

Fire Safety Aspects  
of  
Polymeric Materials

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VOLUME 10  
MINES  
AND  
BUNKERS



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A Report by  
National Materials Advisory Board  
National Academy of Sciences

**Fire Safety Aspects  
of  
Polymeric Materials**

**VOLUME 10  
MINES  
AND  
BUNKERS**

**Report of  
The Committee on Fire Safety  
Aspects of Polymeric Materials**

**NATIONAL MATERIALS ADVISORY BOARD  
Commission on Sociotechnical Systems  
National Research Council**

**Publication NMAB 318-10  
National Academy of Sciences  
Washington, D.C.  
1980**

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VOLUME 10 – MINES AND BUNKERS  
Fire Safety Aspects of Polymeric Materials

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Printed in U.S.A.  
Library or Congress Card No. 77-79218  
ISBN 087762-231-0

## NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This study by the National Materials Advisory Board was conducted under Contract No. 4-35856 with the National Bureau of Standards.

Printed in the United States of America.

## FOREWORD

This volume is one of a series of reports on the fire safety aspects of polymeric materials. This work reported here represents the results of the first in-depth study of this important subject. The investigation was carried out by a committee of distinguished polymer and fire technology scholars appointed by the National Academy of Sciences and operating under the aegis of the National Materials Advisory Board, a unit of the Commission on Sociotechnical Systems of the National Research Council.

Polymers are a large class of materials, most new members of which are man-made. While their versatility is demonstrated daily by their rapidly burgeoning use, there is still much that is not known or not widely understood about their properties. In particular, the burning characteristics of polymers are only now being fully appreciated and the present study is a landmark in the understanding of the fire safety of these ubiquitous materials.

In the first volumes of this series the committee has identified the limits of man's knowledge of the combustibility of the growing number of polymeric materials used commercially, the nature of the by-products of that combustion and how fire behavior in these systems may be measured and predicted. The latter volumes deal with the specific applications of polymeric materials, and in all cases the committee has put forth useful recommendations as to the direction for future actions to make use of these materials safer for society.

Harvey Brooks, Chairman  
Commission on Sociotechnical Systems

## ABSTRACT

This volume in the series on the Fire Safety Aspects of Polymeric Materials focuses on the fire safety aspects of natural and synthetic polymeric materials prevailing or constituting the substance of mines and bunkers. The methodology of fire scenario development is described and mine fire scenarios are presented. Fire dynamics and the materials used in mines are then critically reviewed. Design criteria for mines, mine equipment, and mine fire detection and suppression systems are examined in detail and smoke and toxicity hazards are identified. Conclusions are drawn and appropriate recommendations are set forth. —

## VOLUMES OF THIS SERIES

Volume 1	Materials: State of the Art
Volume 2	Test Methods, Specifications, and Standards
Volume 3	Smoke and Toxicity
Volume 4	Fire Dynamics and Scenarios
Volume 5	Elements of Polymer Fire Safety and Guide to the Designer
Volume 6	Aircraft: Civil and Military
Volume 7	Buildings
Volume 8	Land Transportation Vehicles
Volume 9	Ships
Volume 10	Mines and Bunkers

## PREFACE

The National Materials Advisory Board (NMAB) of the Commission on Socio-technical Systems, National Research Council, was asked by the Department of Defense Office of Research and Engineering and the National Aeronautics and Space Administration to "initiate a broad survey of fire-suppressant polymeric materials for use in aeronautical and space vehicles, to identify needs and opportunities, assess the state of the art in fire retardant polymers (including available materials, products, costs, data requirements, methods of test and toxicity problems), and describe a comprehensive program of research and development needed to update the technology and accelerate application where advantages will accrue in performance and economy."

In accordance with its usual practice, the NMAB convened representatives of the requesting agencies and other agencies known to be working in the field to determine how, in the national interest, the project might best be undertaken. It was quickly learned that wide duplication of interest exists. At the request of other agencies, sponsorship was made available to all government departments and agencies with an interest in fire safety. Concurrently, the scope of the project was broadened to take into account the needs enunciated by the new sponsors as well as those of the original sponsors.

In addition to the Department of Defense and the National Aeronautics and Space Administration, the total list of sponsors of this study now comprises Department of Agriculture, Department of Commerce (National Bureau of Standards), National Fire Prevention and Control Administration, Department of Interior (Bureau of Mines, Division of Mining Research, Health, and Safety), Department of Housing and Urban Development, Department of Health, Education and Welfare (National Institute of Occupational Safety and Health), Department of Transportation (Federal Aviation Administration, U.S. Coast Guard), Department of Energy, Consumer Product Safety Commission, Environmental Protection Agency, and the Postal Service.

The committee was originally constituted on November 30, 1972. The membership was expanded to its present status on July 25, 1973. The new scope was established after presentation of reports by liaison representatives which covered needs, views of problem areas, current activities, future plans, and relevant resource materials. Tutorial presentations were made at meetings held in the Academy and during site visits, when the committee or its panels met with experts and organizations concerned with fire safety aspects of polymeric materials. These site visits (upwards of a dozen) were an important feature of the committee's search for authentic information. Additional inputs of foreign fire technology were supplied by the U.S. Army Foreign Science and Technology Center and NMAB staff.

## ACKNOWLEDGEMENTS

In the drafting of this report, valuable inputs were made by a large number of people. Special thanks go to the members of the Mines and Bunkers Panel that consisted of Frank E. Karasz, Chairman; Charles F. Reinhardt; Arnold Rosenthal; Giuliana Tesoro and to the liaison members David Forshey; Herbert C. Lamb; Irving Litant; and Arnold Weintraub. The substantial written contributions by Ernest B. Altekruze and Robert B. Williamson are very much appreciated.

I would also like to acknowledge with thanks Barna Toekes, Engineering and Management Consultant, for his contributions in organization and editing much of the report.

The following people at the Bureau of Mines, Pittsburgh, were especially helpful: Dr. Robert F. Chaiken, Mr. Harry C. Verakis, Mr. J. Navy, Mr. D. Burgess, Mr. R. W. Van Dolah, Mr. M. Herzberg, and Mr. J. Kuchta.

My apologies to those we may have inadvertently omitted.

I acknowledge with gratitude the assistance in this project of Dr. Robert S. Shane, NMAB Consultant.

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Scope and Methodology of the Study

The charge to the NMAB Committee on Fire Safety Aspects of Polymeric Materials was set forth in presentations made by the various sponsoring agencies. Early in its deliberations, however, the committee concluded that its original charge required some modification and expansion if the crucial issues were to be fully examined and the needs of the sponsoring organizations, filled. Accordingly, it was agreed that the committee would direct its attention to the behavior of polymeric materials in a fire situation with special emphasis on human-safety considerations. Excluded from consideration were firefighting, therapy after fire-caused injury, and mechanical aspects of design not related to fire safety.

The scope of the committee's study includes: (1) a survey of the state of pertinent knowledge; (2) identification of gaps in that knowledge; (3) identification of work in progress; (4) evaluation of ongoing work as it relates to the identified gaps; (5) development of conclusions; (6) formulation of recommendations for action by appropriate public and private agencies; and (7) estimation, when appropriate, of the benefits that might accrue through implementation of the recommendations. Within this framework, functional areas were addressed as they relate to specific situations; end uses were considered when fire was a design consideration and the end uses were of concern to the sponsors of the study.

Attention was given to natural and synthetic polymeric materials primarily in terms of their composition, structure, processing, and geometry (i.e., film, foam, fiber, etc.), but special aspects relating to their incorporation into an end-use component or structure also were included. Test methods, specifications, definitions, and standards that deal with the foregoing were considered. Regulations, however, were dealt with only in relation to end uses.

The products of combustion, including smoke and toxic substances, were considered in terms of their effects on human safety; morbidity and mortality were treated only as a function of the materials found among the products of combustion. The question of potential exposure to fire-retardant polymers, including skin contact, in situations not including pyrolysis and combustion was addressed as deemed appropriate by the committee in relation to various end uses.

In an effort to clarify understanding of the phenomena accompanying fire, consideration was given to the mechanics of mass and energy transfer (fire dynamics). The opportunity to develop one or more scenarios to guide thinking was provided; however, as noted above, firefighting was not considered. To assist those

## MINES AND BUNKERS

who might use natural or synthetic polymers in components or structures, consideration also was given to design principles and criteria.

In organizing its work, the committee concluded that its analysis of the fire safety of polymeric materials should address the materials themselves, the fire dynamics situation, and the large societal systems affected. This decision led to the development of a reporting structure that provides for separate treatment of the technical-functional aspects of the problem and the aspects of product end use.

Accordingly, as the committee completed segments of its work, it presented its findings in the following five disciplinary and five end-use reports:

- Volume 1 Materials: State of the Art
- Volume 2 Test Methods, Specifications, and Standards
- Volume 3 Smoke and Toxicity (Combustion Toxicology of Polymers)
- Volume 4 Fire Dynamics and Scenarios
- Volume 5 Elements of Polymer Fire Safety and Guide to the Designer
- Volume 6 Aircraft Civil and Military
- Volume 7 Buildings
- Volume 8 Land Transportation Vehicles
- Volume 9 Ships
- Volume 10 Mines and Bunkers

### 1.2 Scope and Limitations of This Report

This report specifically examines the polymeric materials used in mines and bunkers. Underground mines and bunkers can be conceived of as two- or three-dimensional underground structures that are closed systems dependent on forced ventilation.

The term "mines" is used in this report to convey the traditional meaning of the word — i.e., the space and operations used in recovering solid mineral or organic deposits on the surface or underground. Not included, however, is the recovery of liquid or gaseous deposits such as oil, natural gas, and liquefied sulphur. The term "metal and non-metal" is used to designate all mines that do not produce coal, an accepted practice of the U.S. mining industry. Since underground mines are more susceptible to polymeric fire hazards than surface mines, emphasis is placed on this type. Ancillary structures including mills and preparation plants are excluded from consideration in this report.

A large number of underground mines are coal mines, man-made voids carved out of combustible material. They usually contain heavy powered equipment and methane is constantly diffused from the walls. There typically are several exit corridors. Egress from the greatest number is by slope, drift, or adit; egress from many is by a combination of slope, drift, adit, ladder, vertical hoist, and elevator; egress from a few is by vertical hoist alone. Underground coal mines generally are structured horizontally or on a slight slant (two dimensions). Metal mines usually do not contain combustible ores or gases, but they go deeper than and contain

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much more wood than coal mines and make frequent use of explosives. They often are constructed in a multi-layered fashion (three dimensions).

Only those bunkers that are underground spaces similar to mines in layout, construction, usage, human occupancy, or intensity of activity are considered in this report, and the term "mines" is used in the text to include both mines and bunkers. Bunkers that are used for storage, living, or recreational purposes must have good access and egress routes, be compartmentalized to control fire spread, and have a smoke ventilation system. Aside from these considerations, the problems of polymeric materials usage and fire safety are analogous to those involved with other facilities of similar function, and reference should be made to Volumes 7 and 8 in this series, Buildings, and Land Transportation Vehicles. Bunkers used for liquid storage are outside the scope of this report, and bunkers constructed for military purposes are not discussed because of security reasons.

Fire ignition sources in mines and bunkers vary, but the most frequent are electricity (arcing or overheating), welding, and mechanical heat (friction). The special problems of limited access, forced ventilation, and powerful ignition sources require that great care be exercised in the use of polymeric materials to avoid any additional fire hazard because of ease of ignition, rapid flame spread, and evolution of smoke and toxic fumes.

### 1.3 Bunkers — A Special Consideration

A bunker originally was considered to be a large bin, a bin for fuel on shipboard, a sand pit, or some other artificial fortification. Today, it is normally thought of as an underground or aboveground fortification to seclude humans, ammunition, or other supplies. However, underground space is used in many other ways. Some of these underground installations are similar to mines (i.e., they have limited access and have a soil or rock overburden), and, in some cases, they are actually located in spaces that were formerly mines.

Underground space may be classified as to its depth from the earth's surface, method of formation, earth strata, or use. To relate to conventional (aboveground) buildings, the following end-use classification is presented:

1. Storage — One of the principal uses for underground space, including natural caves, is for storage (e.g., dry storage for goods; refrigerated storage; storage of records, agricultural products, petroleum products, gold and other precious metals, and munitions). Underground facilities are particularly well suited to cold storage and these represent about one-tenth of the nation's capacity. Some burial spaces also may fit this category.
2. Transportation — Extensive use is made of underground space in the form of vehicular tunnels, subway stations, parking garages, and ancillary facilities. Some garages may be underground extensions of high-rise buildings developed to conserve spaces.
3. Commerce — Underground shopping centers, including various types of

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shops, restaurants and nightclubs, are found in a few scattered locations including Washington, D.C., Crystal City, Va., Atlanta, Ga., and the Kansas City, Mo., area.

4. Manufacturing – Relatively few manufacturing plants are found in underground space but some examples include a precision instrument producer, boat manufacturer, pool table assembler, and printer. These uses usually are limited to those that require a special environment (e.g., free from vibration or with controlled humidity).
5. Agricultural – Natural caves or artificial cellars are widely used for processing and storing wine. Mushroom farms are occasionally located in abandoned limestone mines or other underground spaces. The recovery of guano from natural caves is another usage example.
6. Office Space – Offices are found underground to a limited extent where underground space is being utilized for other purposes (e.g., shopping centers). Others are constructed for defense security purposes.
7. Utilities – Extensive use is made of underground utilities. In addition to extended sewage systems and the simple burial of pipes and cables, there are multi-use tunnels that contain cables and pipes. Some use is also made of underground space for sewage and water treatment plants.
8. Institutional – This includes schools, libraries, museums, and hospitals. These uses represent essentially depository (storage) facilities and temporary living and working quarters, laboratories, lecture halls, and display centers. In most cases, these underground facilities are extensions of high-rise buildings.
9. Habitation – Limited use is made of underground space for human residences. These homes may be designed with a view into an open atrium and have only a few feet of soil cover.
10. Defense – Defense usage most closely fits the conventional definition of a bunker. Included, however, are missile silos, command and communications facilities, aboveground munition bunkers, and air raid or bomb shelters.

These examples are not intended to be all inclusive, but rather to give perspective to the many uses of underground space. Consideration of the Kansas City area, where approximately 25 million square feet of underground space have been developed for many purposes, can contribute to identifying the scope of such development. This area is particularly suited to the development of underground space because of extensive limestone mining operations, suitable geology, and a need for space that makes use of such space economically attractive.

Although the number of people working, living, shopping, or traveling underground is relatively small compared to the total population, it does represent a significant amount and appropriate consideration must be given to fire safety. Examination of a list of uses presented above gives an indication of the wide variety of polymeric materials that will be found in underground space.

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Although the development of underground space has been relatively limited in the United States, this trend may change in the future because of energy considerations and the lack of choice aboveground space. In many cases, the determination will be based on economics.

Major differences that must be examined in considering the fire safety aspects of polymeric materials in underground space as opposed to conventional buildings are the limitations in venting smoke and heat, access by firefighting equipment, and avenues of egress. Fire in an unventilated underground space is an adiabatic process since heat cannot escape or be removed as it is in aboveground fires. Also, the oxygen content will be depleted rapidly and the products of combustion therefore will be different from those in an open fire. On the other hand, if forced ventilation is induced in an underground space fire, both of the above conditions will change abruptly and a wide array of possibilities become feasible.

### 1.4 Committee Viewpoints

Members of the committee are involved with materials research and development, applications, and system design and evaluation; liaison representatives deal with research and development, regulation, procurement, operations, and analysis. Thus, aspects of each material (and its problems) were subjected to a full spectrum of expertise. Full and extensive communication over the lengthy period of the committee's operation provided an unusual base for augmentation of the expertise and rounding of knowledge.

Many statements about the fire safety aspects of polymeric materials appear in each of the reports published as a result of the committee's study. Members of the committee wish to emphasize that such statements, including judgmental ones in regard to fire safety aspects of materials, especially end uses, apply only to the specific situations that pertain (e.g., suitability of a material from a fire safety point of view depends on many factors, including ease of access, ease of occupant egress, proximity of ignition hazard, proximity of other materials, thermal flux and duration of ignition source, ambient oxygen partial pressure, and fire and smoke detection and suppression systems in place). This list is not all inclusive, but only indicative of the kinds of concerns that must be considered in making a materials selection.

Statements in this volume must not be taken out of context and applied to the use of identical materials in other situations. In addition, the changing nature of the problem as time goes on and additional experience is acquired must be recognized by the reader as it was by the committee. This viewpoint must be emphasized so that information that appears in all published reports of this committee's study is not misused by taking it out of context.

### 1.5 Organization of This Report

Chapter 2 in this report summarizes the conclusions and recommendations of

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the committee. Chapters 3–6 are devoted to a review of the state of the art of the subject material.

Specifically, Chapter 3, Fire Dynamics and Scenarios, includes statistics on mine disasters, explains development of fire scenarios, and presents several such fire scenarios. These scenarios of mine fires involving polymeric materials are inspired by real incidents and attempt to illustrate the most frequent hazardous situations. These scenarios are analyzed with attendant explanations of related fire dynamics. However, the reader is cautioned against accepting these synthesized scenarios as reports of actual events.

In Chapter 4, Materials, the potential contribution of polymeric materials to mine and bunker fires is described. Examined in detail are natural and man-made materials, their application in the mining environment, and expected behavior in a fire situation. Emphasis is placed on specific danger and prevention areas.

Chapter 5, Design Criteria in Mine Safety and Hazard Control, reviews present knowledge, explores fire and explosion control, and describes the mine environment and applied materials and equipment with relation to fire and explosion hazard. The effect of imposed regulations upon design, materials selection, and operating practices is then examined; areas of current and proposed research that would improve mine fire control are delineated.

In Chapter 6, Smoke and Toxicity, experimental and clinical data are examined, and the effects of temperature of combustion on various materials are explored. Considerations specific to mine and bunker environments are presented.

In the afterword, general and societal considerations are discussed. The implications of mine disasters to workers, mining economics, and society in general are considered. The role of legislation and union activity in mine safety also is briefly explored.

Appendixes present statistics on fires in United States and United Kingdom mines; a review of the combustion products of polymers and the physiological hazard of selected combustion products; a review of toxicity; information concerning the evaluation of the hazard of smoke, toxic fumes; and measurements of smoke opacity.

## CHAPTER 2

### SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

#### 2.1 Introduction

This chapter summarizes the conclusions derived and recommendations advanced by the committee after reviewing the state of the art and current, ongoing research efforts. No attempt has been made to rank these conclusions and recommendations or to offer quantitative definition of the efforts proposed. General conclusions are presented without associated recommendations followed by specific conclusions and recommendations, which are a summary of those presented in Chapters 3 through 7. For a full exposition of the committee's views, the reader is referred to the conclusions and recommendations in each chapter.

#### 2.2 General Conclusions

1. Mining is a dangerous operation. Underground mining is considered to be among the most hazardous occupations today in the United States, with fire and explosion being among the most feared hazards. A mine, in effect, is an underground factory with a maze of corridors; it has low, flat roofs and long, limited escapeways and is dependent on forced ventilation. This confining geometry and limited accessibility intensify the fire hazard.
2. Coal mines are carved out of combustible natural oligomeric and polymeric material (coal) and often contain a highly flammable gas (methane). The walls and roofs of coal mines often are fragile and prone to crumbling and erosion. Large amounts of coal dust, which can form an explosive mixture with air, are generated during production.
3. Metal and non-metal mines are more numerous than coal mines and use much more structural timber, a highly combustible natural polymeric material. These mines often are deeper, have longer egress routes, and have more elaborate, three-dimensional layouts than coal mines. Some of these mines contain flammable, toxic, or radioactive gases.
4. All mines are increasingly employing more powerful equipment for production, wheeled transportation, conveying, and construction. These machines use large amounts of high-voltage electricity, are prone to frictional overheating and, thus, represent powerful potential sources of ignition. They also contain large amounts of polymeric materials (potential fuels) in the form of electric insulation, hydraulic fluid and hoses, tires, conveyor belts, lubricating oils and greases, and diesel fuel.
5. Mine ventilation systems and mine development techniques also reflect in-

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creasing use of polymeric materials (e.g., brattice cloth and polyurethane foam).

6. Bunkers and other underground spaces exist in many forms or constructions and are used for a great diversity of activities. Some are very similar to mines and many findings in this volume apply to these spaces; however, others are underground extensions of high-rise buildings or transportation systems and are at least partially covered in Volumes 7 and 8 of this series, respectively.
7. All organic polymers will burn if exposed to a strong enough ignition source and supplied with sufficient oxygen.
8. Absolute fire safety of polymeric materials does not exist; there are always trade-offs in safety, utility, and cost.

### 2.3 Specific Conclusions and Recommendations

#### 2.3.1 Fire Dynamics and Scenarios

*Conclusion:* Mine fire scenario development and analysis is important in providing the basis for material selection, design criteria development, test method validation, regulation, personnel training, and research and development efforts. *Recommendation:* Individuals involved in mine fire investigation, development of design criteria, and direction of research and development should be trained to develop and use mine fire scenarios. (See Vol. 4)

*Conclusion:* Several basic processes associated with the burning of polymeric materials in a mine environment are poorly understood. This lack of knowledge limits fire prevention and suppression efforts. *Recommendation:* Ongoing fire research programs should be expanded and accelerated to include: (1) design and performance of medium- and large-scale fire experiments fully instrumented to collect maximum amounts of data related to combustion, explosion, and toxicity on a diversity of materials under a variety of spatial and ventilation conditions; (2) development of scaling factors, knowledge of size and spatial influences, and information on three-dimensional effects; (3) development of theories, schematic representations, and mathematical and computer models of all important fire-related processes susceptible to such treatment.

#### 2.3.2 Materials

*Conclusion:* The selection of materials for use in mines and bunkers is of special concern because of the additional hazards imposed by limited access and egress routes. Still, in selecting polymeric materials with improved fire safety characteristics, competing functional, economic, and safety requirements must be reconciled. Of particular concern are wood (structural timber), ventilation cloth, conveyor belts, electrical conductor insulation, and polyurethane foam used for stoppings even though a particular material is used in small quantity. *Recommendation:* The susceptibility of all these materials to fire should be substantially diminished or usage should be stopped: Methods to decrease the ignitability of wood (e.g., coating

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or precharring) should be developed. The ignitability and rapid flame spread rate of ventilation cloth should be decreased (greatly improved substitutes are available). Electric conductor insulation should be improved, and acceptance requirements should become more stringent so as to exclude polyvinyl chloride. All insulation should meet the more severe requirements. The requirements for foam should be examined and more restrictive specifications (e.g., that would require polyurethane foam to be replaced with something better) should be established. All approved foams should meet the new requirements.

### 2.3.3 Design Criteria in Mine Safety and Hazard Control

*Conclusion:* The fragmented approach to design criteria development for mine hazard control is no longer acceptable (See Chapter 3). *Recommendation:* Design criteria development in the future should be based on an overall systems approach after advanced research efforts produce the necessary input elements.

*Conclusion:* The fire safety of mine operations has improved significantly during recent years, but several of the advances made require further development, modification, or refinement and almost none have been implemented widely. It should be recognized that no study of the cost and benefits of the recommended work has been made. *Recommendation:* Meaningful test methods should be developed for belt conveyor systems: full-scale fire tests should be performed and efficient detection and suppression systems should be perfected. Reliable acceptance test methods should be developed for the rating, selection, and evaluation of conductor insulations in the mine environment. The newly developed hydraulic fluids (water-in-oil emulsion types) should be perfected or a suitable replacement found. The development of new types of fire-sensing instruments should be continued and their application augmented. The development of tube bundle technology should be continued and expanded to other areas of mine fire safety applications. Spontaneous combustion research should be continued and accelerated in anticipation of the development of deeper seams and the western coal mines. The development of mine fire prevention and suppression technology should be continued. Development of methods of methane drainage, face ignition quenching, remote mine sealing, and fire and smoke protection in shafts should be perfected as should coal dust explosion barriers, sound suppressants, and structural reinforcements. Surface mining vehicle and machinery fire protection programs should be more fully utilized. The programs and the systems developed should be applied to large haulage vehicles, augers, drills, shovels, and drag lines.

### 2.3.4 Smoke and Toxicity

*Conclusion:* Data relating to the toxicity of combustion and pyrolysis products of materials in experimental or actual fires are sparse; available studies are designed only to identify lethal levels. Little is known of the additive or synergistic effects of toxic agents. *Recommendation:* A central agency should be established to collect

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and analyze data and promulgate information regarding the toxicity of the combustion and pyrolysis products of polymeric materials in test and actual fires. Studies should cover the incapacitating effects as well as the lethality of individual toxic agents and their likely combinations. Toxicity data on fire victims also should be collected by paramedical rescue personnel and medical centers.

## CHAPTER 3

### FIRE DYNAMICS AND SCENARIOS

#### 3.1 Introduction

Man has experienced fire for many thousands of years. As with other useful but potentially dangerous and destructive forces, it became imperative that he learn to use and control fire. Practical solutions for many fire situations were developed gradually and empirically, largely on the basis of post-fire investigation and without full understanding of the processes associated with ignition, combustion, fire spread, detection, and extinguishment. This approach, however, is no longer acceptable given society's increased technological capability and awareness of the value of human life and safety. Thus, a more sophisticated approach to fire prevention and control is required especially in the highly hazardous mine environment.

Although the number of fatalities resulting from mine fires is relatively small, fires together with explosions are a dreaded hazard in mining, particularly coal mining, and the potential for loss of life and property from these disasters is substantial. (Statistics on mine fires in the United States and the United Kingdom are presented in Appendix A). It therefore is of the utmost importance that the best available methods be used to assess and analyze the sources of the hazards. The continuing mechanization of coal mining, which involves the use of hydraulic equipment, plastics and large quantities of electricity, has intensified the chance of fire while minimizing loss of human life from non-fuel accidents.

The concept of using fire scenarios as a tool for gaining a better understanding of mine fires is introduced in this chapter. Fire scenario development and analysis are described and selected scenarios are presented. The state of the art of fire dynamics also is discussed in terms of the characteristics of mine fires, the properties of fumes behind the fire zone, the forces developed by these fumes, and the ventilation disturbances caused by fires. Gaps in knowledge are identified and approaches for developing improved fire prevention and control measures are proposed.

#### 3.2 Mine and Bunker Fire Scenarios

Real fire situations in mines, especially during the initial stages of development, are seldom observed by trained personnel. How a fire was initiated often can be deduced by carefully examining the remaining evidence, and the sequence of events often can be reconstructed with reasonable reliability; however, in some cases, most evidence is completely destroyed and any attempt at analysis is restricted to mere speculation. The development and analysis of fire scenarios therefore can be of great value by permitting alternative fire development sequences to be considered,

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by lending support to speculations and deductions, and by providing guidance for the design of useful experiments.

### **3.2.1 Guidelines for Development**

Mine fire scenarios are best based on real fire incidents that lend themselves to plausible extrapolation of the important elements. Fortunately, mine fire reports are compiled by the U.S. Bureau of Mines (BuMines), and there is a large number of real incidents from which to choose. In this section, the important physical elements of a mine fire that belong in a scenario are considered. Major emphasis is placed on the physical behavior of fire rather than on the human element even though it is recognized that people enter the scenario by preventing, detecting, extinguishing, or starting the fire and by escaping from or being injured or killed by the fire.

#### **3.2.1.1 Pre-Fire Conditions**

The important elements of a fire incident generally are established long before the incident. The physical layout of the mine, the structural elements used, and the equipment selected decisively affect the events that lead to a fire incident, and a great deal of attention must be given to these pre-fire conditions.

Consequently, the first step in the development of a mine fire scenario should be to gather all important pre-fire data. Included may be information on the general layout of the mine; the production rate; the number of personnel employed per shift; the location of conveyors and vents; vent flow direction and volume; the type and physical condition of the mining, transportation, and auxiliary equipment employed; maintenance records and housekeeping conditions (e.g., the accumulation of coal dust/oil mixture on working machinery); and the location and condition of permanent and movable electric power distribution lines, switch gear, and failure protection equipment. The basis for materials selection also should be examined; where and how materials were used and stored should be established; and compliance with applicable codes, regulations, and procedural instructions should be considered.

#### **3.2.1.2 Ignition Source**

The typical fire scenario starts with ignition, which may be characterized as the bringing together of an energy source and a combustible substance in the presence of an oxidizing atmosphere so that a self-sustaining exothermic reaction occurs. Ignition sources in mine fires usually involve electric arcs; overheated conductors; or the frictional heat that results from electrical or mechanical failures, malfunctions, or accidents. Spontaneous combustion of materials also occurs with some frequency, and human error (welding or improper or unauthorized use of fire or electric heat) is another contributor. If possible, the ignition source should be characterized quantitatively in the fire scenario in terms of:

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1. Maximum temperature ( $^{\circ}\text{C}$ ),
2. Energy release rate (cal/sec or watts),
3. Time of application to target (sec), and
4. Area of contact ( $\text{cm}^2$ ).

In considering the ignition of solid materials (e.g., polymers, coal, coal dust and oil mixture), it is most important to recognize that a "strong" source will ignite the target whereas a "weak" one may not. The "strength" of the source depends on the energy flux and the time of application to the target or on the product of these two. Ignition of gaseous targets, on the other hand, can occur with a very weak source even if the flashpoint temperature is reached only for a moment. The methane and air mixture frequently encountered in coal mines is such a target and its flash point, which depends on its concentration, is important.

### 3.2.1.3 Material First Ignited

Of major importance in developing a mine fire scenario is definition of the target material first ignited by the energy source. This first step in the fire chain — and a favorable point at which to break it — represents a transition from a transient (accidental) energy release to an uncontrolled exothermic reaction of combustible fuel and oxygen that is capable, if not checked, of accelerated growth to catastrophic proportion. Whether ignition occurs under a given energy release depends on the physical and chemical properties of the target material; therefore, a detailed description of these properties is essential if the probability of ignition is to be assessed properly.

Most organic gases, liquids, and solids will ignite if heated to a sufficiently high temperature in the presence of an adequate oxygen supply. Combustible gas mixtures and certain dust and air mixtures (e.g., coal dust) are ignited more easily than liquids and solids. In coal mines, where such mixtures are unavoidable, the concentration of the gaseous (or dust) fuel must be reduced below the flammable limit by a well designed, high-volume forced ventilation system. Thus, it is important in mine fire scenarios to define the type, concentration, and temperature of various fuels (or dust) and the ventilation air velocity (ft./min.) or rate of replacement ( $\text{ft.}^3/\text{min.}$ ).

Liquid organic fuels also can be ignited quite easily depending on their physical state (pool, foam, mist, or spray) and temperature, and these parameters are important in the fire scenario. If the temperature of an organic pool is increased above the flash point, ignition of the fuel vapors above the pool will occur and the pool will sustain burning. In a mine environment, the most common organic liquids are hydraulic fluids, lubricating oils and greases, and diesel fuel. It is quite common, for instance, to find an accumulation of mixtures of oil and grease and coal dust on work equipment (cutters) and transport equipment (trolleys and conveyors). Although the total prevention of such an accumulation is rather difficult (if not impossible), good housekeeping practices should require frequent removal. All these

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elements are of importance and should be considered in the development of fire scenarios.

Quite frequently solid polymeric materials are the first materials ignited in a mine. These combustibles comprise electric insulation, hydraulic hoses, rubber vehicle tires, conveyor belts, ventilation cloth or polyurethane foam used for temporary or permanent seals, and structural timber. The coal bed itself (although not considered as polymeric material) and coal dust, its fragmented product, also can be early targets of ignition. How easily a solid polymeric target will ignite depends on the chemical composition and physical form of the material.

Generic terms such as polystyrene and polyurethane are not adequate to describe synthetic polymers. Most of these materials contain a variety of additives; some are composed of several polymers; and some exhibit an altered chemical composition as a result of reaction with the environment. All of these factors can substantially modify the combustibility and fire-sustaining characteristics of the base polymer. Surface texture (smooth or frayed), form (solid, rigid, or flexible foam), structure (open or closed cell), and density and layer thickness (surface to volume ratio) are physical properties that, together with geometric configuration, have a significant effect on the behavior of a polymeric material in a fire situation.

The thermal properties of solid targets play a vital role in determining ease of ignition. Since the ignition of a solid requires that the temperature of its surface be raised to some critical value (i.e., the ignition temperature), heat conduction from the exposed surface to the interior will affect the time of ignition. This heat-transfer mechanism may become crucial to a scenario if the heat flux is of relatively short duration. Material properties of thickness and thermal diffusivity (i.e., the ratio of thermal conductivity to heat capacity) as well as heating rate and physical thickness determine whether a target material behaves in a "thermally thin" or "thermally thick" manner (see Volume 4 of the committee's report). The ignition time of a "thermally thick" material is relatively independent of physical thickness; it is controlled by "thermal inertia" the product of heat capacity (per unit volume) and thermal conductivity. The ignition time of "thermally thin" materials (e.g., vent cloth fabrics used in mines) is proportional to the product of heat capacity and physical thickness.

In the case of composite structures, the properties of the layers used under surface films or sheets (e.g., the materials supporting belts) also will affect ease of ignition. To be considered are the strength of the bond between the exposed and the supporting layer, the thickness of the layers, and the thermal conductivity of the supporting material.

The geometric configuration of a material also can influence ease of ignition. Flat surfaces and single solid members generally are more difficult to ignite than closely stacked pieces or members having folds and crevices. Similarly, vertical or downward-facing surfaces are more susceptible to ignition than those facing upward because of increased heat transfer from a rising convective heat plume.

#### 3.2.1.4 Combustion Types – Flaming and Smoldering

Some combustible materials burn in either a smoldering or a flaming mode, but generally only solids with very low thermal conductivity (e.g., plastic foam or fiber pad) can smolder. Whether a material burns in the smoldering or flaming mode may be determined by the ignition source. A high-temperature ignition source (e.g., an open flame) usually will initiate flaming combustion whereas a low-temperature source (e.g., an overheated wire) is more likely to result in smoldering combustion. A restricted air supply like that in a closed compartment or the interior of partitions also is more likely to result in smoldering combustion.

Smoldering combustion is characterized by a slow spread rate, a relatively low temperature, the absence of visible flame, and the production of smoke and gas. In developing mine fire scenarios it is important to note that the products of smoldering combustion are different from those of flaming combustion and that a transition to flaming combustion after a long smoldering period may result in a rapidly spreading fire because of the preheating of the fuels and the accumulation of combustible gases during smoldering. In addition, smoldering or deep-seated fires are difficult to extinguish (i.e., a gaseous extinguishing agent may extinguish flames but the residual charcoal may continue to burn by "glowing combustion" and the flame might rekindle after the extinguishant has dissipated). Flaming combustion is characterized by visible flames, a high temperature, and a rapid spread rate. Its presence usually does not go undetected for long. Thus, smoldering combustion is generally the more insidious hazard, and the possibility of its occurrence should be considered carefully in investigating accidents and developing scenarios.

#### 3.2.1.5 Fire Propagation

The course of a fire after ignition is determined by the rate of fire growth and the time at which various defensive actions are initiated. These factors are therefore very important elements in the mine fire scenario.

Fires grow by spreading over the surface of an ignited fuel element, by spreading from one contiguous target to the next, or by jumping across a gap from one fuel element to the next. The rate of fire propagation over a horizontal or downward-facing solid surface generally is rather slow. However, the fire can spread rapidly if the material is "thermally thin" or has been preheated by convection or radiation or if there is forced ventilation. If the physical layout permits, upward propagation (e.g., through shafts and vertical ducts) will occur very rapidly and at a progressively increasing rate. If the originally ignited material is separated by a gap from the nearest secondary combustible target, it will either die out or spread across the gap. "Jumping the gap" can occur by a variety of modes. The secondary target can be preheated (by convection or radiation) until it pyrolyzes and emits flammable vapors that spread across the gap and are ignited. If the primary burning material is a thermoplastic, it may spread the fire by melting and dripping burning droplets onto the secondary material.

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The specific environment prevailing in mines and bunkers will have a great effect on the rate of fire spread. The normal forced ventilation in mines will greatly accelerate fire spread; however, when forced ventilation is stopped, oxygen is consumed rapidly and fire spread is greatly decelerated. An effective, frequently practiced means of controlling fires in mines consists of inhibiting oxygen flow to the fuel by sealing off the fire-affected area. When this is done, however, the concentration of combustible gases increases and an explosion or reignition of the fire at an accelerated rate can occur when ventilation is restarted. Additionally, if the burning material is a structural support and is mechanically weakened by the fire, the mine shaft or duct can collapse and alter the fire spread situation by limiting or enhancing ventilation and curtailing extinguishing or sealing operations.

The foregoing illustrates why it is unwise to make any change to the mine ventilation system without careful consideration by and agreement among competent, responsible persons. In coal mines, miscontrol of ventilation during a fire has resulted in explosions and in rapid, upwind burning of the coal ribs and roof. The subject is further discussed below.

### 3.2.1.6 Evolution of Smoke and Toxic Gases

During the early stages of a mine fire, the forced ventilation system usually provides abundant oxygen, but when ventilation is interrupted, the fire environment rapidly becomes oxygen lean. This situation results in incomplete combustion and the production of highly toxic gases and fumes. Depending upon the types of polymeric material present, the typical products of incomplete combustion may include carbon monoxide, hydrogen cyanide, nitrogen oxides, ammonia, hydrogen sulfide, phosgene, and many other compounds. Most of these are highly toxic to human life. Smoke (suspended solids) is also dangerous to life in that it can plug airways and carry adsorbed gases, liquids, and residual heat to the respiratory tract.

Underground mine access and egress routes usually are very limited and the spread velocity of toxic fumes and gases generally is more important than the spread velocity of the fire itself. Thus, the response to a fire situation in a mine is different from that in a building or aboard a ship or airplane where the first response usually is an attempt to extinguish it with something immediately available (e.g., a cup of coffee, water, or a cloth). In a mine, the first response must be an immediate start of evacuation while simultaneously cutting off the ignition source; only then can an attempt to extinguish the fire be made.

In assessing the effects of fumes and toxic gases in a mine fire scenario, the following points should be considered:

1. Because of their physical and chemical properties, smoke and gases offer an opportunity for early fire detection and initiation of evacuation and extinguishment operations. Thus, an efficient alarm and communications system is extremely important.
2. Smoke and gases can rapidly incapacitate personnel; therefore, evacuation

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operations are of paramount importance.

3. The high concentrations of smoke and fumes present in a mine fire dictate that firefighters carry complete oxygen support systems when downwind of the fire. Dense smoke also may curtail rescue and fire control efforts on the downwind side.
4. The high concentrations of gases and fumes also can have residual effects on mine equipment and materials. Exposed machinery may corrode or be covered with a flammable, corrosive and often electrically conductive film.

### 3.2.1.7 Detection

The first detection of the fire is a critical element in a mine fire scenario because of the time required to evacuate personnel through limited escape routes. Automatic detection equipment may be sensitive to heat or to the particulate or gaseous products of combustion. Fire detectors are most effective in mines when located on or near face-cutting equipment and in the vent system downstream of active operations.

How automatic detection equipment responds to products of combustion is important and may depend on the concentration of gases, the particle size of smoke, the velocity of smoke and gases flowing past the detector, the orientation of the detector chamber to the flow, and the sensitivity setting and operating characteristics of the detection instrument. In scenario development it is important to remember that under different ventilation conditions the same materials will produce smoke having different particle sizes and will have different combustion characteristics. In addition, the characteristics of the smoke may change as it "ages" and smaller particles agglomerate into larger ones.

### 3.2.1.8 Extinguishment

At some point in a mine fire scenario, extinguishment and fire control activities will be initiated. A consideration of extinguishment techniques is beyond the scope of this study, but it should be noted that the effectiveness of control and extinguishment efforts depends on the burning characteristics of the polymeric materials, the spread rate of the fire, and the time lapse between first ignition and detection. The accessibility of the fire scene to firefighters and the time required to reach the scene also are factors to consider in mine fires.

### 3.2.1.9 Summary of Essential Scenario Elements

The mine fire scenario should describe all significant factors and events in the development of the fire and should cover as many as possible of the following points:

1. The pre-fire situation should be described.
2. The source of ignition energy should be identified and described in quantitative terms.

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3. The first material to be ignited should be identified and characterized in terms of its chemical and physical properties.
4. Other fuel materials that play a significant role in the growth of the fire should be identified and described.
5. The path and mechanism of fire growth should be determined; particular attention should be given to fuel element location and orientation, ventilation, compartmentation, and other factors that affect fire spread.
6. The possible role of smoke and toxic gases in detection, fire spread, and casualty production should be determined.
7. The possibility of smoldering combustion as a factor in the fire incident should be considered.
8. The means of detection, time of detection, and the state of the fire at the time of detection should be described.
9. Defensive actions and evacuation procedures should be described, and their effects on fire control should be determined.
10. Interactions between personnel in the mine and the fire should be detailed.
11. The time and sequence of events, from the first occurrence of the ignition energy flux to the final resolution of the fire incident, should be established.

The complete scenario should permit generalization from the particular incident described, and it should provide the basis for exploration of alternative paths of fire initiation and for analysis of the effects on fire control of changes in materials, design, and operating procedures. As noted earlier, the scenario should be based on real fire incidents or should take some of its elements from real fire incidents. These incidents should be fully documented by a post-accident investigation report and an analysis designed to determine how and where the fire started and progressed until its termination. The scenario also can be based on a report of a fully instrumented, full-scale test burn. In either case, the development of a fire scenario will remain an art rather than a scientific presentation of irrefutable evidence until existing fire dynamics knowledge is augmented by additional research. Nevertheless, if constructed to be as complete and as accurate as possible, the fire scenario can be an effective tool for use in improving the fire safety of mining operations by increasing man's ability to visualize and comprehend the events.

### 3.2.2 Guidelines for Analysis

Analysis of well developed, plausible scenarios is an effective methodology for developing economical and efficient methods of fire prevention and control in mines and bunkers. One method of fire scenario analysis involves the careful examination of each element of the fire incident, the posing of relevant questions regarding each, and the identification of alternatives that could have prevented the incident. In conducting such an analysis, the following should be considered:

1. Pre-Fire Situation — Were existing codes, standards, and operating procedures adequate? Were they enforced? If not, what should be done to correct the

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situation? Were the materials and equipment used properly selected? Were the materials in good physical condition and was the equipment properly maintained? What housekeeping practices and conditions prevailed prior to the fire incident, and what actions should be taken to correct any deficiencies?

2. Ignition Source – What was the ignition source and for how long was it in contact with combustible material? Could the ignition source be eliminated by education or by design?
3. Ignited Material – What were the chemical and physical characteristics of the ignited material (its shape, form, and application)? Where was it located in relation to walls, equipment, and other combustible materials? Did melting or dripping of the ignited material affect fire spread? Did the ignited material collapse? What was the heat-release rate at the time the ignited material was fully involved? Could another less flammable or more fire-retardant material have been used in place of the ignited material? Were flammability tests on materials intended for this application available and adequate?
4. Combustion Type – Did smoldering precede flaming? If not known, was the ignited material capable of smoldering? What were the volume and composition of gases generated by the smoldering fire? Given the prevailing ventilation conditions, how quickly did a dangerous concentration of smoke and toxic gases develop and spread?
5. Fire Spread – How much time elapsed before the originally ignited target was fully involved in the fire? What was the mechanism of ignition transfer to a second combustible material? What was the flame spread rate and how did it change as ventilation conditions were altered? What effect did the material properties of the first two materials ignited have on the rate of fire spread? Would material substitutions and design modifications have affected fire spread?
6. Smoke and Toxic Gases – Of what value were smoke detectors? Did their absence or presence and location have an effect on the final outcome? Did dense smoke hinder escape. Which fuels contributed significantly to the decrease in visibility? What effects did toxic substances have on personnel (i.e., extent of injuries, interference with escape efforts, and deaths)? Which toxic substances were most responsible for injuries and from which fuels did they evolve?
7. Extinguishment – How much time elapsed between ignition, first detection, start and finish of evacuation, and initiation of extinguishment efforts? Which extinguishment or fire control techniques were used and how successful were they? Would the use of different extinguishment techniques or materials or better trained firefighters have improved efficiency or reduced injuries and damages.
8. Secondary Effects – Did any secondary occurrences such as a rekindling of the fire, explosions, flashovers, and post-flashovers occur? What caused these

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incidents? Did structural collapse occur? If so, was any code violated? Was any change in ventilation conditions involved? Were established procedures followed?

### 3.2.3 Selected Mine Fire Scenarios

In order to demonstrate that fire scenario development and analysis is a productive methodology for improving the fire safety performance of polymeric materials in mines, a number of scenarios are presented below.

It must be emphasized that these scenarios are not considered to be perfect or, in some cases, even satisfactory. Most of these incidents were based on actual mine fires; however, sufficient documentation was not always available, examination was not always adequate, and follow-up experimental demonstration of undetermined causes, occurrences or consequences was sometimes lacking. Thus, these scenarios also illustrate the importance of in-depth data collection and follow-up examination, including experimental demonstration.

#### 3.2.3.1 Insulation and Hydraulic Hose Fire Caused Short Circuit (Sorrel and Lyon, 1973)

##### Summary

The fire occurred when a trailing cable short-circuited on the reel of a cutting machine at the face of the mine. The nearest office of the U.S. Bureau of Mines was notified by the superintendent: he stated that all men, except persons engaged in firefighting activities, were on their way to the surface. Another inspector was sent to the neighboring coal mine, which was connected with the mine involved, to issue an order requiring that all persons be withdrawn from and be prohibited from entering the neighboring mine.

At the time of the fire, 150 employees were underground at the mine involved, and 112 were underground at the neighboring mine. All employees escaped unassisted and there were no injuries. Property damage was confined to the cutting machine. The investigation was completed the following day.

##### Pre-Fire Conditions

The mine was opened by three shafts and one slope. Of the 301 men employed, 255 worked underground and produced an average of 4,000 tons of coal per day. The room-and-pillar system of mining was used, but pillars were not extracted. At least two separate and distinct travelable passageways, one of which was ventilated by intake air, were maintained between the working sections and the surface.

The mine was ventilated by an axial-flow fan that was properly installed on the surface and equipped with the necessary safety devices. The mine surfaces ranged from damp to dry; loose coal and coal dust were not permitted to accumulate in active workings. Rock dust, in ample quantities, was applied to within 40 feet of the working faces, including open crosscuts.

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Coal was transported from the areas in shuttle cars, discharged onto belt conveyors, and transported to a mine-car loading facility. Men were transported underground in battery-powered, track-mounted personnel carriers. Underground, the coal was discharged from drop-bottom mine cars into a hopper and then transported by belt conveyor to the surface.

Electric power (4160 volts ac) was purchased from a local utility company to operate a 300-kilowatt rectifier located on the coal-producing section. This supplied 275 volts dc power for the electric face equipment. The 4160 volts ac was reduced to 480 volts for the underground belt conveyor motors. The frames of 80 percent of the electric face equipment were grounded by means of silicon diodes; the remaining 20 percent were grounded by means of trailing cables. The trailing cables were of the flame-resistant type, and all were equipped with suitable short-circuit protection.

