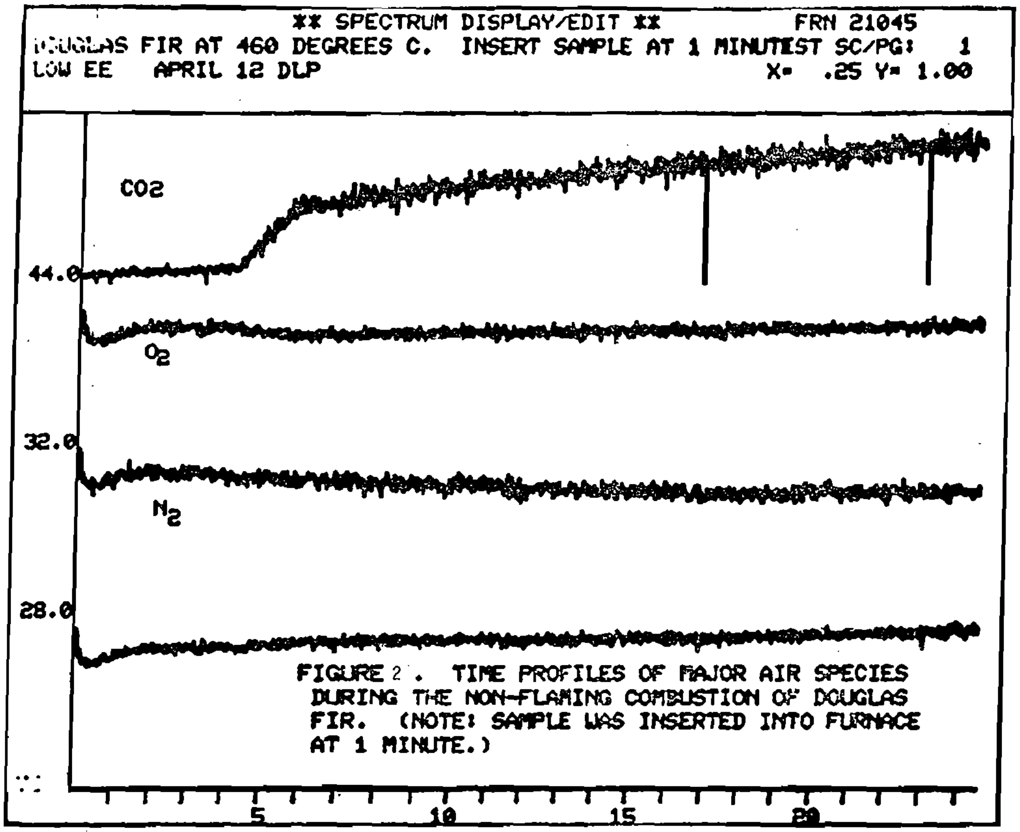

FIGURE 2 . TIME PROFILES OF MAJOR AIR SPECIES DURING THE NON-FLAMING COMBUSTION OF DOUGLAS FIR. (NOTE: SAMPLE WAS INSERTED INTO FURNACE AT 1 MINUTE.)

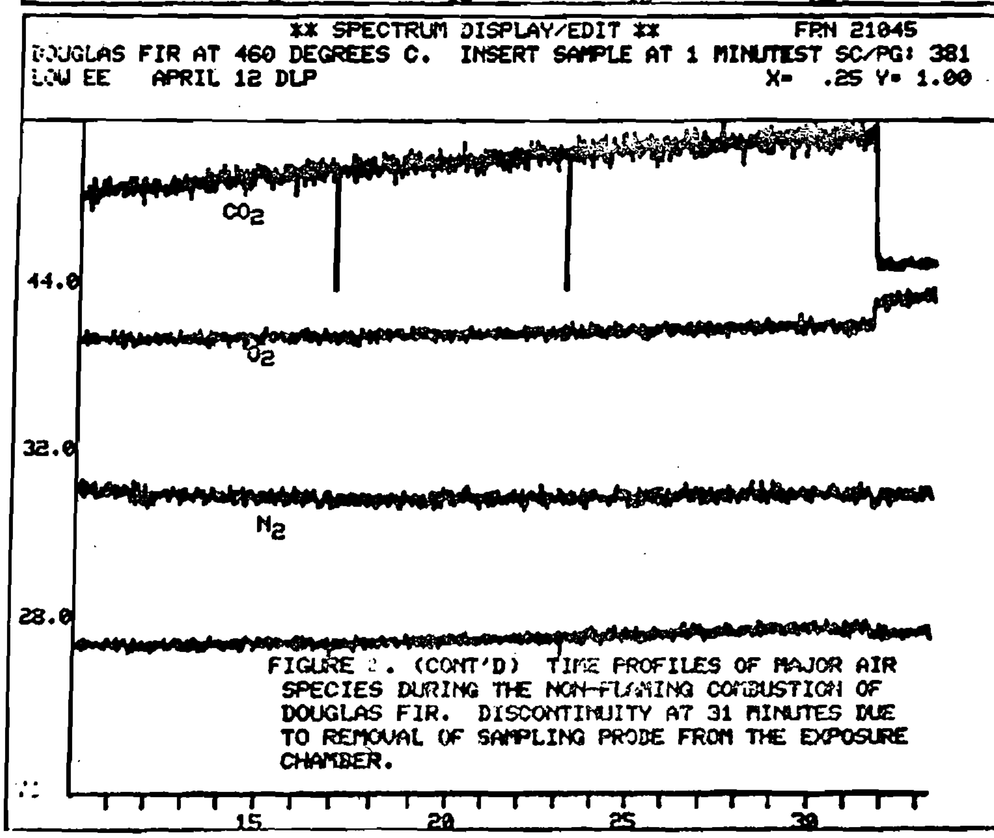

FIGURE 2 . (CONT'D) TIME PROFILES OF MAJOR AIR SPECIES DURING THE NON-FLAMING COMBUSTION OF DOUGLAS FIR. DISCONTINUITY AT 31 MINUTES DUE TO REMOVAL OF SAMPLING PROBE FROM THE EXPOSURE CHAMBER.

the production profile of CO_2 and O_2 and N_2 levels as a function of combustion time for Douglas fir. The sample was inserted into the combustion chamber at 1.0 minutes. The initial O_2 and N_2 fluxuation below 1.0 minutes is probably due to the initial equilibration of the exposure chamber atmosphere.

In the second part of Figure 2, the effect of removing the sampling tube from the chamber can be seen at 31.0 minutes. At that time, the CO_2 and O_2 levels return to the normal atmospheric levels discontinuously, showing the effective time constant for the measurement of these species. When the major organic ions were studied in a similar manner for nonflaming degradation of both polystyrene and Douglas fir, profiles similar to that shown for CO_2 were measured. The difference in production rate of the major organic products in the flaming combustion of polystyrene can be seen in Figure 3. The onset for the production of styrene, toluene