The machine involved in the fire was a permissible type rubber-tired cutting machine equipped with a 125-horsepower cutting motor, a 45-horsepower pump motor, and two 500-foot lengths of No. 4/0, single conductor, Type W flame-resistant cable. The cable contained one permanent splice approximately 8 feet from the reel entrance gland and was protected by a short-circuit relay. The relay was adjusted to operate at an instantaneous current of approximately 1,825 amperes and to lock out if a solid short circuit occurred. The hydraulic system of the cutting machine contained approximately 95 gallons of flammable hydraulic fluid. The approved record book indicated that the machine had been inspected by a qualified person 12 days before the fire.

Firefighting equipment was readily available. It consisted of dry-chemical fire extinguishers, water under pressure with sufficient fire hose to reach each working face, and rock dust.

### **Description**

When the fire occurred, the cutting machine had finished cutting the face of an entry on the intake side of the working section, and the machine operator's helper sumped the bar of the machine in the right rib of the left crosscut. The trailing cable then short-circuited on the reel and ignited the jacket of the cable. The fire spread to the outer jackets of the hydraulic hoses. The helper and the regular machine operator immediately left the machine without actuating the fire-suppression system installed on the machine, deenergized the power, and notified the men on the working section to proceed to intake air.

A trained mine-rescue team was dispatched to the fire area. The line brattice had been installed to within 10 feet of the face with 13,000 cubic feet of air reaching the end of the brattice. The fire hose, which was connected to the end of a 2-inch waterline, was extended to the entry and water was applied directly to the fire. During the firefighting operation, the fire-suppression system on the machine was thermally actuated. The fire was extinguished approximately 1-3/4 hours after it started.

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### Analysis

The machine involved was provided with an operative fire-suppression system that consisted of 40 pounds of dry chemicals and two manual actuators. The actuators were readily accessible, but the system was not manually actuated. The system contained eight spray nozzles, four of which were directed toward the reel compartment. Adequate firefighting equipment was readily available.

The machine involved was examined by a qualified electrician 12 days before the fire. The trip relay for the trailing cable in the face box was in operative condition. The only splice in the trailing cable was a permanent splice 8 feet from the reel entrance gland. The cable insulation on the cable next to the reel was brittle and cracked due to excessive heat. This was possibly due to oxidation or migration of the polymeric insulation plasticizer. Approximately 50 feet of the trailing cable was on the reel at the time of the fire. The hydraulic oil tank remained intact, and the oil in the system was not a factor in the fire.

The fire started as a result of a high-resistance fault in the trailing cable. The resistance of the fault limited the current to a value lower than needed to actuate the circuit protective device. The resultant arcing ignited the insulation.

Analysis of the scenario suggests that:

1. Electrical equipment should be inspected by qualified persons as often as necessary to ensure safe operating conditions. The inspection should include an examination of the trailing cable on reels.
2. Operators of electrical equipment should be trained to actuate fire-suppression devices.

### 3.2.3.2 Fire Caused by Spontaneous Combustion — Smoke, Heat, Toxic Gases (Matekovic, 1971)

#### Summary

During his normal duties, the day-shift fire boss detected smoke, heat, and carbon monoxide gas at the base of a pillar located two entries (about 200 feet) from a previously sealed area in the mine. He notified the mine superintendent who telephoned a mine inspector making a spot safety inspection in another section of the mine. An investigation was started immediately. The cause of the incipient fire was determined to have been spontaneous combustion; there were no injuries.

#### Pre-Fire Conditions

The mine was opened by four slopes, one drift, and one shaft into the coal bed, which ranged from 20 to 25 feet in thickness. A total of 206 men, 179 underground, were employed on one maintenance and two coal-producing shifts per day, 5 days per week. Average daily production was 4,000 tons of coal.

The entries were developed by the room-and-pillar method. Entries were driven on 80-foot centers and crosscuts were turned on 90-degree angles at 80-foot inter-

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vals. During initial development, approximately 8 feet of coal was extracted adjacent to the immediate roof, leaving between 12 and 17 feet of bottom coal, 7 feet of which was recovered during second mining.

During development of one of the entries that was close to the fire, excessive heating was encountered. This forced mining operations to be discontinued and the entries to be sealed. Due to natural physical conditions, the area was subject to heavy bumps, heaving, sloughage, and fractures in the bottom coal.

Firefighting materials consisting of portable firefighting units, waterlines, high-pressure rock-dusting machines, and rock dust materials for construction of seals were available at the mine. Twelve 2-hour and six 1-hour self-contained breathing units were available on the surface. Sixteen 45-minute Chemox units also were available at fire stations located underground. The use of these units was not required during sealing operations.

The last regular federal inspection of this mine had been completed two months before the fire. A spot safety inspection was in progress in another area of the mine at the time.

### Description

The day-shift fire boss discovered smoke and detected carbon monoxide gas when approaching the seals during his regular inspection. He called the mine superintendent who, with a small crew, proceeded to the area. Tests were made to measure the carbon monoxide and methane content in the mine atmosphere. Temporary fire-resistant plastic curtains were installed to exclude the air from the affected area. The mine superintendent ordered all persons not engaged in correcting the condition to leave the mine.

The company and the federal mine inspectors arrived and tested the air with a carbon monoxide gas detector; the carbon monoxide content was 250 parts per million. A 2-inch fire hose was installed and water was applied to the hot area. An hour later the air was tested again and only 50 parts per million of carbon monoxide were present.

Three temporary seals of 3 inch by 12 inch by 4 foot planking were started to seal off the area. These were cored by three permanent seals constructed of 6 inch by 8 inch by 3 foot ties laid longitudinally "skin to skin," filled with inert material, and plastered on the outside. Sealing operations were completed on the following day.

### Analysis

The smoke, heat, and carbon monoxide were caused by spontaneous combustion. This scenario suggests only that the daily patrol of this area should be maintained.

#### 3.2.3.3 Major Mine Fire and Fatalities Caused by Arcing Trolley Cable (O'Rourke et al. 1971)

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### Summary

The fire occurred in the straight-mains section of the mine. Of the 125 persons underground, 11 were working in this section. Nine of these persons escaped and two were killed. One additional person died accidentally 21 days later fighting the fire. The fire began when the end of a trolley wire fell in an entry (empty track) of the straight mains section and came in contact with the grounding clamp attached to the track rail.

### Pre-Fire Conditions

A total of 349 persons, 263 working underground, were employed on 3 shifts per day, 5 and 6 days per week. Coal production averaged 5,850 tons per day.

The mine was opened by one slope and five shafts into the coal bed, which averaged 84 inches in thickness in the fire area. The immediate roof consisted of wild coal, laminated shale, and sandstone. The floor was hard shale and fire clay. The volatile ratio of the coal in this mine was 0.39, indicating that the coal dust was explosive. The mine was developed by the room-and-pillar method and pillars were recovered. Entries were driven in sets of four to seven, 16 feet wide, with crosscuts at suitable intervals. The mine was ventilated by three propeller-type exhaust fans that provided 940,000 cubic feet of air per minute. Auxiliary fans were used to ventilate the working faces. Required tests for methane and other hazards were made.

Continuous-type mining machines were used and loaded into shuttle cars, transported to loading ramps, and transferred onto steel mine cars. The loaded cars were gathered by section trolley locomotives and placed in sidetracks for further transportation by tandem locomotives to the rotary dumps at the shaft bottom. Coal was hoisted to the surface preparation plant from a bin at the bottom.

Electric power was purchased at 26,000 and 28,000 volts ac and transformed to 7,200, 3,000, 440, 220, and 110 volts ac for use on the surface and underground. Direct-current power at 290 volts was provided for underground use by 11 conversion units provided with the required safety devices.

The dc power circuit in the straight mains was supplied with 290 volts by two 750 kilowatt, silicon diode rectifiers. These rectifiers were located approximately 2,500 feet and 3,500 feet from the working faces. The circuit breaker on the closer rectifier was set at 3,500 amps and on the farther rectifier, at 3,300 amps. The direct-current power was transmitted over a 400 milli circular mills cooper trolley wire along the entry to the working section. The negative circuit consisted of 70-pound rail track extended along the road haulageway. This track was parallel to a negative 1,000 milli circular mills copper cable that extended to the working section. Up to this point, single-bonded 40-pound rail track was used for entering branches. A 7,200 volt ac power cable, supported by messenger cable suspended from the roof in the entry, supplied the power centers and portable rectifiers which provided 550 volts ac and 250 volts dc for use by the face equipment.

A trained and fully equipped mine rescue team was available at the mine. Water-

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lines, fire hose, high-pressure rock-dusting machines, and 2,000-gallon-capacity water cars, properly equipped, were available underground.

### Description

A stoper operator, in the course of tracing a pressure failure on a roof bolting machine, opened a canvas check installed in an entry and observed yellow smoke. He closed the check and went to notify the foreman of the fire. The two men then traveled through several entries and crosscuts until they met a shuttle car operator. Due to the dense smoke, the foreman instructed the other two men to notify the crew to leave the section. He then attempted to locate the source of the smoke but dense smoke in several entries forced him back to a section still having clear air. He was able to reach and open a trolley switch in a crossover that was one of the power sources to the trolley wire in the track leading to the smoke-filled section. He then ran to a mine phone, notified mine officials and the crew in a nearby mine section and instructed a motorman to open the other trolley switch that supplied power to the fire area.

Meanwhile, the other two men notified the utility man and the men in the adjacent entries. They all assembled at the check curtain of their entry. A continuous-miner operator and a roof bolter decided to return for their safety lamps. When the roof bolter did not return, the operator followed him as far as he could, called several times but received no answer, and returned to the assembled group.

The group then proceeded out of the mine. On the way they met the foreman and informed him that the roof bolter was still in the section. A mason who had been installing a stoping on the right side of the mains also was not accounted for at this time.

The section foreman of the adjacent mains arrived and the two foremen started to force fresh air through the affected entries. These efforts proved futile.

The assistant superintendent issued orders to evacuate all other areas of the mine and to short circuit the ventilation at the crosscut. Checks were erected across the intake entries at this point. A mandoor was opened into the left return, and a hole was made in the stoping in the right return. Efforts to locate the missing men also were futile.

Several state and federal inspectors arrived and the first sign of an active fire soon was observed by two inspectors and two foremen when the plastic check across the entry melted. A waterline paralleling the haulage road was broken to allow the water to flow into the fire area and the quantity of air passing over the fire was further reduced by opening additional manddoors. A 2,000-gallon water car arrived at the scene and the fire was attacked directly.

A sampling station was established to monitor the air returning from the fire area in the left return and an hour later it was found that combustibles had reached a dangerous point. All persons were withdrawn from the mine.

Officials of the coal mine company, the United Mine Workers of America

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(UMWA), a local rescue organization, and the U.S. Bureau of Mines jointly planned rescue of the two missing men. Accordingly, the drilling of boreholes into the face area was started immediately, and as these holes penetrated the mine workings, efforts were made to contact the trapped men by lowering phone communications. Geo-phones also were used to detect sound vibrations underground; however, these efforts were futile. Ultimately, approximately 90 boreholes were drilled into the mine workings in and around the fire area, and various materials were introduced through these holes in an effort to control the fire.

Five days after the start of this incident, it was decided that the trapped men could not have survived the gases produced by the fire. Since direct attack was ineffective, it was agreed that the fire area would be flooded with water pumped from the surface through boreholes into the face areas. Eight days later, expansion foam was introduced from the surface through 13 boreholes into the intake airways near the fire area.

The maximum high-water level was reached on the eighteenth day. On the twentieth day, mine rescue teams entered the area and direct firefighting was resumed; however, the fire had spread beyond its last known location. Due to increased concentrations of combustibles, all persons were again withdrawn from the mine. On the twenty-first day, a state mine inspector was accidentally drowned during the firefighting operations.

During the next six months, underground dams were erected remotely to raise the water level, the mine was repeatedly inspected, roof sections were reinforced, bulkheads were erected, and the mine was purged with nitrogen and flooded with water. After an inspection made at the company's request 168 days after the fire was detected, rehabilitation work was permitted in several sections of the mine. Attempts to recover the entombed men were to be pursued without interruption. After all information indicated that the fire was extinguished 281 days after the original incident, it was decided to de-water the area behind the bulkheads and it was estimated that approximately 50 million gallons of water were impounded behind these bulkheads.

Recovery operations proceeded slowly because many seals had to be removed, crosscuts made, and sampling stations for gas analysis established as each area was reopened. The ventilation system also had to be modified continuously.

The body of the roof bolter was found in 3 feet of water, several days after recovery operations started and almost 18 months after the fire began. The body of the mason was found in a crosscut the next day.

At that time, it became necessary to modify the ventilation system significantly. Concurrently, the entire mine was completely inspected to determine whether it was feasible to resume operations. Almost 26 months after the initial incident, production was resumed in all but one of the active workings of the mine.

### **Analysis**

The fire most probably began when the end of the trolley wire fell and came in

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contact with the grounding clamp attached to the track rail. The trolley wire and insulating anchor were found lying on the mine floor at the compressor nipping station. Examination of the trolley wire and the attached anchor indicated that the clamp attaching the hanger to the trolley wire was partially consumed by electrical short circuit. Evidence indicated that heat had softened the vinyl-type insulation in the hanger bell used to anchor the trolley wire. The trolley wire and the soft insulation then pulled free from the hanger bell, allowing the end of the trolley wire to drop to the mine floor and strike one of the compressor ground clamps. This resulted in the partial destruction of the anchor and the ground clamps. The second ground clamp with a negative and frame ground conductor was intact.

Analyses of samples of coal and coke collected in the area of the compressor nipping station indicated that temperatures had been higher in the roof area than near the bottom. After removing the trolley wire anchor bolt assembly, samples were collected from the inside of the hole and at the roof line. The analyses of these samples indicated that the temperatures had been higher inside the hole than at the roof line outside the hole. This indicated that the hanger probably had been grounded and had generated heat which softened the insulation in the bell and thereby allowed the trolley wire to drop to the mine floor and strike the negative ground clamp, thus initiating the fire.

Analysis of this scenario suggests that:

1. In addition to the anchoring device, an insulated hanger should be provided at the ends of trolley wires and trolley feeder wires to prevent the wires from making contact with the mine floor or mine track rails if the anchoring device fails.
2. Circuit breaker short-circuit trip settings should be consistent with the power transmission system. The power transmission system should be evaluated periodically to determine if adequate short-circuit protection is provided during normal mining and idle periods.
3. When any smoke or abnormal amounts of fumes are detected in a mine, a thorough search should be initiated and continued until the source is determined and eliminated.

### **3.2.3.4 Cutting Machine Caused Fire (Jarvis, 1967)**

#### **Summary**

The fire occurred on a mining machine at the face of a working place in the mine. The fire apparently started in the area of the cutting motor and the resulting arcs and flame ignited accumulations of oil and coal dust on the machine, some of the hose in the hydraulic system, the front tires, and wiring. The fire was fought directly with dry-chemical fire extinguishers and water and was completely extinguished the same day. The 18 men working in the only section active at the time of the occurrence assisted in fighting the fire. There were no injuries, and damage was

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confined to the machine, which was considered to be a total loss.

### **Pre-Fire Conditions**

The mine was opened by drifts into the coal bed. Of the 43 men employed, 40 worked underground. An average of 700 tons of coal per day was loaded by a mobile loading machine into rubber tired mine cars.

The mine was developed by the room-and-pillar method. The immediate roof in the fire area varied from firm to fragile shale. The mine was classified as nongassy. Ventilation was induced by a propeller exhaust fan installed on the surface. Loose coal and coal dust had not accumulated in dangerous quantities at the time of the last federal inspection before the fire and rock dust had been applied to within 30 feet of all faces.

The mining machine involved in the fire was equipped with a 50-horsepower cutting motor and a 30-horsepower pump motor. Except for the accumulations of oil and coal dust on the machine and the condition of the cutting motor, it was maintained in good mechanical condition. The machine was equipped with two parallel 300-foot lengths of single conductor, No. 1/0 flame-resistant trailing cables that were without short-circuit protection. The hydraulic system for the machine, which ruptured during the fire, had a capacity of 90 gallons and was filled with flammable hydraulic fluid.

Firefighting equipment consisted of a 30-pound dry chemical system on the mining machine, dry-chemical fire extinguishers on each mobile unit and at strategic locations, and a high-pressure rock-dusting machine with ample quantities of rock dust.

### **Description**

The fire occurred when the mining machine operator and a helper completed undercutting the face of a working place and began turning the machine to start a crosscut to the left. Intensive arcs and flame suddenly issued from the area of the cutting motor and ignited accumulations of oil and coal dust on the machine, some of the hose on the hydraulic system, the front tires, and wiring. The operator actuated the firefighting system on the machine and had the power removed before the rapidly spreading fire and dense smoke forced retreat from the immediate area.

A line curtain was erected and the contents of all fire extinguishers at the mine were emptied on the machine; however, the fire continued to burn. Meanwhile, a pump was installed and 500 feet of 2-inch plastic water line was run to the fire area.

Water was applied to the fire, and it was extinguished about 1-1/2 hours later. A small dam was built with bags of rock dust to contain the water to cool the machine and material in the fire area. State and federal inspectors assisted in the firefighting operations and kept the area under constant supervision until it was determined that the area had cooled to the extent that there was no danger of rekindling.

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### Analysis

The fire apparently started in the cutting motor, which was known to be in poor operating condition. The resulting arcs and flames ignited accumulations of oil and coal dust on the machine, some of the hydraulic hoses, the front tires, and the wiring.

This analysis suggests that:

1. Trailing cables should be provided with suitable short-circuit protection, and there should be some means for disconnecting power from the cable.
2. Electric equipment should be inspected as often as necessary to ensure safe operating conditions, and any defect should be corrected promptly.
3. Mining equipment should be cleaned as necessary to prevent oil and coal dust from accumulating on its surface.
4. Consideration should be given to the use of fire-resistant hydraulic fluid in mining equipment.

### 3.2.3.5 Polyurethane Foam Fire Caused by Spontaneous Combustion (Freemen 1969)

#### Summary

The second-shift mine foreman detected the fire in a crosscut between the intake and return air courses of the mine. The fire occurred when urethane foam applied to a cinder block and wood stopping ignited spontaneously. Of the 64 men in the mine, 15 were in areas ventilated with air that passed by the fire. An hour after the fire was detected company officials ordered all men except those attempting to control the fire out of the mine. The fire was extinguished completely within the next hour. No injuries occurred and property damage was confined to the stopping and foam machine.

#### Pre-Fire Conditions

The mine was opened by two drifts, three manways, three return airways, a rock tunnel, and two openings. The coal was of high-volatile bituminous rank and the coal dust was highly explosive. A total of 244 men were employed and an average of 4,000 tons of coal per day was produced with ripper-type continuous miners.

Development was by the room-and-pillar method. The mine was classed as gassy. Ventilation was induced by two axial-flow fans driven electrically and exhausting 420,000 cubic feet of air per minute.

Materials and tools for firefighting purposes were placed at strategic locations throughout the mine. Self-generating oxygen breathing units and gas masks were maintained underground, and self-rescuers were available in all active working sections.

#### Description

On the day of the fire, three cinder block stoppings and one combination cinder

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block and wood stopping separating the intake and return airways had been coated with urethane foam on the first shift. When the crew finished coating the stoppings, they cleaned the equipment, left the portable foam machine near the stoppings, placed the spray gun in a bucket containing acetone near the machine, and departed for the surface. The 8 foot by 20 foot slant was provided with two cinder block stoppings equipped with 6 foot by 8 foot wooden doors and was erected to form an air lock.

About 45 minutes later, the foreman detected black rolling smoke in the haulage entry, an intake airway. Upon investigating, he found the smoke coming from the slant connecting with the right back raise, an idle section. Unable to approach close enough to determine the cause of the smoke, he suspected it might be from the 2,300-volt power cable. He immediately telephoned the surface and notified the superintendent. The crew working near the fire was contacted and instructed to retreat and remain on intake air until given further instructions.

The general mine foreman, superintendent, and safety committeemen departed immediately for the trouble area. Enroute they disconnected the 2,300-volt power. The mine officials entered the smoke area and discovered flame issuing from the 5-gallon bucket containing acetone in which the urethane foam spray gun had been left to soak. The flame was extinguished immediately with a 20-pound dry chemical fire extinguisher and the bucket was removed from the area. A small fire detected at the lower left corner of the wood and cinder block stopping was extinguished with three bags of rock dust. The general mine foreman and an employee entered the return air course and traveled with the air to the back of the stopping. They found the wood door and the frame around the door on fire. This fire was controlled but not extinguished using two 20-pound dry-chemical fire extinguishers. At this time, officials ordered all men, except those engaged in controlling the fire, to leave the mine.

Fire control continued by water bucket brigade and rock dust while a fire hose was obtained from fire stations and connections made to the nearby waterline outlet. When the fire hose was placed in service, the entire area on the intake side of the stopping was soaked thoroughly. The hose then was passed through a hole broken in the stopping and the fire on the back side of the stopping was extinguished immediately.

The fire ignited a small amount of coal near the stopping, burned all the foam from the wood and cinder block stopping, burned part of the wooden door and frame, destroyed all hoses and plastic connections on the foam machine, and charred a timber set about 7 feet away from the stopping. The three nearby cinder block stoppings also coated with urethane foam that day were examined and charred foam material was found at several places. Foam material on these stoppings ranged up to 14 inches in thickness.

### Analysis

Prior research has shown that a thick mass of urethane foam can ignite spontane-

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ously. The charred foam material found on the stoppings involved in this fire indicated that the fire started spontaneously in foam applied in a thick mass.

Analysis of the scenario suggests that:

1. Permanent stoppings should be constructed of solid, substantial, incombustible material.
2. The thickness of the foam layer on a single pass should not exceed 4 inches. Subsequent applications should not be made until the first layer is cured and is no longer tacky when touched. Foam applications of 1 inch are adequate for sealing purposes.
3. Workmen assigned to apply urethane foam should be instructed in the proper application procedure and should be informed of the hazards involved.
4. Areas freshly coated with urethane foam should be inspected for heat.

### **3.2.3.6 Conveyor Belt and Coal Dust Fire Presumably Caused by Frictional Heat (Gay 1970)**

#### **Summary**

The fire of undetermined origin occurred near the belt conveyor head where the conveyor discharged onto the main slope belt in the mine. Smoke was discovered coming from the air shaft at the main fan by the second-shift mine foreman, who was working the third shift as a watchman at the surface facilities of the mine. No injuries were sustained by persons fighting the fire, and property damage was confined to the conveyor belt and accessories.

#### **Pre-Fire Situation**

The mine was opened by a 40-foot shaft and a 350-foot slope into the high-volatile coal bed, which averaged 50 inches in thickness. A total of 39 men were employed, and an average of 500 tons of coal was produced per day.

The mine was being developed using the room-and-pillar method and conventional equipment. Pillars were not being extracted. The immediate roof was hard shale of undetermined thickness. Ventilation was induced by a propeller fan exhausting 50,000 cubic feet of air per minute. The mine surfaces ranged from wet to dry, and dangerous accumulations of loose coal and coal dust were not present in the active underground workings.

Three belt conveyors were used. One was installed in the slope and extended from the slope bottom to a coal-storage bin on the surface, a distance of approximately 400 feet. The other two conveyors extended into the mine approximately 3,240 and 1,800 feet, respectively. The conveyor belts were 36 inches wide and were equipped with slippage and sequence switches.

Electric power at 13,200 volts ac, reduced by a bank of three transformers, was utilized to supply 440 and 220 volts ac to the surface motor installations and the No. 2 belt conveyor drive motor.

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### Description

When the mine ceased operations for the week, the belt conveyors were emptied of coal in transit to the surface. The mine forman had observed no unusual conditions at this time. At midnight, the second-shift mine foreman, who was assigned the duty of surface watchman, saw smoke coming out of the fan opening and immediately notified the mine president who assigned another foreman to accompany the first in investigating the fire. The two men walked down the slope and, at the bottom, discovered an active fire in the vicinity of the No. 2 belt head. They reported their findings to the president and requested aid from the fire department of the two nearby towns.

Water was pumped from fire trucks and from a nearby river into the mine at several locations. The prolonged burning of the belt ignited wooded roof supports along the belt entry and a third coal pillar near the belt head. The volume of air was reduced by opening the explosion door at the fan. Line brattices were used to direct the ventilation air at the sight of the fire. Several permanent stoppings were opened to permit smoke and fumes to enter the main return.

The heat generated by the fire weakened the bolted roof and it fell along the length of the entry from the slope to the entrance crosscut. Loading of the burning material was started at three locations. The fire was considered totally extinguished when the fallen material was completely removed 11 days after inception of the fire. Approximately 800 linear feet of conveyor and 400 feet of rope-supported structure were destroyed by the fire.

### Analysis

The exact cause of the fire could not be determined because of the extensive damage. It is believed, however, that the fire began after the belt was stopped at the end of the last production shift when frictional heat from a defective bottom belt roller ignited the conveyor belt and accumulated coal dust.

Analysis of the scenario suggests that:

1. Coal dust and loose coal should not be permitted to accumulate in dangerous quantities under, along, or around belt conveyor structures.
2. When stopped prior to idle periods, belt conveyors should be inspected carefully in their entirety.
3. Belt rollers and bearings should be lubricated frequently and should be inspected frequently and thoroughly to determine whether there are any broken bearings or "frozen" rollers. Any defects found should be corrected promptly.
4. The velocity of air along belt conveyors should be limited.

#### 3.2.3.7 Coal Bed Fire Caused by Blasting (Fanok and McMonies, 1970)

##### Summary

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The fire occurred in the coal bed after 40 charged boreholes were fired simultaneously at the faces of the east and north approaches in a new shaft being developed. All of the workmen were on the surface when the fire occurred. The fire, which was confined to the east approach, was extinguished by flooding the bottom of the shaft with water. There were no injuries and no property damage.

### **Pre-Fire Situation**

A total of 31 men were employed constructing a new ventilation shaft at this location. The shaft was 18 feet in diameter and 483 feet deep. At the time of the fire, four approaches in the coal bed were being developed. Each 17 foot by 8 foot approach was to extend 30 feet into the shaft bottom.

Ventilation in the shaft was induced by two auxiliary-type blower fans located on the surface and powered by 20-horsepower motors. Corrugated tubing, 20 inches in diameter, extended from each fan to within 9 to 5 feet of the shaft bottom.

Firefighting equipment was readily available on the surface. It consisted of water from three 1,000-gallon storage tanks, six 20-pound multipurpose fire extinguishers, and an adequate supply of rock dust.

### **Description**

Prior to the fire, six men were drilling boreholes in the coal face of the east and north approaches. In order to eliminate an overhang at the face of the east approach, boreholes, about 2 feet deep, were drilled — two in the roof strata (one in each corner) and three about 4 feet apart in the coal bed near the roof. A total of 35 holes, 6 feet deep, were drilled in the coal face of the north approach. Each hole in the east approach was charged with a half stick of explosive and each hole in the north approach was charged with four or five sticks of explosive. All charged holes were stemmed with incombustible material and the leg wires of the detonators were connected in series.

After the entire crew was hoisted to the surface, the power was disconnected from the shaft, the two fans were stopped, and the ends of the fan tubings were closed and raised about 5 feet up the shaft. The 40 charged holes then were fired simultaneously from a 220-volt ac circuit on the surface. The fan tubings were opened and lowered from the surface and the two fans restarted. About 30 minutes later, the men were being lowered into the shaft when they encountered smoke about 50 or 60 feet from the top of the shaft. The men were hoisted to the surface immediately.

Shortly thereafter the bottom of the shaft was flooded with water from three 1,000-gallon storage tanks and a nearby creek. About 10 tons of rock dust also were dropped into the shaft.

The following day, after approximately 150,000 gallons of water had been pumped into the shaft, no smoke could be observed and no carbon monoxide was

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detected in the air returning from the shaft. The water level was 10.5 feet above the bottom of the coal bed when pumping was discontinued.

Five days after the blasting, with the water removed from the shaft, the two fans operating and no indication of fire in the shaft, company officials and personnel of the U.S. Bureau of Mines were lowered in a bucket to the bottom of the shaft. A careful examination indicated that the fire was extinguished. In the east approach, coke was found on the roof and ribs for a distance of 10 feet out from the face; methane was being freely liberated from the upper right and left corners.

### Analysis

The fire probably started when a fired shot or series of shots, which were overburdened and/or underburdened, ignited gas being emitted by the feeders. Analysis of the scenario suggests that:

1. Ventilating fans should not be stopped and tubing providing face ventilation should not be removed during blasting operations.
2. Boreholes should be properly placed, charged, and stemmed to prevent misfires or blown-out shots.
3. An examination for fires should be made as soon as the smoke and dust from blasting operations is removed by ventilation in the shaft.

### 3.2.3.8 Coal Fire Caused by an Electric Arc and a Subsequent Explosion (Dobis, et al. 1965)

#### Summary

The fire occurred along the north mains track haulageway of the mine. An explosion of the distillate by-products from the burning coal and other combustibles in the high-temperature, lean-air environment occurred about an hour later, shortly after the main ventilating fan, which had been stopped by a foreman for 15 to 20 minutes, was restarted.

When the fire began two foremen and five workmen were engaged in miscellaneous work near the scene of the occurrence and a foreman and two workmen were trammings the continuous-mining machine involved in the fire. Six men died of asphyxiation and one man, who was found unconscious, died en route to a hospital. The foreman and two workmen engaged in trammings the continuous miner escaped through the drift portal.

The fire was initiated by a short circuit when the top of the traction pump drive on the stripped-down continuous miner being trammed on the north mains track haulageway contacted the energized trolley and/or trolley feeder wires. The resulting electric arc and flame ignited the rubber belting used for insulation on top of the traction pump drive, head coal and ribs, hydraulic hoses, and oil. U. S. Bureau of Mines investigators believe the explosion originated at the scene of the fire because the intentional stopping of the main ventilating fan permitted distillate by-products from the burning coal and other combustibles to accumulate in the high-

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temperature, lean-air environment. These gases were ignited when the fan was restarted and they were enriched and moved into the fire zone. The force of the explosion extended through the north mains entries, a distance of about 1,800 feet, and was dissipated as it traveled toward the drift openings and through the fan shaft.

### **Pre-Fire Conditions**

A total of 160 men were employed, 140 underground, and an average of 3,100 tons of coal was produced per day. The mine was opened by three drifts and a shaft into a high-volatile coal bed, which averaged 80 inches in thickness. Analysis of a raw coal sample taken from the coal bed in the mine showed a volatile ratio of 0.46 percent, indicating that the coal dust was explosive.

A block system of mining was followed. Multiple entries in sets of four to nine were 12 to 15 feet wide, and crosscuts were made at intervals of 80 to 105 feet. Mining in two sections was accomplished with conventional mechanical equipment, a ripper, and a borer-type continuous mining machine. Pillars were being partially extracted in two working sections. Roof bolts were being used in all active areas of the mine.

The mine was classified as gassy. Ventilation was induced by an axial-flow exhaust fan installed on the surface. Overcasts and permanent stoppings were constructed of incombustible material. Main doors were not used or needed. Check curtains and line brattices were used to conduct air to the face areas. The air from all parts of the mine was returned to the upcast fan shaft. Each section was ventilated by a separate split of air.

The mine surfaces ranged from dry to definitely wet. Water sprays were used on the two continuous miners, on all roof-bolting machines, and at several of the main belt heads to allay the dust at its source. Uniform dust surveys had been made in the mine since it was opened. Apparently the application of rock dust prevented further spread of the explosion.

Electric power at 110, 220, 440, 4,160, 7,200, and 23,000 volts ac and 3,200 volts dc was used on the surface and at 440, 4,160, and 7,200 volts ac and 300 volts dc was used underground.

The trolley wire was installed on bell-type insulators, 8 to 20 feet apart, at least 6 inches outside the rail and had a vertical clearance ranging from 54 to 69 inches from the top of the rail along the haulage. Circuit protection for the dc trolley and feeder system was provided by automatic time delay reclosing circuit breakers at the rectifier stations.

A state-trained and fully equipped mine rescue team composed of company personnel was maintained at the mine. Self-rescuers were provided for employees underground and were kept in boxes in the working areas of the various sections. Emergency escapeways from each working section to the surface were in safe condition for travel and reasonably free from obstructions.

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### Description

Prior to the fire, production in the mine was discontinued and a borer-type continuous miner was being trammed from the surface to the west mains faces, a distance of approximately 10,800 feet. The machine was partly dismantled to facilitate tramping through restricted areas. The tramping operation was performed by two men and supervised by the shift foreman. Seven other men were deeper inside the mine. One section foreman and two men were rock dusting in the west mains area; another section foreman and three men were moving equipment in the north mains area.

As the continuous miner approached the junction of west mains, after being moved some 4,000 feet towards its destination, the top of the traction pump drive of the machine came in contact with the energized trolley and/or trolley feeder wires. The resulting short circuit caused intense arcing and flame that ignited the coal roof and ribs and the rubber belting used as insulation; the hydraulic hoses and oil ignited later. The shift foreman, who was standing 30 to 40 feet behind the continuous miner when the fire started, instructed the two men to try to extinguish the fire while he proceeded by personnel carrier to the power switches to de-energize both the ac and dc power circuits; however, since the personnel carrier received its power from the trolley wire, the shift foreman had to reclose the dc switch. He tried to contact the trapped men by pagephone but received no response; he then telephoned the superintendent and suggested that the main ventilating fan be stopped to prevent smoke from entering the sections where the seven men were working. The superintendent agreed and shut down the main ventilating fan. Meanwhile, the two men at the continuous miner expended the contents of a small fire extinguisher and applied 15 to 20 bags (30 pounds) of rock dust to the fire. These efforts were ineffective, and one of the men, while getting a hose, also tried unsuccessfully to contact the trapped men by pagephone. After the hose was connected to a nearby waterline, water was applied to the burning materials, but both men were forced to retreat because of the rollback of dense smoke. They and the shift foreman then returned to the surface.

An hour after the fire began or 30 minutes after the fan was restarted, a team entered the mine and found the first evidence that an explosion had occurred. They attempted to contact the trapped men without success, examined the situation, and cut the trolley wire to remove the short circuit.

Rescue teams subsequently found that several manddoors and stoppings had been blown out by the explosion, causing short circuiting of ventilation. Twenty-one incipient fires also were found and extinguished. As the rescue operation proceeded, stoppings were erected, the ventilation system modified, and air hoses were connected.

Approximately 11 hours after the original incident, one section foreman was found unconscious some 4,600 feet from the fire area. He was removed immediately but died on the way to the hospital. Shortly thereafter, the bodies of two men

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were found 2,000 feet from the fire area, and the bodies of four men, 1,600 feet from the fire area.

When the seven victims were found, it was discovered that they had thirteen self-rescuers. The inner and outer lids of two of these units were detached from the cartridges indicating that they could have been used; however, the nose clips were not in place. Two extra unused self-rescuers also were carried by the aforementioned men. A self-rescuer removed from the cannister but not activated for use was found in the carrying receptacle on the belt of the section foreman, who was found unconscious; an unused self-rescuer found nearby may have been discarded by him. The four victims in the north mains had seven self-rescuers; however, no evidence was found to indicate that the victims had attempted to use them.

Immediately after the bodies of the victims were brought to the surface, all work was directed to fighting the fire by direct methods. While water was being applied at several points, work was started to reinforce and tighten the plastic stoppings that had been erected during the initial exploratory trips and to replace the temporary stoppings with concrete block stoppings. Efforts to move out the falls and hot material were started on the fifth day after the exploration. On the tenth day, the continuous miner was uncovered. During the next seven days, the moving out of the hot material continued, and the roof and ribs were supported by crossbars, posts, and numerous roof bolts. Moving out of the hot material was completed 27 days after the fire occurred. The fire area then was cooled with water and kept under surveillance for several shifts. No one was injured during the recovery operations.

### Analysis

The circumstances under which the gases accumulated and the soot residue from the fire and/or explosion was determined indicate that the gases entering the explosion were primarily the distillate by products of coal in a high-temperature environment with a low or diminishing oxygen-air content. The gases contained several hydrocarbons, carbon monoxide, and possibly a small amount of free hydrogen. Soot and coke were observed in all eight entries for distances of approximately 2,350 feet out from and 600 feet in from the junction of west mains. Twenty-one smoldering fires were found extending 1,350 feet from the origin of the explosion. The force of the explosion radiated from the fire area and traversed distances of about 1,300 feet out from and 600 feet in from the area. Thirteen concrete block stoppings were blown out; four other stoppings were displaced. Man doors in undamaged stoppings were either blown off or blown open. Five overcasts were destroyed and one was damaged. The force of the explosion also reached the surface and one of the explosion doors at the fan was blown open but explosive forces dissipated rapidly as they traveled toward the drift openings.

Disconnecting switches were not installed in the dc trolley and trolley feeder lines. Improper or inadequate short-circuit protection in the dc power system permitted the intense arc.

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No employee was stationed on the surface to receive and dispatch emergency calls originating in the mine. No attempt was made to restrict the velocity of the air over the fire and reduce the amount of smoke and gases brought by the air current into the inner mine workings, and no attempt was made to short circuit the contaminated air from the fire into the return. The main ventilating fan was stopped intentionally for 15 to 20 minutes and then restarted without proper consideration of consequences — a disastrous explosion resulted.

The location of the bodies indicated that the trapped men had tried to reach safety; arrows and chalk markings made by the victims on stoppings and track rails were found in several locations. Six men died from asphyxiation following the mine fire and explosion; a foreman found unconscious 22 hours later presumably died of carbon monoxide poisoning while enroute to a hospital. Only 2 of the 13 self-rescuers found in the possession of the 7 victims showed evidence of attempts to use them.

It appears that this fire occurred when a continuous miner being trammed in the mine came in contact with the energized trolley and/or trolley feeder wires; the resulting short circuit caused intense arcing and flame that ignited the coal roof and ribs and hydraulic rubber belting used as insulation. When the main fan was stopped, explosive gases accumulated in and around the fire zone; when the fan was restarted, some of the oxygen-enriched gases were moved into the fire area where they were ignited.

Analysis of the scenario suggests that:

1. When moving bulky equipment along mine routes where clearances are small, special precautions should be taken to insure that: (a) no men are working near the area; (b) power wires are deenergized along the travel route; (c) all employees connected with the tramping operation are thoroughly trained concerning procedures, the location of cutout switches, and the location and use of firefighting equipment; and (d) a surface dispatcher is posted to relay emergency calls.
2. All organic materials used in underground operations should be reevaluated for fire safety at reasonable intervals to keep up with advancing technology. These materials include conductor insulation, temporary insulation, hydraulic fluid and hoses, tires, conveyor belt material sealants, and brattice cloth material.
3. Control of ventilation, both surface induced or modified underground, should be directed by the best available technical authority; decisions should be based on the latest known information concerning the subsurface situation (especially the location of men underground in case of fire or imminent fire/explosion situation).
4. The safety of all men underground should be improved by: (a) training them to use self-rescuers and to carry such units at all times, (b) training them in the procedures to be followed in case of fire or explosion, (c) training them

to erect barricades in an emergency, and (d) training them in firefighting procedures.

5. Underground electrical equipment should be provided with the best protection technology can offer, including adequate short-circuit protection for dc power systems and disconnecting switches in trolley and trolley feed wires at adequate intervals and near the beginning of each branch line.

### **3.2.3.9 Conveyor Belt and Timber Fire Caused by Electric Arc (Phillips, 1969)**

#### **Summary**

The fire was discovered at a metal overcast along a belt conveyor about 180 feet from the belt conveyor drive. The fire was initiated when electrical arcing ignited combustible materials. The arcing was caused when a roof fall dislodged a metal overcast onto the 480-volt ac power wires.

Because it was the miners' vacation period, only two men were in another part of the mine when the fire occurred. There were no injuries, and property damage was confined to a 25-foot section of the belt conveyor, a portion of the 480-volt ac power wires, and several wooden timbers. The fire apparently did not spread rapidly because the belt entry and surrounding territory were clean and well covered with rock dust. The fire was extinguished the same day, and the area was kept under surveillance until it was completely cooled by the application of water.

#### **Pre-Fire Condition**

The mine was opened by three drifts and nine curcular shafts into the high-volatile coal bed, which averaged 84 inches in thickness. The coal dust was explosive.

A total of 204 men were employed, 164 underground, and production averaged 4,500 tons of coal per day. Because it was the miners' vacation period, the mine was idle and only one section foreman and a pumper were in the mine when the fire occurred.

The immediate roof in the fire area was composed of 10 inches of coal, which was left to help support a fragile shale about 2 feet in thickness. The mine was classified as gassy. Ventilation was induced by three axial-flow exhaust fans. The belt entry, the supply-track-haulage road, and a parallel entry were used as intake airways. All of the entries in the area of the fire were adequately rock-dusted. Suitable firefighting equipment and materials were provided throughout the mine.

Shuttle cars transported coal from the face regions to the dumping point on each section. Well installed, flame-resistant belt conveyors took the coal to the surface preparation plant.

Electric power at 12,000 volts ac was conducted underground through two boreholes and reduced to 7,200, 4,160, 440, 220, and 110 volts. The high-voltage circuits were protected against overloads by oil circuit breakers equipped with

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instantaneous and time overcurrent relays and ground fault trip relays. The underground belt drive motors were operated with 440 volts ac.

### Description

A resident near the mine fan smelled smoke and informed a company official. The general superintendent entered the mine and other company officials followed shortly. A search of the entire mine was made and the fire was discovered about 2 hours later by the general superintendent. He immediately deenergized the power. The fire was extinguished with the contents from two fire extinguishers and four bags of rock dust, which were obtained from the nearby belt conveyor drive. Although the flame was completely extinguished, additional water was applied for several hours to cool the fire area. The fire area then was patrolled until the investigating committee arrived.

Difficulty in locating the fire was due to the smoke and fumes being diverted directly into the return airways through the opening created when the overcast was dislodged. As the fire area was being rehabilitated, it was determined that the overcast was no longer needed for ventilation purposes; therefore, block stoppings were erected separating the intake and return airways.

### Analysis

When the roof fall dislodged the metal overcast onto the 480-volt ac power conductors, a fault occurred between two phases of the secondary circuit and the resistance of the fault was too high to permit sufficient fault current to flow and open the fuses in the primary circuit. The resultant electrical arcing ignited the wooden timbers and belt conveyor.

Analysis of this scenario suggests that grounding transformers, a current-limiting resistor or an equivalent grounding device, and an automatic circuit breaker equipped with a ground-trip circuit should be installed in the secondary circuits from the delta connected transformers to provide ground fault protection for the electric circuits and equipment.

### 3.3 Fire Dynamics

Fire is one of the major hazards of underground mining. The inherent danger of fire is greatly exacerbated by the nature of mines — i.e., restricted areas, limited accessibility and egress routes, forced ventilation, the presence of bulky equipment with high-power electric components, roof support problems, a potential for explosive concentrations of dust and gas in the air. A fire situation in a mine is further complicated by the often complex layout of the mine and the associated airflows and velocities in various sections of the mine.

Given this situation, it is that the nature and behavior of fire in a mine environment be well understood. Extensive work has been done in this area by many nations and a body of information developed on the basis of experience and post-

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fire investigations. Government and industrial regulations based on this knowledge have greatly improved fire prevention and control.

New and more sophisticated approaches are needed, however, to further reduce or eliminate the hazards of mine fires. Research efforts directed toward the in-depth understanding of the highly complex processes associated with mine fires should be continued and expanded. Of particular importance are well designed, medium- and large-scale experiments and the collection and correlation of the great variety of data needed to develop meaningful theories and models.

The material presented below is paraphrased or quoted from a report by Greuer (1973). It is intended to summarize the state of fire dynamics knowledge related to mine fires. Please note that only the quoted words are Greuer's and some judicious deletions have been made without altering the meaning.

### 3.3.1 "Properties of Mine Fires"

#### 3.3.1.1 "Modes of Fire Propagation"

Mine fires propagate: "1) through localized heat feedback from the flames; 2) through all over heat feedback from the fumes . . ." "Fires of the first type are controlled by the same mechanisms as unconfined fires in the open . . ." (i.e., radiation and convection from the flames and hot gases heat the combustible material in the immediate vicinity of the fire before they mix with the general airstream. The latter does not become hot enough to ignite or to generate gaseous fuel from the combustible material). Because combustion occurs only in the immediate vicinity of the combustible material, considerable quantities of oxygen can pass through the fire without being consumed. Fires of this type are therefore frequently called unconfined or oxygen-rich fires.

The second type of fire occurs where the general air stream becomes hot enough to generate gaseous fuel from the combustible material, along which it passes. This type of fire grows until all available oxygen is consumed, limiting the heat development and frequently is termed "confined" or "fuel-rich" because the high temperatures required for this type of fire propagation are, outside of mines, reached only in confined passages.

Although most accidental mine fires being started by relatively small ignition sources, develop into oxygen-rich fires and stay oxygen-rich, fuel-rich fires have been much more thoroughly studied. Figure 1 is a schematic representation of a fuel-rich fire. The fire has already passed through the cooling zone and only heat transfer processes due to forced convection occur (i.e., the walls of the airway are cooled and the air is heated).

In the charcoal zone, the carbonized residue of the fuel which still is hot enough to react with the oxygen in the air is burned. The heating of the ventilation air continues, and its oxygen content is reduced.

In the combustion section of the pyrolysis zone, the volatiles produced by the decomposition of the combustible material are burned in the ventilating air. The gas

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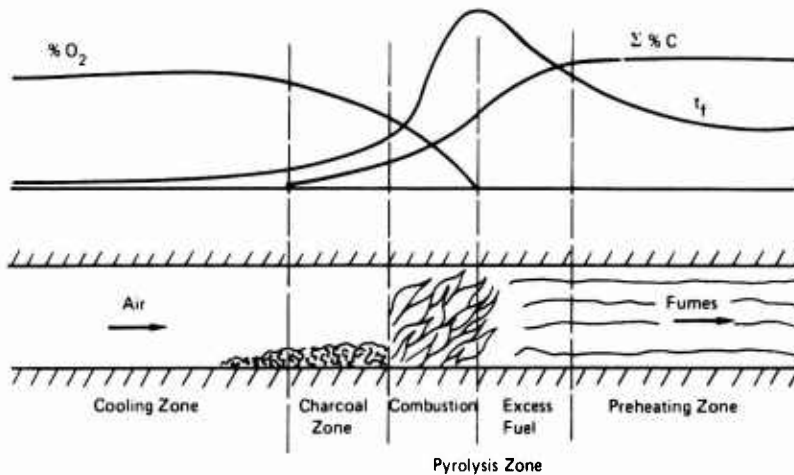


Figure 1. Zones developed by fuel-rich fires (Greuer, 1973).

temperatures rise to a maximum and the oxygen content is reduced to zero. In the excess fuel section of the pyrolysis zone, the fumes are sufficiently hot to cause pyrolysis of the combustible material. The absence of oxygen will, however, prevent combustion and the pyrolysis products remain as excess fuel in the fumes. The heat consumption of the pyrolysis causes the temperature of the fumes to drop.

Final cooling of the fumes occurs in the preheating zone where the airway section in front of the fire is preheated and dried. Heat is transferred from the fumes to the airway mainly by forced convection, but radiation also may be involved close to the pyrolysis zone.

Figures 1 and 2 illustrate the zones of a fuel-rich and an oxygen-rich fire respectively. Because volatiles evolve only in the immediate vicinity of flames, no pyrolysis zone exists in the latter. The decrease in the oxygen content and the increase in the carbon content of the airstream as well as its temperature increase in the combustion zone will be less for oxygen-rich than for fuel-rich fires.

### 3.3.1.2 Controlling Mechanisms and Equilibrium States

In an unconfined fire with one-dimensional flame spread (Figure 3), the relation between the rate of flame advance,  $V$ , and the width of the fire,  $L$ , will be as shown by curve 1 in Figure 4. For  $L < L_0$ , no propagation of the fire takes place due to inadequate heat transfer ahead of the flames. For  $L > L_0$ ,  $V$  will increase with  $L$  as the emissivity and height of the flames increase until the extension of the fire,  $L$ , has reached such a magnitude that  $V$  is no longer influenced by  $L$ . If  $D$  is the depth of the fuel bed consumed by the fire,  $\sigma$  its specific weight and  $B$  the velocity with which the fire penetrates the fuel bed, the rate of fuel added to the fire (per unit width of flame front) is  $V \cdot D \cdot \sigma$  and the rate of fuel consumption is  $L \cdot B \cdot \sigma$ . In a fully developed fire,  $V$  and  $L$  are constant with respect to time and  $V \cdot D \cdot \sigma = L \cdot B \cdot \sigma$  hence

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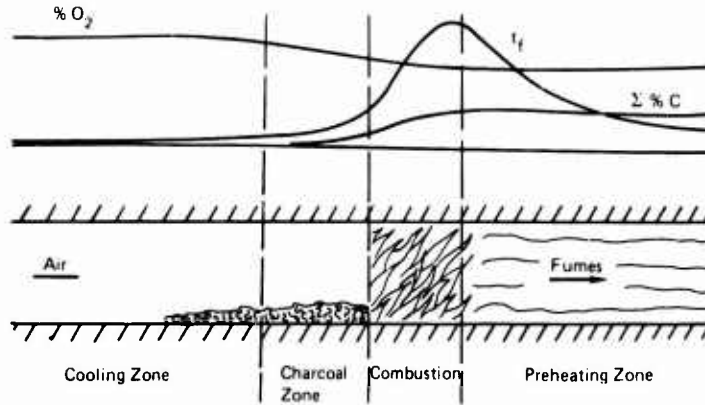


Figure 2. Zones developed by oxygen-rich fires (Greuer, 1973).

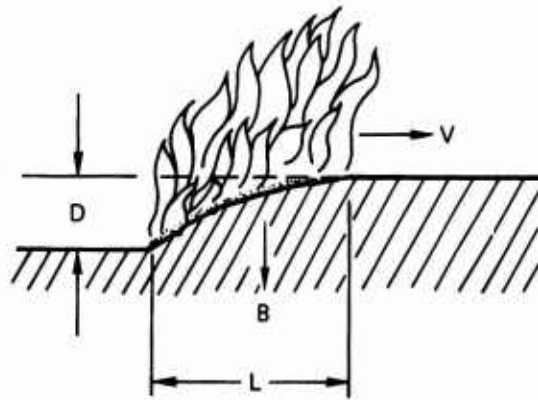


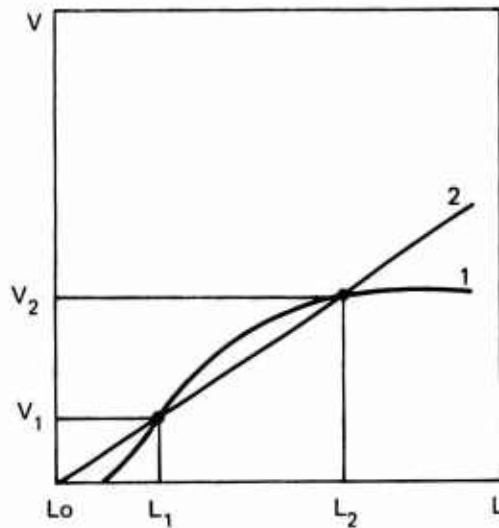
Figure 3. Model of one dimensional spread of fire.

$V = (B/D) L$  (as indicated by curve 2 in Figure 4). Possible values of  $L$  and  $V$  are indicated by the two intersections of curves 1 and 2. Of these,  $LV$ , is, however, not a stable condition (since for  $L < L_1$  curve 1 shows  $V < (B/D) L$ , which indicates a decreasing fire, and for  $L > L_1$  it shows that  $V > (B/D) L$ , which indicates an increasing fire). If a fire is initiated with  $L < L_1$ , it will die out, and if it is initiated with  $L \geq L_1$ , it will adjust itself to the condition  $L = L_2$ .

The rate of fuel added to a fire in a mine roadway or duct is best expressed by the dimensionless parameter:

$$V \dagger = C \cdot V \cdot D \cdot \sigma \cdot P_f / (V_a \cdot \sigma \cdot A)$$

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*Figure 4. Relationship between V and L in unconfined fires.*

where  $C$  = the mass of air required for complete combustion of unit mass of fuel,  $P$  = the perimeter of the roadway,  $f$  = the fraction of perimeter that is covered with combustible materials,  $V$  = air velocity,  $\sigma_a$  = the specific weight of the air, and  $A$  = a cross section of the roadway.

Analogously, the rate of fuel consumption is expressed by:

$$L\dot{+} = C \cdot L \cdot B \cdot \sigma \cdot P \cdot f / (V_a \cdot \sigma_a \cdot A)$$

During its early stages a fire in a mine roadway or duct is controlled by local heat transfer effects close to the fuel surface and therefore, it behaves like an unconfined fire (Figure 5). As the fire increases, however, additional heat transfer from the fumes will occur and provide an additional increase of  $V\dot{+}$  with  $L\dot{+}$  which becomes very large when the temperature of the fumes exceeds the threshold beyond which pyrolysis of the fuel becomes very rapid. A peak is reached when  $L\dot{+} = 1$  when all the oxygen in the air supply is consumed. A further increase in  $L\dot{+}$  results in a decrease  $V\dot{+}$  since excess fuel causes the temperature of the fumes to drop.

Since for fuel rich fires the pyrolysis zone has to have a certain length and considerable cooling of the fumes due to heat transfer to the walls occurs and since a considerable temperature difference between combustible material and air must exist to facilitate heat transfer, the heat quantities needed to ignite a fuel rich fire are most probably much higher than predicted. A burning rate of 40 lb/min of mineral oil over 10 minutes in a ventilation current of 22,000 ft<sup>3</sup>/min was about the minimum to start a fuel rich timber fire.

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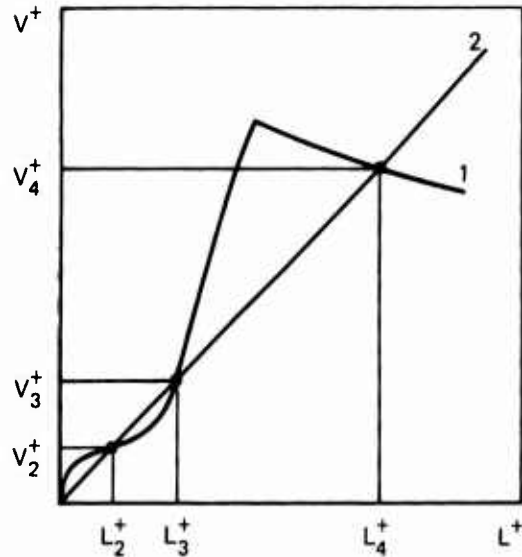


Figure 5. Relationship between  $V^*$  and  $L^*$  in confined timber fires.

### 3.3.1.3 Observations in Accidental and Experimental Mine Fires

Timber has played a prominent role in most large mine fires and almost all published observations on the properties of accidental fires deal with timber fires; hence, systematic experimental investigations have concentrated on them. "However, the fire controlling mechanisms and the relationship of the dominating parameters do not depend on the type of combustible material so that the insights gained from timber fires can be used for other fires, too."

The great number of fire experiments conducted routinely by experimental mines all over the world usually aim at testing the inflammability or fire resistance of materials and equipment used underground or at measuring the efficiency of fire extinguishing devices. Since the fires have usually no opportunity to develop fully to an equilibrium state, the results obtained from these tests have little general validity.

#### (1) Composition of Combustion Products

The composition of combustion products can be calculated when the fuel composition and the air/fuel ratio is known. For industrial fuels . . . charts exist which relate  $\text{CO}_2$ ,  $\text{CO}$  and  $\text{O}_2$  concentrations in the fumes with the fuel/air ratio. It is concluded that most accidental mine fires are oxygen rich fires since they are started by relatively small ignition sources.

#### (a) Fumes and Dispersion

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The fumes have a tendency to form a layer along the roof. In unventilated or laminar ventilated airways this layer is dispersed by molecular motion only, which is a very slow process. Turbulent dispersion requires that the kinetic energy of the turbulent particles, formed by the ventilating air current is high enough to overcome the buoyancy forces. Since this kinetic energy is proportional to the air velocity, a certain minimum velocity is required for the turbulent dispersion of such layers.

In little-ventilated airways the fumes will therefore mainly travel and the fire will propagate along the roof. In inclined descensionally ventilated airways air can flow into the fire down-hill along the floor whereas the fumes are travelling and the fire is spreading uphill along the roof.

The velocities with which mine fires spread in unventilated airways or with which they spread in ventilated airways upwind against the air current are small compared with those in other directions. Their propagation is easier to control, too. Backing of smoke can be fought by increasing local air velocity and using transverse brattice or shields to block the lower cross section of the airway. No systematic investigations on fire propagation velocities against air currents and few on the extension of backed smoke layers are known although many of the insights gained from the studies of gas layers would be transferable to these problems.

Fire propagation as well as the backing of smoke against the airflow has so far always been negligible in West German coal mines. The reason is most probably the high air velocities associated with longwall mining. Only a few cases are known where the backed smoke reached extensions of up to 100 ft. Fires propagating along the roof against the ventilating air current could always be extinguished easily.

In the experimental coal mine of the United States Bureau of Mines the length of the backed smoke layer was 100 ft. with an air velocity of 120 ft./min. 50 ft. with 180 ft./min., and 10 ft. with 230 ft./min. In the best known instance of backed smoke which was in 1910 at Whitehaven Colliery in Great Britain with 372 yards against an intake ventilation speed of some 325 ft./min.; 86 men were lost. In this case, however, the ventilation must have been descensional and one can suspect that intermittent airflow reversals occurred.

In fire experiments in timbered tunnels the fire velocity against the airflow did not exceed 20 ft./hr. However, in high volatile coals the rate of propagation outward can be both rapid and extensive whereas its rate of travel inward is fairly slow or negligible. On occasion the rate of spread can be 150 ft./hr. against a ventilation speed of 150 ft./min.

### **(b) Heat of Reactions**

The heat of reaction for complete combustion is equal to the lower calorific value of the fuel. For incomplete combustion it must be corrected by subtracting the heat of combustion of any unburnt fuel due to lack of oxygen or dissociation.

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One has to consider, furthermore, that the products of combustion can include solids as well as gases.

The calculation of the adiabatic flame temperature is relatively cumbersome, since, in addition to the specific heat variations of the combustion products, their composition changes with temperature, due to dissociation, must be considered. Besides trial and error methods the use of charts is therefore advisable.

Calculations of adiabatic flame temperatures are based on the assumption of a perfectly mixed gas stream passing through the fire. This assumption holds for fuel-rich fires but not for oxygen-rich fires. Therefore, one can, for the latter, expect a wide range of flame temperatures being present in one and the same fire.

It is possible to estimate the highest temperature the fumes can theoretically reach after the combustion products have been mixed with the excess air. In oxygen-rich timber fires a higher temperature than 1,692°F has never been observed. To determine the temperature of the fumes requires the same calculations which are necessary for the calculation of the adiabatic flame temperatures. An additional complication is that many pyrolysis products enter the fumes between the flame-zone and the gas sampling point.

Experience shows that the temperatures of the fumes behind oxygen-rich timber fires are considerably lower than 1,700°F. If they were this high, a pyrolysis zone would develop and the fire would become fuel-rich. Behind fuel-rich fires the temperatures are much lower than the adiabatic flame temperatures. The reasons for this are the large heat transfer from the flames to the walls of the airway, caused by the high flame temperatures and the addition of gaseous pyrolysis products at temperatures lower than those of the gas stream.

### (2) Coal Fires

Coal fires, especially coal dust fires, are more frequent than timber fires. However, less attention is given them in the literature and very few results on systematic fire experiments have been published. The reason may be that they are less dangerous than timber fires. Although coal dust is a material with one of the lowest ignition temperatures encountered underground, the rate of growth of a fire in coal dust is low. It is about 3 1/2 inches/hr., dropping to 2 in./hr. when the coal dust is mixed with stone dust. Coal dust fires, therefore, do not pose any serious threat to life or production. The danger of coal dust is instead as an igniter and fuse to other more flammable materials. "Lump or solid coal fires are usually not too serious a risk to life either, especially in their early stages." Coal, has approximately 5 percent volatiles in anthracite and 40 percent volatiles in high volatile bituminous coal. However, this is a much lower volatile content than wood which has 75-85 percent volatiles. Substantial distillation of volatile matter only begins at about 600°F and becomes rapid at about 1,300°F whereas the corresponding temperatures for wood are approximately 400 and 550°F. Also the coal ignition temperatures are higher, although the latter are not constants but depend on oxygen concentrations, exposure times, mineral contents, etc.

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Due to its economic importance as one of the principal energy sources, the combustion of coal in industrial processes has been the subject of a vast number of investigations. This does not however apply to the accidental combustion of coal in underground mines, where, except for fire extinguishing equipment, no systematic work seems to have been done. Due to the complexity of fire, it would be risky to try to develop a model for such fires.

Since coal is a fuel that is difficult to ignite one can expect coal fires, at least for higher ranking coals, to be oxygen-rich fires. Fuel-rich fires will mainly occur as a temporary phenomenon after a reduction in ventilation.

Few data have been published on the composition of combustion products of open underground coal fires. All deal with oxygen-rich fires, probably due to the limited extension of the fuel beds provided.

No data have been published so far on fuel consumption, extension and velocity of coal fires.

### 3.3.2 Temperature of Fumes Behind the Fire Zone

All major forces exerted by mine fires on the ventilation can be considered as thermal forces. For their determination the knowledge of the temperature changes, caused by the fires, is indispensable. This applies less to flame- or pyrolysis zones, which are comparatively short, than to the much longer airway sections downwind of the fire which can experience considerable temperature changes, too.

The temperature of the fumes leaving a flame- or pyrolysis-zone is changed by mixing with other air currents and by heat exchange with the airway walls. The effects of mixing are easy to describe. Except for the entropy, each individual property of the mixture is equal to the mass-weighted arithmetic mean of the same properties of the constituents. No further detailed discussion of mixing processes is therefore necessary. Less simple to describe are the heat exchange processes.

#### 3.3.2.1 Steady State Heat Exchange with Airway Walls

The assumption of an infinite heat capacity of the rock surrounding an airway leads to constant rock temperatures and to a steady heat exchange process between air and rock. If the rock, before exposure to the fumes with the temperature  $t_f$ , had assumed the average temperature  $t_a$  of the ventilating air, the heat transfer  $dq$  from the fumes to the rock can be described by:

$$dq = \alpha (t_f - t_a) P dL$$

where

$\alpha$	=	heat transfer coefficient
$P$	=	perimeter of airway
$L$	=	length of airway

This will cause a change of temperature in the fumes by:

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$$dt_f = - \frac{dq}{G \cdot c_p}$$

where  $G$  = mass flow rate of fumes  
 $c_p$  = constant pressure specific heat of fumes

With

$t_{f0}$  = temperature of fumes at the beginning of the airway ( $L=0$ ) one obtains

$$t_f = t_a + (t_{f0} - t_a) \exp - \frac{\alpha P L}{G \cdot c_p}$$

The mean temperature of the fumes in the airway, which is frequently used for the determination of thermal forces, is:

$$t_{fm} = \frac{1}{L} \int t_f \cdot dL = t_a + \frac{t_{f0} - t_a}{L} \cdot \frac{G \cdot c_p}{\alpha P} \left( 1 - \exp - \frac{\alpha P L}{G \cdot c_p} \right)$$

### 3.3.2.2. Non-Steady-State Heat Exchange with Airway Walls

A more accurate treatment has to take into account the limited heat capacity of the rock surrounding the airways. Whenever a heat exchange between the air and the walls occurs, a gradually thickening layer of rock with temperatures between the original rock temperature and the air builds up. This layer forms an insulation and lets the heat exchange decline with time.

Due to the importance of accurate temperature precalculations in deeper mines with climatic difficulties, many attempts at the calculation of the non-steady state heat exchange between air and rock have been made. Within the scope of this report it is impossible to quote every single paper which exists on this topic. Only those, which became better known because they suggested an improvement of existing solutions and whose results are applicable to mine fires shall be discussed.

The non-steady state heat exchange between rock and air is a very complex problem since it comprises (1) the heatflow by conduction within the rock, (2) the heat transfer by convection and radiation from the rock to the air or vice versa, and (3) the heat transfer associated with mass flow.

Heat flow by conduction can be determined with the help of Fourier's equation of heat conduction:

$$\frac{\partial t}{\partial \tau} = a \nabla^2 t + \frac{1}{c \cdot \gamma} W$$

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where

- $t$  = rock temperature
- $\tau$  = time
- $a = \frac{k}{c \gamma'}$  = thermal diffusivity of rock
- $k$  = heat conductivity of rock
- $c$  = specific heat of rock
- $\gamma'$  = specific weight of rock
- $W$  = heat generation per unit volume inside rock

In applying this equation on the heat exchange in mine airways, the following assumptions are usually made: the rock is homogeneous and isotropical, the temperature of the rock surrounding the airway is uniform at the beginning of the heat exchange, the airway has a circular cross section, the heatflow parallel to the airway is negligible, no heat sources or sinks exist in the rock, no change of phase of the rock humidity occurs.

Fourier's equation of heat conduction can then be expressed in cylindrical coordinates in the following form:

$$\frac{\partial t}{\partial \tau} = a \left( \frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} \right)$$

Under the additional assumptions: the original rock temperature remains preserved at a sufficient distance from the airway; the wall temperature equals the air temperature (heat transfer coeff.  $0 < \infty$ ); the air temperature along the airway does not change with time.

### (1) Mass Transfer

In the preheating zone of a fire, where significant pyrolysis or other chemical reactions no longer take place the main sources for heat transfer by mass transfer are the condensation and evaporation of water. Principally, heat transfer by mass transfer cannot be considered separately from heat transfer by convection at the surface and from heat flow by conduction in the interior of a wall, since the mass transfer changes the thermal properties of both the surface and interior. Due to its technical importance a vast amount of research has been done on this problem; this report has to limit itself to such work done on mine airways.

### (2) Velocity of Fire Propagation

Fire propagation along a roadway is due to heat transfer by radiation and convection. The latter takes place as natural convection, caused by air movement as the result of buoyancy forces of the hot fumes and as forced convection, caused by the

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ventilating air current. Since the air movements creating the convection provide the fire at the same time with fresh oxygen, heat transfer by convection has a larger influence on the propagation of fires than radiation. And since the air velocities as the result of buoyancy forces are quite low, forced convection in the direction of the ventilating air current is usually considerably larger than natural convection.

A fire in an unventilated or little ventilated airway will therefore spread in both directions, upwind and downwind. Since the oxygen supply upwind is better, the propagation velocity in this direction may even be higher than downwind. The higher the velocity of the ventilating air current becomes, however, the stronger the tendency of a fire to spread downwind.

### (3) Radiation

Nonpolar symmetric molecules such as  $O_2$ ,  $N_2$  and  $H_2$  are relatively transparent to thermal radiation. Heat transfer radiation is, therefore, neglected under ordinary ventilation conditions with few exceptions by ventilation engineers. Polar, unsymmetric molecules, such as  $CO_2$ ,  $H_2O$ ,  $CO$ ,  $SO_2$  and many hydrocarbons can enter into thermal radiation exchange appreciably at the temperatures encountered in mine fires. Their contribution to the heat exchange between fumes and airway walls should therefore be assessed and if necessary taken into account.

The order of magnitude of heat transfer by radiation from a gas to a black surrounding can be calculated by:

$$Q_r = \sigma A \left( \epsilon_g T_g^4 - \alpha_b T_w^4 \right) = \sigma * 10^8 A \left[ \epsilon_g \left( \frac{T_g}{100} \right)^4 - \alpha_b \left( \frac{T_w}{100} \right)^4 \right]$$

where  $\sigma * 10^8 = \text{constant} = 0.1723 \text{ Btu/ft.}^2 \text{ } ^\circ\text{R}^4 \text{ hr.}$

$A$  = area of black surrounding

$\epsilon_g$  = emissivity of gas at temperature  $T_g$

$\alpha_b$  = absorptivity of gas at temperature  $T_g$  for radiation from a black body at temperature  $T_w$

If the surrounding is not black but gray with an emissivity  $\epsilon_{gr}$ , the net heat transfer can be found by considering successive absorptions and reflections. Hottel and Egbert (1942) performed a calculation for  $\epsilon_{gr} = 0.8 - 0.9$ , the range most frequently encountered. They suggest the use of a factor  $\epsilon_{eff}$  to take into account the deviation of a gray from a black surrounding and find that this factor can be approximated by:

$$\epsilon_{eff} = \frac{\epsilon_{gr} + 1}{2}$$

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The emissivity  $\epsilon_g$  is a function of the gas concentration, the thickness of the gas body and the temperature. Because concentration and thickness complement each other in their effects on the radiation, it is possible to consider the emissivity as a function of their product. It has become customary to express the concentration by the partial pressure  $p_c$  of the radiating gas, measured in atmospheres and the thickness by the average length of paths for the radiant beams, measured in feet. Jakob (1959) shows as an example a diagram for the emissivity of  $\text{CO}_2$  as a function of the product  $p_c L$  and the temperature  $T_g$ .

### 3.3.3 Forces Developed by Fumes

Temperature changes of the ventilating air, caused by mine fires, have two major effects on the ventilation:

- a throttling effect,
- a natural draft effect.

Before both effects are numerically assessed it seems advisable to define the energy scales in which they are measured.

Energies in mine ventilation are either expressed per unit weight of air (ft.-lb./lb.) and then called heads ( $h$ ), or per unit volume of air (ft.-lb./ft.<sup>3</sup> = lb./ft.<sup>2</sup>) and then called pressures ( $p$ ). Since the relationship between unit weights and volumes is the specific weight  $\sigma$  (lb./ft.<sup>3</sup>), heads and pressures are related by the specific weight, too:  $h = p/\sigma$ .

Within a ventilation system  $\sigma$  can undergo considerable changes. This has the consequence that equal energy quantities must sometimes be expressed by considerably different pressures, a fact which complicates the application of energy balances. To overcome this difficulty but still to maintain the use of the familiar unit of pressures, heads are frequently expressed as pressures by multiplying them with a constant conversion factor, based on a standard specific weight of  $\sigma = 0.075$  lb./ft.<sup>3</sup> and the factor 1/5.194 inches WG/(lb./ft.<sup>2</sup>).

$$h \text{ (ft.)} \cdot \frac{0.075}{5.194} = h \text{ (in. WG)}$$

The throttling effect arises from the summation of heat and pressure losses which result from temperature changes in a mine fire. It will occur mainly in the immediate vicinity of the fire. A certain additional throttling effect is caused by the changes in kinetic energy of the prevailing air current. (For a sophisticated mathematical treatment of these relationships and effects see Greuer's Report pp. 68-71).

The great number of misleading statements found in the literature concerning the natural draft makes it advisable to first discuss its definition and the more popular methods for its determination.

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Natural draft is caused by the conversion of heat into mechanical energy, which is then available to propel the air and to overcome friction losses. For such a conversion under steady state conditions cyclic processes are necessary, which are provided by every loop of the ventilation network. The amount of heat converted in a cyclic process into mechanical work is indicated by the area enclosed by this process in a p-v diagram. This statement can easily be proved by applying the first law of thermodynamics, in ventilation frequently called the energy equation, in the form:

$$v dp + dV_a^2 / 2g + dZ + dh_L = 0 \quad Z = \text{elevation}$$

for airways without fans to a loop, which results in:

$$-\oint v dp = \oint dh_L$$

$\oint dh_L$  is the sum of all friction losses experienced by the air, flowing through this loop,  $\oint v dp$  is the energy necessary, to balance these losses.

If, in the airways of the loop, mechanical energy  $dw$  is exchanged between air and surrounding (fans, dropping water, etc.), one obtains

$$-\oint v dp + \oint dw = \oint dh_L$$

In this case both, the heat energy  $\int v dp$  and the mechanical energy  $\int dw$  have to balance the losses.

The natural draft expressed as energy per unit weight of air is called the natural ventilation head  $h_N$  and its magnitude is consequently:

$$h_N = -\oint v dp$$

Natural draft is always tied to a cyclic process, to a loop. Statements on natural draft without specifying the loop where it is developed are not too meaningful.

$$\sigma_a dZ + dp = 0$$

For the loop formed by the raise and the hose one obtains:

$$-\oint (\delta_f - \delta_a) dZ = \int dp$$

and since  $-\int (\delta_f - \delta_a) dZ = p_N$  and  $\oint dp$  is the reading of the manometer, the latter indicates  $p_N$ .

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### **3.3.4 Qualitative Prediction of Ventilation Disturbances Caused by Fires**

Throttling and natural draft effects can cause considerable changes in the quantity of ventilating air currents and sometimes even reverse their direction. These changes are not limited to the airway at a fire but can occur in neighboring airways as well.

The dangers caused by air quantity reductions can in nongassy mines be neglected. In gassy mines they can, however, lead to formation of explosive mixtures with all their pertinent dangers, which are especially obvious when the explosive mixture travels through the firezone.

Airflow reversals can be the cause of even more severe hazards. CO-laden air can enter the intake airways and poison large sections or all of the mine. In gassy mines explosive mixtures can be formed since every airflow reversal is preceded by a period of airflow reduction. Even in non-gassy mines explosions can be caused by explosive fumes, which after a reversal of airflow reach the firezone again.

Ventilation disturbances in the form of smoke layers have been discussed. Since they are an easy to survey local phenomenon and can always be fought by local air velocity increases, no further comments seem to be necessary.

#### **3.3.4.1 Horizontal Airways**

Open fires in horizontal airways, with only negligible temperature changes in following non-horizontal airways, have a throttling but no natural draft effect. The result is an airflow decrease in the airway on the fire and all airways in series with it. Due to smaller friction losses in these airways, the ventilating pressure of the airway on fire will increase and counteract the throttling effect. Air quantity decreases of up to 30 percent were observed, however, rockfall may have been at least partially responsible.

A reversal of airflow in the airway on fire and the pertinent airway in series cannot occur. It is, however, possible in diagonal airways, which are connections between parallel airways, whose airflow direction is determined by the resistance ratios of the parallel airways.

#### **3.3.4.2 Ascensionally Ventilated Airways**

Open fires in ascensionally ventilated airways also cause a throttling as a natural draft effect. If the temperatures or the elevation changes behind the fire are not too small, or the air quantities are not too large, the natural draft will usually be stronger than the throttling effect and increase the airflow. If enough combustible material is present, the increased oxygen supply will then intensify the fire so that considerable natural drafts are finally developed.

The increase in airflow in the airway at fire is accompanied by a decrease in parallel airways. If the original ventilating pressures for the parallel airways are small, even airflow standstills and reversals with all their dangerous consequences

can occur. Remedies for stabilizing the airflow in parallel airways are an increase of the resistance of the airway on fire, which would at the same time reduce the oxygen supply and fire intensity, and an increase in the ventilating pressures. The latter aim can be accomplished by increasing the fan pressure or by lowering the resistance in the intake and return airways to the parallel airways.

#### **3.3.4.3 Descensionally Ventilated Airways**

Open fires in descensionally ventilated airways cause, besides the ever present throttling effect, a natural draft, which is opposed to the original ventilating pressure and has a tendency to decrease or even reverse the airflow. A decrease in airflow usually decreases the intensity of the fire, too. The reduced natural draft, again permits a larger air supply, which in turn increases fire intensity and draft. Except for the case of limited natural drafts due to small elevation changes behind the fire and a lack of combustible material or for the case of very high original ventilating pressures, one can expect a violent fluctuation of the airflow in descensionally ventilated airways on fire.

Whether a permanent airflow reversal takes place depends on several factors. There have to be sufficient elevation changes for the fumes on both sides of the fire. A fire at the bottom of a shaft or raise will not develop enough natural draft to initiate a reversal, a fire at the top not enough to maintain it.

The oxygen content of the fumes is usually considerably lower than that of the fresh air. It is especially low behind fires of high intensities. If these high intensities effect an airflow reversal, the fire is at first ventilated with oxygen poor air, which will reduce the fire intensity. If the plug of oxygen-poor fumes, travelling back through the fire, is long enough, no permanent reversal will be possible. When decrease of airflow, standstill or reversal take place as early as possible permanent reversal may occur. This can be supported by a low original ventilating pressure acting on the airway, or by a fire developing fast to a high intensity.

Permanent reversal after a longer fire duration can occur, when the fire is supplied with oxygen from damaged compressed air lines or from other airways, joining the return airway of the fire.

While in ascensional ventilation airways parallel to the airway fire are endangered by airflow standstills and reversals, in descensional ventilation the airway on fire itself is endangered most. The decrease in air quantity in the descensionally ventilated airway causes, like the throttling effect in horizontal airways, an increase in the ventilating pressure of parallel airways.

The means to stabilize the airflow in the descensionally ventilated airway is to increase the ventilating pressure acting on this airway. This can be done by increasing the fan pressure and by throttling parallel airways.

Since the throttling effect as well as the natural draft have a tendency to reduce the airflow, fires in descensionally ventilated airways usually don't reach the intensity of fires in ascensional ventilation and propagate with a considerably slower velocity.

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### 3.3.4.4 Examples of Airflow Reversals

For each of the three possibilities discussed above, fires in horizontal, ascensionally and descensionally ventilated airways, one example of an airflow reversal in a mine fire is given below.

#### (1) Horizontal Airway

At the Dukla mine (CSR) two parallel ventilation splits were connected by a diagonal airway. The throttling effect of a fire (July 7, 1961) in one of the splits reversed the airflow in the diagonal airway and allowed fumes to flow into the intake airways of the other split. As a result 108 miners were killed.

#### (2) Ascensionally Ventilated Airway

In the Roche-la-Moliere mine on June 30, 1928, a fire in the raise 3-4 close to junction 4 occurred. The developed natural draft at first caused an airflow reversal in airways 8-7-5-2, 7-6-3 and 6-5. Here, 48 miners were killed. Later, after the fire had moved down the raise away from 4 towards 3, the airflow normalized again in these airways but a short reversal in airway 4-1 occurred.

#### (3) Descensionally Ventilated Airway

Woropajew (1957) describes a fire in a Russian coal mine, working a dipping seam. The fire started in the descensionally ventilated raise 2-3-4 at point 3. The natural draft reversed the airflow in the raise and finally became so strong that even in the intake airway a reversal occurred.

### 3.3.4.5 Suitable Ventilation Plans

Suitable ventilation plans are of great help for every type of ventilation planning and, therefore, for the prediction of ventilation disturbances caused by mine fires, too. They should contain the main features of the ventilation system, without confusing details and the significant ventilation data. The former should comprise the airways, location of fans, ventilation doors, regulators, seals and dams, ventilation curtains and ducts, crossings, explosion barriers, production workings, trolley and Diesel haulage roads. The latter should include direction and magnitude of air currents, concentrations of hazardous gases, measuring stations, elevations of airways, fan heads or pressures and mine ventilating heads or pressures for the individual airways. If it is found too difficult to enter these data into the plans, they should be kept in up to date reference files, which can be used in conjunction with the ventilation plans. That such plans are possible is proved by the fact that they are required by law in several countries.

For the planning of fire fighting measures additional plans should be provided, which contain information on the water and compressed air pipeline systems, stored fire fighting and survival equipment, telephone lines, etc. They should be plotted in the same scale and perspective as the ventilation plans to facilitate

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simultaneous use.

### (1) Plans in Use

The ventilation plans actually used vary widely. The simplest type is based on plan maps, which in many cases suffice, especially when all mine workings are more or less situated in one plane.

For more complex layouts of openings, as results from mining more than one coal seam or ore deposits with a larger vertical extension, plan maps become too confusing and perspective plans are preferred. The type of projection, if not prescribed by law, is usually a compromise between clarity of the map and the ease with which horizontal and vertical distances can be read from the map.

Occasionally, but not too frequently, models are used as a three dimensional image of a ventilation system. The Dutch coal mines favored these, built from wires of different colors to indicate the function of airways. The work involved in changing the models and the prohibitive costs of keeping records for certain time periods and providing copies required that the models be used only in addition to other ventilation plans.

Quite frequently simplified ventilation plans are derived which show only the more important airways of a ventilation system. This is especially the case when ventilation network calculation are performed and one tries to keep the number of airways going into the calculation as small as possible. Another reason is to gain a better understanding of the mutual interaction of the airways comprising the system. Several types of such simplified plans are in use.

When ventilation network calculations were still mainly performed manually, with many ventilation engineers it became popular to represent ventilation plans in an abstract form resembling electric wiring diagrams. In these plans the configuration of the network is more conspicuous than in map plans or perspective drawings. Airways in series or parallel can be grouped together and replaced by equivalent resistors. In controlled splitting the number and location of the necessary regulators to enforce the wanted airflow distribution is more easily found. In natural splitting the diagonal airways, which cause difficulties in network calculations, are more easily detected.

An even clearer picture of the network configuration is obtained when in schematic ventilation plans the crossing of airways or the overlapping of loops are as far as possible avoided. Since plans of this type are most widely used in Poland (where they are required by law for every mine) they are usually known by their Polish name as "canonical plans". They are, however, gaining increasing popularity in other countries as the basis of emergency plans, too, since they are especially suited to detect possible instabilities in ventilation systems.

To judge the influence of several pressure sources in a ventilation network on the stability of the airflow in selected airways qualitatively and, as far as possible, quantitatively the Polish engineer Budryk suggested the use of a so-called "closed

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schematic plan" nowadays more frequently called a "Budryk plan". Characteristic for this plan is that the airway, whose stability is to be judged, forms the boundary between those parts of the network which are dominated by one of the pressure sources. Although quantitative predictions about the stability of an airway are only possible for comparatively simple networks, the Budryk plan allows valuable conclusions as how to increase the stability of this airway. The name "closed plan" originates from the fact that every air current is thought to be short circuited through the atmosphere (which in fact it is).

Every airway or group of airways, whose stability must be investigated and every new location of a pressure source leads theoretically to a different Budryk plan. In the practice of fire emergency plans ventilation engineers usually limit the airways to escape routes or stability boundaries, beyond which no airflow reversal should occur and the location of the pressure sources to airways where natural drafts can be created by fires. Even if no actual Budryk plans have been plotted, familiarity with the principles on which they are based can be of considerable help in selecting the right measures to stabilize the airflow in critical airways.

### Definition of Ventilating Heads and Pressures

It has been mentioned that the data contained in ventilation plans should include mine ventilating heads or pressures. These are differences in the energy content of the air between two points of the network, or, when the two points are the beginning and end of an airway, changes in the energy content of the air when moving through this airway. Since they indicate the stability and economy of existing airflow as well as the direction of potential airflow, their use has become very popular with ventilation engineers.

According to the above definition of heads and pressures, mine ventilating heads  $h_{MV}$  are energy differences per unit weight and mine ventilation pressures  $p_{MV}$  per unit volume of air. Being differences in energy contents they can be determined from the energy equation in the following form:

$$v dp + dZ + \frac{dV_a^2}{2g} + dh_{MV} = 0$$

$$dp + \delta dZ + \frac{\delta}{2g} dV_a^2 + dp_{MV} = 0$$

A comparison with the energy equation in the form:

$$v dp + dZ + \frac{dV_a^2}{2g} + dh_L - dh_F = 0 \quad h_F = \text{fan heads}$$

$$dp + \delta dZ + \frac{\delta}{2g} dV_a^2 + dp_L - dp_F = 0 \quad p_F = \text{fan pressures}$$

### 3.3.5 Quantitative Predictions of Ventilation Disturbances Caused by Fires

If the natural and throttling effects are known or can be calculated from other data, the influence of a fire on the airflow distribution in a ventilation system can be determined in a ventilation network calculation. If sufficient data on the network as the basis of the network calculation and a computer for the execution of the calculation are available, this is no great effort.

Where this is not the case and the calculations have to be done manually, ventilation engineers investigating the influence of a fire must quite frequently be content with abridged and simplified network calculations for the immediate vicinity of the fire. Since it is usually here that the fire has the greatest influence on the ventilation, these calculations can be very useful. The accuracy expected from the results determines the extent of permissible simplifications. To keep the manual work in tolerable limits, ventilation engineers, moreover, limit the network calculations frequently to the investigation of especially critical states, like the criteria for airflow standstills and reversals.

Network calculations for the vicinity of the fire are usually based on pressures, since the specific weight of the air in a limited area, except for the changes caused by the fire itself, remains fairly constant. As pointed out above, it makes no difference in principle if ventilation calculations are based on energies per unit weight (heads) or energies per unit volume (pressures) and ventilation engineers traditionally prefer the pressure approach.

### 3.4 Conclusions and Recommendations

*Conclusion:* The fire propagation process over the surface of solid polymeric materials is not completely understood. The process is viewed primarily from results of experimental evidence and is only partially supported by semi-empirical theories. *Recommendation:* Theories fully describing the fire propagation process should be developed and should be based on extensive experimentation at various scales accompanied by accumulation and correlation of a large volume of data.

*Conclusion:* Fuel-rich fires are fairly well described in the literature, but no schematic representation of oxygen-rich fires (except for timber) have been published in the past. *Recommendation:* Oxygen-rich fires should be thoroughly investigated, documented and described, and a schematic model for this process should be developed.

*Conclusion:* Mine fires, seldom remain at steady state because of the physical confinement. Thus, an originally oxygen-rich fire becomes a fuel-rich fire after the available oxygen is exhausted. (This situation also can reverse if ventilation is ap-

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plied subsequently, as in the incident described in section 3.2.3.8.9 above). The non-steady-state fire propagation process is not fully understood. *Recommendation:* A mathematical model should be developed to describe and predict the non-steady-state burning process.

*Conclusion:* Most early mine fire experiments were directed toward testing the flammability (or fire resistance) of materials and equipment. Since such fires have usually no opportunity to reach an equilibrium state, the results have little general validity. *Recommendation:* Design and conduct experiments in which steady-state conditions are reached for meaningful data generation.

*Conclusion:* Fire propagation velocities against air currents (frequently encountered in real mine fires) have not been investigated even though the results of such studies could be directly applied to understanding the phenomena. *Recommendation:* Experiments should be conducted to study in detail the development and velocities of smoke (gas) layers and fire spread under a wide range of ventilation conditions and duct inclination angles.

*Conclusion:* Coal dust fires, although more frequent and having lower ignition temperatures than timber fires, have not been studied, probably because of their low propagation rate. These fires, however, can act as ignition sources to dangerous secondary fuels, especially the synthetic polymers that are gaining increased utilization in mines. Even worse is the potential of coal dust fires to become coal dust explosions. *Recommendation:* Systematic fire experiments should be conducted on coal dusts of various origin, composition, and size distribution corresponding to real mine environments.

*Conclusion:* There has been surprisingly little work done on the composition of the combustion products of fuel-rich (open, underground) coal fires, whereas the oxygen-rich coal fire has been studied extensively. Specifically, information on the process of ignition, composition of combustion products, and propagation velocity of fuel-rich coal fires is lacking. *Recommendation:* The importance of medium- and large-scale coal mine fire experiments has been recognized and such experiments are now being conducted. It is obvious that these experiments are very expensive and difficult to perform especially with the added requirement of protecting the environment. It is of utmost importance to continue and expand these experimental programs to generate the lacking information. However, because of the high cost, full advantage should be taken of these experiments to extract all possible fire-related information. They have to be well designed, well planned, and fully instrumented not only for the primary information sought but also for all possible side effects and information.

*Conclusion:* Theoretical approximation of mine fire dynamics has been based on one- or two-dimensional representations in the past. These appear to be inadequate for the complete understanding, description, and prediction of airflow phenomena in mine fires. *Recommendation:* Develop a three-dimensional model in order to closely approximate buoyancy phenomena and associated flow reversals that devel-

## FIRE DYNAMICS AND SCENARIOS

op in mine fires. This may require extensive large-scale experimentation and a complex mathematical approach. Of particular interest is the study of the interaction of natural draft, induced ventilation and throttling effect of the fire itself.

*Conclusion:* Ventilation plans employed to date generally are suitable for most contingencies. They are overly simplified, however, for reasons of convenience and economy. Better plans could substantially improve the efficiency of fire suppression.

*Recommendation:* After sufficient information and understanding of the essential elements of fire dynamics become available, a highly sophisticated, general computer ventilation model should be employed. The basic model could be programmed to individual mines and updated frequently as mine development progresses. Such a model it would provide rapid, optimized solutions and available options in case of fire incidents.

### 3.5 References

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## CHAPTER 4

### MATERIALS

#### 4.1 Introduction

Selection of a polymeric material possessing the optimum fire safety characteristics for a particular application is a complex and difficult task because so many factors must be considered. General fire-consciousness in system design, the use of structural materials with improved fire safety characteristics, fire and explosion potential detection equipment, and firefighting procedures and equipment are equally important aspects of coping with fire hazards and must be viewed together and analyzed in a systems approach to the problem. In addition, in evaluating polymeric materials with improved fire safety characteristics, competing fire safety requirements must be assessed and trade-offs made (e.g., a decrease in ease of ignition or flame spread that also leads to an increase in the production of smoke or toxic combustion products might not be tolerable in situations where egress is limited).

##### 4.1.1 Fire Safety Characteristics of Polymeric Materials

No organic polymeric material can withstand intense and prolonged heat without degradation, even in the absence of oxygen. Given sufficient oxygen and energy input, *all* organic materials will burn. (Metals also will exhibit some undesirable characteristics under these conditions.) There are, however, several methods for reducing the fire hazard of polymeric materials including:

1. Developing and using polymers with fire safety characteristics that are inherently better than those of the well-known materials. (Some materials of this type are available commercially now, but most are very expensive.)
2. Improving the fire safety characteristics of available, low-cost materials with fire retardants (i.e., by coating the surface of the materials or by incorporating a fire retardant into the bulk material at some appropriate processing stage).
3. Combining two or more materials in a way that utilizes the best properties of each (e.g., placing steel plates on each side of a plywood slab).

Polymers may be fire retarded by introducing fillers such as alumina trihydrate or active compounds into the bulk material. The former lowers the fire load either by absorbing heat or by diluting the fuel. The latter, usually halogen, phosphorus, nitrogen, antimony or boron compounds, may be used in synergistic combination. One may also distinguish between reactive and non-reactive retardants according to whether or not they form covalent bonds with the polymer.

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The burning of a polymeric solid is essentially a three-stage process consisting of a heating phase, a thermal pyrolytic phase, and an ignition phase. The behavior of a polymer during the initial heating phase depends considerably on its composition. Thermoplastic compositions generally will melt between 100°C and 250°C. The loss of rigidity that occurs at the softening point of such materials and the subsequent decrease in melt viscosity as the temperature increases in many cases allow these liquids to recede from the ignition source at a sufficiently rapid rate to prevent their subsequent pyrolysis and ignition. This phenomenon apparently has led to some erroneous conclusions based on small-scale tests concerning the flammability of such compositions in a real fire situation. Thermosets and most natural polymers, such as wood and cellulose, remain essentially unchanged dimensionally during this early heating phase.

At some later stage in the heating phase, thermal decomposition occurs with the evolution of gaseous products whose flammability will depend upon the chemical composition of the original material. The temperature and rate at which this stage occurs depends upon the thermal stability of the material and the chemical decomposition reactions occurring under the existing fire conditions. The flammability of a solid is determined largely by its behavior at this stage in the burning process. The establishment of a self-sustaining flame is predominantly dependent upon the generation of sufficient fuel gases from thermal pyrolysis to produce a flammable oxygen-fuel mixture close enough to the solid fuel so that sufficient heat can be transferred from the flame to the solid surface by radiation or convection to sustain pyrolysis at an acceptable rate. This means that the flame zone usually is spatially removed by some small distance from the fuel surface. A separation of flame and solid fuel is necessary in order to allow dilution of the pyrolytic fuel gases with sufficient oxygen to make the mixture flammable.

Pyrolysis generally proceeds in three closely related stages. Between 100°C and 250°C, sufficient thermal energy is available only for such low energy reactions as the elimination of functional groups, usually from the end of the chain, and of small molecules like water and hydrogen halide. Between 250°C and 500°C, sufficient energy becomes available to break the highest energy chemical bond usually contained in the structure of most polymers.

These reactions often can lead to the "unzipping" of polymer chains and the dissemination of flammable monomer or small chemical fragments. Both products can sustain gas-phase flame reactions; however, in some cases, these fragments will recombine, which leads to the formation of aromatic condensed ring systems that are stable under the pyrolytic conditions. When this happens, a third stage of the pyrolysis begins and the aromatic condensed structures are condensed further at temperatures near 500°C with the eventual elimination of most elements other than carbon. The result is a carbon char that is highly insulating and difficult to ignite at normal oxygen concentrations. If the char can be maintained in a viscoelastic state during the intermediate pyrolysis stage, the gases evolved will be trapped in the

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viscous liquid and the char will expand into a carbon foam. The formation of this special type of pyrolytic char is called intumescence. Such char-forming reactions are desirable because they convert a flammable polymer to a less flammable char while simultaneously reducing the quantity of flammable gases. If such a conversion can proceed because of the nature of the polymer structure in the absence of phosphorus, halogen or heavy metal additives, highly toxic by-product gases are eliminated and the off-gases are no more toxic than carbon dioxide or carbon monoxide.

With increasingly higher temperatures, the rate of production of the gaseous degradation products increases until a mixture with the oxygen of the air is reached that exceeds the flammability limit and ignition occurs. Continued burning at this stage is dependent upon the transfer of sufficient heat from the flame to the condensed phase to maintain an adequate supply of flammable gaseous decomposition products and, of course, upon the presence of a supply of oxygen in the surrounding atmosphere sufficient to support combustion. The chemical reactions, generally occurring in the gas phase at flame temperatures, are free-radical in nature.

### 4.1.2 Fire-Retardant Mechanisms

There are four major mechanisms for altering the flammability of common commercial polymers:

1. Alteration or reduction of the heat of combustion of the total polymer composition.
2. Inhibition of the gas-phase combustion reactions.
3. Alteration of the condensed-phase pyrolytic reactions to enhance the formation of char.
4. Application of an intumescent coating (exposure of the coating to the thermal flux of a fire expands the coating into thermally stable intumescent char, which then protects a substrate from the ignition source).

### 4.1.3 Economic Factors

Cost is an important aspect of fire hazard reduction. Thermally stable polymers with superior fire safety characteristics may be too expensive for routine use. The application of fire-retardant coatings is sometimes a cost-effective approach; however, it is limited to a relatively small number of uses.

The cost of fire retardation by the incorporation of a fire retardant in the polymer varies greatly, depending on the particular compound or treatment used and the performance level desired. Fire retardation normally increases the cost of the material, except when the desired measure of protection can be obtained with inexpensive inert fillers.