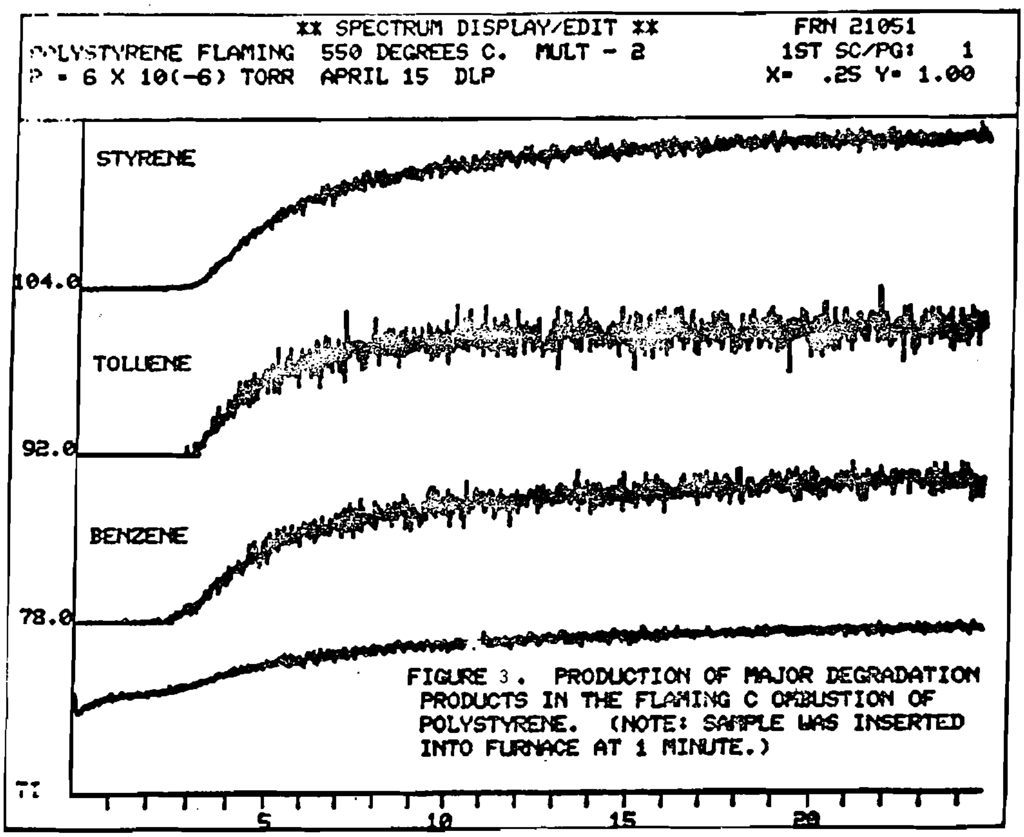

FIGURE 3. PRODUCTION OF MAJOR DEGRADATION PRODUCTS IN THE FLAMING COMBUSTION OF POLYSTYRENE. (NOTE: SAMPLE WAS INSERTED INTO FURNACE AT 1 MINUTE.)

and benzene is approximately two minutes earlier for flaming combustion than for nonflaming combustion.

Accomplishments: Gas chromatographic methods have been developed for the analysis of HCN in blood samples and for the analysis of HCN and HCl in combustion atmospheres. In addition, MS/computer studies have been carried out showing the temperature and time profiles for the production of major and minor degradation products formed in the flaming and nonflaming combustion of materials.

Potential Applications: Analysis techniques developed during the current funding period can be used to understand the toxicities of combustion atmospheres that are formed when polymeric materials burn. Data obtained using these techniques can be used to evaluate any unusual hazards that may exist in the use of these materials in our environment.

Future Milestones: Analytical techniques are being developed to allow easy rapid microscale determination of toxin levels in biological tissues. In addition, new analytical techniques are being devised to better characterize the levels of atmospheric toxins produced during combustion. As an example, using the directly interfaced mass spectrometer and an Ar/O_2 atmosphere may allow the determination of the levels of CO_2, CO and HCN with time at various combustion temperatures to better understand what particular degradation temperature poses a maximum risk as defined by the production of these major toxicants.

Reports and Papers:

1. "Physiological and Toxicological Aspects of Smoke Produced During the Combustion of Polymeric Materials," Final Report to the National Bureau of Standards, Contract No. 7-9005, March 20, 1978.

2. I. N. Einhorn, D. A. Chatfield, K. J. Voorhees, F. D. Hileman, R. W. Mickelson, S. C. Israel, J. H. Futrell, and P. W. Ryan, "A Strategy of Analytsis of Thermal Decomposition of Polymeric Materials," *Fire Research, 1,* 41-56 (1977).

Institution: University of Washington, Seattle

Grant No.:

Grant Title: Human Behavior in Fire Situations: A Study of Post-Fire Interviews

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NBS Scientific Officer:

Project Summary: Little is known about how people behave during fire incidents. Ultimately, veridical models of human behavior during fires should be developed, but first it is essential to obtain a data base drawn from interviews with victims and witnesses. Progress has been made in this area by Wood and Bryan, but it is clear that substantial work is still needed.

Research on obtaining testimonies on crimes indicates that an interviewer's leading questions can lessen the accuracy of responses. Our preliminary interviews with fire officials indicate that obtaining accurate information from witnesses of fire may be particularly difficult. Particularly where arson is suspected, insurance is an issue or the consequences are dire, people tend to distort the truth in order to avoid personal responsibility. Further, earlier work on post-fire interviews has been lacking in important information on how people assess fire situations, their decision processes and intentions underlying their behavior.