## 4.2 Specific Polymeric Materials

### 4.2.1 Wood

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By volume, more wood is used in mines than any other polymeric material. Serving principally to support walls and overheads, timber is more readily ignited than coal, but it has been accepted because of its cost-effectiveness, slow charring rate, and good strength retention under fire.

Fire-retardant treatments and coatings available for use with lumber and wood-base products are described in Volume 1 Materials-State of the Art, Chapter 2, Sections 3 and 4.3, and Chapter 7. The chemical treatments reduce the hazard of initial ignition; decrease the rate of surface flame spread, the initial rate of heat release, and the total smoke development; and render the material less subject to after-flaming and afterglow. These treatments increase the cost of the wood products by 50 to 100 percent and have some effect on moisture absorption, appearance, strength, machining, gluing, and finishing characteristics. Most of these treatments also are limited to applications in low-moisture environments, and a mine atmosphere typically has a relative humidity of 90 percent. There is also some question about the role of flame retardants in wood in producing toxic gaseous products during combustion.

The use of fire-retardant coatings for wood generally has been more limited than the chemical treatments because thick films applied in several coats are required and special care must be taken in high-humidity environments. In work recently completed at DeBell and Richardson (Baum 1977), fire-retardant polyimide/fungicide formulations for coating mine timbers were screened. The curable polyimide appeared to be flame retardant and evolved a minimum of fumes when exposed to a flame. The question of whether rot increases the flammability of timber still remains open.

At the Pittsburgh Mining and Research Center, precharring of wood to a depth of 2 mm is being evaluated as a means for making it less flammable. Evaluation using laser ignition reveals that a combination of zinc chloride impregnation plus precharring is the best treatment.

### 4.2.2 Thermoplastics

#### 4.2.2.1 Polyvinyl Chloride

The flammability characteristics of and fire-retardation methods for polyvinyl chloride (PVC) and its formulations are described in Volume 1, Section 5.3.3. PVC is one of the lowest priced of the commercial thermoplastic polymers and has been sold commercially for more than 35 years. It can be formulated into a wide variety of compositions with properties varying from soft elastomers to tough rigid polymers. (The applications of PVC in mines are discussed below in Section 4.3). It is the least flammable of the low-cost large-volume thermoplastics because of its high (greater than 50 percent by weight) chlorine content. The flammability of the many available commercial formulations can vary widely from relatively low in the absence of an outside flux to rapid burning, depending on the nature of the materials added (e.g., plasticizers, fillers, impact modifiers, and reinforcements).

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When exposed to a flame or to excessive heat, PVC can emit hydrogen chloride at relatively low temperatures in a highly endothermic process. This, together with its high chlorine content, accounts for the low flammability of the uncompounded polymer since the hydrogen chloride keeps oxygen away from the surface of the plastic. Decomposition products vary according to the amount or type of the compounding ingredients used during fabrication but may include benzene, hydrocarbons, char, and other fragments.

Chlorinated or phosphorus-based plasticizers particularly phosphates and chlorinated paraffins, also are used in large quantities to reduce the flammability of plasticized compositions. Phosphates, particularly tricresyl phosphate, cresyl diphenyl phosphate and 2-ethylhexyl di-*n*-hexyl phosphate, traditionally have been added to PVC as plasticizers. They also enhance fire retardance; flame-out times are excellent.

By far the largest usage for PVC in mine applications is in pipe; pipe fittings; conduit, wire, and cable coatings; and belt conveyors.

### 4.2.2.2 Styrene Polymer.

The general types of commercial styrene polymers and their flammability characteristics are described in Volume 1, Section 5.3.2. Of the various polymers, copolymers, graft polymers and blends in this group, the high-impact polystyrenes (HIPS) and the blend/graft copolymer of acrylonitrile/butadiene/styrene (ABS) are the most widely used. Fire-retarded versions of both of these materials, generally obtained by the addition of halogenated additives (chlorinated aliphatics and aliphatics and decabromo diphenyl ether) with or without antimony oxide, also are used. Part or all of the halogen component may be incorporated in the form of halogenated polymers, such as PVC, in blends. The cost of the better fire-retarded materials is about twice that of the materials that are not fire retarded and their application is limited by cost considerations.

The major styrene polymer in pipe, fittings, and conduits is ABS. Low weight, easy fitting, low corrosion, and competitive cost are its major advantages over metal. The fire safety aspects of ABS pipe have been discussed widely. Obviously, buried waste pipe presents no fire hazard, but the use of ABS pipe in exposed locations could lead to propagation of fires under some conditions and should be avoided in mine applications.

### 4.2.2.3 Polyolefins

The polyolefins, principally low-density polyethylene (PE), high-density polyethylene and polypropylene (PP), comprise a U. S. market in excess of 10 billion pounds. The amount used in mines is relatively small but growing.

The polyolefins can be tailored and formulated to offer a great variety of properties including variations in processability, heat resistance, rigidity, light stability, printability, friction, static properties, foam stability, strength, and toughness as

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well as flammability (see Volume 1, Section 5.3.1).

Chemically, polyolefins are very similar to paraffin wax, and they burn in much the same way — i.e., they ignite easily, burn with a smoky flame, and melt as they burn. Polyolefins produce less smoke than polystyrene, and the degree of melting and dripping can be enhanced or decreased by choice of molecular weight, cross-linking, fillers, additives, etc. The mechanism of burning, products of combustion, and flame-retarding formulations are described in Volume 1, Section 5.3.1.

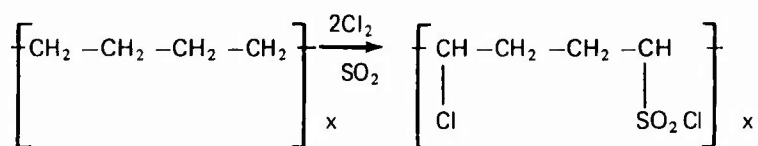
Flame-retardant formulations generally are produced by compounding with highly halogenated organic compounds in combination with antimony oxide. These formulations exhibit improved resistance to ignition in low thermal energy environments. Flame spread rates also can be reduced, but all known fire-retardant polyolefin compositions burn readily in a fully developed fire.

Electric cable coatings are made from the various density grades of polyethylene, sometimes cross-linked and sometimes partially foamed for modified dielectric properties. Cold water pipe, cisterns, tanks, and waste pipe are common applications for medium- and high-density PE and PP. Polypropylene often is used in drainage fittings.

Polyethylene can be chlorinated in the presence of light or a free radical catalyst. The chlorine content, and therefore the properties of the product, can vary considerably depending on the extent of chlorination and the reaction conditions. Flammability decreases directly with increase in the chlorine content.

The flammability characteristics of these materials resemble those of poly(vinyl chloride) and poly(vinylidene chloride). Hydrogen chloride is a major combustion product.

Polyethylene can be chlorosulfonated by methods similar to those used in the chlorination already described. The reaction is represented by:



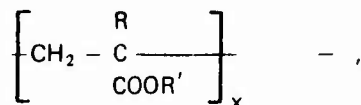
As in the chlorination, the properties of the composition can be varied widely by controlling the extent of chlorosulfonation and the reaction conditions. As expected, the flammability of the polyethylene is reduced as the chlorosulfonyl chloride content is increased. Flammability has not been thoroughly studied although hydrogen chloride and sulfur dioxide are major products of combustion.

The volume of chlorinated and chlorosulfonated polyethylene used in mines is relatively low, but the latter is used extensively as fire-resistant electrical wire and cable insulation in rail cars and other places where flammability control is essential.

### 4.2.2.4 Acrylics

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The acrylics are polymers formed from acrylic (R = H) or methacrylic (R = CH<sub>3</sub>) esters according to the formula:



where R' represents an alkyl radical. The major plastic in the group is the homopolymer of methyl methacrylate (R' = CH<sub>3</sub>), a crystal clear material that softens at about 100°C.

Poly(methyl methacrylate) (PMMA) ignites readily and softens as it burns. Burning rate, fuel load and smoke production are less than for polystyrene. In burning, PMMA undergoes "unzipping" pyrolysis (reverting to monomer) from the heat of the ignition source, the heat of combustion, or other environmental energy. The volatile products of pyrolysis then burn in the gas phase.

Although halogen and antimony compounds have been used to reduce the burning rate and ease of ignition of PMMA, less effort has been devoted to its fire retardation than to that of other polymers. This is due partly to the fact that for most applications it is difficult to affect the "unzipping" depolymerization mechanism so characteristic of this polymer. Fire-retarding additives also usually impair the excellent transparency and aging characteristics of the polymer.

When acrylics are used as glazing, particularly in relatively large areas, the potential fire hazard should be analyzed carefully. There is probably little justification for the use of acrylics in mines.

### 4.2.2.5 Nylon

Nylon is the generic name for synthetic polymers with amide groups occurring repetitively in the main chain (see Volume 1, Section 5.3.5).

The properties of 20 variants of aliphatic nylon are tabulated in the *Modern Plastics Encyclopedia* (1975).

Nylon plastics play a role in mines. They appear in small molded parts such as window and door hardware, spigots, valves, and appliance components. Nylon film has been proposed for use as air ducting.

Many tests indicate that nylon plastics have low flammability. They generally self-extinguish after exposure to an ignition source because they drip when ignited, which removes the flame front and hot polymer from the burning part. If dripping is prevented, the nylon burns with a smoky flame.

Fire-retarded formulations generally are prepared using phosphorus or halogen-containing additives with or without addition of antimony or iron oxides. Under some circumstances, halogens greatly increase the flammability of polyamides, presumably by greatly accelerating the degradation to volatile fuel fragments. The addition of drip promoters, such as thiourea, has been proposed, and hydrated

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alumina also has been used. None of these systems, however, prevents a nylon from burning in a fully developed fire.

Many molding and extrusion compositions contain glass fibers or particulate mineral fillers (as much as 60 percent by weight) to enhance certain engineering properties. Such filled materials may burn more readily than their unfilled counterparts because the fillers tend to reduce dripping. The highly filled materials, however, have a lower fuel value.

Nylons currently are used in mines in relatively small items that have not posed serious fire safety problems. However, larger items (e.g., tanks, large castings, and other structural applications) are being considered, and more attention needs to be given to analysis of the fire hazards that might be introduced.

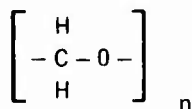
### 4.2.2.6 Polycarbonates

Polycarbonates are a class of polymers generally considered to be extremely tough and to combine clarity with high impact resistance. (These materials are discussed in Volume 1, Section 5.3.9.) The polycarbonates are significantly less flammable than unmodified styrene, olefin, or acrylic polymers. Their fire resistance has been improved by the addition of halogenated materials as additives or copolymers.

It is the toughness, clarity, and impact resistance of the polycarbonates that make them attractive for use as helmets, face shields, and glazing material in mine applications. Many of the housings, handles, etc., of small appliances and tools also are of polycarbonate. Before applying polycarbonate glazing in large areas, however, an analysis should be made of the effect of its use on the fire safety of the system.

### 4.2.2.7 Acetals

The acetals are linear homopolymers or copolymers of formaldehyde (i.e., polymethylene oxide):



(Copolymers employ ethylene oxide or other similar comonomers).

Acetal parts find significant applications in plumbing fixtures (ballcocks, faucets, showerheads, etc.), window and door hardware, and handles and mechanical components in appliances. They are used in relatively small amounts in mining. (Acetal chemistry and flammability properties are reviewed in Volume 1, Section 5.3.7).

The acetal plastics are strong, stiff, and tough. They are considered to be engineering resins because of their predictable design, processing, and end use character-

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istics. The acetals are easily combustible. They burn with very little smoke and a nonluminous flame and little oxygen is required. Molecular weight and percent of filler dictate the amount of dripping that will occur. The products of combustion are carbon dioxide, water and some carbon monoxide.

Phosphorous-based systems have been suggested as flame retardants for acetals, but no commercial success has been achieved in this direction. On the other hand, acetals are used in relatively small parts where they do not present major fire hazards.

### 4.2.2.8 Polyesters

The polyesters considered here are the linear thermoplastic poly(ethylene terephthalate) (PET), poly(tetramethylene terephthalate) (PTMT), and their modifications. (The cross-linked styrenated polyesters are discussed with thermosetting materials in Section 4.2.3.3.) These polymers burn with a smoky flame accompanied by melting and dripping and little char formation. Fire-retarded grades generally are prepared by incorporating halogen-containing materials as part of the polymer molecules or as additives. Metal oxide synergists frequently are included. These fire-retarded systems are resistant to small ignition sources in low heat flux environments but still burn readily in fully developed fires.

These polyesters are being increasingly used in components of mine surface vehicles. A recent example is the replacement of zinc die cast headlamp moldings by polyester moldings.

### 4.2.3 Thermosetting Resins

Thermoset polymers are distinguished from the thermoplastics discussed above in that they become chemically cross-linked during the final molding. The final product is set into shape by primary chemical bonds and, for most practical purposes, no longer can be melted, reshaped, or dissolved.

Because of their brittle nature, thermosets are used almost exclusively in conjunction with various inorganic or organic fibrous reinforcements and various types of powdered fillers. These reinforcements and fillers often comprise more than half of the final composition and can alter the flammability or fire safety of the total composite significantly; therefore, it is important to consider the total composition before deciding upon the flammability characteristics or fire safety of these materials.

Because of their cross-linked nature, thermosets generally do not soften or drip when exposed to a flame. Such resins are inherently fire retardant and will pass many common laboratory tests without the need of a fire-retardant modification or additive. Their fire retardance, however, is a function of the mechanical stability of the insulating char and is limited by the resistance of elemental carbon to oxidation.

#### 4.2.3.1 Phenolic Resins and Molding Compounds

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Two general types of first-stage phenolic resin are produced depending on the catalyst, the phenol/formaldehyde ratio, and the reaction conditions. These are called resoles and novolacs, respectively. The physical properties of the phenolic resins vary widely depending on the type, kind, and amount of filler used; the kind of reinforcement used, the phenol/formaldehyde ratio, the type of curing catalyst; and other formulation variables.

Phenol/formaldehyde polymers are practically always used in conjunction with fillers or fibrous reinforcements. The modified polymers are char-forming and do not readily support combustion in the absence of external energy input (see Volume 1, Section 5.4.1).

The major use of phenolic resins is in resin-bonded wood for plywood sheeting, and such composites generally are less flammable than corresponding systems based on wood alone. The second largest application of phenolic resins is as binders in fiberglass insulation. About 10 percent resin (based on the glass) is used to bond the glass fibers to give dimensional stability to the insulating material. In this configuration (i.e., large surface area and inert substrate), the resin can burn more readily than in a dense solid form such as a laminate. The system does not readily propagate a flame but can propagate fire by "punking" (glowing combustion). "Punking" can be overcome by use of various nitrogen-containing reactants (melamine, dicyandiamide, etc.) in the phenolic resin. These compositions are used for special applications.

Molded phenolics have been used extensively in various electrical applications due to their combination of desirable electrical, mechanical, and fire-resistance properties. In some applications, these resins are being replaced by special thermoplastics that have lower fabrication cost.

### 4.2.3.2 Urea/Formaldehyde and Melamine/Formaldehyde Resins

The basic chemistry, properties, and applications of urea/formaldehyde and melamine/formaldehyde resins are summarized in Volume 1, Section 5.4.7. The only significant use of these amino resins in mines is for resin-bonded wood applications.

### 4.2.3.3 Unsaturated Polyester Resins

The unsaturated polyester resins are prepared by condensing a saturated dibasic alcohol and both a saturated and an unsaturated dicarboxylic acid into a prepolymer (or first-stage) resin. The latter then is dissolved in a vinyl monomer, usually styrene. The cured resin is produced by free radical copolymerization of the styrene monomers and the unsaturated acid residues.

Phthalic anhydride is used most widely as the saturated acid component. The resins usually are compounded with a reinforcing fabric (generally glass cloth or mat) with or without filler before curing.

The burning characteristics of unsaturated polyesters can be modified by the

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addition of inorganic fillers; the addition of organic fire retardants; the chemical modification of the acid, alcohol, or unsaturated monomer component; and the chemical combination of organometallic compounds with the resin. A wide variation in flammability characteristics can be achieved by using one or more of these modifications. Flame spread ratings of 25 or less, as measured by ASTM Test E-84, have been attained by using chlorendic acid with antimony oxide as synergist. Such low flame spread ratings now can be obtained in the absence of opacifying antimony by using the more efficient bromine-substituted monomers.

Both fire-retarded and unretarded polyester resin formulations yield copious amounts of smoke when exposed to fire because styrene is the major product of pyrolytic decomposition and styrene burns with a very smoky flame. The high smoke values have been reduced only marginally by the use of relatively large amounts of inorganic fillers such as alumina hydrate.

The relative toxicity of halogenated polyester resins has been a subject of considerable discussion ever since their introduction in 1953. The chlorine contained in these compositions generally has been shown to be converted largely, if not quantitatively, into hydrogen chloride.

Reinforced polyester formulations find applications in panels, pipes, ducts, and tanks. The flammability hazards associated with these materials in mining applications is incompletely defined at this time. Generally, a high degree of fire retardance can be incorporated into unsaturated polyester compositions using available technology.

### 4.2.3.4 Epoxy Resins

Epoxy resins generally are prepared by reacting a first-stage polyfunctional epoxy compound or resin with a basic or acidic cross-linker (or "hardener") to yield a thermoset product cross-linked by ether or ester linkages. The basic epoxy resin can be prepared in a variety of ways although the most common is the reaction of a polyphenolic compound with epichlorohydrin.

The flammability characteristics of these resins can be significantly improved by adding halogen and antimony compounds, the former as either an additive or copolymer. The halogen compounds generally increase the tendency for generation of smoke on ignition. Epoxy resins frequently are loaded heavily with inorganic fillers, and hydrated alumina as a filler can decrease flammability. Epoxy resins are used principally to seal pipe joints, as plastic-based paints, as mortar for bonding either new or old concrete, and as epoxy composites for electrical applications.

Little or no fire hazard is introduced by the use of epoxies in construction due to the nature of the compositions and their applications, locations, and quantities.

### 4.2.3.5 Furan Resins

Although furan resins currently are little used in mining applications, they might be used more extensively in the future. Furan resins are prepared by reacting

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furfuryl alcohol and an aldehyde — most frequently formaldehyde. Urea is often used as a modifying agent. The resins are hardened in situ with an acidic substance added just before application. A typical curing agent would be p-toluenesulfonic acid. Although no specific literature reference has been found that describes fire-retardant methods for furan resins, fire-retardant formulations are available commercially.

### 4.2.3.6 Amine Resins

Amine resins are thermoset resins prepared by the reaction of an amino compound with an aldehyde. The reactive amino groups ( $-\text{NH}_2$  or  $-\text{NH}-$ ) are characteristically present as amides. The two most important commercial materials are based on urea and melamine used with formaldehyde.

Little work has been done to develop fire retardance in amino resins because of their relatively high heat resistance and low flammability and their predominant use in applications where flammability is relatively unimportant. A variety of phosphorus and boron compounds have been used to reduce flammability when required.

The various amino resins find limited application as coatings on a variety of metal and reinforced plastic panel substrates. Hardness, durability, abrasion resistance, and easy colorability are the prime reasons for their use.

### 4.2.4 Elastomers

The fire safety aspects of elastomers are largely determined by their chemical structure. From this point of view they may conveniently be assigned to the several distinct groups described below. A more complete description of these compounds is found in Volume 1, Chapter 5.

#### 4.2.4.1 Hydrocarbon-Based Elastomers

The hydrocarbon-based elastomers principally comprise natural rubber, synthetic cis-polyisoprene, polybutadiene, styrene-butadiene rubber (SBR), butyl rubber, and ethylene-propylene rubber. These rubbers are low-cost materials with good mechanical properties and, thus, are used in large volume applications such as automobile and truck tires. SBR rubbers are widely used in belting. They do, however, burn readily and produce much smoke. Fire-retardant additives reduce flame spread and ease of ignition from low energy ignition sources but do not prevent burning in an intense fire situation. Alumina trihydrate is receiving intensive study as a filler to reduce flammability and smoke production in these elastomers. A good future seems to exist for fluorocarbon rubbers as a coating and for primary construction in hose and cable.

#### 4.2.4.2 Chlorine-Containing Elastomers

The chlorine-containing elastomers include polychloroprene, rubber hydro-

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chloride, chlorinated ethylene polymers and copolymers (chlorinated polyolefins), and epichlorohydrin rubbers. These materials are significantly more fire retardant than the straight hydrocarbon rubbers, but they generate extensive black smoke and hydrogen chloride gas when exposed to a fully developed fire.

Chlorinated elastomers, particularly polychloroprene (more commonly designated as Neoprene), are widely used where fire retardance is important. Some large-scale applications are in electrical insulation, foamed seat cushions, and conveyor belts.

### 4.2.4.3 Nitrile Rubbers

Nitrile rubbers are copolymers of butadiene and acrylonitrile. The ratio of butadiene to acrylonitrile is similar to the ratio of butadiene to styrene in SBR. The cyanamide group imparts to these elastomers some of the properties of the halogen-containing rubbers but also constitutes a potential toxicological hazard.

### 4.2.4.4 Polyurethane Elastomers

Polyurethanes are polymers containing the group  $\text{-NH-CO-O-}$ . They are formed typically through the reaction of a diisocyanate and a glycol. Because a variety of glycols or esters can be coupled with different diisocyanates, a large variety of linear polymers can be obtained in this way. These elastomers are cross-linked by including a controlled amount of a polyfunctional monomer (e.g., a triisocyanate or trihydric alcohol) in the reaction.

Fire-retardant grades, generally based on bromine-and/or phosphorus-containing additives, are available, but they still burn in intense fires. Smoke generation is generally less than with hydrocarbon elastomers, but some hydrogen cyanide gas may be generated. The major use of polyurethane elastomers is in foams and in belts when extreme toughness is needed. A future use in mines is for strata reinforcement. (The uses of polyurethane foams are described below in Section 4.3.4).

Reaction injection molded (RIM) polyurethanes are finding increasing use on automobile exteriors in such applications as front and rear fender extensions, front fender skirts and panels, and front or rear fender fillers; applications in utility vehicles can be expected to follow.

### 4.2.4.5 Polysulfide Rubbers

The polysulfide rubbers, also known as thiokols, are polymers composed of aliphatic hydrocarbon chains connected by di-, tri-, and tetra-sulfide links. Because of their outstanding resistance to hydrocarbon solvents, they are used extensively as sealants in aircraft fuel tanks and pressurized cabins but have only limited applicability elsewhere.

### 4.2.4.6 Silicone Rubbers

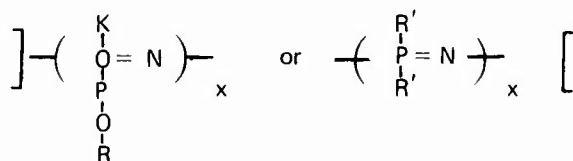
Silicone elastomers generate relatively little smoke, are reasonably fire retardant

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in air, and, when burned, have low fuel value. They burn slowly and produce no flaming drip. They are relatively expensive (less so than fluorocarbons, but more so than hydrocarbon rubbers) and their mechanical properties are marginal for many applications. Silicones, however, do offer a most promising combination of fire safety aspects, physical properties, and cost, and they are used in electrical insulation and seat cushions.

### 4.2.4.7 Phosphonitrilic Elastomers

Phosphonitrilic elastomers represent another example of "inorganic elastomers". The phosphorus-nitrogen backbone:



supplies the flexibility required for elastomeric properties and contributes little fuel value. The various side groups (R, R') affect many of the characteristics of the elastomers including flammability (e.g., long hydrocarbon side chains would increase flammability whereas fluorocarbon side chains would not contribute to flammability but could contribute to undesirable pyrolysis products).

These phosphonitrilic materials are in the early stages of development, and much needs to be done to define their utility and applicability for various uses. This includes the definition of the combustion and pyrolysis products contributed by the phosphorus and nitrogen. They represent, however, one of the main hopes for a low-smoke, low-flammability elastomer.

### 4.2.5 Foams

Polymeric foams generally are complex multicomponent systems that may contain fibers and various fillers. Polymeric foams can be divided into rigid and flexible foams. Syntactic foams are another type that are essentially polymers surrounding tiny hollow spheres of another polymer or glass. Flexible foams generally have an open cell structure whereas rigid foams usually have a closed-cell structure.

Since more of a foam's surface is exposed to atmospheric oxygen, its rate of pyrolysis and burning is greater than that of the base polymer. The low thermal conductivity of foams tends to concentrate the heat on the surface of the structure rather than to dissipate it to underlying material or substrate. The result is rapid heating and pyrolysis of the surface material when exposed to a flame. This often leads to an extremely rapid flame spread rate; however, other factors may moderate this effect considerably (e.g., the small amount of potentially flammable material per unit volume in low-density foams results in a very small amount of total heat

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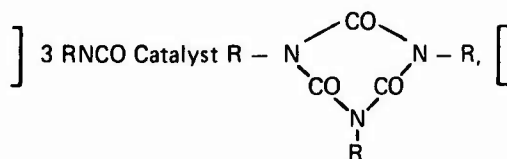
being available per unit area for flame propagation).

If the foam material is a thermoplastic such as polystyrene, the heat of a flame rapidly melts the foam adjacent to it, and the material may recede so fast from the flame front that there is no real ignition. A highly crosslinked thermoset foam, on the other hand, behaves in an entirely different manner. Since little or no melting occurs, the surface does not recede from the flame front, and the foam is rapidly ignited. The flame then spreads if the foam is flammable. Under the same conditions, a fire-retarded foam pyrolyzes rapidly in the vicinity of the flame, leaving a carbonaceous char on the surface of the material. This highly insulating char protects the remainder of the material from the effects of the flame. Since carbon itself is combustible, the continued impingement of a radiant heat flux can generate continued combustion, but the low density of the surface char generally does not produce sufficient heat to sustain burning in the absence of surface heat radiation.

### 4.2.5.1 Polyurethane Foams

Polyurethanes are the reaction products of a dihydroxylic or polyhydroxylic compound or resin and a diisocyanate or polyisocyanate. Polyurethane foams are prepared by modifying the fundamental reaction of an isocyanate and an alcohol to produce a permanent cellular structure in the basic polyurethane during its polymerization by the controlled introduction of a gas phase. (The applications of polyurethane foams in mines are discussed below in Section 4.3.4).

An important reaction is the trimerization of isocyanate to produce an isocyanurate ring:



The isocyanurate ring introduces a trifunctional cross-link. It is thermally more stable than the urethane from which it is derived and can be used to reduce the flammability of polyurethanes. Isocyanurate structures can be produced by the use of excess isocyanate in the presence of an isocyanurate catalyst such as a tertiary amine.

The cellular nature and low thermal stability of polyurethane foams generally influence their flammability. Because of the low thermal conductivity, the high surface heat flux generated from an ignition source, can cause almost instantaneous conversion of a polyurethane to flammable gases. This often results in very rapid surface flame spread and high flaming temperatures once the surface is ignited. In general, fire retardance is imparted to polyurethane foams by the chemical incorporation of halogen and/or phosphorus compounds.

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Although polyurethanes themselves are nontoxic, the pyrolytic combustion gases have been shown to contain considerable quantities of toxic gases. Significant amounts of hydrogen cyanide have been detected in polyurethane combustion products, but its relative toxicity in gaseous mixtures containing large amounts of carbon monoxide has not been definitely established.

### 4.2.5.2 Polystyrene Foams

Low-density polystyrene foam is used as thermal insulation, and high density foam is used for structural applications. The major fire hazards from cellular polystyrene are the potential for high burning rate, high smoke production, and rapid flame spread. These are, of course, highly dependent on location, geometry, orientation, and relationships to other materials. Ignition and burning rates also are affected by composition (e.g., use of flame retardants), ignition source, and thermal environments. There is little justification for the use of polystyrene foam in mining applications.

### 4.2.5.3 Poly(vinylchloride) Foams

Flexible poly(vinylchloride) (PVC) foams find greatest application in coated fabrics, clothing, and seating where they probably have little effect on fire safety. High-density foams of varying flexibility are used for flooring in nonresidential buildings, and the flammability hazard of PVC in this application can vary depending on the type and amount of plasticizer used in the composition.

Rigid vinyl foamed extruded shapes are being used increasingly as exterior and interior trim, window casing, sandwich core material, and siding. The flammability of such materials is low, however, because of the high density and thermal conductivity of most of the products, the absence of significant amounts of flammable plasticizers, and the high concentration of inert fillers generally used in the formulations.

### 4.2.5.4 Rubber Foams

Practically any elastomer can be made into a flexible foam. When a chemical blowing agent is used in a dry-compounding recipe, the foam rubber generally is referred to as sponge rubber. Sponge rubber is made mostly from natural and styrene-butadiene rubber although silicone and fluorocarbon sponge rubbers also are available.

Latex foam rubber is made by beating air into compounded rubber latex. Fluorocarbons with or without air are used as foaming agents in some processes. Natural or styrene-butadiene rubber or blends of the two are widely used.

The approaches to fire retardation in these materials are generally the same as those employed with the same bulk (i.e., non-foamed) elastomer, except that post-treatments similar, in principle, to those applied to wood and wood products are possible because of the cellular nature of foams.

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### 4.2.5.5 Urea/Formaldehyde Foams

Urea/formaldehyde foams are made by mechanically frothing two aqueous reaction streams in a special applicator gun. Foam comes from the gun in fully expanded form, much like shaving cream. It sets in 10 to 60 seconds, cures in 2 to 4 hours, and dries in 1 to 2 days. The outstanding properties of these foams are their relatively good fire safety (low smoke production, low flame spread rate, and low fuel value), good insulation efficiency (K factor = 0.18 to 0.20), good sound insulation, pest repellence, injectability into inaccessible cavities, and lack of pressure build-up. Urea/formaldehyde foams have no flexural strength and poor dimensional stability and should not be left exposed since they are easily mechanically damaged. Currently available formulations also suffer hydrolytic instability at high humidity, which almost certainly rules out their use in certain mining applications where a high degree of moisture is present.

### 4.2.5.6 Phenol/Formaldehyde Foams

Phenol/formaldehyde foams have been known for a long time, but their commercial utility has been very limited due to the friability and corrosivity resulting from the residual strong acid used in their preparation. Such foams do exhibit the normal good fire-resistance characteristics of phenolic polymers but have a tendency to undergo "pinking" (glowing combustion). Recently, progress has been made towards overcoming these shortcomings, and slab stock, spray applications, laminates, and injection molded foams are in various stages of commercial development. These foams vary from 100 percent open-cell to 80 percent closed-cell materials; they have K values ranging from 0.19 to 0.23 depending on density and temperature. Phenolic foam roof insulation is reported to be the first plastic foam to obtain a Class 1 rating for an insulated steel roof deck construction.

## 4.2.6 Fibers

### 4.2.6.1 Natural Fibers

#### 4.2.6.1.1 Cotton

Cotton is essentially cellulose, which is rich in moderately reactive hydroxyl groups and will burn under a wide variety of conditions. Cotton in the form of fiber, yarn, or fabric can be treated with fire retardants in order to reduce its flammability. Metal oxides and organophosphorus compounds currently are the successful potentially acceptable, durable fire retardants for cotton and rayon fabrics.

#### 4.2.6.1.2 Wool Fibers

Wool textiles generally are less flammable than cellulose and are used extensively in carpeting and seat covers. High concentrations of hydrogen cyanide have been found in the pyrolytic off gases from wool products. Fire-retardant methods

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for wool have not been studied as extensively as those for cotton, but, generally, the flammability of wool is decreased by treatment with organophosphorus compounds or specific salts of polyvalent metals.

### 4.2.6.2 Commodity Synthetic Fibers

Synthetic fibers represent the "commodity" items of the textile industry and are produced in larger total volumes than cotton and wool combined. Such fibers include rayon, acetate, nylon, polyester, olefin, and acrylic. No fibers in this group can be considered to offer protection against direct exposure to flame.

Blended fabrics made of yarns containing two or more fibers of different chemical composition and properties have attained great commercial importance in textile markets. Fiber blends pose synergistic fire hazards that often lead to unexpected flammability characteristics (e.g., the inclusion of even small amounts of cotton in a polyester fiber garment can lead to a severe flammability hazard because the nonfusible cotton prevents dripping of the fusible polyester, thus increasing the fuel available for burning).

#### 4.2.6.2.1 Specialty Synthetic Fibers

Fibers formed from higher-melting-point or nonmelting polymers with a significant aromatic or heterocyclic ring content resist ignition, do not spread flame, and, in garments, offer a wearer protection for a brief period against injury by direct flame impingement.

The available fibers with these properties are Nomex (poly-[m-phenylene isophthalamide]) and Kevlar (poly [p-phenylene terephthalamide]). A polybenzimidazole (PBI) fiber, that offers the wearer protection against flame impingement is available in developmental quantities.

#### 4.2.6.3 Inorganic Fibers

Inorganic fibers are important for some end uses. Glass fibers, for example, melt at about 515°C and do not burn. However, they generally are treated with organic finishes to enhance their resistance to abrasion and to improve other functional properties. The flammability hazard of glass fibers in actual use, therefore, is significantly modified by the presence of these organic materials.

### 4.2.7 Fire-Retardant Coatings

The use of fire-retardant coatings is one of the oldest methods for protecting flammable and nonflammable substrates from reaching ignition or softening temperatures. Fire-retardant coatings are either intumescent or non-intumescent. Fire-retardant coatings are particularly useful in reducing the flame spread characteristics of almost any type of organic substrate. The fire-retardant coatings should be formulated so as not to sustain combustion. However, substrates that thermolyze to yield flammable vapors cannot be protected by coatings in the event of a fully developed fire.

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### 4.2.7.1 Alkyd Coatings

The non-intumescent, fire-retardant coatings with the largest sales are based on chlorinated alkyds predominantly prepared from chlorendic anhydride or tetrachlorophthalic anhydride. By using the proper chlorinated acids, coatings that have properties comparable to those of conventional coatings and that are also fire retardant can be made.

Fire-retardant additives also are commonly added to alkyd resins. Halogenated additives such as chlorinated paraffins are most commonly used in these coatings because of their low cost. Antimony oxide is the most commonly used synergist in these applications.

### 4.2.7.2 Intumescent Coatings

Intumescence is defined as "an enlarging, swelling, or bubbling up (as under the action of heat)." Intumescent coatings are used to protect flammable substrates such as wood and plastics from reaching ignition temperatures. They also protect nonflammable substrates, such as metals, by preventing them from reaching softening or melting temperatures.

Conventional intumescent coatings contain several ingredients that are necessary to bring about the intumescent action: (1) a catalyst that triggers the first of several chemical reactions in the coating film, (2) a carbonific compound that reacts with the catalyst to form a carbon residue, (3) a spumific compound that decomposes producing large quantities of gas which cause the carbonaceous char to foam into a protective layer, and (4) a resin binder that forms a skin over the foam and keeps the trapped gases from escaping. Apart from these key ingredients, intumescent coatings also may include many other ingredients used in conventional coatings (e.g., pigments, driers, leveling agents, and thinners).

Nonconventional intumescent coatings are those in which the elements of intumescence are built into the resin itself. (See Volume 1, Section 8.4). For example, a clear intumescent epoxy coating has been prepared by the reaction of triphenyl phosphite with an epoxy resin prepared from epichlorohydrin and bisphenol A. The coating is prepared by adding the amine catalyst to the premixed epoxy-(triphenyl phosphite) resin just before it is applied. The coating consists of 100 percent solids.

## 4.3 Specific Usage of Polymeric Materials in Mines

As mentioned earlier, wood used as structural timber is the largest volume of polymeric material used in underground mines. Its application and fire safety characteristics have been discussed in Section 4.2.1 and will not be repeated here.

Coal also is considered to be a natural polymeric material and, of course, it constitutes the substance and the product of all coal mines. It is flammable and subject to very rapid combustion. Coal dust, freely generated in mining, is not only easy to ignite but can also form an explosive mixture with air. However, since the

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presence of coal is unavoidable in coal mines, it does not constitute a subject for *material selection*. For these reasons, coal is not discussed in Volume 1 or in this chapter; however, its fire safety aspects are dealt with elsewhere in this volume.

### 4.3.1 Ventilation Cloth

Brattice cloth is used to block selected passageways in order to direct increased air into the working face or to serve as seals for emergency ventilation procedures (e.g., in the event of fire or other mine disaster). It may be used in the form of a curtain, an air bag, or a parachute anchored to the mine roadway, ceiling, or walls. Typically, the brattice cloth has been made of jute, cotton, nylon, polyester reinforced PVC, or neoprene. Fire-retardant variants are used.

Murphy (1972) has compiled data illustrating that performance in a large-scale trial in an experimental mine correlates well with the flame spread index determined using ASTM Method E-162 and that a flame spread index of 25 or less is reasonably safe for ventilation cloth. Fire-retarded versions of jute, cotton, and polyvinyl chloride film and woven glass cloth used in the mine experiment had flame spread index values of less than 25 and flame propagation of not more than 5 fpm at 400 fpm air velocities.

If for some reason superior performance is required, Nomex<sup>®</sup>, Kevlar<sup>®</sup>, or PBI fabrics should be considered. Nylon or polyester fabrics would provide excellent wear properties, but it is not certain whether available flame-retardant formulations will meet the stringent coal mine safety requirements.

### 4.3.2 Conveyor Belts

Frictional heating of conveyor belts is the cause of about 8 percent of reported fires, and when a belt ignites, it may conduct the fire over great distances. Controlling this hazard by proper materials selection and by improved operating procedures has been reasonably successful.

A conveyor belt consists of a conveying cover, a carcass, and a bottom or pulley cover. It is constructed of elastomers (natural or synthetic rubber, polyvinyl chloride, or neoprene), fabric (cotton, glass, asbestos, nylon, polyester, rayon), fiber cord (cotton, nylon, rayon, polyester), and wire cord (brass or zinc-coated steel). The elastomer is used for the top and bottom covers of the belting and for bonding together the fabric and cords. The Rubber Manufacturer's Association tabulation of elastomers most commonly used in belting is reproduced in Table 1; other less common materials are listed in Table 2. Examination indicates that neoprene will best meet fire safety and general performance requirements in mine applications; polyvinyl chloride is a second choice. Selection will be dictated by economics.

Once an appropriate elastomer is chosen, the fiber to be used in the cord or fabric can be selected considering required strength, durability, humidity, and temperature exposure as well as cost factors. Evidence indicates that the fiber plays a secondary role in fire safety performance; however, one must remember that a

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*Table 1. Rubbers Most Commonly Used in Belting.*

ASTM Designation D1418-71A	Common Name	Composition	General Properties
CR	Neoprene	Chloroprene	Good ozone and sun-checking resistance, good resistance to petroleum based oils and to abrasion. Also good flame resistance. Used extensively underground in mine conveyor belts due to its flame-resistance characteristic.
NR	Natural	Isoprene, Natural	Excellent resistance to cutting, gouging, and abrasion. Good elasticity and resiliency. Not oil resistant.
IR	Polyisoprene	Isoprene, synthetic	Same properties as natural.
IIR	Butyl	Isobutylene- Isoprene	Excellent resistance to heat. Very good resistance to ozone and aging. Good resistance to abrasion. Not oil resistant.
NBR	Buna N	Nitrile Butadiene	Excellent resistance to vegetable, animal and petroleum oils.
SBR	SBR	Styrene- Butadiene	Excellent abrasion resistance and good resistance to cutting, gouging and tearing. Good heat resistance. Not oil resistant.
BR	Polybutadiene	Polybutadiene	A synthetic rubber in the general purpose field. Can be used alone or in blends with Natural or Styrene-Butadiene Rubber. Has excellent abrasion resistance and high resiliency, and excellent low temperature resistance.

NOTE: Adapted from Rubber Manufacturers' Association, 1973

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*Table 2. Other Synthetic Rubberlike Materials Used in Belting.*

ASTM Designation	Common Name	Composition	General Properties
FMQ	Silicone	Modified-Polysiloxanes	Excellent high and low temperature resistance. Can be made to give fair oil resistance. Poor physical properties at room temperatures.
CSM	Hypalon	Chloro-Sulfonyl-Polyethylene	Excellent ozone, weathering and acid resistance. Good abrasion and heat resistance. Fair oil resistance.
ABR	Acrylic	Acrylate-butadiene	Excellent for high temperature oil and air. Poor water resistance. Poor cold flow.
CIIR BIIR	Chlorinated and Brominated Butyl	Chlorinated or Brominated Isobutylene-Isoprene	Same general properties as Butyl except it can be adhered to or used in combination with other polymers.
AFMU	Teflon Kei-F	Tetrafluoroethylene resin	Excellent high temperature properties, chemical resistance and physical properties.
PVC	Vinyl	Polyvinyl Chloride resins	A thermoplastic material which has very good abrasion. Excellent flame resistance. Also has good resistance to animal and vegetable oils. Limited temperature range.
AU EU	Urethane	Polyester Polyether	Exceptional abrasion, cut and tear resistance.
EPM	Ethylene Propylene Rubber	Ethylene-Propylene	A general purpose synthetic which has good aging, abrasion and heat resistance.
EPDM	Ethylene Propylene Rubber	Ethylene-propylene-diene-Terpolymer	Same as EPM.
CO	Hydrin	Polychloromethyl Oxirane	Excellent oil and ozone resistance. Good flame resistance and low permeability to gases. Fair low temperature properties.
ECO	Hydrin	Ethylene Oxide and Chloromethyl Oxirane	Excellent oil and ozone resistance. Fair flame resistance and low permeability to gases. Good low temperature properties.

NOTE: Adapted from Rubber Manufacturers' Association, 1973

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thermoplastic fiber in a thermoplastic elastomer belt might melt and separate in the event of slippage and excessive pulley friction and, thus, avoid a friction-induced fire incident. Thermoplastic fibers for this purpose are either nylon or polyester; the thermoplastic elastomer for this application is polyvinyl chloride.

When using PVC, a plasticizer generally is required. Given the choice of phthalate ester or phosphate ester plasticizers, the former increases the flammability hazard whereas the phosphate esters reduce the fire hazard.

The U. S. Bureau of Mines has developed a set of requirements, designated Part 18, under which belts must pass two tests: one to measure flame propagation after direct flame ignition and the other to measure resistance to drum friction ignition. In current work at Factory Mutual Research Corporation (1976), attempts are being made to conduct belt fire tests in a full-scale simulated mine gallery where ceiling radiation effects enter the situation.

### 4.3.3 Electrical Conductor Insulation

The problem of fire safety of electrical conductor insulation in mines is essentially the same one faced by electric utilities and in naval vessels, industrial installations, and all types of buildings. Polyvinyl chloride has been the principal resin used for almost all applications since about 1938. Above 600 volt ratings, PVC generally is not used; rubber, neoprene or cross-linked polyolefins are employed.

Cross-linked polyolefins are employed in about 5 percent of installations because the flammability codes or the design engineers specify cross-linked products to improve protection against overloads and hot ambients or surges. These materials must pass the horizontal flame test specified by Underwriters Laboratories, Inc., in UL 44, Paragraph 3.0.

Large industrial complexes and utilities use cross-linked polyolefins as insulation in armored cables that are used exclusively for power distribution circuits. The armored cable provides improved crush resistance. When high reliability is required in the presence of high temperatures or high current density, higher cost materials can be justified. These materials must pass the horizontal test specified in UL 44, Paragraph 3.0, but the vertical test, FR-1, specified in UL 44, Paragraph 74, is optional. Nonarmored (hypalon-jacketed or neoprene-jacketed) constructions are used for control circuits. PVC is used in about 75 percent of these applications (UL 83, Paragraph 74). However, once again, cross-linked polymers (UL 44, Paragraph 74) are installed for higher reliability.

Silicone insulation is used in such places as steel mills where conductor temperatures above 90°C are found. Silicone rubber also is used to justify a higher temperature of operation in the rewiring of old buildings where space is limited. This insulation is required to pass the horizontal flame test specified in UL 44, Paragraph 3.0, and, in some instances, the vertical flame test FR-1 specified in UL 44, Paragraph 74.

The insulation used in electric generating stations must pass the vertical flame

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test FR-1 specified in UL 44, Paragraph 74, and the vertical tray test specified in Institute of Electrical and Electronic Engineers (IEEE) 383. Ethylene-propylene rubber (EPR) or cross-linked polyolefins with hypalon or neoprene jackets are used in fossil fuel power stations, and EPR or cross-linked polyolefins containing halogenated additives with hypalon or neoprene jackets are used in nuclear installations. Thermoplastic fluoropolymers are beginning to find increased use in nuclear power plants.

Cables frequently are grouped (e.g., in trays or conduits) in large facilities such as industrial plants, hospitals, commercial establishments, and electric generating stations and often are almost inaccessible. A fire under these circumstances can lead to loss of power, dense smoke, destruction of considerable length of cable, etc. Many of the standard flammability tests are performed on single insulated conductors. The practice of grouping cables does present a serious fire hazard. (The relatively recent fire at a New York City telephone exchange has served to emphasize the hazard of vertical and grouped cableways and the flammability of PVC insulation in an actual fire.) In the field, the conditions for flame propagation are very different when cables with flame-retardant insulation or covering are installed in large numbers. Some safeguards include installation of automatic sprinklers, smoke detectors, use of improved flameproof coverings, and an automatic carbon dioxide flooding system.

Newman (1976) has shown that PVC conduit or nonmetallic sheathed cable exposed to fire evolved enough HCl to affect human escape potential from a building. Under the same conditions, wiring systems using steel raceways would not adversely affect escape potential.

### 4.3.4 Sealants

Mine tunnel walls and ceilings generally are composed of easily degradable shale, and sealants are required to protect them from the effects of air, moisture, and mechanical abrasion and to control methane diffusion and generation. A sealant that also serves as a thermal insulation is desirable. Ease of application over irregular and wet surfaces, rapid curetime, and mechanical toughness are additional requirements.

Urethane foam appeared to meet all these requirements and its acceptance was rapid. However, fire and toxicity hazards soon became apparent, and the use of urethane foam as a sealant in mines now is essentially prohibited.

Replacements for urethane foam are the subject of ongoing investigations. Sprayed fibrous reinforced cement is one possible solution, and sprayed water-base epoxy sealant also may be effective (Franklin et al. 1977). Sodium silicate is effective on sandstone walls.

Coatings to protect existing polyurethane sealant installations also are being sought. Warner (1975) reports that, in a full-scale gallery test, concrete with steel fibers was an effective fire-inhibiting coating over an existing urethane installation.

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### 4.3.5 Hydrocarbon Fuels

Gasoline is not used in U.S. underground mines, but diesel fuel traditionally has been used in metal and nonmetal mines to power locomotives, shuttle cars, bulldozers, loading machines, and other equipment. The use of diesel oil in coal mines in similar applications is fairly recent; therefore, fire and accident statistics are meager. It is expected, however, that the fire safety performance of diesel oil in underground mines should somewhat parallel that of hydraulic fluids. Gas welding equipment (e.g., oxygen-acetylene welders) is commonly used in mines, but special precautions are taken both before and during welding operations.

### 4.4 Conclusions and Recommendations

*Conclusion:* Materials flammability hazards are of great concern in coal and mineral mines because of the limited access and egress routes, the need for forced ventilation, and the ever present energetic ignition sources. If adequate attention is paid to access routes, compartmentalization, and smoke ventilation systems during design of bunkers, materials selection problems are the same as in other buildings with comparable occupancies.