Therefore, our major focus will be on how to obtain accurate information from witnesses about what was seen and how and why they and others responded to fire incidents. We will begin by reviewing literature on previous research on obtaining post-fire information from witnesses. Next, we plan to obtain the cooperation of the fire department to observe the conduct of actual post-fire interviews. Finally, based on the literature, psychological theory, and information obtained from our observations of actual interviews, we will develop our own interview format. If we can obtain the cooperation of the fire department, we will undertake a pilot study to assess the adequacy of our method.

Progress Report: As of this report, formal work on the project has only just begun. Initial contacts have been made with the investigating section of the Seattle Fire Department and their continued cooperation is likely.

Accomplishments: See above

Potential Applications: The project should provide a standardized procedure and format for obtaining post-fire information from victims and witnesses. The data base resulting from its application could provide valuable information pertaining to models of human behavior in fire situations and the reduction of counter-productive behaviors.

Future Milestones: After developing an interview format and procedures, we hope to pilot our interview techniques with the cooperation of the fire department.

Reports and Papers: None

Institution: University of Wisconsin, Madison

Grant No.: NBS Grant-G7-9019

Grant Title: A Review of Behavioral and Physical Characteristics of the Developmentally Disabled

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NBS Scientific Officer: Dr. Bernald M. Levin

Project Summary: The objective of this project is to provide a comprehensive review of the research literature regarding the behavioral and physical characteristics of developmentally disabled individuals who are potential residents of "non-institutional" group housing in the community. The purpose is to familiarize policy makers on fire (life) safety standards of the expected capabilities and characteristics of these individuals in order to evaluate fire safety impact in such structures.

The literature review includes a definition and discussion of the concept of developmental disabilities and presents an overview of the individual characteristics of mental retardation, cerebral palsy, epilepsy and autism. The research reviewed is organized into three sections. The first presents a description of the present occupants of community housing for the developmentally disabled. The second section examines the characteristics of individuals who now reside in institutions for the mentally retarded or other developmentally disabled but are the major source of future residents of group homes. Since the group most likely to reside in, or to be a potential resident of community based housing is mentally retarded, the concluding section of the paper reviews the literature on the functioning levels of severely retarded individuals (below IQ 50). The factors included in the review are those with the highest relevancy to self preservation in an emergency or fire situation.

Progress Report: The term "developmental disabilities" refers to persons with substantially handicapping conditions due to mental retardation, cerebral palsy, epilepsy and/or autism. The concept represents an attempt to bring together individuals with similar service needs under one federal/state program. Developmentally disabled individuals often have multiple handicaps and there is considerable clinical overlap between individual conditions.

It is extremely difficult to determine the prevalence of developmental disabilities in the United States. Part of this difficulty is because not all persons who are mentally retarded, cerebral palsied, epileptic or autistic are also considered to be developmentally disabled. The term includes only persons with chronic, severe (often multiple) handicaps which exist from birth or early childhood. It is difficult to determine the extent and degree of these substantially handicapping conditions. Based upon state estimates, approximately 10 million persons or 4.43 percent of the general population will have one or more of the developmental disabilities in FY 1978.

The past decade has witnessed a dramatic change in philosophy regarding provision of residential care for developmentally disabled individuals. The guiding principle of "normalization" has influenced the nation to redesign its housing of disabled individuals to homes which are small in size and community based. Since 1967, the number of residents in large public institutions has steadily declined. Concurrently, a significant increase in the development of community based residential facilities has taken place. Considerable information is available about the models and types of these community structures.

Few studies, however, are available which describe the functioning of the community based homes and the characteristics of individuals which they serve. But one study which is of particular value in this regard is O'Connor's (1976) recent study on community residential facilities (CRF's). The survey covered over 9000 residents living in 611 community residential facilities for the developmentally disabled in 20 states during the period 1972 to 1974. The age distribution of these residents is found to follow an approximated normal distribution curve with the age group of 21-25 as the mode. Close to one half of the residents (48.76%) were 16 to 30 years old. Approximately nine of ten residents (89.5%) were mentally retarded, with or without other handicapping conditions. Only one third (34.4%) of the mentally retarded residents were free of an additional handicap. One tenth (10.9%) had impairments in speech. Of particular interest is the fact that one fourth (24.4%) of the sample were multiply handicapped. "Multiply handicapped" in this sense was defined by O'Connor to refer to more than two handicapping conditions.