*Conclusion:* In selecting polymeric materials with improved fire safety characteristics, competing functional, economic, and safety requirements must be reconciled.

*Conclusion:* Wood represents the largest volume of polymeric material used in mines. It ignites more readily than coal and it rots readily in a mine environment. It may be that rotted wood is a greater fire hazard. *Recommendation:* Research to find a practical method for controlling the ease of ignition and flame spread of mine timbers should be continued. The method of precharring wood to a depth of 2 mm to reduce flammability should be evaluated in a full-scale trial.

*Conclusion:* The ventilation cloth used to direct air currents during normal working and emergency conditions can contribute to the fire safety hazard by igniting easily and spreading flame rapidly. *Recommendation:* The tentative guideline specifying that ventilation cloth exhibit a flame spread rating of less than 25 in ASTM Method E-162 should be continued until evidence indicates that it is not sufficient. Fibers (e.g., Nomex® or PBI) that can out-perform any now used for ventilation cloth are available and under development.

*Conclusion:* Conveyor belts are a frequent source of fires because of friction against pulleys and accumulated spillage of conveyed materials. The use of neoprene or plasticized PVC in belts has improved their fire safety. *Recommendation:* Phosphate ester plasticizers should be used instead of phthalate esters to fire retard PVC, provided that the phosphate plasticizer does not increase toxic smoke generation.

*Conclusion:* The flammability and smoke toxicity problems caused by electrical conductor insulation in mines are the same as those confronted in utility applications, industrial installations, and aboard ships in that PVC cables in grouped cableways will burn, spread flame, and emit toxic hydrogen chloride vapor. *Recom-*

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*mentation:* The present requirements for cable flammability performance should be increased.

*Conclusion:* A practical replacement is needed for polyurethane foam as a sealant for mine tunnel walls and ceilings. The presently preferred sprayed steel fiber reinforced concrete is effective but its application is cumbersome. *Recommendation:* More convenient methods for applying the sprayed fiber reinforced concrete should be sought, and aqueous emulsions of cross linkable thermoset resins that can be used to seal mine tunnel walls and ceiling should be developed.

### 4.5 References

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## CHAPTER 5

### DESIGN CRITERIA IN MINE SAFETY AND HAZARD CONTROL

#### 5.1 Introduction

(Secretary of the Interior, 1974; Nagy and Hall 1974; Chaiken and Burgess 1977; and Mitchell and Verakis, 1975.)

Resources extracted from the earth by mining have long been essential to mankind. Mining, even in its crudest form, provided materials for implements, weapons, jewelry, and coins. As societies grew more sophisticated and complex, the products of mining became even more important and contributed immeasurably to the development of systems for transportation, communications, electric power generation, heating, construction, industrial production, defense, and agriculture.

Mining today is a large-scale industrial activity involving the use of heavy electric-powered machinery (i.e., sophisticated high-productivity mining machines, extensive rolling and conveying transportation equipment, hoists, and large ventilation systems). All of this factory-like activity, however, occurs in a highly hostile environment. Surface mines are subject to falls and other dangers, but underground mines are more hazardous. Access and egress routes must be excavated and maintained in a structurally safe condition; electricity must be conducted into the mines to power lights and all production and transportation equipment; artificial ventilation must be maintained to provide sufficient oxygen for personnel and, often, to dilute toxic gases and combustible dust and gas; and structural integrity must be maintained to prevent collapse, to seal walls against abrasion, and to prevent water or gas seepage into the mines.

The layout of a mine, unlike any other industrial facility, changes continuously as mine development (i.e., production) progresses. This requires that power lines be extended, ventilation systems altered, and critical materials and supplies be relocated; it requires a continual lengthening of access, egress, and transportation routes. In addition, exhausted mine areas, which represent potential reservoirs for water or gas accumulation as well as alternate escape or ventilation routes, are subject to structural failures and must be maintained.

Advanced design criteria are needed to eliminate or reduce the hazards in mines, and the development of such criteria is the subject of this chapter. (Efforts to control mine safety and hazards through legislation are described in Appendix B.)

#### 5.2 Approaches to Design Criteria Development

The traditional approach to mine safety and hazard control has been frag-

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mented. As hazards were discovered during post-fire or explosion investigations, the problems were corrected, but little thought was given to the interaction between the elements (i.e., each material and each piece of production and transportation equipment used in a mine was considered as a separate fire or safety hazard).

A more sophisticated method for dealing with mine safety and hazard control is the systems approach. When applying this approach, the entire mining operation including all equipment used is considered to be one system. The effect of each component on the whole system is examined and alternate pieces of equipment or materials are evaluated on the same basis.

One way of utilizing the systems approach is to develop fire scenarios like those described in Chapter 3 to examine the effect of the incident on the whole system and to assess the probable impact of alternate materials or equipment on the development and outcome of the incident. The decision tree described by Roux (1977) is a valuable tool for applying the systems approach as is computer modeling, which permits rapid evaluation of a great number of alternates.

To utilize the systems approach in developing new design criteria for mines, the contents of the mine system must be considered in relation to fire processes, and the mine system may be viewed as consisting of:

1. Fuels — gases and dust; structural lumber or other materials; combustible components of production equipment, conveyor systems, transportation equipment, conduits, electrical distribution systems, and ventilation systems (including insulation materials, hydraulic hoses and fluid, conveyor belts, ventilation cloth, etc.); sealants, stoppings, and barrier materials; wall surfaces and mine products; materials and equipment worn or carried by personnel; and stored materials and supplies.
2. Ignition sources — sources of spontaneous ignition; potential sources of arcs and sparks in all employed equipment; potential sources of electrical overheating in equipment; potential sources of mechanical (frictional) overheating in equipment; and applied sources of flame or arc (welding, brazing, smoking, etc.).
3. Fire propagation potential — mine layout and natural drafts; ventilation effect; forced drafts and their routing and available alternates; air velocity and quality, effect of potential fire on combustible gas development; modification of draft effects and air quality considering available fuels and their location; available alternates for ventilation routing and air velocity and its effect on fire propagation; potential effect of fire on structural integrity and collapse potential; and effect of structural modification on fire propagation (evolution of combustible gases alteration of draft effects, and accessibility for vent modification).
4. Fire detection and suppression systems — number, quality, and location of portable and permanent (local and remote) fire detection sensors (temperature probes, gas analyzers, particulate detectors, etc.); number, quality, and

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location of fire suppression devices, equipment, and materials (installed on face cutter, transportation equipment, sprinklers, portable and stationary equipment, rock dust piles, etc.); number, availability, and quality of trained firefighting personnel, maintenance crew members, and miners; extent and quality of communications systems; extent and quality of fire disaster plans and models; and availability and quality of enforcing authority.

The complete application of the systems approach in developing design criteria that provide for mine safety and hazard control requires a greater understanding of fire dynamics and related processes than is possible today. For example, the seaworthiness of a damaged ship can be ascertained quickly, and the effect of corrective actions (e.g., flooding selected compartments) can be investigated rapidly using a scale model. Similarly, alternative mine ventilation patterns for use during a fire could be investigated using mathematical and computerized models, but several of the input parameters have not yet been established. One- and two-dimensional models of ventilation-throttling developing in a mine fire situation have been used and they provide a valuable starting point. However, it appears that a full three-dimensional model is required and the development of such a model will be extremely complicated, difficult, and expensive. Several aspects of fire propagation mechanisms also are poorly understood. The most reasonable way of investigating these areas appears to be through experimentation at various scales. Such programs now are under way, but scaling factors have not yet been established to provide even empirical means of approximation. These research programs also are expensive and further work is needed.

Thus, although the objectives of mine design criteria have been brought into focus and the approach to criteria development is well delineated, the means to achieve the goals are not yet available. The following discussion does not pretend to be all inclusive but rather attempts to present a broad overview of the state of the art and of recent developments in the most important areas of mine safety hazard control. Considered are fuels; ignition sources; and fire detection, ignition quenching, and composite systems. Some topics are discussed in greater detail than others primarily for purposes of illustration.

### **5.3 Belt Conveyors**

**(Diamond, 1960; Nutter, 1977; Harstein and Forshey, 1976; Kuchla, 1978)**

The belt conveyor was introduced as a means of underground mine transportation in Great Britain at the turn of the century and was adopted by the U.S. coal mining industry in the early 1920's. Initially considered to be an experimental curiosity, the device gained popularity rapidly because of the cost savings and improved operational efficiency its use made possible.

Belts, however, can cause ignition and contribute to fire spread. They are made of combustible polymeric materials and their drive system tends to overheat when mechanical components malfunction. Belt conveyors are installed along relatively

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long horizontal distances and often on the air intake side of ventilation systems.

Belt conveyors are used extensively today in mines all over the world, and it is estimated that 24 million linear feet of belting was in service in 1977 in U.S. underground coal mines alone. Statistics show that between 1952 and 1969 at least 15 percent (134 out of 877) of reported coal mine fires in the United States were attributable to conveyor belt ignition, and 70 percent of these belt fires were caused by frictional heating (e.g., involving a stuck roller or snarled belt in the belt drive assembly).

Extensive efforts have been made to provide safer belt conveying systems: in-depth investigations have been conducted to define the problems; fire-resistant belting has been developed; small- and large-scale combustion experiments have been performed; and a large number of safety regulations have been established. These efforts have resulted in a drastic reduction in belt fires (i.e., to an average of less than two per year between 1970 and 1977), but the increasing use of these systems and the potential fire and toxic hazard dictate that additional development work be undertaken. Particularly needed are improved flammability and flame spread tests, an evaluation of the toxicity of belt combustion products, and improved fire detection and suppression systems.

### 5.3.1 Description

Conveyor belts generally consist of three elements: a top or conveying cover, a carcass, and a bottom or pulley cover. The carcass is usually a textile fabric woven of one or a combination of the following: cotton, glass, asbestos, nylon, polyester, rayon, other fiber yarns, and wire cords or cable (usually brass- or zinc-coated steel). The top and bottom covers usually are made of thermosetting or thermoplastic elastomer, which also is used to bind together the various components of the belt carcass (e.g., the plies or layers of fabric and/or cords of natural or synthetic fibers and steel).

A fiber or yarn is selected for use in a textile cord on the basis of its physical properties (i.e., strength, elongation, aging, dynamic fatigue resistance, adhesion characteristics, mildew resistance, heat resistance, and other properties). In fabrication, very small fibers are twisted together to form "singles," two or more "singles" are twisted together to form "plies," and two or more "plies" form a "cable." Synthetic yarns are produced by extrusion or by slitting extruded or blown film. Yarn sizes are denoted by numbers (Hank) in the American system depending on the material (i.e., cotton, asbestos, glass, etc.). Continuous filament synthetic fibers are measured by "deniers" (grams per 9000 meters of yarn) or by the new, universal "tex number" (grams per 1000 meters of yarn).

Fabric is woven from warp yarns, which run lengthwise, and filling yarns, which run crosswise. The properties of the fabric depend upon its construction, the material from which it was made, and the type of weave. The most common weaving patterns are plain, twist, basket, and leno. Modifications of these weave patterns are

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produced by using a warp yarn that is stronger than the filling yarn. Fabrics made in this way often are used for the belt carcass and include the woven cord, solid woven, and straight warp weave.

Materials used for the top and bottom cover of mine conveyor belting are SBR rubber, neoprene rubber, and PVC. The manufacturing methods used for rubber belting are more complex and expensive than those used for PVC belting. Many types of rubber are available and they can be blended and mixed with various chemicals to produce required physical properties. They are compounded, pre-formed into sheets, and cured (chemically cross-linked) on flat or rotary presses. PVC belting is made essentially of PVC homopolymer and a phthalate ester or other plasticizer. Manufacturing methods consist of relatively simple continuous coating operations. It is generally conceded that rubber belting is more abrasion resistant than the PVC type (especially to mixtures with a high rock content); however, total life cost and initial cost may be traded off between the two types.

A recent investigation (Hartstein and Forshey 1976) reports that SBR rubber belting exhibits good flame resistance and is less hazardous than neoprene or PVC belting in terms of toxic combustion products. Manufacturers of PVC belting (Nutter 1977), on the other hand contend that: (1) thermoplastic PVC belt will melt and separate when exposed to excessive frictional heat (thus preventing it from acting as a source of ignition), (2) PVC is inherently flame resistant, and (3) properly chosen formulations of PVC with flame-retardant additive will minimize the spread of an externally produced fire and the formation of hydrogen chloride vapor.

Most U. S. coal companies use a combination of PVC and rubber belting with rubber being used more on the main lines and PVC, on panel and butt entries. According to Nutter (1977), approximately 8 million of the 24 million linear feet of belting in use in underground coal mines is the PVC type.

### 5.3.2 History of Hazard Control

Following World War II, rubber conveyor belts gained rapid acceptance in British coal mines because of their contribution to improved operation efficiency. In September 1950, however, a disastrous fire occurred in the Creswell Colliery in England and 80 men lost their lives. This disaster was caused by a stalled rubber belt that ignited and helped the fire to spread at speeds estimated at 100 yards per hour. Following this disaster, the National Coal Board directed all belt manufacturers in Great Britain to proceed immediately with the development and production of a fire-resistant belt. The National Coal Board also established specifications for the acceptance of fire-resistant conveyor belting, and these included a mandatory drum friction test. This test, as currently used in England, is more severe than the International Standards Organization (ISO) or the European standard drum friction test.

The U. S. Bureau of Mines, in response to the Creswell incident, also established a set of requirements, designated Schedule 28, under which conveyor belts have

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been qualified for use since November 1955. Two tests are required – one to measure flame propagation and the other, ignition. A drum friction test to qualify belts for use in underground mines has not yet been adopted in the United States in spite of the overseas experience and recommendations of PVC belt manufacturers.

Early British work to develop fire-resistant belting involved treating the duck to render it fireproof or fire resistant and substituting a fire-resistant material (e.g., neoprene or PVC) for the rubber in the belt. Since the chemicals used to fireproof the fabric adversely affected the properties of the carcass, efforts were concentrated on finding the proper fire-resistant material for the belting itself. Neoprene was not manufactured in England and was considerably more expensive than PVC; therefore, the latter material was preferred and was the first to be approved for use in coal mines operated by the National Coal Board. The same type of PVC belting, which was supported by a nylon woven carcass, was introduced in U.S. mines in the mid-1950's. Early samples appeared to be flimsy and rapidly developed "edge wear", but they also exhibited good abrasion resistance and other advantages in actual use. The neoprene belting then available exhibited poor adhesion of cover to fabric, developed considerable gouging and stripping, and was significantly more expensive.

Since the 1950's healthy competition has developed between manufacturers of rubber and PVC conveyor belts and has resulted in great improvements in belt properties, price, and fire safety. This competition is stimulated both by the ever-expanding market and by the increasing stringency of government regulations.

The number of belt-related mine fires has been reduced drastically in the United States during the past two decades. This is attributed to the development and use of flame-resistant belting, as specified by state and federal regulations, and other belt-related directives. In England, there has been no reported belt ignitions due to frictional heat buildup since PVC belts were introduced.

### 5.3.3 Current Research and Future Trends

Current and projected efforts to improve conveyor belt system design criteria are focused on advancing understanding of the basic fire processes (including generation of toxic gases); developing improved tests of flammability, flame spread, and frictional heating behavior, and designing sophisticated detection and suppression systems.

### 5.3.4 Fire Tests

The Federal Schedule 28 test designated to determine the fire resistance of coal mine conveyor belts is considered of questionable reliability. This test is performed on a small sample ignited in a chamber with a Bunsen burner and the duration of combustion is noted at a single, fixed air velocity. Recent larger scale experiments indicate that the results of this test are not sufficiently conservative since frictional heating behavior and toxicity of evolved gases are not considered. The U.S. Bureau

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of Mines is conducting in-house and contracted experimental programs to ascertain the facts.

In one investigation (Harstein and Forshey 1976), the thermal oxidative decomposition products of the basic belt materials and some of their pure ingredients were analysed in great detail. These data provide a valuable starting point, but a greater number of samples and pure ingredients must be assessed under a much greater variety of conditions (temperature, air velocity, oxygen content, etc.). Such work is now in progress.

Medium- and large-scale laboratory fire test programs have been and are being conducted to study the behavior of conveyor belt systems. Belts made of SBR rubber, neoprene, PVC, and natural rubber compounds in combination with nylon, rayon, and cotton carcass material have been tested for flammability using various intensities and sources of ignition and air velocity conditions. The ability to sustain flame propagation and the effects of preheating, belt width, and coal dust-grease accumulations also have been evaluated.

Full-scale fire tests have confirmed some of the laboratory-scale results and trends, and the inadequacy of the existing fire retardancy acceptance test has been demonstrated further. In these experiments, temperature profile versus duct length and time from ignition were studied to shed further light on fire-related phenomena.

In 1978, experiments were under way using full-scale "fire test galleries" having various configurations and slopes, and belts were being tested under various mine fire conditions by varying belt width, air velocity, burning angle, preheating time, ignition heat flux, and coal dust-grease accumulation. Belt fire resistance is determined from measurements of flame spread rate, propagation distance, gallery temperature, and the heat flux at various sections. The results of these tests will be used to develop a more reliable and meaningful laboratory-scale fire-retardance test method that includes a quantitative rating system. The full-scale tests also are utilized to assess the toxic gas formation characteristics of the various belt materials. These results will be compared with the laboratory-scale oxidative thermal decomposition studies mentioned above.

Initial results of the gallery tests indicate that the most important variables are air ventilation rate, ignition heat flux, and distance between the belt and the roof of the simulated mine entry. This information is being used to design the prototype of a laboratory-scale fire-resistance test for conveyor belts.

### 5.3.5 Fire Warning Systems

Existing regulations require that a fire sensor system be installed at each coal mine belt conveyor to stop the belt drive and activate alarms when a belt fire occurs. The sensitivity, response, and durability of the various types of sensor and optimum sensor spacing have been of concern in the past.

In a recent comparison of the various sensors and their characteristics, it was

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found that the thermal point and thermal continuous types are most suitable for mine conveyor belt applications. They exhibited adequate sensitivity for early detection and sufficient durability for the environment and relatively economical. Response time, temperature range setting, and recommended spacing also were established.

Combustion detectors (photo-electric and ionization types) are highly sensitive, but they are not reliable in dust-laden air. They also are susceptible to false activation by combustion products originating in areas other than belt haulageways. The same limitation applies to carbon monoxide detectors. Optical type detectors (UV and IR) also are sensitive, but their effective range is limited and sensitivity to extraneous light sources presents additional problems.

Future developments in this area, aside from technical refinement of the instruments, must be directed toward the systems approach to design. For example, the continuous monitoring of the entire mine with a "tube bundle" detection system will allow measurement of the differential of air quality between belt haulageways and surrounding areas; therefore, the use of the more sensitive combustion detectors eventually may be preferred for this advanced design configuration.

### 5.3.6 Suppression of Conveyor Belt Fires

Existing regulations require that automatic fire extinguishing systems (sprinkler or deluge type) be installed at coal mine belt conveyor drives in accordance with specified belt areas and water flow rates and supplies. Provisions are made for use of alternative foam or dry powder chemical systems, including specifications for such systems. The gallery experiments described above were utilized to evaluate the efficiency of the various suppression and detection systems in a simulated belt haulageway with various belts and under a variety of fire conditions. The adequacy of pertinent regulations also was assessed.

Automatic water sprinklers with self-contained actuators were found to be reliable and economical and to require little maintenance. The importance of sprinkler spacing was determined and the effects of water pressure, detection temperature, and spray density were evaluated. The primary disadvantage of such sprinkler systems is their failure when the contents freeze — a possible contingency near the earth's surface.

High expansion foam systems provide rapid fire suppression with low water requirements but maintenance requirements were high, delivery rates were slow, and gaps developed at the haulageway roof because of ventilation effects. The foam systems also are prone to failure at freezing temperatures.

Fire suppression systems employing multipurpose dry powder chemicals worked rapidly, required a relatively small amount of chemical, and operated at low temperatures. The disadvantages of such systems are that individual design is required to provide proper powder dispersion, maintenance requirements are high, and cooling capacity is small (creating the potential for re-ignition).

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The initial results of these tests confirmed the adequacy of existing regulations and provided additional knowledge concerning the operation and applications of the various systems. A more comprehensive conclusion concerning what methods to use in particular situations and how to integrate these in an overall system design remains to be developed.

### 5.4 Wire and Cable Insulation (Taylor 1977)

In mine fires, wire and cable insulation frequently has been the first material ignited by such sources as an overheated conductor or electric spark. The burning insulation often ignited secondary fuels, smoke and toxic fumes were generated as it decomposed, and the conductor was exposed in an uninsulated form. Examination of wire and cable insulation as a potential fire, fume, and toxic hazard is therefore an important design consideration. Although wire insulation fires have long been of concern to the mining industry, uniform criteria and test methods have been lacking.

A program recently initiated by the Department of Transportation (Taylor 1977) is aimed at establishing criteria for test methods; developing standard tests for flammability, smoke emission, toxicity, and integrity; and applying these tests to wire and cable insulating materials presently in use and to the newer polymeric materials being proposed. Although this study is being conducted primarily for the rapid transit industry, its results should provide valuable data to the mining industry, as well as all others, since rapid transit tunnel and mine requirements for electrical power and large equipment in confined spaces are very similar. The results, however, will have a low probability of application to trailing cables, which are reported to rank high among causes of mine fires.

The intermediate results and conclusions of this program are presented below.

#### 5.4.1 Test Program

In July 1976, the Department of Transportation (DOT) awarded a contract for the study of electrical insulation. The stated objective of this contract is:

to determine whether any of the currently used electrical insulations can provide a fire safe environment in terms of very low flame propagation, smoke and toxic gas evolution . . . and determine whether any of these can meet criteria which will be established by taking into account the fire hazards inherent in transit systems. This study is directly applicable to wire insulation used in mines.

Although the portion of the (DOT) study dealing with test method development is outside the scope of this chapter, it should be mentioned that criteria were developed for the desired test methods and that all existing test procedures were evaluated. Some test procedures were modified or new ones developed as needed to provide meaningful standard tests for flammability, smoke emission, circuit integrity, and toxicity of wire and cable insulation materials.

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Samples of the various insulation materials and wire and cable constructions then were obtained from suppliers and subjected to the newly developed standard tests. When the committee received a report on the program (Taylor 1977), it was not complete, but interim results were available and preliminary conclusions were offered by the program manager (except for small animal toxicity which was not complete).

### 5.4.2 Test Results

The following materials and constructions were subjected to the test program:

*Single Wires (74 total samples)*

Poly(ethylene-chlorotrifluoroethylene) (Halar®) (E-CTFE)

Polyimide (Kapton®)

Mica

Silicone Rubber

Poly(fluorinated Ethylene-propylene) (Teflon®) (FEP)

Poly-tetrafluoroethylene(Teflon®) (PTFE)

Poly(ethylene-tetrafluoroethylene) (Tefzel®)(ETFE)

XL Polyethylene (PE)

XL Polyolefin

XL Polyvinylchloride (PVC)

Braids

Glass

Nomex®

*Multiconductor Cables*

Kapton® (twisted, no jacket)

Polyolefin/polyolefin jacket

Silicone rubber/silicone rubber jacket

Teflon®/Teflon® jacket

Tefzel®/Tefzel® jacket

Tefzel®/Shield/Tefzel® jacket

The flammability tests indicated that:

1. The selected test method is capable of providing repeatable test results.
2. The selected test method is capable of providing sufficient information to categorize the behavior of various insulation materials and constructions when exposed to fire.
3. The selected test method is capable of providing sufficient information to determine which materials and constructions provide a fire safe environment in terms of flammability and to rank these materials and constructions accordingly.
4. Overall, silicone rubber and polyimide (Kapton®) insulations perform best, and the performance of the basic insulation can be improved by construction features such as braids and jackets.

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The smoke emission tests revealed that:

1. The National Bureau of Standards (NBS) chamber method is a viable approach to testing electrical wire and cable insulation materials.
2. It will be possible to use the test results to categorize the smoke emission characteristics of the candidate insulation.
3. It will be possible to use the test results to rank the materials and constructions in terms of their ability to provide a fire safe environment in terms of smoke emission.
4. It will be possible to use the test results to develop standard length versus AWG size for wire and cable testing and to establish realistic acceptance criteria with respect to what is available.
5. The Teflon®, Kapton®, and mica insulations have the lowest smoke emission. As can be expected, any constructions that add other materials to the basic material decrease smoke emission performance (e.g., Kapton® alone performs better than Kapton® with Nomex® braid).

The circuit integrity tests indicated that:

1. The BIW test (BIW test = Boston Insulated Wire test. Details are available from Boston Insulated Wire and Cable Co., 65 Bay St., Boston, Mass. 02125 or in the cited article), is a practical test for measuring the integrity of single-wire insulation during and after exposure to flame.
2. It will be possible to use the test results to categorize and rank insulation materials and constructions with respect to their ability to provide a fire safe environment in terms of circuit integrity.
3. For single wires, silicone rubber provides the best circuit integrity when exposed to a fire.

Due to the interim nature of the test data, it was not possible to rank the insulations with respect to their ability to present a fire safe environment. It is intended, however, that this ranking will be done for each of the four tests of interest (i.e., flammability, smoke emission, toxic gas evaluation, and circuit integrity). It also is intended that some method will be derived to develop a combined hazard index for the insulations and constructions that will incorporate all four characteristics. The study contractor appears to recognize that, although flammability, smoke emission, and toxic gas evolution are very important factors in the selection of the insulation material for electric wire and cable for use in rapid transit vehicles, they must be put in perspective with other important characteristics such as abrasion resistance, resistance to contaminants and fluids, installation flexibility, ability to strip for termination, ability to survive mechanical stress and elongation, small bend radius, long life, and good electrical properties (e.g., high insulation resistance and high dielectric withstand voltage).

The insulation materials and constructions therefore also will be ranked in terms of these characteristics. By establishing this further ranking, it is postulated that the information made available to the rapid transit system designer will be in the most

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usable form. The mine operator also can use this information. Based on the interim data, the following preliminary conclusions were drawn:

1. Standard test methods and guidelines for electrical wire and cable insulations are needed.
2. The results of this program will be a significant step towards fulfilling the above need.
3. It has been possible to develop simple, inexpensive, repeatable tests to measure the flammability and critical circuit integrity characteristics of wire and cable.
4. The study will not be complete until the toxicity tests are completed.
5. It appears that there are insulations and constructions presently available that can provide a fire safe environment in terms of flammability, smoke emission, and circuit integrity.
6. The results of this study will provide valuable data to all industries and are not limited to rapid transit system design.
7. The results of this study must be considered with other wire and cable insulation and construction selection criteria.

### 5.5 Hydraulic Systems (Ladov and Law 1978)

Hydraulic systems have been present in underground mines ever since power equipment was introduced. With the advance of mining technology, the machinery has become more powerful and larger and the hydraulic systems have become more complex.

Hydrocarbon-based hydraulic fluid systems have long been recognized as a serious fire hazard. In many mine fires, a malfunctioning electrical ignition source ignited the hydraulic hose and hydraulic fluid directly or through the burning electric insulation. The hydraulic system then ignited a secondary or tertiary fuel, often with the aid of externally accumulated coal dust and grease, and a large-scale fire resulted.

Counter measures to eliminate or minimize this hazard involve:

1. Improved design to physically separate the electrical and hydraulic components of power machinery.
2. Improved design of hydraulic hoses and connections to render them fire resistant and leakproof.
3. Development of fire-resistant hydraulic fluids.
4. Design of self-contained fire detection and suppression systems to combat a developing hydraulic fire.

Items 1 and 2 are outside the scope of this study and Item 4, which is not unique to hydraulic systems, is discussed later in this chapter. Thus, only current research efforts dealing with the development of fire-resistant hydraulic fluids are discussed below.

The use of fire-resistant hydraulic fluids in underground mining equipment has

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increased during the past 20 years. Different countries have adopted different legislative philosophies concerning these fluids (i.e., the use of fire-resistant fluids is required in essentially all hydraulic systems used underground in the United Kingdom and is advised [as an alternate to fire-suppressant devices on unattended hydraulic systems] in the United States).

In 1975, a research program concerned with improved fire safety of coal mine hydraulic systems was initiated (Ladov and Law 1978). Its objectives are to develop design and performance criteria for fire-resistant hydraulic fluid systems for use in underground equipment in U. S. coal mines and to develop fire-resistant hydraulic fluids for use in systems meeting these criteria. Prior to initiation of the experimental portion of this program, published U.S. and foreign experience with fire-resistant hydraulic fluids was reviewed together with the cost-performance features of the various classes of available fire-resistant hydraulic fluids. Work under this program was not yet complete in early 1978; however, preliminary results are available and are summarized below.

A review of the state of the art indicated that available fire-resistant hydraulic fluids are classified by the International Standards Organization (ISO) as follows:

<i>Class</i>	<i>Description</i>
HS-A	Oil-in-water emulsions containing a maximum of 20 percent combustible material (usually containing 95 percent water)
HS-B	Water-in-oil emulsions containing a maximum of 60 percent combustible material (usually containing 40-45 percent water)
HS-C	Water-glycol solutions (usually containing at least 35 percent water)
HS-D	Water-free fluids (usually phosphate-ester-containing fluids)

It was concluded that the HS-B fluids were the most promising for possible use in underground hydraulic systems, specifically in continuous miners, shuttle cars, and roof bolters; therefore, development of advanced water-in-oil emulsions was initiated. Since the contract under which this program is being conducted specifies that fire-resistance levels not be compromised, the interrelations between physical properties of the oils, the emulsions, and their water content and the fire-resistance of the emulsions were carefully investigated. Fire-retardancy was measured by the procedures published in Federal Schedule 30 and in Factory Mutual Standard 6930.

The ensuing investigation established the target relationships and guided the development of an experimental fire-resistant hydraulic fluid, designated XRL1110. Concurrent with fluid selection, the establishment of performance criteria also was pursued, and the following interim necessary feasible parameter development has been visualized:

1. Definition of emulsion stability
2. Rust and corrosion performance
3. Performance evaluation in prevailing types of pumps (vane, axial piston and gear pumps); and

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4. Definition of limiting operating temperatures, pressures, and maintenance (filtration) recommendations.

The XRL1110 fluid was manufactured in facilities approximating those of commercial producers, its reproducibility in commercial production was evaluated, and a nine-month mine demonstration test in two continuous miners (one using both constant variable volume axial piston pumps with hydraulic pressures up to 3200 pounds per square inch and the other using three tandem gear pumps operating at hydraulic pressures up to 1700 pounds per square inch) was initiated. The results of the first five months of the testing period were available to the committee, and it appears that the experimental fluid has performed satisfactorily both as a lubricant and as a fire-resistant hydraulic fluid. Initial inspections of both pumps and fluid indicated that:

1. Four production batches of XRL1110 have met the performance criteria stipulated in the research contract, demonstrating that the fluid can be manufactured in normal production facilities in a reproducible manner.
2. Essentially all problems possibly related to hydraulic system malfunction were not related to lubricant performance.
3. The apparent viscosity and water content of the emulsion remained essentially unchanged.
4. Contamination levels were in the range of 3 to 8 milligrams per 100 in one miner and higher in the other unit, which required a lubricant change.
5. The fire resistance of the XRL1110 used in both miners remained good (as measured by the Schedule 30 test procedure).

These intermediate results seem to indicate that successful performance can be expected for the entire test period. The final results also may shed light on areas that need further development (e.g., improved mechanical performance, corrosion protection, and improved hydraulic fluid filtration).

### 5.6 Polyurethane Foam

(Wilde, 1972; Walter Kidde and Co., 1974, Mitchell et al. 1964 and 1966; Nagy, 1973; Stephenson, 1968; Vines, 1973; Trolley, n.d., Franklin et al., 1977)

Polyurethane foam is a tough cellular material usually produced on site from a two-component mixture, dispersed through a nozzle, and sprayed onto a surface. During the resulting exothermic chemical reaction, chemically or physically generated gas bubbles expand the mixture up to 30 times in volume.

Urethane foam has been used in mines since the early 1960's. It serves as an excellent sealant and insulator for ventilation controls and strata. It is tough, flexible, and easily applied, and it expands during curing and has good adhesion qualities. The foam, however, is flammable and subject to spontaneous combustion, and its decomposition products represent a significant toxic hazard.

Past developments in foam technology were concerned with application technique, testing, flammability, flame propagation research, and the use of flame-

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retardant additives. More recent research has concentrated on fire dynamics, toxicity of foam combustion products, and development of fire-resistant coatings.

### 5.6.1 Description

Polyurethane foam is formed by the reaction of a polyisocyanate with a hydroxyl compound. A typical formulation used in mines will contain approximately 50 percent diphenyl methane di-isocyanate, 30 percent polyether polyol, 6 percent tri-chloroethyl phosphate, 15 percent trichlorofluoro-methane, and small amounts of catalysts and an emulsifying agent. The foam is made by mixing the components and spraying the mixture on the desired surface. The heat of reaction between the polyol and the isocyanate vaporizes the trichlorofluoromethane whose expansion produces the foam. The trichloroethyl phosphate is included as a fire retardant.

Urethane foam application usually requires no preparation of dry, wet, or dusty surfaces of coal, rock, metal, wood, concrete, or fabric. It is used in mines to:

1. Provide stoppings in recovery operations following fires and explosions.
2. Provide stoppings, overcasts, bulkheads, and door frames that are resistant to air leakage, low-level ground movement, and blasting vibrations.
3. Control the weathering of exposed strata.
4. Reduce heat and moisture transfer from rock to the ventilating air and facilitate airflow.
5. Seal strata against efflux of gases (i.e., methane, radioactive gases).
6. Provide non-load-bearing walls (e.g., those required for auxiliary ventilation ducts and underground explosive magazines).
7. Control ground water seepage at low hydraulic heads.
8. Reduce condensation and freezing in machines, pipes, and air shafts.
9. Hold shaped charges against vertical walls.
10. In case of a rescue operation (and only in such an emergency), consolidate and seal burning gob and fill voids. This is a hazardous usage.

The use of urethane foam in mines was accepted rapidly because of its obvious contribution to productivity and cost savings. However, fire and toxic effect incidents soon curtailed widespread use.

The disadvantages of using urethane foam in mines are that:

1. It is easy to ignite.
2. It has a high flame spread rate.
3. The possibility of spontaneous ignition exists (but only within four hours after application and only if improperly applied).
4. The smoke and gases produced on combustion are toxic.
5. It tends to develop fires that virtually deplete the air or oxygen (in contrast to wood and coal fires that go out at between 10 and 15 percent oxygen content).
6. Flammable solvents may be used to clean equipment.
7. Specialized equipment may be used for foam application (e.g., mixing nozzle,

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pumps, and mixing chamber).

8. Extensive operator training is required to ensure proper proportioning and mixing of ingredients, choice of ingredients, application technique, protection and against the personal hazards involved in application.

The advantages of urethane foam derive from its outstanding properties in mine applications and include its:

1. Low porosity and permeability, which makes it an effective sealant against air, moisture, methane, and radioactive gases.
2. Strong adherence to strata and mine constructions, including damp and dusty surfaces.
3. Low thermal conductivity, which makes it a good thermal insulator.
4. Ability to expand on curing, which facilitates application over irregular surfaces and in filling voids.
5. Flexibility, which minimizes detrimental effects of ground movement and development of cracks.
6. Relatively high shear-strength in comparison to other sealants.
7. Rapid curing time.
8. Applicability in very humid environments because curing is accomplished by chemical reaction (rather than by water evaporation).
9. Ease of application (i.e., the availability of self-contained, portable packs for application in remote areas).
10. Low cost (both material and application labor) due to ease of application and speed of construction.

### 5.6.2 Hazard Control

The application of urethane foam in mines started in the early 1960's. In 1964, Mitchell et al. reported that it had been used successfully in experiments to construct stoppings, seal mine surfaces, control water efflux, and serve as insulation. They described the foam formulations, application techniques, and physical properties of the foam as well as the fire and potential toxicity hazards; presented results of large-scale simulated coal mine fire tests and various laboratory flame spread and thermal deformation tests; and proposed a flame penetration test as an acceptance requirement.

A later report by these same researchers (Mitchell et al. 1966) is devoted entirely to the fire hazard of urethane foam in mines. It describes a large number of mine and gallery fire tests and presents an analysis of the results. Application recommendations, including limitations, are made and four certification tests (i.e., excess or residual tolylene diisocyanate [because of toxicity], water-vapor permeability [to estimate foam quality], flame spread, and flame endurance) are proposed. The report also covers spontaneous ignition of urethane foam (its causes and prevention methods).

In September 1967, a serious coal mine fire killed nine men at the Michael

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Colliery in England (Stephenson 1968). It was concluded that the fire was initiated by spontaneous heating of coal and reached disastrous proportions when the polyurethane lining started burning. Subsequently, five large-scale experiments were conducted to study the behavior of polyurethane foam when subjected to igniting agents of different intensity. It was concluded "that polyurethane foam as at present constituted is an unacceptable risk and that its use in and near the entrances to all mines should be discontinued." Apparently this was not to be, however. In 1972, a British researcher (Wilde) described seven large-scale experiments designed to study several aspects of polyurethane foam fires, including ignition, flame spread, fume composition, temperature profile, effects of fire retardant surface coatings, and burning of treated timber downwind of polyurethane fire. This report examines the applicability of using the foam to seal mine fires (rather limited) and offers conclusions on experimental results but no recommendations concerning the use or rejection of urethane foam in mines.

More recent U.S. investigations revealed that at least 10 mine fires reported during 1964 and 1974 involved urethane foam (8 in coal mines and 2 in metal and nonmetal mines). Although this incident rate is relatively low, it is serious enough to warrant consideration of significant modifications or alternate approaches. This committee possessed no information that would explain the discrepancy between the British and American experience with urethane foam although it is readily admitted that there may be subtle differences in composition and application. It is not very likely that chemical composition should be a factor, but the differences in application technology or prevailing strata may offer an explanation.

Today, pursuant to government order less than a mile remains in certain metal mines of the many miles of passageways in coal, metal, and non-metal mines that were coated with urethane foam. Recognizing the considerable fire and toxicity hazard that these installations represented, the U.S. Bureau of Mines sponsored a series of experiments to evaluate various surface coating materials suitable to protect the existing installations from excessive flammability and flame spread (Walter Kidde and Co. 1974). The results of this program indicate that fibrous concrete appears to be the most effective coating; it exhibits excellent strength and adhesion, and minimal spalling, and an application of only 1/2 to 1 inch (preferably 1 inch) provides the desired protection. In order of decreasing efficiency, the other coating materials evaluated were: Shotcrete (same as fibrous concrete without the steel fibers), Fireguard (a magnesium oxysulfate cement containing perlite), Mandoseal (a vermiculite cement), mineral wool, and sodium-silicate-based coatings. It is discouraging to note that the application of even the two best materials is difficult, that material is lost because of rebounding, and that it is difficult to achieve a uniform coating thickness. These problems, however, are not considered to significantly alter the test results and it may be that experience will improve the application technology. Assuming that such improvements will be made, the report indicates that at least two (and possibly four) acceptable and economical protective

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coatings are available to provide sufficient fire protection for existing urethane foam installations.

The same report also describes successful fire testing of a new fire-resistant foam, designated X-103S. In the experiment, flame did not spread on the surface of the foam upon application of an intense ignition source, and it was concluded that the material does not present a fire hazard even without a protective coating.

Other efforts to modify or replace traditional polyurethane foam also have been undertaken. Callery Chemical, under a contract to the U.S. Bureau of Mines, has formulated a number of modified urethane and isocyanurate foams that offer vastly improved fire-retardant properties compared to standard urethane foam (Vines 1973). Coatings formulated with portland cement, mineral wool, and vermiculite have been developed and can be sprayed on with day-process equipment. This is a process that involves no mixing of dry material and no clean up of equipment. In addition, the equipment does not get plugged with cement after a mine power loss. Franklin et al. (1977) have reported that two spray coat applications of a water-based epoxy sealant have substantially reduced shale degradation in a coal mine. Material and application costs seem reasonable, and endurance (after 18 months) appears to be noteworthy, but no details concerning the fire and toxicity hazard or comparison with urethane foam were presented.

### **5.7 Mine Fire Detection**

**(Nagy and Hall 1974, Hertzberg 1978, Hertzberg and Litton 1976)**

The seriousness of the fire hazard in mines was recognized by Congress when it enacted the Federal Coal Mine Health and Safety Act of 1969. Section 311 of the Act establishes numerous requirements for fire protection including the use of fire detection devices. The requirements for these devices are amplified in the standards published in the Federal Register to implement the Act.

There is little doubt that rapid and reliable fire detection is the essential first step in any fire-suppression or alarm system and escape plan. Initially, emphasis was placed on detecting methane-air face ignitions and dust explosions and the early activation of quenching devices. More recently, efforts have concentrated on the detection of fires during their early or incipient stages. Current research programs include the continuing development of a tube bundle sampling technique, development and evaluation of new types of fire sensors, and general studies of the problem of spontaneous combustion.

#### **5.7.1 Sensors and Systems**

The traditional methods of detecting the presence of fires may be classified by the type of detector used as follows:

1. Thermal contact sensors that respond to the temperature or the rate of temperature increase at a point or along a continuous line. Examples are thermocouples, bimetallic elements, the fusible plug of a sprinkler head, and twisted

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wire with insulation that melts at a given temperature. These sensors generally must be located close to the fire if they are to operate successfully.

2. Optical sensors that respond to the light emitted by a fire or flame. These sensors are limited by field of view constraints and are subject to blockage by dust.
3. Combustion product detectors that can be installed locally or at remote areas to sense carbon monoxide, carbon dioxide, visible smoke, submicrometer particles (invisible smoke), or a variety of other pyrolysis products carried by ventilation or fire convection currents.
4. Aerodynamic sensors that respond to the flow disturbances caused by the fire. These sensors are useful for explosion detection but are rarely used for fires.
5. Human observers, the most versatile and sensitive "sensors". These observers, however, are present only part of the time in limited areas and cannot be present in sealed areas, gobs, and other inaccessible places.

Current practice generally assumes the presence of and depends heavily on human observers. The only current coal mine requirements for automatic fire sensors relate to their use with underground conveyor belt haulageway protection. The regulations are written in terms of thermal point type sensors (or combustion product sensors if they offer equivalent protection). Metal and non-metal mine regulations require fire alarm systems; however, automated sensors to activate the alarms are not required.

Fire detection systems currently used and under development in mines can be categorized as:

1. Attended equipment systems,
2. Unattended equipment systems,
3. Ignition suppression systems,
4. Spontaneous combustion detection system, and
5. Whole-mine monitoring systems.

When fire suppression systems are installed on attended equipment, the operator usually must detect the hazardous condition and must activate the suppression equipment. Use of fire-resistant hydraulic fluid would make suppression equipment superfluous on this type of system.

Properly installed devices (e.g., water sprinklers and temperature sensors) are used to detect fires on unattended equipment, such as belt conveyor drive units and automatic loading stations, and to activate suppression systems. Additional manual activators also are required on some systems. If equipment uses a hydraulic fluid, fire-resistant hydraulic fluid must be used in conjunction with the suppression systems.

### 5.7.2 Recent Developments

#### 5.7.2.1 Tube Bundle Sampling

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Building on British work conducted between 1968 and 1972, the development of a continuous monitoring technique is being pursued (Hertzberg and Litton 1976). The method involves the pneumatic, sequential sampling of many points in a system through branching tube bundles that lead to a simple analytical station of high sensitivity, good reliability, and convenient location. The samples can be analyzed for a large number of components such as carbon monoxide, oxygen, methane, or products of combustion (for the detection of rapidly developing fires).

An obvious advantage of this system is the potential for monitoring many sampling stations, including inaccessible sealed areas, at frequent intervals on a continuous basis. Its limitations are relatively slow response time, due to long lengths of narrow sampling tubes, and wall-diffusion losses for submicrometer smoke particles. These limitations were quantitatively evaluated by measuring tube transit times and smoke particulate transmissions as a function of tube length, diameter, and pressure drop (Hertzberg and Litton 1976).

### 5.7.2.2 Detection of Spontaneous Heating

The gob regions of mines can now be routinely monitored for spontaneous heating by sampling tube bundles. This system was developed at the Somerset mine in Colorado (Hertzberg 1978), and the initial system monitored 38 points in various intakes, returns, working sections, and sealed areas for carbon monoxide and oxygen. Regions as far as a mile away from the sensing station were routinely monitored, and it was possible to follow the actual growth of a spontaneous combustion situation in a conventional room and pillar section. Although the system is adaptable to gobs, abandoned regions and sealed areas of a mine where the human observer is not present, it also can be used in attended areas to detect problems sooner than the human observer. System instrumentation, tubing arrangements, and power supply now are being refined.

### 5.7.2.3 Spontaneous Combustion Research

The main factors that contribute to spontaneous combustion in coal mines are: (1) the intrinsic reactivity of the coal, (2) the geometry and configuration of the seam, (3) the geological conditions and structure of the seam and its surroundings, and (4) the mining method and ventilation conditions. The intrinsic reactivity of the coal is the concern of a current program initiated by the U.S. Bureau of Mines (Hertzberg 1978). The self-heating characteristics of the coal are being determined with an adiabatic calorimeter, and the calorimeter data show that various other methods of evaluating relative reactivities correlate well with one another. The rate of temperature rise correlates well with the rate of production of carbon monoxide (CO) and carbon dioxide. Coals with high rates of CO production per unit volume of oxygen absorbed also have high self-heating rates in the adiabatic calorimeter. The CO index correlates well with the initial oxygen content of the coal. The development of these correlations and analysis of various coal deposits are expected

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to enhance the meaningful utilization of the tube bundle system.

### 5.7.2.4 Development of Sensors

In the hope of achieving greater mine safety, advanced sensor development is being pursued. Laboratory studies indicate that submicrometer particles are more universal indicators of spontaneous self-heating than CO generation. Other mine combustibles such as wood, cellulose, and plastics generate these particles at temperatures much lower than those at which they generate CO. A highly sensitive and inexpensive sensor for these particles has been developed (Hertzberg 1978) and is being evaluated for in-mine performance. The sensor is compatible with a properly designed tube bundle sampling system.

The development of ultra-violet and infra-red sensors for use in ignition suppression systems also is being pursued. When developed, such sensors should help to prevent methane ignition in the face areas of coal mines. Other current projects are concentrating on the evaluation and testing of new sensors (e.g., ionization detectors and semiconductor sensors) and their performance under normal and pyrolytic conditions.

### 5.8 Ignition Quenching and Fire Suppression (Furno 1978, Liebman et al. 1976, Liebman and Richmond 1978, King, 1978)

#### 5.8.1 Mine Face Ignition Quenching (Furno 1978)

The incidence of frictional spark ignition at the mine face has increased significantly with the advent of the continuous mining machine. The major hazard of a face ignition lies in the possibility that it may initiate an extensive coal dust explosion.

The research that resulted from the 1969 Act focused on the following approaches to the face ignition problem: (1) the reduction of methane concentration through improved face ventilation, water infusion, and methane drainage; (2) the reduction of the incendiary tendency of tool bits through improved metallurgy of the bit or reduced bit speed; and (3) the development of an ignition-quenching device that might be incorporated into the design of a continuous miner.

The Gravier system, which may be called an ignition-quenching device, was developed in the 1940's. Its early application was for fixed installations and adapting it to machine-mounted applications was recognized as a formidable problem. Difficulties included the vibration and shocks on a continuous miner, roof falls, the dusty and humid atmosphere, and the awkward geometry within which the flame detection and extinguishant dispersal are required to operate.

Research in this area was started in the United States in the early 1960's. It was directed toward developing a system that would provide rapid detection of an incipient methane-air ignition, an extinguishing agent that would be effective

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against such ignitions, and an agent dispersal method that would ensure adequate temporal and spatial distribution of the extinguishant. The resulting device utilized ultra-violet flame detectors, dry powder extinguishant (potassium bicarbonate), and an explosive dispersal system (primacord). A workable model eventually was developed and successfully tested. It consisted of a 2 inch diameter, 2 foot long scored aluminum tube fitted with the dry powder and primacord and mounted on a base plate. The model had several shortcomings in that it generated unacceptable noise and a dust and grease accumulation could cause a malfunction. These and other problems subsequently were investigated in late 1972 (Furno 1978). This effort led to the development of a cannon type dispersal system that utilized mono-ammonium phosphate propelled by high-pressure nitrogen through a diaphragm ruptured by an electric detonator upon signal from an ultra-violet detector. It was determined in trials that five cannons were required to provide adequate protection for a ripper-type miner and six cannons, for a continuous-type miner. This equipment was a technical success; however, space limitations make use of the required number of quenching devices impractical.

A quenching device utilizing a commercially available extinguisher filled with Halon 1301 or a hybrid system of this chemical also has been developed (Furno 1978). The extinguisher is a spherical bottle equipped with a dispersion nozzle and an explosive release device that is actuated by the signal from a flame detector. Halon 1301 was found to be a very efficient extinguishing agent by itself; however, its effectiveness improved when it was used in combination with water or with dry powder (potassium bicarbonate), and these hybrid systems are preferred for future investigation because of their synergistic action. The fire extinguishment characteristics of this device were investigated, and the generation of toxic fumes (HBr and HF) was determined at various quenching delay times and corresponding fireball diameters. In addition, the system was tested for utilization on a tunnel-boring machine that now is being used experimentally as a new method of entry development and that can develop into a frictional ignition hazard like other coal mining machines.

### **5.8.2 Coal Dust Explosion Barriers (Liebman et al. 1976; Liebman and Richmond 1978)**

Coal dust explosions are a constant hazard in underground coal mining operations. Such disasters usually follow accidental ignition of a methane pocket or roof layer, which may develop sufficient violence to pick up, disperse, and ignite coal dust lying on nearby mine surfaces. A self-generating dust explosion then can develop and propagate for great distances in the mine. Inerting the coal dust by spreading rock dust on the mine surfaces has been the traditional means of controlling dust explosions in U.S. coal mines; however, rock dusting is not completely adequate for conveyor beltways, transfer points, wet roadways, parked mine cars, return airways, longwalls, and isolated sections.

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The passive water barrier system that has been tested and used abroad appears to be an attractive means of defense against coal dust explosions and has become the principal means of protection in a number of countries. Such barrier systems normally are made up of a number of water-filled containers or tubs mounted in the vicinity of the mine roof. During a dust explosion, the dynamic pressure of the air resulting from the air motion ahead of the propagating flame tilts or shatters the water containers to release and disperse the water, which acts to suppress the oncoming explosion. However, European research indicates that the effectiveness of these barriers is limited to a moderately strong dust explosion; the water barriers fail when the explosion is weak since the dynamic pressure is not strong enough to fracture or tip the water containers. These studies also show that the passive water barrier is not effective when less than about 200 feet from the explosion initiator.

Three experimental water barriers designed especially for the suppression of slow moving coal dust explosions have been developed and tested (Liebman, et al. 1976). One of these barriers, a modified version of a West German type, responds to dynamic pressures generated ahead of an explosion to tilt the tub and release its water for the suppression of the oncoming explosion. The other two barriers operate in response to increased static pressure developed ahead of the explosion. Tests indicate that the first barrier begins to release its water at air speeds as low as 50 feet per second and that the other barriers will operate at a rise in static pressure of as little as 0.5 psi.

The barriers were found to be effective in stopping coal dust explosions propagating at speeds as slow as 100 feet per second. One charge of 180 pounds of water was sufficient to suppress explosions in a single entry with an average cross section of 55 ft<sup>2</sup>. Results of the tests indicated that the minimum distance between the barrier and explosion initiator should be about 75 feet. The barrier system's effectiveness in suppressing explosions remains high when as little as half of the water of a single barrier (90 pounds) is spilled prior to the flame arrival. Its effectiveness is diminished, however, when the barrier is located a great distance (more than 300 feet) from the explosion initiator.

A plan has been developed to test these water barriers in a working mine on a trial basis. The plan calls for installation of all three types, of closely specified sizes, distances, and spatial arrangement for the protection of a beltway. Actual performance behavior will be utilized as the basis for refinements and the development of specifications and to stimulate widespread application of the new type of coal dust explosion barriers.

### **5.8.3 Remote Sealing System for Extinguishing Coal Mine Fires (King 1978)**

Uncontrolled coal mine fires are of great concern to the mining industry because they cannot be directly extinguished and may require that the entire mine be sealed. The conventional practice of constructing airtight stoppings from within the

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mine is difficult and can involve a high fire or explosion risk; therefore, this approach cannot always be used. In search of a more desirable approach, the U.S. Bureau of Mines explored the concept of remote sealing from the surface and found fly ash to be a suitable sealant for this purpose. This technique minimizes the risk to the firefighter, limits the sealing to the established fire area, and expedites the mine recovery operation, thus reducing potential costs and production losses.

The system was developed to control the Federal No. 1 mine fire and explosion in 1963 (private communication M. Jacobson). The complete system includes: (1) a sonar probe and closed circuit television camera for initial probing of the mine entry to be sealed, (2) a fly ash or fly ash-cement system for constructing the seals, (3) a froth foam topping system for completing each seal, (4) a combustion type inert gas generator for conveying the fly ash and inerting the sealed area, and (5) acoustical equipment for assessing the completion and integrity of a seal.

The remote sealing of an underground coal mine fire requires considerable planning to resolve logistic and site preparation problems and to ensure that all the operational phases are properly coordinated. Initially, a probe is lowered through a borehole to determine the geometry or nature of the passageway to be sealed; the borehole must be cased and grouted to prevent water seepage and it subsequently serves as a sealant borehole. In the second phase, two adjacent boreholes are drilled to deploy the acoustical equipment that is used to monitor the formation of the gross fly ash seal and then the passageway is filled with the fly ash bulk sealant that is pneumatically transported from a supply truck on the surface. In the final phase, a froth foam topping is added to fill the crater formed by the fly ash and to complete the seal; the foam is formed in place at the bottom of the borehole. An inert gas generator is used to minimize the explosion hazard during the fly ash filling phase and to inert the sealed area of the passageway. In addition, a modified fly ash mixture must be used if a watertight seal is required. All components of the system are mounted on skids or trailers.

The probe assembly used in the first phase includes a low-light-level closed circuit television camera (CCTV) for visual observation of the downhole conditions and a sonar ranging device for accurately determining dimensions of the passageway or distances to large objects. It also is equipped with a rotator to facilitate scanning and a remote reading compass to establish probe orientation. The probing information is useful to determine the suitability of borehole locations, sealing material requirements, potential obstructions to sealing, and reliability of mine maps and engineering surveys.

Another instrumentation system that is vital to the success of the remote sealing operation is one that monitors the filling of the mine passageway and determines the integrity of the seal. The system developed in this work uses acoustic devices, namely a high-intensity speaker and a sensitive microphone. The speaker and microphone probes are lowered into boreholes that are on opposite sides of the sealant borehole. These probes are usually at least 50 feet from the seal being constructed.

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The theory of operation is based on the proven premise that a decrease in the level of signal received by the microphone is proportional to a decrease in the open area of the passageway being sealed. In this system, the speaker probe transmits an amplified sonic pulse from a random noise generator. The sound is picked up by a ceramic microphone and transmitted to a sound level meter in the control console. A signal processing module subtracts background noise, and the signal then is displayed on the control console and correlated with prior information to define the completeness of the seal. Sensitivity of the seal checking system is greatest as the seal nears completion (greater than 99 percent). Both microphone and speaker units are intrinsically fire and explosion safe.

Over the past 15 years, several attempts have been made to apply the remote sealing concept in underground fires in active coal mines, but most of these efforts have achieved only limited or no success because of inadequate sealant materials, serious equipment limitations, or insurmountable mine water problems. A partially successful effort occurred a few years ago when a prototype of the present remote sealing system was used to isolate and extinguish an underground fire at the Eastern Associated Coal Corporation's Jaonne mine in Rachel, West Virginia. This fire resulted from a derailment and subsequent short circuit that caused a fan stoppage and made it necessary to evacuate the mine. An attempt was then made to seal remotely. The remote sealing was made from two surface sites that were over 2500 feet apart and located on opposite sides of a hill above the mine. Six seals were constructed and each required drilling two adjacent boreholes to accommodate acoustic seal checkers. The boreholes were 600 feet deep or less.

Three of the seals were 95 percent ash topped with urethane foam, and the other three were 100 percent fly ash. Most of these required approximately 150 tons (95 percent seal) or 250 tons (100 percent seal) of fly ash. Those that were completed with a foam topping required at least 2200 pounds of foam. The sealing operation was carried out using liquid nitrogen tankers to provide the inert gas for deploying the fly ash and inerting the completed seals.

A gas monitoring system was useful in indicating the effectiveness of the completed seals, the adequacy of the inert gas supply system, and the potential gas explosion hazard before and during the remote sealing operation. The carbon monoxide and oxygen levels decreased to approximately 0.01 percent within about 60 days after the fire began; thereafter, they were essentially constant until the remote sealing was started. In comparison, the methane and carbon dioxide concentrations increased and reached maximum levels of approximately 30 and 4 percent respectively within about 80 days.

Because of supply and delivery problems with the liquid nitrogen system, it was not possible to maintain an inert atmosphere in the sealed area for extended periods during the recovery phase. Nevertheless, the seal emplacements by the mine rescue teams were thought to be sufficiently successful so that the mine was reventilated

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within a few days after completion of the seals. A prompt carbon monoxide build-up emergency was quickly responded to by the fire-control managers who "saved the day". The fact that the mine was reventilated prior to its recovery was a significant accomplishment despite the incomplete sealing. This field experience has been very useful in current efforts to develop a more reliable and acceptable remote sealing system for use by the mining industry in fighting mine fires.

As noted above, this effort was not totally successful; it helped even though technically it was a failure. It was the failure that led to the subsequent development of the CCTV and the inert gas generator. The costs to use the system are so high (from \$500,000 for a relatively small job such as the Joanne mine to many millions of dollars for other scenarios) that it is the "last resort" choice (private communication M. Jacobson).

### **5.8.4 Mine Shaft Fire and Smoke Protection System (Nagy and Hall 1974)**

As metal and non-metal mines become deeper, larger and more mechanized, the fire danger increases because of increased fuel loading in the mines and restricted access. This hazard was emphasized by the Sunshine mine fire at Wallace, Idaho, in May 1972. Ninety-one miners lost their lives in this disaster.

To help solve this health and safety problem and to better protect the production capability of the nation's mines, development of a mine shaft fire and smoke protection system for metal and non-metal mines was initiated by the U.S. Bureau of Mines. The methodology for hardware development and in-mine testing followed that used in the Bureau's successful program to develop automatic fire protection systems for large mobile mining equipment. A contract to evaluate the non-coal mine shaft fire and smoke hazard problem and to develop and demonstrate a reliable mine shaft fire and smoke control system was awarded in 1974. This system was to be flexible in design so that with modifications it would be applicable to the majority of metal and non-metal mine shafts and adjoining shaft stations.

As a result of the fire and smoke problem analysis portion of the contract, design criteria for a mine shaft fire and smoke protection system were developed and the first system design was generated. It utilizes thermal, carbon monoxide, and ionized-particle smoke detectors and remotely controlled smoke doors and sprinklers. The system protects both the shaft and shaft station areas. The surface control unit receives the fire warning signal via multiplex wiring through two separate routings, and underground control units and odor alarm are activated from the surface to warn the miners at each shaft station and elsewhere.

The sprinklers and doors can be opened or closed from either their local control unit or the master control unit on the surface. Fire warning horns and lights and mine evacuation signals at the underground units also can be controlled from the surface control unit. Automatic sprinkler actuation currently is not a feature of the system but could be added easily.

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A shaft and shaft station mock-up subsequently was built and system component tests were conducted. These included smoke tests of possible sensors to be used in the shaft system and test fires in the fire box. This box was used to contain the fire in the mock-up and the in-mine testing. The program concluded with the completion of actual fire tests.

After the mock-up testing, the final design was developed for the mine shaft fire and smoke protection system prototype to be installed at the 3000 foot level of Consolidation Silver Corporation's Silver Summit shaft near Wallace, Idaho. The system then was installed in the shaft and in-mine fire tests were conducted.

The contract was extended for an additional 15 months to permit installation of the prototype system in at least two operating mine shafts, long-term reliability testing, and conduct of cost-effectiveness evaluations of optional system designs and uses.

It appears that the first-generation mine shaft fire and smoke protection system has a fast response to fire situations and that the presence of sprinklers in the shaft and shaft station area is much more effective in extinguishing fires than the commonly used shaft-collar water rings. The cost of the system is estimated to be from \$10,000 to \$40,000 per shaft station level, depending on the desired sophistication of the system. This is a considerable investment, but given the cost of a shaft and the increased protection provided to the miner, the system represents a significant contribution to underground mine safety. However, it has been suggested that the following simple-to-achieve things would be a major contribution to life safety in mines: properly teaching use of self-rescuers, maintaining positive ventilation in hoist rooms, having a trained mine rescue team available, maintaining an effective escapeway, and maintaining co-activated fire doors.

### **5.9 Surface Mining Equipment Protection Systems (Johnson 1976)**

In surface mines, protection from equipment-generated fires is best provided by protection devices for subsystems (e.g., vehicles and stationery machinery). As surface mining trucks, shovels, bulldozers, etc., become larger, the danger to drivers during a fire emergency increases. The cabs usually are located high above the ground, and the access ladder usually is next to the engine compartment where most vehicle fires occur. In addition, some operating compartments are cramped and egress is difficult. This increasing fire hazard is illustrated by the records of mine equipment operator injuries resulting from fires or because a driver jumped from his vehicle to escape a fire.

To help solve this problem and better protect expensive pieces of equipment, the U.S. Bureau of Mines has developed reasonably priced, reliable automatic fire protection systems. The prototype systems sense the flame and/or heat of a fire and suppress the fire with a B-C class, dry chemical (either automatically or upon manual activation). The first system was developed in and was successfully demon-

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strated during in-mine fire tests on a 100-ton-capacity truck. Other systems have been developed and in-mine tested on coal augers and large bulldozers. Future plans call for modification and long-term endurance testing of alternate systems on large drills, shovels, and draglines.

### **5.9.1 Automatic Fire Protection Systems for Large Haulage Vehicles (Johnson 1976; Johnson and Forshley 1977)**

As mine haulage vehicles become larger, the fire hazard increases because of the increased height of the cab above ground, the location of the ladder, and the driver's inability to see the fire in time to escape because of the position of the cab on the vehicle. To alleviate this problem and better protect expensive equipment, the U.S. Bureau of Mines sponsored two efforts to develop automatic fire sensing and suppression systems for large haulage vehicles (Johnson and Forshey 1977).

One of these efforts was aimed at defining the large mobile vehicle fire problem and developing improved fire system design criteria to solve it. Another objective of the first work was to find the most fireprone class of equipment and to solve its fire problem using a system flexible enough to be applied to other large mobile mine equipment. This hazard analysis study resulted in development of "dual sensing, automatic with manual override, fire detection and suppression system" for rear-dump haulage trucks with a capacity of over 100 tons.

Prototypes of the system were built and demonstrated in actual truck fire tests and long-term in-mine endurance tests. The system protects the engine compartment and fuel tank area with improved components and features optical and thermal sensors; automatic controls with manual override; and fixed fire extinguishers with pressurized B-C class dry chemical. Control panels are located in the cab and can be activated manually via switches at ground level. Automatic engine shutdown was not a feature of the prototype system, but such a design alternative could be added easily. The system is flexible enough for use, with modifications, on most large mobile mining equipment.

As part of the second effort, the automatic fire protection system prototype was to be installed on the 100-ton mine truck and long-term reliability testing was to be performed. This testing resulted in development of a second-generation system that then was subjected to long-term on-vehicle testing in 1974. During the testing, an accidental fire occurred on the test truck and the prototype system automatically sensed and extinguished the fire. Fortuitously, the Bureau's program demonstrated success in a real verification.

### **5.9.2 Fire Protection System for Coal Augers (Johnson 1976, Technology News 1976)**

Following the open pit truck fire work, the U.S. Bureau of Mines expanded its mine equipment fire protection efforts to surface coal mining. This involved letting a contract to the Lease AFEK Corporation of Raleigh, North Carolina, to modify

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and test in-mine a low-cost automatic fire protection system for surface coal augers. This system was fabricated and then tested on a Compton auger at the Cedar Coal Company, Chelyan, West Virginia. The AFEK system features point-source heat sensors and two independent dry chemical extinguishing subsystems, one for each engine and operator area on the auger. The system was subjected to six months of in-mine testing and test fired in 1975.

The validation tests indicated that an effective, reliable, and economical fire suppression system can be developed and that:

1. Such a system can be installed for approximately \$2,200.
2. The system requires little maintenance and is simple in design.
3. The use of a nonpressurized extinguisher ensures reliable discharge even after prolonged non-use by using the charging gas to violently disturb the dry chemical before discharge.
4. This type of extinguisher can be readily recharged in the field without special equipment and by relatively untrained people.
5. The point-type thermal sensors are not damaged by vibration, shock and environmental conditions.
6. The system's having its own battery power provides for 24-hour protection independent of the auger electrical system either attended or unattended.

### **5.9.3 Fire Protection of Surface Mining Machinery (Johnson 1976 and 1978, Nagy 1978)**

In 1975 the U.S. Bureau of Mines entered into a cooperative agreement with the Ansul Company, Marinette, Wisconsin, to help in the evaluation of a new, pneumatically operated, low-cost, automatic fire protection system. On-vehicle testing on front-end loaders and haulage trucks was the main activity of this project, and Ansul's system currently is being further tested and refined.

The Bureau's most recent work concerning improved fire protection systems involves testing AFEX-type system on large bulldozers. The Bureau's Twin Cities Mining Research Center, Minneapolis, Minnesota, is conducting this in-house project with the help of Lemmons and Company, Boonville, Indiana. By the spring of 1976, the AFEX system had been installed on a Giat/Allis HD 41 tractor at the company's Boonville and Sholes mine for approximately six months. The system was test fired during March 1976 and the dry chemical appeared to cover the fire hazard areas of this large bulldozer well. No extinguishant entered the cab and the system expelled the 40 pounds of dry chemical in approximately 15 seconds, which would give the operator enough time to shut down his machine and exit.

Concurrent with the bulldozer fire system work, the Bureau is working with various mines, fire protection equipment companies, and mine equipment manufacturers to make available rugged, cost-effective, automatic fire protection systems for other classes of large, mobile mining equipment (e.g., shovels and large down-hole drills). Also under way is a major metal and non-metal health and safety

program to improve fire protection for shafts and shaft stations.

#### 5.10 Conclusions and Recommendations

*Conclusion:* The fragmented approach to design criteria development for mine hazard control is no longer acceptable. *Recommendation:* All basic information and techniques needed to apply the overall systems approach in mine safety and hazard control should be developed.

*Conclusion:* Belt conveyor systems still represent a major fire hazard in mines; acceptance test methods seem inadequate and large-scale fire testing is incomplete. *Recommendation:* Test methods that provide a meaningful and quantitative rating of the flammability, flame spread, and toxicity of combustion products of belting materials should be developed. A drum friction test (being close to real-life conditions) for use as an acceptance standard should be developed and adopted. Large-scale fire gallery tests on belt conveyor systems should be completed or, if necessary, continued to collect all the important data. These data should be correlated with small-scale test data and utilized for acceptance test and design criteria development. Development of more sensitive, reliable, and economical fire detection, alarm, and suppression systems for belt conveyors should be continued using overall system design principles.

*Conclusion:* The fire safety of wire and cable insulation materials has improved in recent years, but no universal test methods are available for behavior classification. *Recommendation:* Simple, reliable test methods should be developed or adopted to evaluate flammability, smoke emissions, toxic fume evolution, and circuit integrity of wire and cable insulations applicable to mine installations. A combined "hazard index" rating system including these and other criteria important in mine hazard evaluation should be developed.

*Conclusion:* As the size and number of continuous miners and other underground power equipment employed increases, the size of the hydraulic systems employed also increases. The petroleum-based hydraulic fluids represent a definite fire hazard, and the currently available fire-resistant hydraulic fluids (water-in-oil emulsions) are insufficient in terms of mechanical and chemical performance (corrosion). *Recommendation:* The development of the HS-B type hydraulic fluids should be continued as an interim measure, but emphasis should be placed on development of a water-free fire-retardant hydraulic fluid that has qualities equal or superior to petroleum-based fluid.

*Conclusion:* Development and refinement of fire sensing devices has progressed, but their full potential has not yet been explored. *Recommendation:* Development and refinement of all types of fire sensor should be continued and their utilization in the most promising applications should be supported, but this should not be a reason to avoid using state-of-the-art technology currently.

*Conclusion:* The tube bundle information relay system recently employed in U.S. mines and used in more than 40 mines in United Kingdom and Germany for

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sampling gases is being considered a breakthrough although 9 years old. It has already resulted in great advances in mine safety improvements. This system also has been employed in the chemical industry for many decades for sampling gases and liquids and for pneumatically transmitting information and command signals. *Recommendation:* The tube bundle as an information relay system should be further exploited for mine safety applications. Existing knowledge and ongoing research concerning the use of tube bundles as a gas sampling device should be exploited and expanded. The absorption of submicrometer particles by various tubing materials (or coatings) should be investigated. The use of tube bundles for liquid sampling, pressure differential sensing, liquid level indication, and temperature sensing (liquid filled tube) should be explored. The use of tube bundles for transmitting command signals (opening or closing doors) and activating alarms and fire or explosion suppression devices should be developed. Tube bundles also should be utilized as back-up systems for electrically operated equipment.

*Conclusion:* The problem of spontaneous combustion in U.S. coal mines is gaining increased attention for two reasons: the development of deeper seams and the exploitation of western mines, which are more susceptible to this hazard. *Recommendation:* Recent studies dealing with the characteristics of spontaneous combustion and their detection (e.g., by tube bundle sampling) should be accelerated to minimize this hazard in the new coal mines.

*Conclusion:* Applied technology development in underground mine fire and explosion prevention and suppression has made significant advances in recent years. *Recommendation:* Development of methane drainage technology should be continued. Face ignition quenching systems for continuous miners and tunnel boring machines should be refined, and these quenching devices should be integral parts of new machines. The demonstration and refinement of coal dust explosion barriers should be continued, and their optimum location in relation to face areas should be identified. The remote sealing technology recently developed for the control of coal mine fires should be perfected. The ongoing mine shaft fire and smoke protection system development program should be amplified; this system should be installed in metal and non-metal mines.

*Conclusion:* Fire protection of surface mining vehicles and machinery can be greatly improved by the installation of automatic fire detection and suppression systems. *Recommendation:* Existing development efforts should be continued and new ones initiated as needed to provide fire protection equipment for trucks, large haulage vehicles, augers, large downhill drills, shovels, and draglines. Fire detection and suppression systems should be integral parts of new surface mining vehicles and machinery.

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## CHAPTER 6

### SMOKE AND TOXICITY

#### 6.1 Introduction

The toxicity problems encountered in a mine or bunker fire tend to change as the fire progresses. At the time of ignition, the atmosphere is oxygen-rich and the toxicity is similar to that of the combustion products of the materials involved; later, the atmosphere is oxygen-lean and the toxicity is similar to that of pyrolysis of the same materials. Toxicity arises from the presence of combustion products in a given location. The major factors that influence human survival during a fire in a confined space are:

1. Thermal energy – The hazard to human health is either that of local thermal damage, usually of the skin or respiratory airway, or generalized thermal shock.
2. Decreased atmospheric oxygen concentration – This factor is associated with all materials undergoing oxidation at a rapid rate. The health hazard is that of deprivation of an essential amount of available respiratory oxygen. In fires occurring in mines or bunkers, decreased oxygen may rapidly become a significant factor.
3. Carbon monoxide and other noxious gases and aerosols – Like other organic materials, any polymer undergoing less than complete combustion in the presence of oxygen yields carbon monoxide. The toxicological consequences of human exposure to carbon monoxide have been extensively reviewed (National Advisory Center on Toxicology 1973, Stewart 1976). Carbon monoxide is the major single cause of fatalities in most fire situations and is especially significant in the oxygen-lean atmosphere that develops in mine and bunker fires. Depending on the types of organic materials present, the pyrolysis or combustion of polymers may produce, in addition to carbon monoxide, combinations of toxicants including hydrogen cyanide, sulfur compounds, nitrogen oxides, halogen acid gases, vaporized fumes of other halides such as ethyl bromide, organic gases such as ethyl bromide, aldehydes like acrolein, and such exotic compounds as the highly toxic bicyclic phosphates from some plasticizers (Petajan et al. 1975).
4. Smoke – Massive exposure to smoke may result in direct mechanical plugging of airways or smoke particles may carry adsorbed gases or liquids or residual heat to various parts of the respiratory tract and produce injury by direct contact. Smoke also obscures vision, impedes escape, and hinders firefighting efforts. (See Appendix C).

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5. Fear, panic, or incidental trauma – These factors are recognized causes of incapacitation and death in fires.
6. Pre-existing or concurrent psychophysiological disease or impairment – Pre-existing heart disease has been established as a significant factor in fire deaths. Acute alcohol intoxication also may be a factor, and the disabled obviously are at a great disadvantage. These are only a few of the more apparent diseases and impairments affecting an individual's ability to escape and survive.

Mines and bunkers are examples of confined spaces in which fire represents a serious hazard. They may be remote from outside firefighting assistance and avenues of egress may be limited and difficult. The materials in mines and bunkers that are most likely to undergo combustion or pyrolysis are natural and synthetic polymers (for the purpose of this chapter, fuels, lubricants, and hydraulic fluids are excluded) including wood, wool, cotton, paper, other cellulosic materials, and a wide range of synthetic polymeric materials. Polymeric materials currently in use in mines and bunkers are described in Chapter 4. There generally are no specific requirements regulating noxious gas generation for materials used in mines and bunkers under fire conditions.

### 6.2 Perspective on Experimental Data

The number of studies concerned with noxious gases and smoke resulting from thermal degradation of polymeric materials has increased during the past 10 years. Pyrolysis or combustion products of the polymers used in mines and bunkers have been found to include carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), hydrogen cyanide (HCN), oxides of nitrogen (NO<sub>x</sub>), ammonia (NH<sub>3</sub>), hydrogen sulfide (H<sub>2</sub>S), phosgene (COCl<sub>2</sub>), and many other compounds. The physiological hazards of these gases are described in Appendix D and Kimmerle provides a more detailed compilation of effects at various atmospheric concentrations (1974).

From fires in confined spaces, the predominant toxic thermal degradation product is CO. Incapacitating or lethal amounts of CO can develop within minutes. Appendix E presents a brief review of CO toxicity. The net physiological response from CO and other thermal degradation gases is far from clear although awareness of this problem and the difficulties in assessing it are increasing.

Fire situations can have an extremely complex toxicology. If a lethal CO atmosphere is not reached, other lethal or disabling factors still may be present. For example, in the series of experiments reported by Cornish and Abar (1969) pulmonary injury from HCl developed in the absence of lethal effects from CO. A more subtle effect noted by Effenberger (1972) is that burning polystyrene does not cause rats to die or develop significant amounts of carboxyhemoglobin, but rather the styrene it yields apparently has an immobilizing effect on rats. If this interpretation may be extended to fires involving humans, death could result because ability to escape from the fire is impaired.

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Smoke presents a number of hazards and occurs in a wide variety of compositions. Smoke basically is a mixture of carbon particles and materials evolved from combustion. It may contain irritants adsorbed on the particles and be mixed with thermal decomposition gases. The hazards of smoke may be physical (blocking vision or airways), physiological (local or systemic chemical irritation, toxicity, or heat injury), or psychological (fear and panic). Appendix C surveys the hazards from smoke and describes current measurement techniques.

### 6.2.1 Experimental Work

Ultra Systems, Inc., under a U.S. Bureau of Mines contract, is investigating 32 materials commonly carried into mines or bunkers by workers or occupants. The behavior of these materials under controlled pyrolysis conditions is being studied and the materials are assigned ratings based upon various factors, including toxicity.

### 6.2.2 Clinical Data Based on Aircraft Fires

Quantitative toxicological data on mine and bunker fire victims are nonexistent; however, limited data are available on aircraft fire victims and are pertinent in that the synthetic polymers involved are similar. (See Volume 6, Aircraft: Civil & Military). Smith and Associates have described the results of their forensic investigations of several aircraft accidents as follows:

Two commercial aircraft accidents in the United States during the 1960's (Denver, Colorado, 1961, and Salt Lake City, Utah, 1965) contributed greatly to the initiation of the present concern over the toxic hazard of the gases generated in aircraft fires. These accidents were of special significance because careful analysis indicated that few, if any, of the occupants would have suffered significant physical injury from the relatively mild impacts involved; yet, a total of 60 persons perished as a result of thermal and chemical injuries sustained in the ensuing fires.

Carboxyhemoglobin measurements on 16 victims of the Denver crash revealed CO saturations ranging from 30 to 85 percent with a mean of 63.3 percent. Similar analyses on 36 victims of the Salt Lake City accident yielded CO saturations ranging from 13 to 82 percent, the mean being 36.9. The lower carboxyhemoglobin values found in the second accident have been attributed to the fact that fire was present within the aircraft before evacuation could be attempted and that the survival time of many victims must have been shortened by direct thermal effects. It also has been assumed that gases other than carbon monoxide must have contributed to the toxicity of the cabin environment, but there is no supporting evidence for the assumption.

In 1970, blood samples from victims of an aircraft crash followed by fire (Anchorage, Alaska, November 1970) were analyzed for the pres-

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ence of cyanide (apparently the first time such analyses were made on aircraft fire victims). Measurable amounts of cyanide were found in 18 of the 19 specimens submitted, and were accompanied by carbon monoxide saturations ranging from 17 to 70 percent. In the one sample in which cyanide could not be detected, the carboxyhemoglobin concentration, 4.9 percent, did not exceed that which could result from smoking, indicating the probability of death on impact. Blood cyanide levels in these victims corresponded closely with those reported in the literature for victims of structural and vehicular fires ranging from the lower detection limit (circa 0.01  $\mu\text{g/ml}$ ) up to 2.26  $\mu\text{g/ml}$ . The relationship between cyanide levels and carboxyhemoglobin content varied in random fashion, perhaps representing relative proximity of the victims to cyanide-producing materials. Alternatively the varying cyanide levels reported may be due to uncontrolled auto-production of cyanide in and from the tissues.

Nothing in these findings permitted speculation concerning the relative contribution of the two gases to lethality. In addition, there was no way of assessing the possible contribution of other gases that must have been present in the pyrolysis mixture to which these victims were exposed.

### 6.3 Evaluating the Hazards of Toxic Fumes and Smoke

#### 6.3.1 Comparison of Materials

Valid comparisons of different materials must be based on similar or reasonably standard conditions. The desirability for a standardized test procedure pertinent to proposed use application is obvious. However, real fires possess two essentially uncontrollable variables — oxygen supply and temperature — that make selection of such test procedures inherently difficult. Generally, laboratory thermal degradation tests in an oxygen-lean atmosphere are described as pyrolysis tests whereas combustion with actual flame indicates an oxygen-rich atmosphere. Since either pyrolysis or combustion can be the more hazardous depending on the nature of the material being consumed, a standard procedure should take both categories into account, either separately or together. (See Appendix E for guidelines for suggested screening tests.) In the case of fires in mines and bunkers, as previously noted, the atmosphere tends to rapidly become oxygen-lean and higher carbon monoxide levels would be expected earlier than usual.

#### 6.3.2 Thermal Decomposition Temperatures

Fire temperature depends on the pyrolysis and/or combustion processes and also on the caloric value of the product or products consumed by fire. For the thermal decomposition of wood, several analysts have followed a classification of four distinct temperature zones (see Appendix F). However, the committee is unaware of any attempt at such a classification for the multitude of synthetic polymers that

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exist today.

### 6.3.3 Method of Study

Recent literature describes the four types of methods discussed below (see Appendix G).

#### 6.3.3.1 Analysis

Testing to identify the chemical components involved can help in understanding the effect of altering variables such as temperature and oxygen. The relative hazard or lethality of the product can be estimated with reasonable confidence if a single component, such as CO or HCl, is clearly predominant and no other significant source of stress is present. If thermal degradation generates a significant quantity of miscellaneous gases, heat or smoke, the net physiological response is difficult to estimate; however, analysis of such mixtures or their degradation products is becoming less difficult with the development of more sophisticated (and expensive) analytical tools. To compound problems, finished products may be composed of basic elements, antioxidants, fillers, additives, and finishes, and even major percentage components often are not stated.

#### 6.3.3.2 Biological Testing

Data obtained from tests on laboratory animals can be expressed as the  $LC_{7b5_0}$  or concentration expected to produce death in 50 percent of the exposed animals and the  $EC_{50}$  or concentration expected to produce a specified effect, such as incapacitation, in 50 percent of the exposed animals. It is in this latter area of biological test for toxicity that special attention is required. A safer product from the standpoint of a flammability test does not always result in a more desirable product in that:

1. Structure modification or additives may result not only in retarded combustion of the polymer but also in increased toxicity of decomposition gases and/or dense smoke from the smoldering of the polymer when it is exposed to external heat.
2. Many of the more common fire retardants contain halogens, such as chlorine and bromine, that theoretically make possible the production of thermal decomposition products such as hydrogen chloride (HCl), phosgene ( $COCl_2$ ), and hydrogen bromide (HBr).
3. The presence of nitrogen atoms, either in the polymer or in the additives, introduces the possibility of thermal degradation to HCN or  $NO_x$ .
4. Polymers based on propoxylated trimethylpropane polyols and fire-retarded with phosphorous-coating retardants may yield highly toxic bicyclic phosphorous esters when thermally degraded (Petajan et al. 1975).

#### 6.3.3.3 Extensions of Analysis and Biological Testing

## MINES AND BUNKERS

Present models include combined testing, predictive testing, and "room" or large-scale fire tests.

### 6.3.3.4 Epidemiological Studies

Critical epidemiological analyses have been applied to fire toxicity only recently. There is a need for evaluated reports on mine and bunker fires that provide comprehensive casualty data, including a quantitative toxicological and pathological evaluation of the victims. To consider only one decomposition product, a recent discussion of HCN as a major lethal factor in aircraft fires indicates the current interest and concern in this area and also brings attention to the difficulties that may be associated with such analyses.

### 6.4 Special Considerations

Obviously, products or formulations require more stringent evaluation when intended for use in mines and bunkers than for many other applications. The long and tedious escape routes from underground spaces and the relative unavailability of firefighting equipment and personnel inherently expose the occupants to a greater fire and toxicity hazard than exists in more ordinary occupancies. If any new products or formulations are intended for use in mines and bunkers in appreciable quantity, their potential toxicity when burned must be evaluated within experimental guidelines and reviewed in the context of available epidemiological data.

### 6.5 Conclusions and Recommendations

*Conclusion:* Published data relating to the toxicity of the combustion and pyrolysis products of polymeric materials, individually and in combination with other polymers, are sparse. *Recommendation:* A central agency should be established to collect and analyze data from and promulgate information regarding the toxicity of the combustion and pyrolysis of polymeric materials in test and actual fires.

*Conclusion:* Most toxicity studies relating to the products of combustion and pyrolysis of polymeric materials are oriented toward establishing lethal levels and incapacitation is relatively ignored. *Recommendation:* Studies of the toxicity of polymeric material combustion and pyrolysis products should address incapacitation as well as lethality.

*Conclusion:* Little is known about the additive or synergistic effects of the toxic agents produced from the combustion and pyrolysis of polymeric materials. *Recommendation:* Methods should be established for studying the toxicity not only of individual toxic agents released during the combustion and pyrolysis of polymeric materials but also the toxicity of combinations of such toxicants likely to be encountered in varying fire situations.

*Conclusion:* Clinical toxicity data on the combustion and pyrolysis products of polymers in actual fires is very sparse. *Recommendation:* Guidelines should be established and published for the collection of toxicity data on fire victims by

## SMOKE AND TOXICITY

paramedical rescue personnel and medical centers. These guidelines should specify data collection techniques that will not interfere with first aid or intermediate or definitive medical care.

### 6.6 References

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## AFTERWORD

The nation's energy problem has been discussed in such detail that everyone has some familiarity with it. Solutions to the problem have been proposed in great numbers but too often they are not attainable without a long-term research, development, and demonstration effort. In many cases, the time frame for the practical utilization of new fuel concepts is measured in decades with the turn of the century as a target date.

The ray of light in this dreary picture is the nation's abundance of coal resources. Mines in the United States now provide approximately 600 million tons of coal each year and can continue at that rate for a minimum of 360 years.

As the economic importance of coal and metal increases, the nation must strive to better protect the key production elements — the miners, the equipment, and the supply. Two factors threatening all of these elements are fire and explosion.

Mine fires and explosions have a great impact in that the nation loses a portion of its energy supply. Within the immediate community, their aftermath is devastating. The tragedy of death can be overwhelming, and the closing of the mines inflicts a severe economic hardship on the families of the miners who are deprived of their normal income. The production requirements of other mines are increased and additional employees must be found, which has a significant effect since a new miner is 10 times more susceptible to injury than a miner with a year of experience.

Although polymeric materials have not been the major cause of past accidents and fatalities, they are potentially significant contributors. Materials such as neoprene, polyvinyl chloride, rayon, and nylon are used in material-conveying devices and electrical insulation. Ventilation controls require jute, nylon, or polyester components. Urethane foams are applied on roofs, ribs, and stoppings.

The control of polymeric material usage in mines is rooted in the legislation that covers this facet of safety as well as all others. After experiencing over 10,000 miner fatalities between 1810 and 1910, the Organic Act was passed in 1910 and created the Bureau of Mines, primarily as an advisor to industry. One of its function, however, was to be to determine how to prevent fires and explosions. Public Law 49 of 1941 permitted federal officials to enter mines but only in an advisory capacity. The Federal Coal Mine Act of 1952 provided for enforcement of mandatory regulations.

Coal is only one product of the mining industry, and the mining of other materials was regulated in the Federal Metal and Nonmetallic Mine Safety Act of 1966. The Secretary of the Interior was given authority to promulgate and enforce standards concerning the types of material that could be brought into a mine. This bill, followed shortly by the Federal Coal Mine Health and Safety Act of 1969,

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recognized an urgent need to provide more effective means for improving coal mining techniques in order "to prevent death and serious harm . . ." and provided for promulgation and enforcement of mandatory safety and health standards. In addition, the Act cited, as one purpose, cooperation with the states in enforcement, research, and development.

On May 7, 1973, the Secretary of the Interior issued Secretarial Order No. 2953, which established the Mining Enforcement and Safety Administration (MESA). Essentially, this order separated from the Bureau of Mines the responsibility for administration of the Federal Metal and Nonmetallic Mine Safety Act of 1966 and, except for certain research provisions, the Federal Coal Mine Health and Safety Act of 1969.

The Federal Mine Safety and Health Amendments Act of 1977, which became effective March 9, 1978, repealed the Act of 1966, Section 405 of the Act of 1973, changed the name of MESA to the Mine Safety and Health Administration (MSHA), and transferred the unit from the Department of Interior to the Department of Labor.

MSHA, with about 3,400 employees, has as its primary goal the protection of the 400,000 people employed in the U.S. mining industry through enforcement, engineering, and education. The most formidable enforcement tool at its disposal is the closure order (i.e., if any polymeric material prohibited under regulation is present in a mine in quantity sufficient to create a condition of imminent danger, a MSHA inspector can issue a closure order halting all mining activity and withdrawing the miners until the condition is corrected).

Augmenting the efforts of federal and state regulatory agencies, the United Mine Workers of America (UMWA) attempts to eliminate the causes of accidents, fires, and explosions. The UMWA's Safety Division has increased its visibility and effectiveness in recent years. Following a reorganization in the spring of 1976, 49 full-time staff members were operating under the International Executive Board, with provision for an additional two. Of these, 40 are inspectors who are to spend 4 days each week carrying out inspection responsibilities.

Previous difficulties experienced by UMWA inspectors have been eliminated by inclusion of the Safety Division function in all the contracts, guaranteeing the right of access to any mine when requested by the Local Union Mine Health and Safety Committee. These inspectors are in communication with the state and federal regulatory agencies and can, in the event of any violation involving polymeric materials, request their intervention to resolve the problem. They also investigate and report on all fatal accidents, fires, and explosions involving UMWA members.

## APPENDIX A

### MINE ACCIDENT STATISTICS

#### A. 1 All U.S. Underground Mines

Underground metal and non-metal mines in the United States outnumber underground coal mines by more than six to one; yet, the reported fatalities resulting from all accidents, the fire incidence, and the fatalities resulting from fire are of the same order of magnitude for metal and non-metal mines and coal mines as shown in Table A-1. The figures indicate that underground coal mines are substantially more hazardous than underground metal and non-metal mines but that the number of fatalities resulting from fire is relatively small compared to those resulting from other causes. A substantial reduction in fire incidence after 1970 is also indicated and can be attributed to regulations resulting from Acts of Congress passed in 1966 and 1969.

*Table A-1, Statistics of Reported Fatalities and Fires in Underground Mines\*.*

Type of Mine (number of Mines)	Fatalities All accidents 1970-1974	Mine Fires, Annual Average			
		Incidence		Fatalities	
		1970- 1974	1950- 1970	1970- 1974	1970- 1974
Metal and non metal (15,000)	895	10	50	2**	--
(Coal (7,300))	857	10	50	2	3

NOTE: Data from Chaiken and Burgess, 1977.

\*A reported mine fire is one of longer than 30 minutes duration.

\*\*Excluded 91 fatalities in the 1972 Sunshine Mine Fire.

The U. S. mining industry uses the term "metal and non-metal" mines to refer to all mines other than coal. This terminology originated in Acts of Congress passed in 1966 and 1969 and is maintained throughout this volume.

The seriousness of the fire hazards in coal mines and their economic impact is further illuminated by the statistics presented in Table A-2.

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*Table A-2. Estimated Cost of Fires and Explosions.*

	1971--1974	1960--1964
No. of Fires	80 (1970 - 1974)	280 (1960 - 1964)
No. of major explosions*	3 (1970 - 1974)	6 (1960 - 1964)
Production loss, million tons	5	34
Wages lost, millions of 1974 dollars	28	190
Recovery costs, millions of 1974 dollars	20	80
Idle-plant depreciation, millions of 1974 dollars	10	68
Taxes lost, millions of 1974 dollars**	20	115

NOTE: Data from Chaiken and Burgess 1977.

\*Five or more fatalities.

\*\*20 percent on wages and 39 percent on assumed profit of \$1.50 per ton of coal lost and on sum of idle-plant and recovery costs.

**A. 2 U. S. Metal and Non-Metal Mines and Operations**

Fatality statistics are presented in Table A-3 (Secretary of the Interior 1974) for metal and non-metal mines and are broken down by underground mines, surface mines, and mills and by causes for 1970-1974. The same statistics are presented as a percent of total causes in Figure A-1, and Figure A-2 presents the percentage distribution for the various operations and causes for 1974.

The fatality frequency rate (number of men killed per million man-hours worked) in metal and non-metal mines was 0.36 in 1974, lower than but similar to the rate in the four preceding years. The major cause of work-related deaths, falls of ground, accounts for the same percentage as in the past in underground mines.

It is also evident that metal and non-metal mine fires generally represent only a small fraction of fatality causes (an exception occurred in 1972 when a fire in the Sunshine mine killed 91).

The more general statistics for metal and non-metal underground mines are given in Figures A-3 and A-4, which specifically present the causes and locations of fires

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*Table A-3. Fatalities at Metal and Non-Metal (stone, sand, and gravel) Operations by Causes, 1970-1974.*

Cause	Year				
	1970	1971	1972	1973	1974*
Underground mines:					
Fall of roof, face or back	20	20	20	14	18
Slips or falls of persons	5	5	8	5	8
Haulage	16	3	4	10	4
Sliding or falling materials	2	4	2	-	2
Machinery	7	3	3	6	5
Explosives	2	5	4	3	2
Electricity	2	1	1	3	1
Handling materials	1	2	1	3	3
Suffocation	3	10	-	3	-
Mine fires	1	2	9	2	-
Inrush of materials or water	1	-	-	-	2
Handtools	-	1	-	-	-
Helicopter crash	-	-	-	-	1
Unknown	-	-	-	-	1
Totals	60	56	134	49	50
Surface mines:					
Machinery	22	27	21	34	30
Haulage	14	21	25	23	21
Falls of persons	8	10	6	9	6
Handling of materials	4	4	3	6	6
Falls of ground	9	2	5	8	7
Electricity	10	2	3	8	5
Sliding, falling materials	1	-	2	3	5
Explosives	2	3	-	1	4
Mine fire	1	-	-	-	-
Miscellaneous	2	-	-	1	1
Totals	73	69	65	93	85
Mills:					
Machinery	12	14	19	9	9
Haulage	6	8	4	9	2
Handling materials	7	2	3	2	3
Sliding, falling materials	3	4	3	1	2
Falls of persons	3	5	5	7	3
Electricity	1	1	1	5	1
Explosion of gas	-	1	-	-	-
Explosives	-	1	-	-	-
Suffocation	-	3	-	-	-
Miscellaneous	-	-	-	-	2
Totals	32	39	35	33	22
GRAND TOTALS	165	164	234	175	157

NOTE: Data from Secretary of the Interior, 1974.

\*Preliminary data.