Another valuable study regarding the residential population of group homes has been provided by Landesman-Dwyer, Stein and Sackett,

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Landesman-Dwyer, S., Stein, J. G., and Sackett, G. P. Group homes for the mentally retarded: An ecological and behavioral study. Olympia, Washington: Department of Social and Health Services, Planning an Research Division, 1976.

O'Connor, G. Home is a good place: A national perspective of community residential facilities for developmentally disabled persons. (AAMD Monograph No. 2). Washington, D.C.: American Association on Mental Deficiency, 1976.

(1976). The subjects for the study were 640 residents of 20 of Washington's 43 group homes. The age distribution of residents in the Washington study was similar to the distribution found in the O'Connor study. It approximated a normal distribution with the 22-26 age group as the mode. Again, approximately half of the residents (55 percent) fell into the age range of 17 to 31. This study included an interesting category called the "assistance dimension". For over three quarters of the residents, assistance in activities was not necessary. Nearly two percent of the residents' major activities involved some form of assistance from others. The amount of assistance received and needed was significantly related to both age and level of retardation. Children spent less time in activities requiring no assistance (78%) than did the adults (83%). Severely and profoundly retarded residents received three times as much assistance from others as did mildly retarded residents.

The characteristics of group home residents that these two studies found may be summarized as follows. The majority of residents in community facilities live in homes for 20 or more persons and over half have been previously institutionalized. Most in the group homes are between the ages of 16 and 30. Around 19% are severely or profoundly retarded, approximately 30% are mildly retarded, and 10 to 20 percent have an IQ of above 70. Additional handicaps are present in nearly two thirds of the residents. At least three fourths of the residents in both studies demonstrated cooperative behavior. Positive interaction patterns were evident in between 61 and 69 percent of the subjects in the studies. At least half of the group could speak well enough to be understood by a stranger.

However, in dealing with an individual resident who is developmentally disabled, it has to be kept in mind that individual variability is greater in this group than in the general population.

According to national trends, a large percentage of current residents of public residential facilities for the developmentally disabled will be admitted to community residential facilities. Therefore, the considerable amount of research literature which exists regarding residents of public residential facilities becomes relevant.

Scheerenberger (1978) presents the most recent information with regard to institutionalized developmentally disabled individuals. The study reports demographic features of the population of residents from 239 public residential facilities. The study found that the age of persons in institutions was becoming older with over 50 percent of the population between the ages of 22 and 61. Approximately 44 percent

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Scheerenberger, R. Current trends and states of public residential services for the mentally retarded. National Association of Superintendents of Public Residential Facilities for the Mentally Retarded, 1978 (in press).

were profoundly retarded and 73 percent severely or profoundly retarded. Most of the residents were multiply handicapped with 65 percent having at least one additional handicapping condition and around one third with two or more handicaps in addition to mental retardation.

The survey also indicated that over half, or at least 80,000 of the 151,000 developmentally disabled individuals presently residing in public residential facilities have the skills necessary to be placed in alternative community settings if they were available. The data indicate that 76 percent of the present residents can walk without assistance, 84 percent can communicate verbally and 93 percent have ability to understand the spoken word.

Potential Applications: This literature review provides a foundation for determination of relevant factors for occupancy fire risk parameters in a Fire Safety Evaluation System.

Future Milestones: The literature review is presently in preliminary draft form. The expected date of completion is September 1, 1978.

Reports and Papers:

Overboe, C. J. and Wang, Y. Y. Behavioral and physical characteristics of developmentally disabled individuals. June, 1978, preliminary draft.

Wang, Y. Y. Physical characteristics of mentally retarded individuals. May, 1978, unpublished paper.

ANNUAL CONFERENCE ON FIRE RESEARCH

Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
September 27, 28, 29, 1978

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

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

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Combustion products; fire hazards; fire modeling; fire research; human behavior in fires.

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