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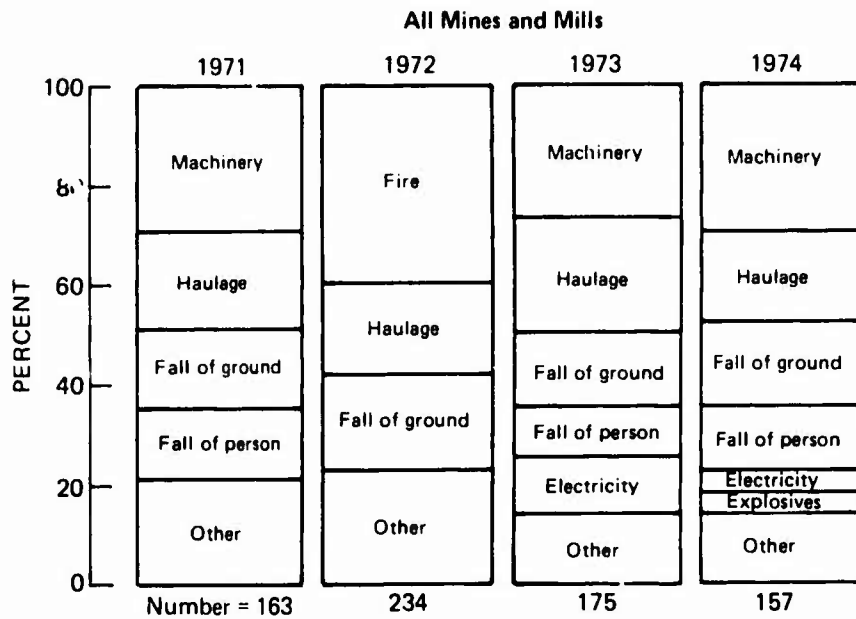


Figure A-1. Fatalities in metal and non-metal operations, percent of total by major causes, 1971-1974 (Secretary of the Interior, 1974).

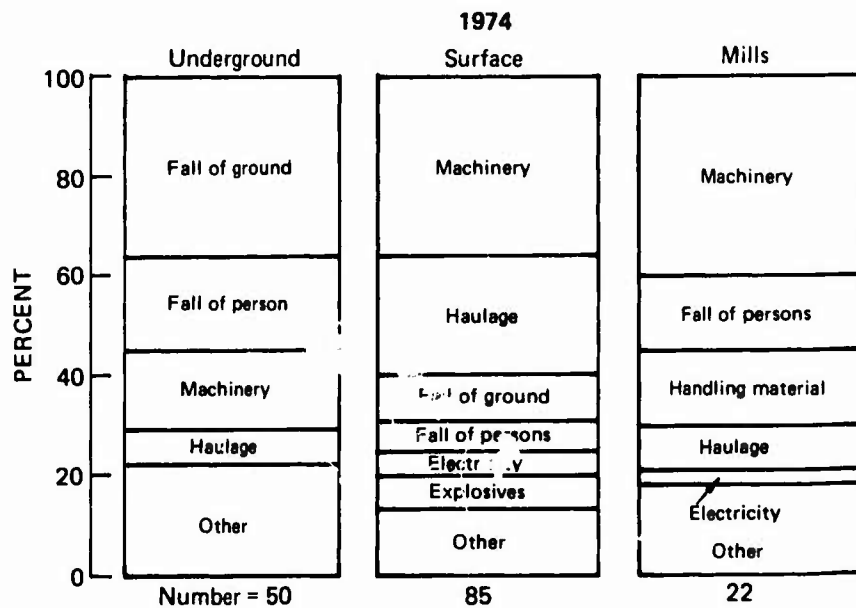
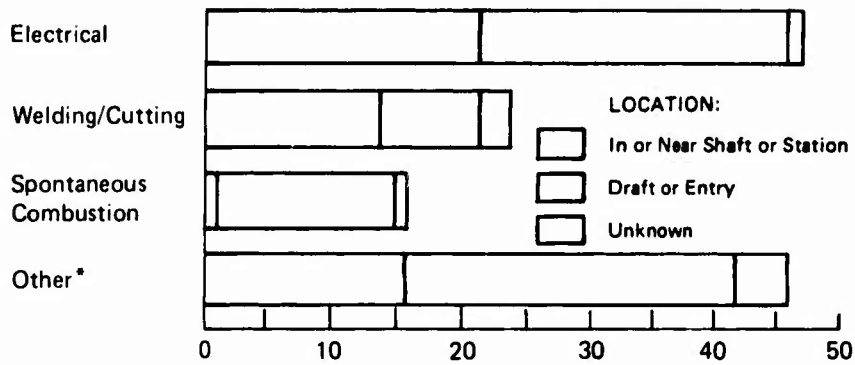


Figure A-2. Fatalities in metal and non-metal operations, percent of total by type of operation and major causes, 1974 (Secretary of the Interior, 1974).

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\*Includes friction, combustible waste ignition, smoking, combustible gas accumulation, blasting, and unknown.

Figure A-3. Cause and Location of Fires and Explosions in Underground Metal and Non-Metal Mines, 1945-1974 (Johnson, 1976).

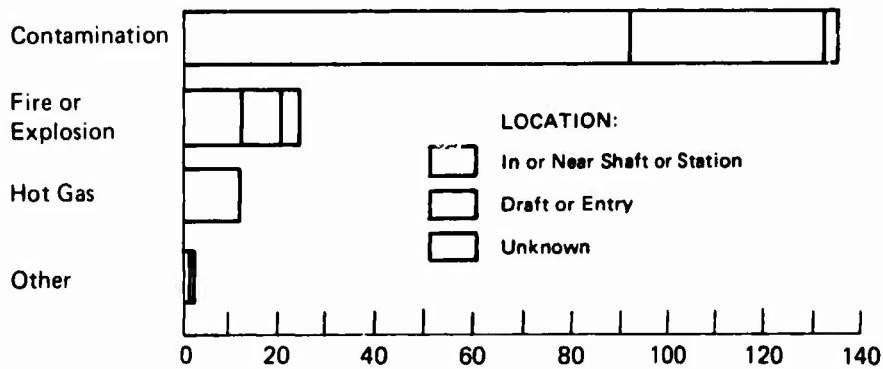


Figure A-4. Cause and Location of Fatalities and Injuries from Fires and Explosions in Underground Metal and Non-Metal Mines, 1945-1974 (Johnson, 1976).

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and explosions and the causes and locations of fatalities and injuries between 1945 and 1974 period. These statistics indicate that most fires occur in shafts and drifts because of electrical defects, waste heat, and friction causes and that most fatalities also occur in shafts and drifts because of contamination sources.

### A. 3 U.S. Coal Mines

Coal mine fatalities, as a rough indication of the seriousness of coal mine disasters, are broken down by cause or source for 1970 in Table A-4 to indicate the relative importance of these causes.

The number of coal mine fires are presented in Figure A-5 for 1954-1974.

A more illuminating set of statistics is presented in Figure A-6, which presents data on the number of injuries and deaths and the number of underground fires for 1954-1973. These figures seem to indicate that safety in this particular area, contrary to some arguments, has been improved by regulation. The dramatic effect of applying legislated standards and procedures is even more apparent when Tables A-5 and A-6 are considered. These tables present figures for fires and explosions and their estimated cost for time periods coinciding with significant legislative actions.

For the lay reader all the above figures may be impressive but without meaningful significance. Mitchell and Verakis (1975) help to clarify the situation by noting that recovery of a mine following a major fire or explosion diverts funds and people from expansion to nonproductive activities. Seldom will a mine be reopened in less than 100 days following a major fire or explosion, and then it often takes years before pre-disaster production and cost-effectiveness can be regained. In one mine, a fire followed by a series of explosions destroyed the retreat workings so completely that eight years of redevelopment were needed to return the mine to a profitable status.

To provide the reader with a clearer understanding of coal mine fires, a study of U.S. coal mine fires conducted by the U.S. Bureau of Mines (1973) is summarized below. This study was initiated in recognition of the fact that several areas of underground coal mines have obvious fire potential. Some of these, like belt heads, have been improved recently by the provision of standby devices. Others have not been studied systematically and improvements have not been incorporated even though fire suppression systems are available. Face machinery, particularly without a water supply, falls in this latter category. In the Bureau of Mines study (1973), mine inspector reports for 1952 to 1970 were used to review the fire histories of electric face machinery.

During this period there were 386 fire incidents; these fires are broken down by machine in Table A-7 and their chronology is shown in Figure A-7.

Table A-8 indicates the number of electrical fire incidents per state for 1952-1970. Eighty percent occurred in West Virginia, Kentucky, and Pennsylvania. West Virginia accounted for the most fires until 1968 when Kentucky had the

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Table A-4. Fatalities at Coal Mines, by Cause, 1970.

Falls of roof and face (includes fatalities from fall of high wall at surface operations)	11	36
Haulage	47	18
Machinery	43	17
Explosions, gas or dust	41	16
Electrical	17	7
All other	14	6
	255	100

NOTE: Data from Secretary of the Interior 1970.

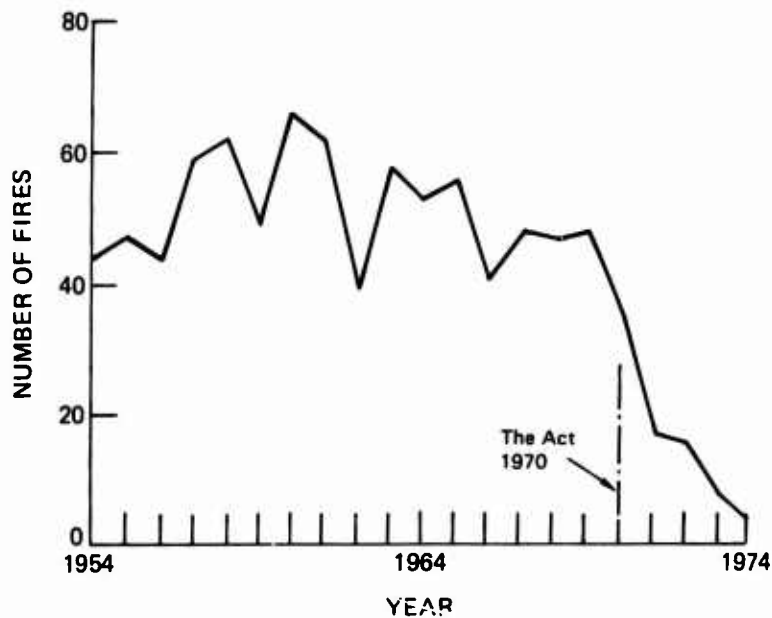


Figure A-5. Fires in Underground Coal Mines 1954-1974 (Mitchell and Verakis, 1975).

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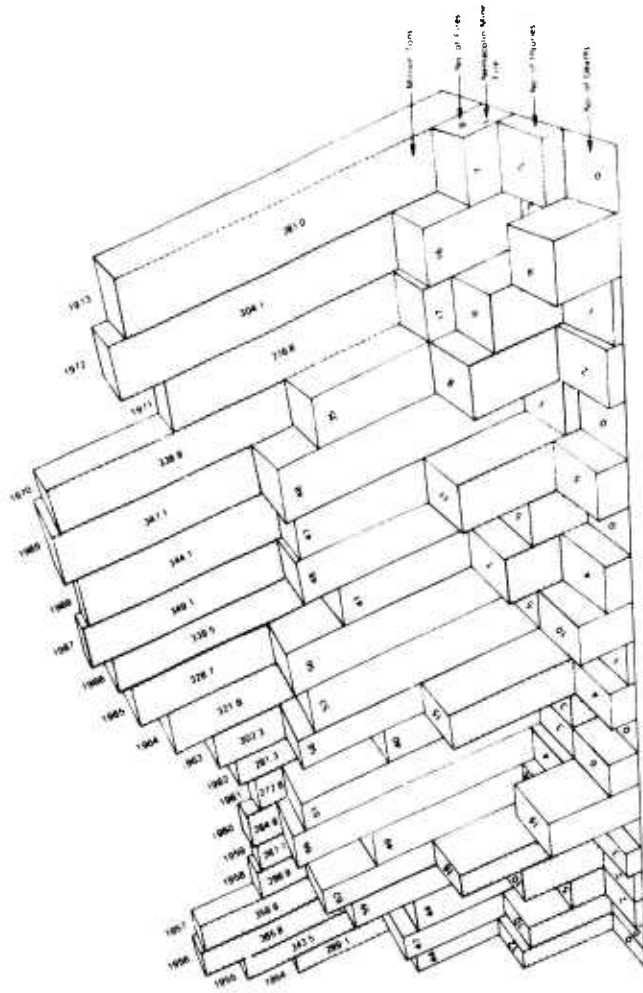


Figure A-6. Data on Underground Coal Mine Fires, 1954-1973 (Nagy and Hall, 1974).

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*Table A-5. Fires and Explosions in Underground Coal Mines.*

	----- PERIOD -----		
	1970-74	1960-64	1965-69
Production, million tons	1440	1498	1723
Number of man-hours, millions	824	823	768
Tons per man-hour	1.8	1.8	2.2
Number of fires	80	280	245
Number of major explosions*	3	6	5
Number of injuries from fire and explosion			
Fatal	63	137	234
Nonfatal	104	189	141

NOTE: Data from Mitchell and Verakis 1975.

\*Major explosions are those in which five or more lives are lost.

*Table A-6. Estimated Cost of Fires and Explosions.*

	PERIOD*----	
	1960-63	1971-74
Production lost, million tons	34	5
Wages lost, millions of 1974 dollars	190	28
Recovery costs, millions of 1974 dollars	80	20
Idle-plant depreciation, millions of 1974 dollars	68	10
Taxes lost, millions of 1974 dollars	115	20

NOTE: Data from Mitchell and Verakis 1975.

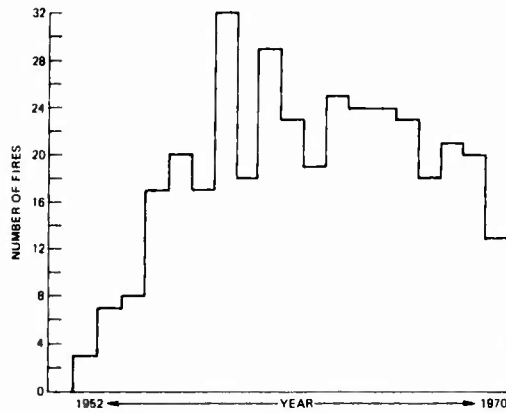
\*The year 1970 is not included because during that transitional period implementation of the Act is not considered to have been as effective as in subsequent years and thus its inclusion would bias the analysis. To compensate for that, the year 1964 is not included in the pre-Act period; however, its inclusion would not have reduced losses.

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*Table A-7. Number of Fires per Machine Type, 1952-1970.*

Machine	Number of Fires
Cutting Machine	169
Shuttle Car	74
Continuous Miner	30
Loading Machine	30
Roof Bolter	21
Roof Drill	4
Face Drill	3
Locomotives & Trucks	36
Non-face Machines	19

NOTE: Data from U.S. Bureau of Mines 1973.



*Figure A-7. Chronology of Mine Electrical Machinery Fires, 1952-1970 (U.S. Bureau of Mines, 1973).*

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*Table A-8. Geographic Location and Number of Electrical Fires, (1952-70).*

State	No. of Fires
West Virginia	167
Kentucky	69
Pennsylvania	71
Virginia	25
Ohio	22
Alabama	8
Tennessee	6
Indiana	5
Colorado	5
Illinois	7
Utah	1

NOTE: Data from U.S. Bureau of Mines, 1973.

most. Between 1966 and 1970, the number of fires per year rose in Kentucky and decreased in Pennsylvania. The reasons for these trends are not clear but the Kentucky situation probably reflects a number of new mine openings.

Beyond data on the type of machine and the physical location of the mine, the inspector reports do not necessarily provide all of the data that might be needed to assess the facts surrounding the fire. In many cases, the reports contain the subjective opinions of the inspectors. In more recent years the completeness of the reports improved markedly; therefore, further discussion of the data will concentrate on the 1960-1970 period even though these data are not always complete and the number of data points in each tabulation vary. One fact, however, is clearly established: of the 386 machine fires, all but two were electrically initiated.

### A. 3.1 Seam Height Versus Fire Frequency

Using the 1960-1970 data, a number of observations can be made. The coal seam height and fire incident data show that fires are more prevalent in coal seams 30 to 80 inches in height. These data, however, most likely reflect the concentration of mining activity in the "low" coal seams rather than characteristics associated with these seams. Table A-9 relates fire incidents with coal seam height.

### A. 3.2 Mine Production Versus Fire Frequency

Those mines from which 500 to 2,000 tons of coal per shift are mined show the

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*Table A-9. Coal Seam Height and Number of Electrical Fires\*.*

Coal Seam Height (in.)	No. of Fires
0-30	7
30-50	96
50-80	88
80-120	23
120-200	5
200-400	1

NOTE: Data from U.S. Bureau of Mines 1973.

\*Only 220 out of 262 reports stated the height of the seam.

*Table A-10. Mine Production and Number of Electrical Fires.*

Production (tons/shift)	No. of Fires*
0-100	9
100-500	56
500-1000	43
1000-2000	48
2000-3000	19
3000-4000	13
4000-7000	2
7000-10,000	2

NOTE: Data from U.S. Bureau of Mines 1973.

\*Only 192 out of 262 reports stated the production of the mine.

greatest number of fires. Mines producing 100 to 500 tons of coal per shift are second in the number of fire incidents. Table A-10 relates the number of fires to mine production. There is nothing in the available information that shows this to be more than coincidence; however, a possible factor is that conventional mining is the

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prevalent method in the smaller tonnage mines and the primary face type of cutting machinery used with conventional mining is the most frequent electrical fire source.

Reviewing the type of cutting machine involved in a sample of 49 fires showed that 42 fires occurred on Joy machines, 5 fires on Jeffrey machines, and 2 on Sullivan machines. Models 10, 11, and 12 of the Joy cutting machines accounted for 40 of the 42 fires and Models 15 and 16 for the remaining 2. The Jeffrey and Sullivan machines are even older than the Joy machines, but the machine features that caused the fires have been corrected on newer models.

### A. 3.3 Mine Size Versus Extinguishment Time

The apparent correlation between mine size and fire incidents carries over into extinguishment. The time required to fight and extinguish machine fires is greatest in the mines producing 100 to 200 tons per shift. If fires where the mine had to be sealed are excluded, the data obtained from the inspector reports for 1960-1970 show that the mean minimum time required to extinguish a fire in mines producing 500 tons per shift was 9.8 hours. The extinguishing time decreased to 5.3 hours for mines producing 2,000 tons per shift and to 1 to 2 hours for mines producing more than 4,000 tons per shift. Even though these values are dependent on the number of fires occurring in the different size mines, which makes the time-loss values for the larger production mines less statistically accurate, the smaller production mines do require more time for fire extinguishment. When fires that required sealing the mine were included in the extinguishing time data, the weighted mean minimum extinguishing time increased markedly, reflecting delays of up to 120 days before consideration could be given to reopening. During the past 10 years, on an average of one machine fire in every four has resulted in sealing.

### A. 3.4 Fire Initiation

The important information to be derived from the fire histories is the source of ignition and those factors that propagate an electrical failure into a fire. The predominant cause of electrical failure has been the trailing cable supplying power to the machine that has caused some 70 percent of all fires. (In the past a differentiation was made between fires where the cable was coiled on the reel and those where it was trailing the machine. After an analysis of the data, however, the U.S. Bureau of Mines concluded that there should be no distinction between such fires because most fires in the cable reel were due to cable damage that occurred off the reel. In the remainder of this discussion, therefore, fires will be divided into those occurring on the machine and those relating to the cable which are grouped as off the machine.)

Between 1960 and 1970, 246 inspector reports contained sufficient detail to permit the source and the cause of the electrical ignition to be identified and these fires are categorized in Figure A-8. One hundred seventy-five were caused by cable failure and the remaining 71 by on-machine ignitions. To further assess the igni-

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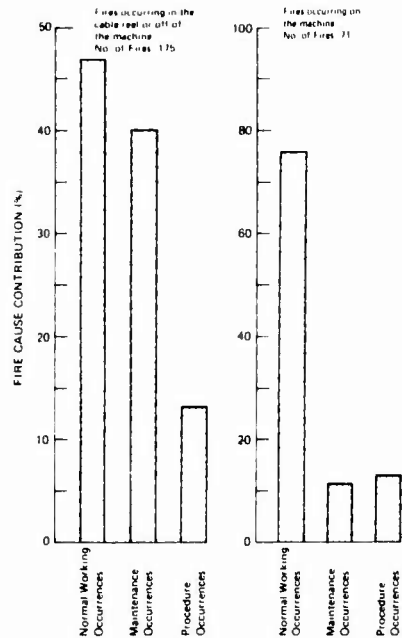


Figure A-8. Fire Initiation Factors and Contribution (U.S. Bureau of Mines, 1973).

tions, three classifications of causes have been established: normal working operations, maintenance operations, and procedural occurrences.

The fires occurring off the machine under normal working operations include trailing cable run overs, crushes, snags on the cable guide, and over-heats on the cable reel in which the trailing cable was judged to be properly spliced and in good condition. Fires included in the maintenance category resulted from trailing cable that or switches or circuit protective devices that were not properly maintained. Those fires that occurred from inadequate, inoperative or non-existent circuit protection devices, misuse of equipment, or the equipment design were placed into the procedure category. The data presented in Figure A-8 show that fires occurring off the machine are significantly associated with equipment maintenance. Fires that occur on the machine, however, usually are attributable to normal working operations. These fires mainly result from short circuits in the cutting motor leads, contactor compartments, and connections on cutting machines.

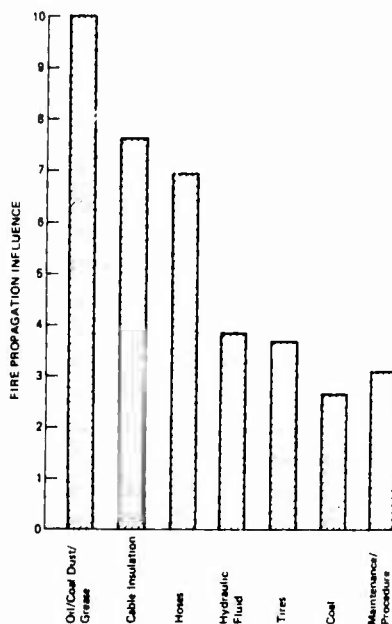
### A. 3.5 Fire Propagation

Although electrical causes are the source of ignition, fires cannot result or a-

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chieve any great magnitude without available fuel. Information obtained from the mine inspector reports permitted only a subjective evaluation of those factors that were primarily involved in the propagation of the fires, but the data are sufficient to permit definition of the major factors. Figure A-9 illustrates the relative influence of seven factors associated with fire propagation. The accumulation of oil, coal dust, and grease present on the machinery was judged to be the major contributor to fire propagation. Other factors, in decreasing order of importance, were the electrical cable insulation, hydraulic hoses, hydraulic fluid, tires, coal, or maintenance and procedure factors previously defined. The latter four factors were involved less than half as often as the three major factors. The difference between the influence of hydraulic hoses and hydraulic fluid on fire propagation is due to the fact that hoses contain the fluid and prevent its ignition even though the hoses have been ignited. The very limited use of flame-resistant hydraulic fluid did not allow assessment of its role in fire propagation. Direct coal ignition by electrical failure is a reasonably minor factor even though most fires occur in highly volatile bituminous seams. However, this refers only to propagation on the machine and does not refer to fire spread to roof or rib.

A comparison of electrical fire propagation factors during 1952-1959 with those during 1960-1970 shows only one significant trend. In both periods, the major contributors to fire propagation were the oil, coal dust, and grease accumulation;



*Figure A-9. Electrical Fire Propagation Influence, 1960-1970 (U.S. Bureau of Mines, 1973).*

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cable insulation; and hydraulic hoses. The influence of the hydraulic fluid was greater during the earlier period, probably reflecting the technological advances in hose materials and equipment design and the more recent practice of segregating electrical and hydraulic lines.

**A. 4 United Kingdom Coal Mines**

In order to put domestic coal mine fire problems in perspective, the following statistics dealing with coal mine fires and explosions in the United Kingdom are presented. Data on fires in United Kingdom underground coal mines between 1968 and 1972 are given in Table A-11 and on explosions, in Table A-12 (Her Majesty's Stationery Office 1973). Figure A-10 (Her Majesty's Stationery Office 1975) presents injury and fatality statistics for 1947 through 1975.

*Table A-11. Underground Fires at Coal Mines in the United Kingdom, 1968-1972.*

Cause of Fire	1968	1969	1970	1971	1972
1. Safety lamps	--	--	--	--	--
2. Shotfiring	1	--	1	--	--
3. Electricity	14	11	8	7	10
4. Spontaneous combustion	7	1	7	7	1
5. Mechanical friction					
(a) Belt conveyors	26	24	32	16	16
(b) Frictional sparking, cutting, or power loading machines	1	--	--	1	--
(c) Others	6	4	3	5	2
6. Contraband	1	1	--	2	2
7. Locomotives	5	2	2	4	3
8. Burning appliances (e.g., oxy- acetylene burners)	--	--	--	1	1
9. Miscellaneous or unknown causes	4	1	1	3	--
TOTAL	65	44	54	46	35

NOTE: Data from Her Majesty's Stationery Office, 1973.

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*Table A-12. Underground Explosions at Coal Mines in the United Kingdom, 1968-1972.*

Cause of Explosion	1968	1969	1970	1971	1972
1. Safety lamps					
(a) Flame	--	--	--	--	--
(b) Electric	--	--	--	--	--
2. Shotfiring					
(a) By explosive					
(i) Unsheathed permitted explosive	--	--	--	1	--
(ii) Equivalent sheathed explosive	2	3	2	--	2
(iii) Others	--	--	--	--	--
(b) By exploder or cable	--	--	1	--	--
(c) Unknown	--	1	--	--	--
3. Electricity					
(a) At face working or roadhead	2	4	2	1	--
(b) Back from face	2	--	--	--	1
4. Underground fires					
(a) Spontaneous combustion	--	1	--	--	--
(b) Mechanical friction	--	--	--	--	--
(c) Others	--	--	--	--	--
5. Contraband	--	--	--	--	--
6. Frictional sparking by cutting or power loading machine	21	19	18	14	5
7. Miscellaneous or unknown causes	2	1	1	--	1
TOTAL	29	29	24	16	9

NOTE: Data from Her Majesty's Stationary Office, 1972.

APPENDIX A

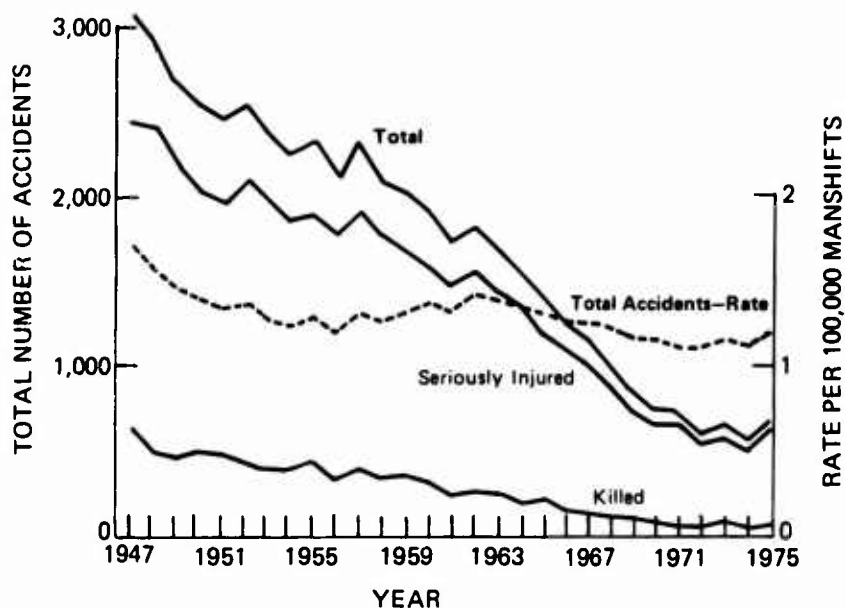


Figure A-10. Accident Rate from All Causes at Coal Mines in United Kingdom, 1947-1975 (Her Majesty's Stationary Office, 1975).

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## APPENDIX B

### MINE SAFETY AND HAZARD CONTROL THROUGH LEGISLATION

(Secretary of the Interior 1974, Mitchell and Verakis 1975,  
U.S. BuMines 1972, *Mesa Magazine* 1977, Barrett 1977).

As in any other industrial venture, the prime objective in mining is the highest possible production at the lowest possible cost. In the early days of mining, human safety aspects probably were low priority concerns if they were considered at all. As society became more complex, the value of human life and recognition of hazards increased, and safety aspects of mining gradually were considered. Progress in this area was slow, however, and it became necessary to impose government regulations in most advanced nations to implement improvements in mining operations. In the United States, records of occupational injury, illness, and death have shown mining to be one of the most hazardous of all industries, and neither the industry nor the states under their own individual laws and regulations have made much progress in protecting mine workers from harm.

Fires and explosions in underground coal mines were the major stimuli of legislative action to upgrade mining health and safety laws. The Organic Act of 1910, the first major legislation affecting the coal industry, was enacted to curb the high death toll of fires and explosions (during the first decade of this century, mine explosions took the life of one miner for each million tons of coal produced). The next piece of major mine safety legislation, the Federal Coal Mine Safety Act of 1952, was a response to disasters in Illinois — in the Centralia No. 5 (1947) and the Orient No. 2 (1951) mines — and was enacted in recognition of the fact that earlier efforts had been effective.

This Act (as amended in 1966) charged the U.S. Bureau of Mines to eliminate underground coal mining disasters without attacking the nondisastrous but statistically more frequent day-to-day accidents involving four or fewer men. The disaster philosophy that generated this Act, however, had many shortcomings: provided little protection in the primary accident areas; and, except for a few vague requirements, provided for no mandatory protection of the miners' health and welfare.

Congress passed the Federal Metal and Nonmetallic Mine Safety Act in 1966. This Act thrust upon the Secretary of the Interior the responsibility for promoting and for minimizing fatalities, injuries, and occupational illnesses in other than coal mines by developing health and safety standards and by enforcing those standards through mine inspections and investigations. In addition, the Act stipulated that mine health and safety was to be promoted through education and training, tech-

## APPENDIX B

nical assistance, and health and safety research and provided for cooperation with the states through a system of state plans.

At this time, public awareness began to focus sharply on the severe health hazards that were present in underground coal mines and the alarming incidence of "black lung" disease (pneumoconiosis) among coal miners. It also became increasingly apparent that the federal government had not and was not responding to the problem. On November 20, 1968, a major disaster in the form of a coal mine explosion occurred at the Consolidation Coal Company's No. 9 Mine at Farmington, West Virginia, and 78 men were killed.

The occurrence of this explosion during the period of intense public controversy over "black lung" disease led to an entirely new philosophy on health and safety in the coal mining industry. In early 1969, Congress began hearings to provide "strong and positive approaches towards improving the health and safety conditions for our nation's coal miners." From those hearings came the Federal Coal Mine Health and Safety Act of 1969. To the uninitiated, the parts of the Act directed to preventing and controlling fires and explosions appear to be only a small part of the whole, but in reality, more than half of the Title I and III requirements are concerned with fires and explosions.

The 1969 Act retained regulations concerning mine closure in event of imminent dangers and unwarrantable failure on the part of the operator and also provided for penalties to be imposed for infractions of statutory requirements and mandatory provisions. It also removed the distinction between gassy and nongassy mines, eliminated the Title I and Title II concept, stipulated that all underground coal mines be treated on the same basis, and contained a comprehensive grouping of statutory requirements covering 26 topics and including 35 mandatory provisions. On November 20, 1970, the original statutory requirements for mine ventilation were further refined by a comprehensive listing of mandatory regulations and instructions.

The U.S. Department of the Interior Mining Enforcement and Safety Administration (MESA) was created in 1973 from organizational components of the U.S. Bureau of Mines. It was to carry out its programs under the mandate of two laws, the Federal Coal Mine Health and Safety Act of 1969 and the Federal Metal and Nonmetallic Mine Safety Act, passed in 1966, and combined the various talents of some 3,400 persons in a variety of functions and programs to reduce or eliminate death, injury, and disease among the 400,000 employees in the U.S. mining industry. The agency integrated its programs through organizational functions of an enforcement activity that ensured compliance with federal regulations, a technical support activity that served as the agency's engineering arm, and an education and training activity (including the recently completed \$20 million National Mine Health and Safety Academy).

Although the 1969 and 1966 Acts provided MESA with different sets of enforcement tools for its specific inspection forces, both contained powerful incen-

## MINES AND BUNKERS

tives for compliance (i.e., MESA had the authority to issue a notice of violation, which sets a time period for correcting the violation, and to close a mine in an immediately dangerous situation). The closure order is part of an overall enforcement scheme that contains several key provisions.

1. When miners are found to be in imminent danger, the affected area of the mine is closed immediately by an inspector until the danger is over.
2. When violation of any mandatory health or safety standard is discovered, the mine operator is issued a notice that establishes a date by which the violation must be corrected and also is assessed a civil penalty.
3. When the operator does not correct the violation within the time set by the notice, the affected area of the mine is closed until the violation is corrected.
4. A violation resulting from the operator's "unwarrantable failure" to comply with a health or safety standard is noted on the first occurrence, and, if it occurs again within a 90-day period, the mine or the affected portion is closed immediately until the violation is abated.
5. Mandatory civil penalties are assessed for each violation of a health or safety standard up to a maximum amount of \$10,000 per violation.
6. Knowing or willful violations are covered by criminal penalties, including penalties imposed upon corporate officials or agents who may have knowingly authorized or permitted violations to occur.

These enforcement powers, especially the ability to close a dangerous section of the mine, give the coal mine inspector forceful, persuasive tools to ensure compliance with the law and, most importantly, result in safer and healthier mines.

The 1966 Act permitted inspectors to issue similar notices of violation and closure orders at metal and non-metal mines and mills but did not provide for mandatory civil penalties for each violation of health and safety standards as the coal act does. It further permitted individual states to operate a mine inspection system in accordance with federal standards and under MESA's supervision. This state plan system helped guarantee that the vast number of metal and non-metal mine operations would be inspected under federal standards without increasing the size of the federal inspection force. Six states were operating under such plans.

The timetables for promulgation of both safety and health regulations for metal and non-metal operations were identical; however, MESA followed a completely different procedure for coal safety regulations and used a third set of procedures for coal health standards. A major difference between the metal and non-metal rule-making procedures and the coal procedures was that metal and non-metal regulations were proposed and finalized in conjunction with an advisory committee drawn from representatives of labor, industry, and state inspection agencies. This committee advised the Secretary of Interior, who ultimately promulgated all federal mining regulations. No such advisory group existed for coal regulations, but the 1969 Act did stipulate that health regulations be formulated with the Secretary of Health, Education, and Welfare.

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Because of these and other discrepancies, Congress enacted the Federal Mine Safety and Health Act of 1977 (Public Law 9-173 as amended by Public Law 95-164). Basically, this act extends to workers in non-coal mines and milling operations the same protections that coal miners already have under the law. Metal and non-metal activities range from large open pit and multilevel underground metal mines to countless small sand and gravel pits, quarries, and dredging operations.

Three new requirements in particular represent significant changes for both MESA (including a change in name to the Mine Safety and Health Administration [MSHA]) and operators in the metal and non-metal area:

1. A requirement for at least four mandatory underground inspections, the same number as required for underground coal operations but three more complete inspections than had been required for the non-coal mining industry,
2. A new mandatory requirement calling for two surface inspections annually.
3. The imposition of mandatory civil penalties.

The imposition of mandatory civil penalties also is provided as a tool for enforcing operator compliance throughout the mining industry (although such penalties were used with coal mine operators since 1970, they could not be imposed on metal and non-metal mine operators).

The 1977 Act continues to provide for closure of all or part of a mine or withdrawal of miners from affected areas when an inspector finds a condition that constitutes "imminent danger". In addition, the "unwarrantable failure" mine closure order that was not formerly applicable to metal and non-metal mines industry is now applied to all of mining. This provision establishes a sequence for the issuing of an order to withdraw miners from hazardous areas based on a violation that was due to the operator's unwarrantable failure to comply with the law and that, while not constituting imminent danger, could "significantly and substantially" contribute to the cause and effect of a mine safety or health hazard.

Although requirements under the new legislation are aimed at streamlining the overall standards-making process, the changes most affect rule making for the metal and non-metal industry profoundly. For example, whereas all coal industry health and safety regulations have been mandatory, existing non-coal industry standards were both mandatory and "advisory". The 1977 Act requires that an advisory committee be named to review all these metal and non-metal advisory standards and to recommend which ones should be made mandatory. The Federal Metal and Non-metal Mine Safety and Health Advisory Committee, for which there was no counterpart in the coal rule-making process, has played a large role in developing non-coal standards; it will be discontinued under the new law, and hearings on metal and non-metal standards will become less formal. All in all, standards-making for the non-coal industry under the 1977 Act will be far less cumbersome and time-consuming than before.

The extent of fire safety enforcement by regulatory agencies varies a great deal between the various industries. In international shipping, for example the least

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stringent fire safety requirements are set by Intergovernmental Maritime Consultative Organization (IMCO), the international regulatory body. The requirements of the "classification societies" governing insurance sales are more strict, providing an incentive for the owner to set fire safety standards above minimum. The actual fire safety regulations adopted by most owners, however, are usually more stringent than those required of him by agencies since it is his own prime concern to protect his investment, vessel, and cargo.

In contrast, the mining industry in the United States and most other developed nations is controlled to a great degree by government. This extensive involvement of government should not be considered alarming; it evolved from the obvious necessity to protect the life and safety of employees of this extremely hazardous industry and the public outcry and pressures based on recognition of this necessity.

Another overwhelming consideration is that no individual mine owner could afford the extensive development efforts and research activities upon which the regulatory agencies base their widespread regulatory, enforcement, and training services. Besides developing and modifying regulations and enforcing them through an extensive inspection system, MSHA provides a well organized training program for miners and seeks continual input from the mining community throughout the entire rule making process.

Finally, the U.S. Bureau of Mines conducts numerous research programs concerning mine fire and explosion prevention at its own facilities, at private institutions, and in cooperation with industrial and academic research organizations. The results and findings of these research programs are made available to mining and supporting industries through publications and technology transfer seminars. The subject of these research programs are the basic elements of fire dynamics as well as practical approaches to fire detection, prevention, and suppression. The successful conclusion of these research activities is expected to provide the elements needed for a sophisticated, systems approach to the development of design criteria for mine safety and hazard control.

**APPENDIX C**

**SMOKE HAZARDS AND MEASUREMENTS  
OF SMOKE OPACITY**

**Excerpt from J. R. Gaskill, "Smoke Hazards and Their Measurement;  
A Researcher's Viewpoint, *Journal of Fire and Flammability*, 4 (1973):  
279–298**

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[Smoke is defined] as the airborne products evolved when a material decomposes by pyrolysis or combustion. Smoke may contain gases, liquid or solid particles, or any combination of these.

*Table 3. Smoke Hazards in Unwanted Fires*

	Property	Hazard	Measurable
1	Opacity	Hinders Escape and Rescue	Yes
2	Lachrymatory Irritant	Induces Panic	No Being Studied
3	Toxicity (Direct)	Incapacitates Kills	No Being Studied
4	Toxicity (Indirect)	Anoxia	No Being Studied
5	Heat	Sears Resp System	No Being Studied
6	Synergism	Combined Effects	No Being Studied

### SMOKE OPACITY

Smoke opacity, or light obscuration, is commonly measured by determining the attenuation of light from a source through a column of smoke onto a photoelectric cell. Table 4 shows the methods commonly used in this country for this purpose. The Steiner Tunnel (ASTM E-84), originally designed to measure the spread of flame across a ceiling surface, has been adapted to measure the obscuration of smoke as it passes through the exit flue. At the present time, this is the only smoke test commonly accepted. However, it has been subject to criticism both because of the location of the sample (some think that wall mounting or floor mounting would be preferable in some cases) and because it represents a limited set of fire parameters.

The XP2 Chamber (ASTM-D 2843) was developed and is used for measuring smoke density from burning plastics. It has been criticized both because of the small size of the sample involved and also the fact that it represents a single set of fire conditions. The NBS Chamber and the LLL modification both measure smoke density - light obscuration - by subjecting the sample to radiant heat (pyrolysis) or to radiant heat in the presence of a pilot flame (pyrolysis plus combustion). The LLL modification to date has consisted of adding a ventilation capability, and we are currently developing a higher radiant heat source. Both the NBS Chamber and the LLL modification have not presently been accepted as standard methods, but are used by a large number of laboratories throughout the country.

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Table 4. Comparison of Smoke Test Systems for Measuring Smoke Obscuration

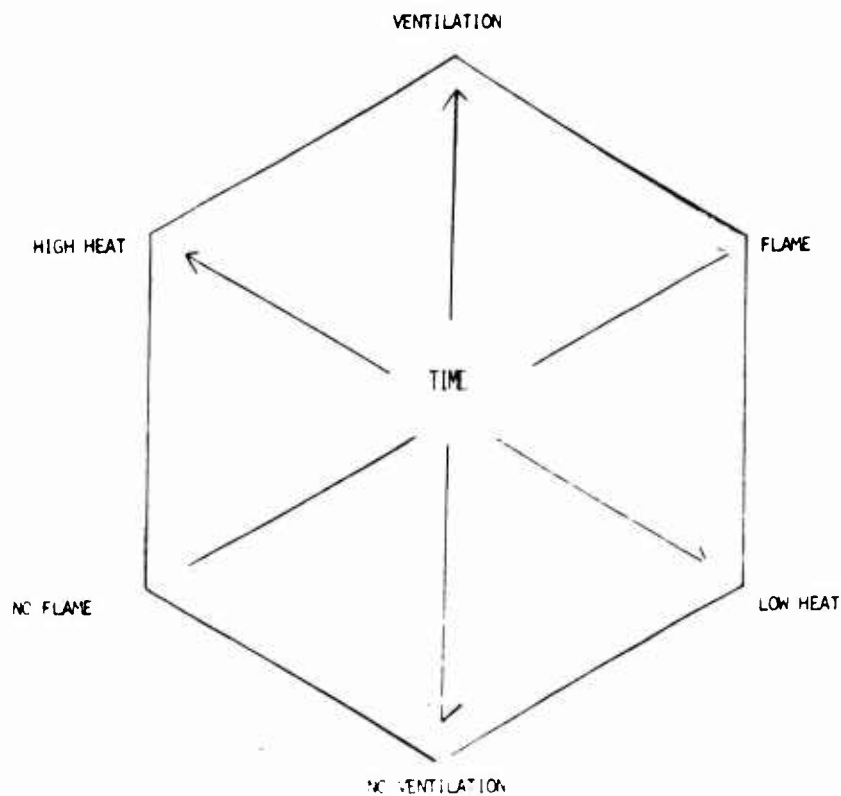
	Steiner Tunnel	XP2 Chamber	NBS Chamber	LRL Chamber
<b>Sample:</b>	Large 36 ft <sup>2</sup>	Small 1 m <sup>2</sup> std (4 m <sup>2</sup> possible)	Small 6.6 m <sup>2</sup>	Small 6.6 m <sup>2</sup>
<b>Test duration (min)</b>	Variable 10	~0.1-1 in 4	0.002-1 in ≤.30 usually	0.002-1 in 30 usually
<b>Heat:</b>	Flame :50% <sup>a</sup>	Flame 40 psi to 5 psi	Radiant + optional flame +20%	Same as NBS 800%
<b>Ventilation:</b>	240 linear ft/min :35%	None Possible	None None <sup>b</sup>	Variable 0 to 20 changes/hr
<b>Heat transfer mode</b>	Primarily convection	Convection/radiation	Radiation + some convec- tion if flaming	Same as NBS
<b>Smoke production mode</b>	Pyrolysis + combus- tion progressing along surface penetration	Combustion-total involvement to partial involvement	Pyrolysis without flame, pyrolysis + combustion with flame—both on sur- face + penetration	Same as NBS, higher heats may result in mostly com- bustion smokes
<b>Smoke measurement:</b>				
<b>Method</b>	Integrated rate	Integrated rate	Accumulation, maximum rate is measured, as is obscuration time	Same as NBS
<b>Reporting</b>	Area under obscura- tion vs time curve compared to that for red oak.	SDR (smoke density rating) in % of smoke obscuration-time curve	Max density, max rate and time, obscuration time	Same as NBS, material smoke obscuration indica- tor sum of SOI's for various fire parameters
<b>Fire parameters possible</b>	2	1	2	8
<b>Equipment:</b>				
Cost	\$40,000	\$1000	\$4000	\$4500
Portability	No	Yes	No	No
Work space (ft)	20 x 30	3 x 5	(Movable)	(Movable)

<sup>a</sup>Not the standard method, but possible with the equipment  
<sup>b</sup>NBS has recently added a ventilation capability, the flexibility is thus ~800%.

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### LLL Approach

At Lawrence Livermore Laboratory we take the view that within the lifetime of a fire, the exposure of any material or material system of interest can be expressed by a series of bracketing parameters (see Figure 1); i.e., the material may be exposed to a low heat or a high heat or something in between. It may be exposed to flame or no flame. It may be subjected to no ventilation, to minor ventilation, or to considerable ventilation. The variable in the fire regimen is the kind, thickness, and attitude of the material.



Variable - Material: Kind  
Thickness  
Attitude

Figure 1. Boundary conditions of a fire.

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We have exposed over 100 different material systems of limited thickness (up to one inch) and in one attitude (vertical) to what we term "low radiant heat" in the presence or absence of flame with no ventilation, or with ventilation rates up to 20 air changes in an hour. Our findings have been reported in the literature [7, 8]. However, a brief description of the methods used and some of the salient results may be of interest.

Figure 2 shows a picture of the LLL Density Chamber, which consists of an 18 cubic foot aluminum box, 3 feet high by 3 feet wide by 2 feet deep. A 3 by 3 inch square sample of the material under test, mounted in a metal frame and held vertically, is slid in front of a radiant heat source operating so that the flux on the surface of the exposed specimen is 2.5 watts per square centimeter. As the sample pyrolyzes it generates smoke which rises and intercepts a vertical light beam located at the top of the chamber and focused onto a photoelectric cell in the bottom. The loss in light transmission is measured by a recorder operating through an amplification system. For the flaming exposure condition, a series of six small pilot flames are positioned at the bottom face of the sample about one-fourth of an inch away in order to ignite any flammable species emitted by the decomposing specimen. In tests where ventilation is a factor, air is admitted through a slot in a horizontal tube located in the lower right-hand edge of the chamber and is exhausted through a port located in the upper left-hand back corner of the chamber.

Table 5 shows the various data obtained in testing a material in our chamber, the calculated values used, and the LLL in-house smoke standards employed to rate the obscuration properties of smoke from various material. Of interest is  $D_s$ , the specific optical density of the smoke. The laws of physics define the optical density of a medium as the logarithm of the reciprocal of the light transmitted through the medium. That is to say, if the light transmitted through a medium is 10% of that incident upon it, the optical density is 1; if the light transmitted is 1%, the optical density is 10, etc. The specific optical density is a calculated value that reduces the area smoking, the volume involved, and the light path all to unity. In other words, it is the optical density that would be obtained if one square unit of material is evolving smoke into a volume of one cubic unit and the light is transmitted through a path of one linear unit. The utility of this specific optical density,  $D_s$ , will be discussed later.

Other values of interest are  $D_m$ , the maximum specific optical density obtained in a test;  $T_m$ , the time it occurs;  $R_m$ , the maximum rate of change of specific optical density;  $T_{r,m}$ , the time at which it occurs; and T-16, the time at which the specific optical density reaches a value of 16. Tests by Shern [9] have indicated that masked observers found it difficult to see through smoke with a specific optical density of 16.

One additional value which we have found useful is the smoke obscuration index (SOI). This is defined by Gross and Robertson [9] as being proportional to the product of the maximum smoke density and its rate of rise and indirectly proportional to obscuration time; i.e., T-16. The mathematical derivation of the SOI is given in References 8 and 9 and is expressed as shown in Table 5.

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**Table 5. Key to Symbols Used and LLL Smoke Density Standards**

Symbol	Definition
$D_s$	Specific Optical Density = $\frac{V}{AL} \left( \log_{10} \frac{100}{T} \right)$
V, A, L	Respectively, chamber volume, exposed sample area, and length of light path – all in consistent units For the LLL Chamber V/AL = 132
T	Light transmission – percent
$D_m$	Maximum $D_s$ attained in a test
$T_m$	Time to attain $D_m$ – minutes
$R_m$	Maximum $d/dt(D_s)$ – minutes <sup>-1</sup> (averaged over 2 min)
$T_{Rm}$	Time at which $R_m$ occurs – minutes
T 16	Time at which $D_s = 16$ in a test – minutes
SOI	Smoke Obscuration Index $D_m R / T_{16}$
	$SOI = \frac{D_m}{2000 T_{16}} \left[ \frac{1}{T_{0.9}} + \frac{1}{T_{0.7}} + \frac{1}{T_{0.5}} + \frac{1}{T_{0.3}} + \frac{1}{T_{0.1}} \right]$

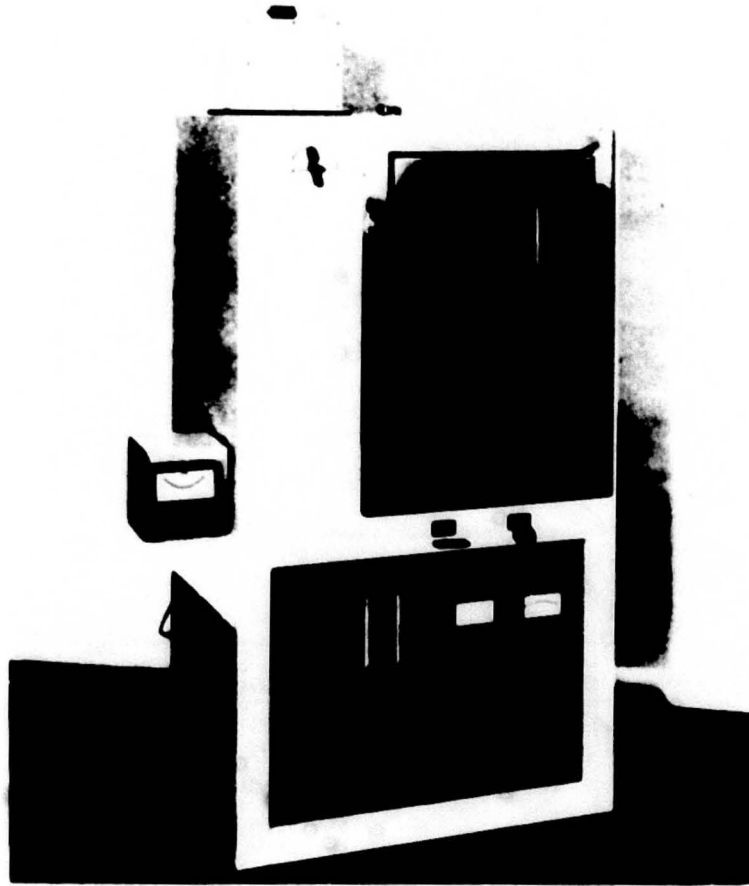
$T_{0.9}, T_{0.7}$ , Time (min.) to reach 0.9  $D_m$ , 0.7  $D_m$ , etc., respectively  
etc.

### LLL Smoke Standards

Item	Values and Description			
$D_m$ Maximum Smoke Density	25 light smoke	25-50 moderately dense smoke	100-400 dense smoke	400 very dense smoke
T 16 Visual Obscuration	10 very slow smoker	10-5 slow smoker	5-1 moderately fast smoker	1 very fast smoker
SOI Smoke Obscuration Index	0-5 safe smoke	5-10 probably safe smoke	10-30 probably hazardous smoke	30 hazardous smoke

Also shown in Table 5 are the in-house smoke standards used at LLL to attach descriptive terms to values obtained for maximum smoke density, obscuration time, and smoke obscuration index. These values, their segregation, and their

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terminology have been based on our experience in the field, plus consultation with others similarly engaged.

### **LLL Results**

A typical smoke density vs time set of curves for red oak, the standard material used in the Steiner Tunnel, is shown in Figure 3. Note that under nonflaming conditions in a closed chamber (or room), smoke density rises slowly first and then more rapidly to a value at which it is considered to be very dense. Under flaming exposure, a considerably lower value is achieved. By plotting the maximum smoke densities obtained against various ventilation rates, the values for red oak are typically shown in Figure 4. As can be seen, it is quite easy to clear away the smoke under the flaming condition, but it is less so under the nonflaming exposure.

On Figure 5 are shown the smoke density-time curves for three, solid, one-fourth inch thick transparent acrylics. Under nonflaming exposure the fire retardant

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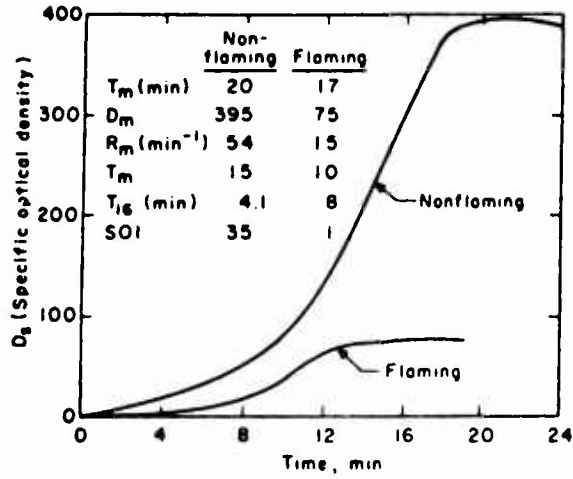


Figure 3. Typical smoke development from red oak.

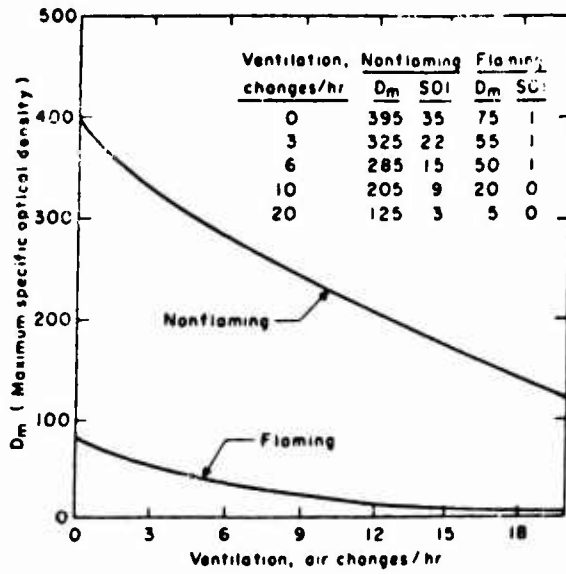


Figure 4. Effect of ventilation on maximum smoke density of red oak.

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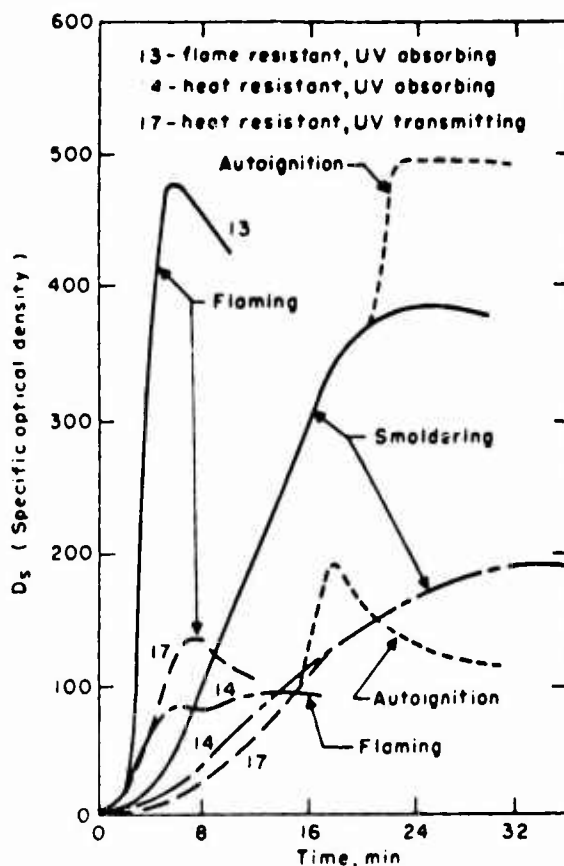


FIGURE 5. Smoke development from three clear acrylics.

variety exhibited a curve similar to that of red oak. The other two materials showed a smoke of noticeably less density. Under flaming exposure, the fire retardant variety quickly yielded a very dense smoke. The other two smoked as fast but to a smaller degree. Of particular interest is the autoignition tendencies of two of the materials. In over half the tests made, these samples ejected flaming species as shown onto the coils of the radiant heater and set themselves on fire, thus producing a much denser smoke than when the phenomena did not occur.

In Figure 6 are shown the effects of ventilation on the maximum smoke densities of these acrylics and one transparent styrene material of the same thickness. Note that under the pyrolysis conditions, the acrylics behaved in a matter similar to wood. The maximum smoke density attained is rapidly lowered with increasing ventilation. On the other hand, ventilation does not seem to help the smoke density under flaming conditions. In fact for two of the materials, a

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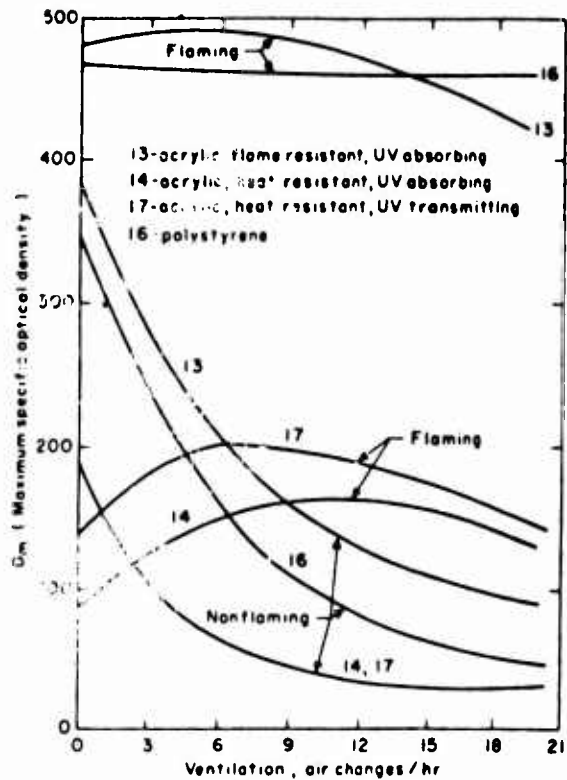


Figure 6. Effect of ventilation on maximum smoke density of three acrylics and one styrene.

moderate ventilating rate of 6 air changes an hour seemed to increase the maximum smoke density. In the cases of the styrene material and the fire-retardant acrylic, ventilation was completely ineffective in clearing away the smoke as far as maximum density is concerned.

Figure 7, showing the smoke development from clear, rigid polyvinyl chloride in two thicknesses, is interesting in that under the flaming condition it does not seem to make any difference whether the materials is one-fourth or one-eighth inch thick.

The data shown on Figure 8 point up the need for testing materials systems in the manner in which they are going to be used. Curves obtained show the smoke-density time curves, for a polyester/epoxide coating on three-eighth inch gypsum wallboard. Under the nonflaming exposure, the results were as expected. The

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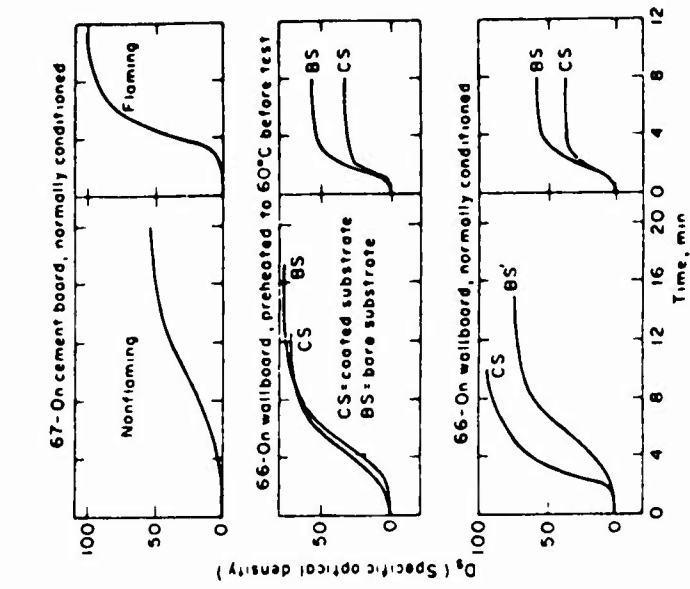


Figure 8. Smoke development of polyester/epoxide coating.

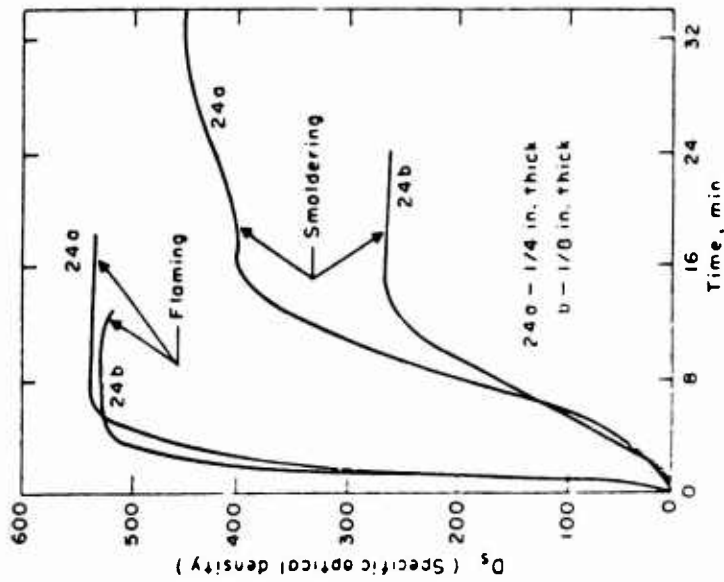


Figure 7. Smoke development from a clear, rigid polyvinyl chloride.

## MINES AND BUNKERS

coated specimen yielded a slightly denser smoke than the bare specimen. However, the opposite was found to be true under flaming exposure when the specimens were tested under the normal conditioning or preheated to 60°C to remove moisture before the test. Tests of the same coating applied to cement board showed somewhat different results. It should be noted that each curve shown represents at least two replicate tests with good agreement between replicates.

As stated above, we have examined and tested over 100 different materials in the LLL smoke chamber. Our findings to date — under the 2.5 W/cm<sup>2</sup> radiant heat flux exposure — can be summarized as follows:

1. Woods, including solid woods, plywood, and other cellulose, show curves similar to those for red oak in the flaming and nonflaming exposures, both with and without ventilation. However, each particular product or material has its own characteristic maximum smoke density value. An exception should be noted in the case of one wood with two different fire retardant treatments. In this case, denser smokes were obtained under the flaming conditions for the material which had been fire retarded.

2. Plastics may be divided into two broad categories: a few which do not produce visible smoke under either flaming or nonflaming exposure; and the vast majority which can be divided into two further classifications. Of those materials, which do produce smoke, exposure to heat alone yields a broad spectrum of smoke densities. Some behave much like wood, slowly building up to a high density; others will build up fairly rapidly, but to about the same density.

In the presence of heat and flame, however, we have observed two separate phenomena:

- (a) plastics which tend to burn cleanly are similar to wood under similar conditions.

- (b) Those that do not burn cleanly; i.e., are fire retarded in one way or another, rapidly evolve dense smokes. These are not readily cleared away by ventilating.

A question arises as to how these results may be used. We grant that these data are obtained in a small-scale test and we agree with Christian [10] that, "No single smoke rating number should be expected to define relative smoke hazards of materials in all situations." Furthermore, we point out that the necessarily large-scale correlating tests needed to verify the applicability of the LLL Chamber tests are yet to be done. Nevertheless, we feel that the results can be used with some judgment by employing the nomograph shown in Figure 9 to evaluate the opacity hazard of a materials system. This chart, the original of which was developed by Gross [9], plots the specific optical density of the smoke at the time of interest against the room geometrical factor; i.e., the volume of the room, the area of the material smoking, and the light path or the distance between the observer's eye and an exit sign.

By putting in the appropriate numerical values for the area of the material in

## APPENDIX C

its intended application, the specific optical density for the time of interest as determined by a test, and including the volume of the room and the distance from an observer or victim, as you please, to the exit sign; one can determine whether or not an opacity hazard exists from smoke involving this material.

### References

7. J. R. Gaskill and C. R. Veith, "Smoke Opacity from Certain Woods and Plastics," *Fire Technology*, 4 (1968), pp. 185-195.
8. J. R. Gaskill, "Smoke Development in Polymers During Pyrolysis or Combustion," *J. Fire & Flammability*, 1 (1970), pp. 183-216.
9. (a) J. H. Shern, "Smoke Contribution Factor in Fire Hazard Classification of Building Materials."  
(b) D. Gross, J. J. Loftus and A. F. Robertson, "Method for Measuring Smoke from Burning Materials: *American Society for Testing and Materials*, (Philadelphia STP - 422, 1966) Fire Test Methods - Restraint and Smoke.
10. W. J. Christian and T. E. Waterman, "Ability of Small-Scale Tests to Predict Smoke Production," *Fire Technology*, 7 (1971), pp. 332-344.

APPENDIX D

SYNOPSIS OF THE PHYSIOLOGICAL HAZARD  
OF SELECTED COMBUSTION PRODUCTS

TABLE D-1. TOLERANCE TO SELECTED COMBUSTION PRODUCTS

Combustion Products	Hazardous Levels for Times Indicated			
	Minutes	$\frac{1}{2}$ Hour	1-2 Hours	8 Hours
Heat (°F)	284	212	150	120
Oxygen (%)	6	11	14	15
Carbon Dioxide (ppm)	50,000	40,000	35,000	32,000
Carbon Monoxide (ppm)	3,000	1,600	800	100
Sulphur Dioxide (ppm)	400	150	50	8
Nitrogen Dioxide (ppm)	240	100	50	30
Hydrogen Chloride (ppm)	1,000	1,000	40	7
Hydrogen Cyanide (ppm)	200	100	50	2

NOTE: Data from Table 1 in C. H. Yuill, "Physiological Effects of Products of Combustion," American Society of Safety Engineers Journal 19 (1974): 36-42. Author notes that table is substantially that set forth in A. J. Pryor and C. H. Yuill, Mass Fire Life Hazard, OCD Work Unit 2537A Final report (San Antonio, Texas: Southwest Research Institute, 1968), and that there is considerable variation among investigators as to what level of a particular gas does constitute a life hazard.

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TABLE D-2. TOXICOLOGY OF SOME HIGHLY TOXIC FIRE CASES--Concentration (ppm) 760 mm, 25 °C

Gas	L.T.V. <sup>a</sup>	Dangerous 0.5 to 1 hr.	Fatal 0.5 to 1 hr.	Effects
CO	50	1,500-2,000 (1 hr.)	4,000	Combines with heoglobin in blood to form carbohemoglobin thereby preventing O <sub>2</sub> transport. CO is a chemical asphyxiant.
NO	n. a.	100-150	400-800	Forms nitrous and nitric acids in presence of O <sub>2</sub> and H <sub>2</sub> O in respiratory tract. Nitrates form methemoglobin while the nitrates lead to edema of the lungs. The latter are more dangerous.
NO <sub>2</sub>	5			
HCl	5	1,000-2,000 (dangerous for brief exposure)	4,350	Neutralizes tissue alkali in upper respiratory tract. Causes death due to edema or spasm of larynx and upper respiratory tract.
Cl <sub>2</sub>	1	50 (short exposure)	1,000 (brief exposure)	Hydrolyzes to nascent O <sub>2</sub> and HCl in respiratory tract.
COCl <sub>2</sub>	0.1	12.5	25 (0.5 hour)	Hydrolyzes to HCl and CO at bronchioles and alveoli of the lungs. Pulmonary edema and asphyxiation.
HF	3	50-250 (brief exposure)	--	Ulceration of mucous membranes, chemical pneumonia.
COF <sub>2</sub>	n. a.	--	--	Hydrolyzes to HF and CO. Similar to COCl <sub>2</sub> .
H <sub>2</sub> S	10	400-700	800-1,000 (high concentrations instantly fatal)	Irritant; combines with alkalis in skin to form Na <sub>2</sub> S; pulmonary edema at high concentrations. Asphyxiant; paralysis of respiratory center.

APPENDIX D

HCN	10	400-700	100-200	Protoplasmic poison. Combines with enzymes associated with cellular oxidation. Death occurs through asphyxiation.
NH <sub>3</sub>	50	2,500-6,500 (0.5 hour)	5,000-1,000 rapidly fatal)	Pulmonary edema.

NOTE: Data from Table VI in J. P. Wagner, "Survey of Toxic Species Evolved in the Pyrolysis and Combustion of Polymers," Fire Research Abstracts and Reviews 14 (1972): 1-23 based on: Effects of Chronic Exposure to Low Levels of Carbon Monoxide on Human Health, National Academy of Sciences Publication 1735 (Washington, D.C.: NAS, 1969); Standard Book No. 309-01735-1. L. T. Fairhall, Industrial Toxicology, Williams and Wilkins, Co., 2nd ed., 1957. M. B. Jacobs, Analytical Chemistry of Industrial Poisons, Hazards and Solvents, Vol. 1, Interscience, 1944); (also 1967). F. A. Patty, Industrial Hygiene and Toxicology, Vol 1. General Principles of Industrial Hygiene and Toxicology, Wiley, 1958, Vol. 2, Toxicology, Wiley, 1967. E. R. Plunkett, Handbook of Industrial Toxicology (New York: Chemical Publishing Company, Inc., 1966). N. I. Sax, Dangerous Properties of Industrial Materials, 3rd ed. (New York: Reinhold, 1968).

\* Lower threshold value: time-weighted average concentrations for a 7 or 8-hour period.

**APPENDIX E**

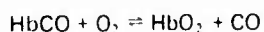
**REVIEW OF CO TOXICITY**

**Excerpt from R. R. Montgomery, C. F. Reinhardt, and J. B. Terrill,  
"Comments on Fire Toxicity," paper presented at the Polymer  
Conference Series (Flammability of Materials Program) Salt Lake City,  
Utah, July 11, 1974.**

## MINES AND BUNKERS

*Carbon Monoxide (CO)*: In poorly ventilated fires with limited O<sub>2</sub> combustion is incomplete and the end products are CO and other degradation products, water, and less heat. Overall, of all the gases generated in real fire situations, CO is acknowledged as the gas that produces the most deaths [21]. The general physiological effect of increasing atmospheric concentrations of this colorless, odorless gas is shown in Table III [20, 33, 34]. Physical exertion, age, health and smoking habits can all affect individual response. Table IV as given in the account of an exposure to an estimated 900-1000 ppm CO from a leaking exhaust pipe into an Anchorage Alaska, sports arena [35], shows the variety of symptoms and the variation in response that may occur.

CO, unlike most poisons, has no known lasting effects if secondary tissue damage from O<sub>2</sub> depletion does not develop [12, 34, 36]. CO readily displaces oxygen from hemoglobin and also interferes with delivery of O<sub>2</sub> to tissues and removal of CO<sub>2</sub> from blood. Irreversible tissue damage may develop if the brain is deprived of O<sub>2</sub> for more than 5-10 minutes. However, adequate O<sub>2</sub> may again displace CO as shown in the equilibrium:



(where Hb means hemoglobin)

We can correlate percent atmospheric CO and time of exposure with blood carboxyhemoglobin. Several reviews [12, 34] discuss this subject in detail and an exhaustive study of the kinetics of uptake and elimination of CO has recently appeared [37].

TABLE III. PHYSIOLOGICAL RESPONSE TO CO (20, 33, 34)

CO in Atm <sup>3</sup>	Response
0.01	Allowable exposure for several hours.
0.04 - 0.05	No appreciable effect after 1 hour.
0.06 - 0.07	Just appreciable effect after 1 hour.
0.1 - 0.12	Unpleasant after 1 hour (headache, nausea).
0.15 - 0.2	Dangerous when inhaled for 1 hour (incapacitation, collapse).
0.3	Estimated danger level for 1/2 hour.
0.4	Fatal when inhaled for less than 1 hour.
1	Fatal when inhaled for 1 minute.

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TABLE IV. SYMPTOMS AND SIGNS OF CARBON MONOXIDE POISONING REPORTED BY 51 ILL PERSONS PRESENT IN THE SPORTS ARENA ON MARCH 20, 1969 (35)

Symptom	35 Broomball Players Percent	7 Hockey Players Percent	9 Adults Percent	51 Total Percent
Headache	91	57	100	88
Dizziness	77	43	11	61
Nausea	49	43	44	47
Tinnitus	43	14	0	31
Disorientation	31	14	0	24
Numbness of feet	26	29	11	24
Blurred vision	20	--	--	14
Numbness of hands	9	--	--	6
Vomiting	3	--	--	2
Loss of consciousness	3	--	---	2

References cited in Montgomery, Reinhardt, and Terrill

12. A.J. Pyror and C. H. Yuill, *Mass Fire Life Hazard*, OCD Work Unit 2537A Final Report Southwest Research Institute (San Antonio, Texas: Southwest Research Institute, 1966).
20. R. E. Reinke and C. F. Reinhardt, "Fires, Toxicity and Plastics," *Mod. Plast.* 50 (1973): 94-5, 97-8.
21. J. Autian, "Toxicologic Aspects of Flammability and Combustion of Polymeric Materials," *J. Fire & Flammability* 1 (1970): 239-68.
33. J. M. Ives, E. E. Hughes, and J. K. Taylor, *Toxic Atmospheres Associated with Real Fire Situations*, NBS Report 10807 (Washington, D. C.: U.S. Department of Commerce, 1972).
34. F. A. Patty, ed., *Industrial Hygiene and Toxicology*, 2nd ed., Vol. 2 (New York: John Wiley, 1963).
35. A. R. Saslow and P. S. Clark, "Carbon Monoxide Poisoning," *J. Occup. Med.* 15 (1973): 490-2.
36. H. Bour and I. McA. Ledingham, "Carbon Monoxide Poisoning," *Progress in Brain Research*, Vol. 24 (New York: Elsevier Publishing Co., 1967).
37. J. A. MacGregor, "Kinetics of Uptake and Elimination of Carbon Monoxide," paper presented at the International Symposium on Physiological and Toxicological Aspects of Combustion Products, Salt Lake City, Utah, March 18-20, 1974.

**APPENDIX F**

**COMBUSTION PRODUCTS OF POLYMERS  
IN FIRES**

## APPENDIX F

In building fires one nearly always encounters pyrolysis and combustion products of cellulosic fuels along with various plastics. Fires are classified according to NFPA categories into four general types [4]:

- Class A: Fires involving ordinary combustible materials (wood, cloth, paper, rubber, and many plastics).
- Class B: Fires involving flammable or combustible liquids, flammable gases, and greases.
- Class C: Fires involving electrical equipment. These are treated as Class A or B fires after the electricity is turned off.
- Class D: Fires involving combustible metals. . . .

Since most enclosure fires are of the class A type, involving cellulosic fuels, it is important to consider the different temperature zones since this controls the fire environment. Based on a review by Browne, [5] described by Beall and Eichner, [6] four distinct temperature zones are given for the Thermal Decomposition of Wood as follows:

- Zone A: Below 200°C. Appearance of noncombustible gases, primarily H<sub>2</sub>O vapor, traces of CO<sub>2</sub>, formic and acetic acids, and glyoxal. Dehydration of sorbed water is complete.
- Zone B: 200° to 280°C. Same gases as in Zone A are produced along with greatly reduced quantities of water vapor and CO. Reactions are endothermic and products are almost entirely nonflammable.
- Zone C: 280° to 500°C. Active pyrolysis takes place under exothermic conditions leading to secondary reactions among the products. Largely combustible products, CO, CH<sub>4</sub>, etc., and flammable tars in form of smoke particles.
- Zone D: Above 500°C. Residue consists primarily of charcoal, which provides an extremely active site for secondary reactions.

The early combustion stages are similar to the pyrolysis stages, modified slightly by oxidation. These stages are categorized as follows:

- Zone A: Similar to Zone A above, but slightly affected by some oxidation processes.
- Zone B: Primary exothermic reaction takes place without ignition.
- Zone C: Combustible gases that are ignitable are produced after secondary pyrolysis. Flaming combustion can occur in gas phase if the gases are ignited. If ignition is not induced flaming may not occur until near the end of pyrolysis when the evolved gases cannot insulate the charcoal layer from O<sub>2</sub>. Spontaneous ignition of charcoal takes place at temperature lower than any of the products evolved.
- Zone D: Greater than 500°C the charcoal glows and is consumed; greater than 1000°C nonluminous flames are supported by the combustion of H<sub>2</sub> and CO.

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These zones illustrate the complexity of cellulosic combustion processes.

In an enclosure one would expect an agglomeration of both pyrolysis and combustion products. This is illustrated in the flow diagram in Figure 1. Conductive heating will induce pyrolysis. This would be limited to the percolation of gases through materials that leave porous char-like residues. Radiation and convective heat transfer are primarily responsible for flame spreading and are longer range. The liquid and solid phases are also present in varying degrees.

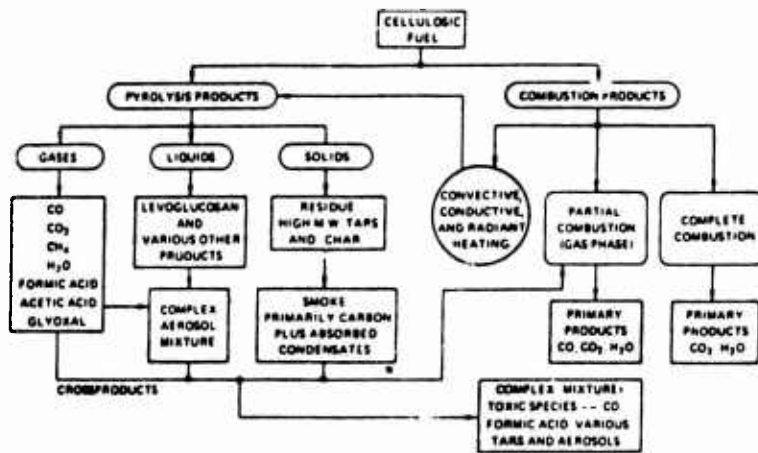


FIG. 1. Flow diagram for pyrolysis and combustion of cellulosic fuels in an enclosure

An enclosure fire of plastics can be represented by the simplified flow diagram in Figure 2. Common plastics are designated by  $\cdot\text{C}\cdot\text{H}\cdot\text{O}\cdot\text{N}\cdot$  type structural

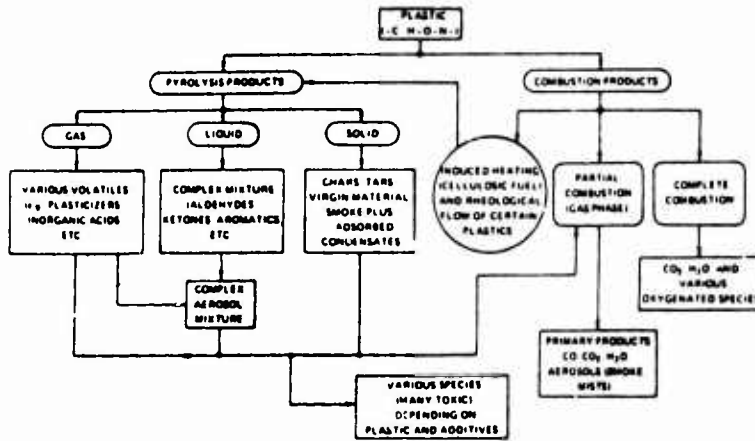


FIG. 2. Flow diagram for pyrolysis and combustion of plastic in an enclosure.

## APPENDIX F

arrangements. Pyrolysis can result from the cellulosic fuels and also from self-induced modes of heating. In addition to the flame-spread mechanisms common to cellulosic fuels a rheological flame spread mechanism occurs with thermosetting plastics. Here molten or flaming drops or even streams of these fluids can drastically alter flame spread mechanisms and require evacuation and extinguishment techniques.

Both pyrolysis and combustion of plastics must be considered as equally important in light of recent studies that indicate many plastics formerly considered self-extinguishing can be burnt continuously from below (bottom burning) by incorporation of a noncombustible wick. [7] Wicking action is nearly always provided by the contents of an enclosure. The chemical and physical modifications of plastics, the incorporation of additives along with the thousands of trade names [8] make it exceedingly difficult to generalize the products as with cellulose fuels. A breakdown into groups such as char formers, vapor formers, and combined effects such as charriers plus vapor formers is helpful. . . . [Summary discussion of certain polymers later in article.]

### References

4. Fire Protection Handbook, National Fire Protection Association, 13th ed., 1969.
5. F. L. Browne, Theories on the Combustion of Wood and its Control, U. S. Forest Products Laboratory, Rept. 2136, Madison, Wisconsin, 1958.
6. F.C. Beall and H. W. Eickner, Thermal Degradation of Wood Components, Forest Products Lab., Report 130, Forest Service, U. S. Dept. of Agriculture, May 1970.
7. D. E. Steutz, Basic Principles in Polymer Combustion, Polymer Conference Series, University of Utah, 21-26 June 1971.
8. Plastics Note 9A, Trade Designations of Plastics and Related Materials, AD-715401 Picatinny Arsenal, Dover, New Jersey, May 1970.

**APPENDIX G**

**EVALUATING THE HAZARD OF TOXIC**

**FUMES AND SMOKE:**

**Selected Examples of Various Methods**

## MINES AND BUNKERS

### Example of Analytical Method

Excerpt from I. N. Einhorn, *et al.*, "Physiological and Toxicological Aspects of Smoke Produced During the Combustion of Polymeric Materials," Proceedings of the NSF/RANN Conference on Fire Research (Washington, D. C. UTEC-MSE 74-083, FRC/UU-29, June 21, 1974., p. 199

### Task 6 – Effect of Fire Retardants on Smoke and Degradation Products [Excerpt]

To date, the major concern of those engaged in the development of fire retardant materials has been the reduction of the ignition tendency and flame propagation. Thus, it has been possible to meet code and regulatory requirements regarding flame spread. However, it is our opinion that the total hazard resulting from incomplete combustion may actually have been increased. A study of several recent fires, in which fire-retarded plastics were involved has indicated that smoke development and the production of copious amounts of toxic decomposition products have resulted in bodily injury or loss of life long before the spread of fire has reached those individuals trapped in the conflagration.

The Mettler Thermoanalyzer has been used to conduct experiments on the effects of environment, heating rate, and % fire retardant in urethanes. Figure 9 shows dynamic TGA curves at different bromine fire-retardant concentrations with rigid-urethane foam.

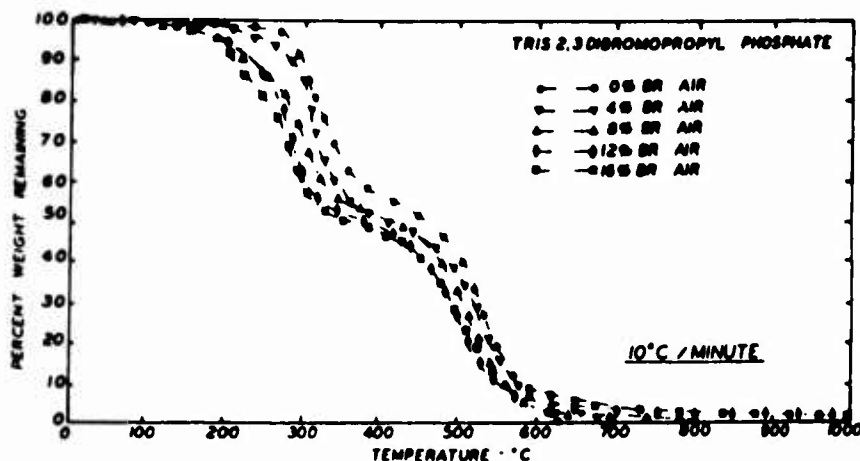


Figure 9. Effect of Fire Retardant Concentration on Thermal Degradation

[Note: TGA = thermal gravimetric analysis]

APPENDIX G

Example of Biological Method

Excerpt from R. E. Reinke and C. F. Reinhardt, "Fires, Toxicity, and Plastics," *Modern Plastics*, 50 (1973): 94-5, 97-8.

**Table V: Toxicity results from thermodegradation products of polymers**

**Part 1: Series of 15-min. exposures using 3 g. of foamed materials. 30 g. of all other materials. Pyrolysis temperatures up to 1364° F. (12).**

Material	Mortality for mice <sup>a</sup>
Polystyrene rigid foam (A or B)	0/10
Phenolic rigid foam	0/5
Wood-wool cement board	1/5
Acrylic rigid sheet	4/5
Wood (cedar)	5/5
Fire-retardant plywood	5/5
Melamine laminate	5/5
Polyvinyl chloride rigid sheet	5/5
Polyurethane rigid foam	5/5

**Part 2: Series of exposures (13):**

No. 1. 6-hr. exposure, 4.7 to 5.5-g. sample.

No. 2. 6-hr. exposure, 5.7 to 6.8-g. sample

No. 3. 10-min. exposure, 2.0-g. sample

	Mortality for rats <sup>a</sup>		
	No. 1, 392° F.	No. 2, 482° F.	No. 3, 1040° F.
Polyurethane A	0/4	1/4	0/2
Polyurethane B	0/4	1/4	0/2
Polyurethane C	0/4	0/4	0/2
Neoprene	0/4	1/4	0/2
Rubber latex	0/4	4/4	0/2
Polyvinyl chloride	2/4		1/2

**Part 3: Series of 30-min. exposures, 5-g. samples (14).**

	Mortality for rats <sup>a</sup>			
	572° F.	752° F.	932° F.	1112° F.
Polystyrene A	0/12	0/12	0/18	11/12
Polystyrene B or C	0/24	0/24	25/42	24/24
4 other PS	0/48	0/48	48/48	48/48
Expanded cork	0/12	5/18	12/12	12/12
Rubber	0/12	12/12	12/12	12/12
Wool	2/12	12/12	12/12	12/12
Pine wood	3/12	12/12	12/12	12/12
Felt	6/12	12/12	12/12	12/12
Leather	12/12	12/12	17/18	11/12

**Part 4: Series of 30-min. exposures, 5-g. samples (14)**

	Mortality for rats <sup>a</sup>				
	392° F.	572° F.	752° F.	932° F.	1112° F.
Polyethylene	0/12	0/12	12/12	12/12	12/12
Fir	0/12	13/18	12/12	12/12	12/12
PVC	0/12	10/12	11/12	12/12	12/12
Celluloid	12/12	12/12	12/12	12/12	12/12

<sup>a</sup>—Mice or rats exposed to products resulting from pyrolysis temperatures indicated. Figures in table show ratio of number of mortalities to number exposed. All temperatures have been converted to °F.

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### References from Reinke and Reinhardt

12. K. Kishatani, J. Fac. Engr. Univ. of Tokyo (B) 21.1 (1971).
13. J. A. Zapp, Jr., Arch. Environ., Health 4, No. 3.335 (1962).
14. H. Th. Hoffmann and H. Oettel., Modern Plastics 46. 94 (Oct. 1969).

### Example of "Combined Analytical and Biological Method

Excerpt from G. Kimmerle, "Aspects and Methodology for the Evaluation of Toxicological Parameters During Fire Exposure," *Journal of Fire and Flammability/Combustion Technology* 1 (1974): 4-51

**Table 51. Toxicity of the Pyrolysis Products of Polyisocyanurate Foams in Rats Tests with Equal Volume (300 by 10 to 5 mm) (12)**

Sample	Fire Retardant	Temp °C	CO ppm	HCN ppm	CO H <sub>2</sub>	Number of Deaths Out of 20
1	No	500	1,100	150	43.5	0
		550	3,000	150	58.9	13
2	Yes	550	1,600	130	43.3	0
		600	2,000	150	52.3	9
3	Yes	600	1,200	75	32.8	0
4	Yes	500	470	25	17.6	0
		600	1,230	100	44.7	3
5	Yes	500	500	45	29.6	0
		560	1,300	120	47.6	11
6*	Yes	600	930	55	27.9	0
		600	1,670	125	48.5	1

\*Sample of polyisocyanurate foam reinforced with foamed glass pellets.

**Table 52. Toxicity of the Pyrolysis Products of Rigid Isocyanurate Foams in Rats Tests with Equal Weight (1.2 Grams per 100 mm) (12)**

Sample	Fire Retardant	Temp °C	Concentration in Air		CO H <sub>2</sub>	Number of Deaths Out of 20
			CO ppm	HCN ppm		
1	No	400	1,000	50	33.6	0
		450	2,800	150	58.2	19
2	Yes	350	1,100	50	23.7	0
		400	3,500	150	39.2	15
3	Yes	350	800	50	19.4	0
		400	2,500	150	39.2	14
4	Yes	300	450	10	17.0	0
		350	1,470	45	42.6	4
5	Yes	300	300	10	12.5	0
		400	2,150	150	52.6	12

First occurrence of mortalities by volume 550° and 600° C  
sometimes none at 600° C  
by weight 350°, 400°, and 450° C

<sup>12</sup> Kimmerle, Unpublished results 1972-1973, Bayer AG, Institut für Toxikologie, Werk Wuppertal, Germany.

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Most of the mortalities can be related to the combined action of carbon monoxide and hydrogen cyanide, but in the case of sample 5, other toxic gases must have caused a more important effect.

Example of Epidemiological Method

Excerpt from B. A. Zikria, *et al.*, "Smoke and Carbon Monoxide Poisoning in Fire Victims," *Journal of Trauma*, 12 (1972): 641-5

TABLE I  
Burn Mortality, New York City (1968 and 1967)

PBST	Total Victims 336 (Survival Time)		Autopsied Victims 311	
	Cases	Per Cent	No. Cases	Per Cent
< 12 hr	283	53	163	60
> 12 hr	158	30	72	23
Not known	93	17	54	17
<b>Total</b>	<b>534</b>	<b>100</b>	<b>311</b>	<b>100</b>

TABLE II  
Respiratory Involvement in 185 Autopsied Victims

	PBST 12 hr (Survival Time)		PBST 12 hr (Survival Time)	
	Cases	Per Cent	Cases	Per Cent
Smoke poisoning or asphyxia only	99	53.5	4	5.6
Resp. tract pathology	11	5.9	28	38.9
Both	20	10.8	1	1.1
Neither	35	29.9	39	51.1
<b>Total</b>	<b>185</b>	<b>100.0</b>	<b>72</b>	<b>100.0</b>

TABLE III  
Respiratory Tract Pathology in 60 Autopsied Victims with 66 Attributions

Pathology	Attrib.	BSAB (avgr.)	(DOA) PBST < 12 hr	(Aver Surv) PBST > 12 hr
Tracheobronchitis	13	41%	5 (5)	8 (12 days)
Pneumonia/pneumonitis	31	45%	9 (8)	22 (21 days)
Pulmonary/edema/congestion	22	67%	17 (16)	5 (4 days)
Lung abscess	1	0%	0 (0)	1 (46 days)
Other*	9	34%	5 (4)	4 (22 days)

\* Emphysema, empyema, bronchiectasis, fibrosis, pulmonary embolus

TABLE IV  
Carbon Monoxide Poisoning in 185 Autopsied Victims, with Death Occurring Under 18 Hr

	Carbonyhemoglobin Sat	Cases	Per Cent
Laboratory determination		(130)	(70.3)
Usually lethal	> 50%	45	24.3
Significant	11%-49%	64	34.6
No contribution	0%-10%	21	11.4
Clinical diagnosis only		14	7.6
No indication		41	22.1
<b>Total</b>		<b>185</b>	<b>100.0</b>

TABLE V  
Carbon Monoxide Poisoning in 72 Autopsied Victims with Death Occurring Over 18 Hr

	Carbonyhemoglobin Sat	Cases	Per Cent
Laboratory determination		(4)	(5.5)
Usually lethal	> 50%	0	0.0
Significant	11%-49%	1	1.4
No contribution	0%-10%	3	4.1
Clinical diagnosis only		4	5.5
No indication		64	89.0
<b>Total</b>		<b>72</b>	<b>100.0</b>

[PBST = postburn survival time]

MINES AND BUNKERS

Another Example of Epidemiological Method

Excerpt from R. M. Fristrom, "Smoke Injury Studies," Proceedings of the NSF/RANN Conference on Fire Research, June 21, 1974. pp. 62-73.

TABLE 1  
CARBON MONOXIDE AND CORONARY  
VASCULAR DISEASE AS  
CAUSES OF DEATH  
107 FIRE FATALITIES

<u>CAUSE</u>	<u>NUMBER</u>	<u>PERCENT</u>
CO ALONE	48	45%
CO + CORONARY DISEASE	35	33%
CO + BURN	5	5%
CORONARY DISEASE ALONE	2	2%
BURN ALONE	15	14%
UNCERTAIN	2	2%

TABLE 2  
CARBOXYHEMOGLOBIN AND BLOOD ALCOHOL  
CASES AGE 18 AND OVER

<u>BLOOD ALCOHOL gm/100ml</u>	<u>COHB% &gt; 40</u>	<u>COHB% 20-40</u>	<u>COHB% &lt; 20</u>	<u>TOTAL</u>	<u>%</u>
NONE	22	3	10	35	(44%)
< 0.05	0	1	1	2	(3%)
0.05-0.15	13	0	1	14	(18%)
0.16-0.25	11	4	4	19	(24%)
> 0.25	<u>7</u>	<u>1</u>	<u>1</u>	<u>9</u>	<u>(11%)</u>
	53	9	17	79	(100%)

CASES UNDER AGE 18  
(NO ALCOHOL PRESENT)

TOTAL ALL CASES	<u>23</u> 76	<u>2</u> 11	<u>3</u> 20	<u>28</u> 107
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APPENDIX G

TABLE 3  
FACTORS RESPONSIBLE FOR  
FAILURE TO ESCAPE FROM FIRES

REASON FOR FAILURE TO ESCAPE	ATTEMPT TO ESCAPE		TOTAL	%	
	YES	NO			UNDETERMINED
CARBON MONOXIDE ALONE	23	6	3	32	29.9%
CARBON MONOXIDE + ALCOHOL	31	6	0	37	34.6%
ALCOHOL ALONE	3	0	0	3	2.8%
BURN (INCL. RESPIRATORY)	5	0	0	5	4.7%
CORONARY OCCLUSION	2	1	0	3	2.8%
INFANT	1	12	0	13	12.1%
INVALID	1	3	0	4	3.7%
EXPLOSION	0	3	0	3	2.8%
CLOTHING FIRES (GENERALLY SUICIDES)	2	3	0	5	4.7%
SUICIDE	0	1	0	1	0.9%
CAR ACCIDENT	0	0	1	1	0.9%
	68	35	4	107	
	(63.6%)	(32.7%)	(3.7%)		