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SURVEY OF FIRE MODELING EFFORTS WITH APPLICATION TO TRANSPORTATION VEHICLES

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16. Abstract

This report presents the results of a survey of analytical fire models with applications pertinent to fires in the compartments of transportation vehicles; a brief discussion of the background of fire phenomena and an overview of various fire modeling concepts are also included. Six analytical fire models have been identified and the basic model design and construction of each is presented along with the data input requirements and output format.

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PREFACE

The Office of the Secretary of Transportation (OST) in its role of overviewing and coordinating transportation fire safety is developing an integrated fire safety program plan. As part of this program plan, OST initiated a study to examine the potential of analytical fire modeling. This report presents the results of that study.

The material presented in this report is intended to enhance the reader's understanding of the various techniques used in fire modeling. Fire dynamics and modeling have been described in sufficient detail to enable the reader to relate fire modeling efforts to fire safety.

It is not the purpose of this report to evaluate modeling techniques or mathematical models. Each methodology and model has been reviewed according to the information available.

The authors* wish to acknowledge the guidance and contributions of Mr. Charles W. McGuire of OST who was the sponsor of this project. In addition, they wish to express their appreciation to Mr. Charles D. MacArthur of the University of Dayton Research Institute, Drs. Henri E. Mitler and Howard W. Emmons of Harvard University, Mr. Ronald Pape of the IIT Research Institute, Dr. Edwin E. Smith of Ohio State University, Dr. James G. Quintiere of the National Bureau of Standards, and Dr. John R. Lloyd of the University of Notre Dame for the valuable information which they provided for this report as well as for their comments and reviews.

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* Marilyn K. Goldberg (RSC) was a principal author of this report.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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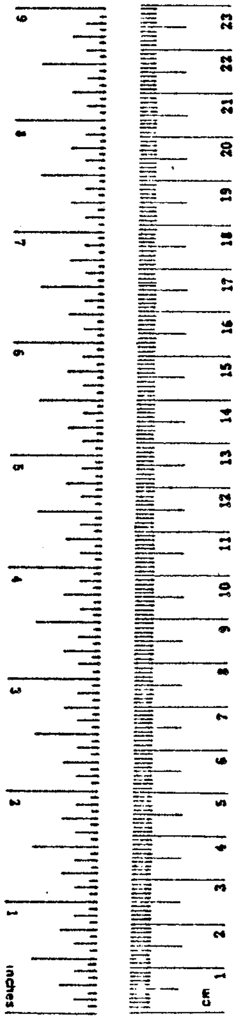
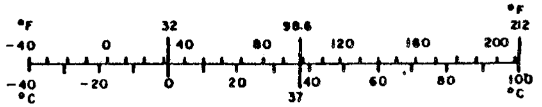
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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GLOSSARY*

Adiabatic	Any change in which there is no gain or loss of heat.
Buoyancy Effect	Heat released from a fire causes the heated gases directly above the flames to expand and to rise. Combustion and pyrolysis products from the fire are carried upward with the hot gases to the ceiling producing a layer of hot gases (smoke, toxic gases, pyrolysis products) at the ceiling.
Code	A system of symbols (such as Fortran) for representing data in a computer.
Conduction	The transmission of heat from one material to another by direct contact of that material to an adjacent material.
Convection	The transmission of heat by the upward motion of heated fluids and the downward motion of cooler fluids which in turn become heated.
Emissivity	The ratio of the radiation emitted by a surface to the radiation emitted by a perfect black body radiator at the same temperature.
Energy Source	See ignition source.
Exothermic Reaction	A chemical change which produces heat.
Fire Point	The lowest temperature at which the flammable decomposed gaseous mixture derived from a heated liquid will burn steadily. (This is a higher temperature than the flash point.)
Flash Point	The lowest temperature at which the vapors of a liquid decompose to a flammable gaseous mixture. (This is not a steady burning and is at a lower temperature than the fire point.)

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*References 1,2,3,4,5,6.

Flashover	The rapid involvement of the combustible contents in a compartment or room fire as they ignite almost simultaneously. A critical transition phase of a fire in a compartment which generally occurs in ventilated compartments (otherwise the fire would tend to smother itself because of the depleted oxygen supply).
Fluid Dynamics	A branch of the physical sciences which deals with the motion of fluids (gases and liquids).
Fluid Mechanics	See fluid dynamics.
Ignition Source	The point from which sufficient heat (energy) is applied to a target (fuel) to cause pyrolysis and burning of the target material. The heat is transferred to the target by conduction, convection, or radiation. Ignition is dependent upon the temperature of the ignition source, the rate at which heat is released from the source, the distance the source is from the target, the area of the target, the material of the target, and the length of time the heat is applied to the target.
Input (Data)	Any data upon which one or more of the basic functions of a program are to be performed, such as computing, summarizing, recording, and reporting.
Input Data Cards	A method of introducing data to an input data device by the use of punched cards. The mechanical method by which data is read from punched cards and fed into a computer.
Isobar	A line drawn through points on a chart which have the same barometric pressure at a given time.
Isotherm	A line on a chart connecting all points of equal temperature.

Laminar Fire	Flame spread by the regular, continous, smooth motion of a flame across a surface.
Mathematical Model	The mathematical representation of a process, device, or concept. The general characterization of a process, object, or concept in terms of mathematics, thus enabling the relatively simple manipulation of variables to be accomplished in order to determine how the process, object, or concept would behave in different situations.
MKS Units or System	Meter-kilogram-second is a technical system of measurements recommended by the International Electrotechnical Commission.
Neutral (Buoyancy) Plane	If hot gas and smoke are flowing out of the upper portion of a doorway, and if cool air is coming into the bottom portion of the doorway, the neutral buoyancy plane is at the position where the pressure difference across the doorway is zero.
Output (Data)	Data obtained or obtainable from a computer.
Plume	The area above the burning surface of a fire which is heated directly by the hot surface including the area into which the hot gases rise above the fire. The exact shape of the plume varies according to the assumptions each fire model makes concerning the plume.
Program (Computer)	A set of instructions or steps that tells the computer exactly how to handle a computer problem. The program usually includes alternate steps or routines to take care of variations. Each time a unit of information is entered (input) into the program, the cycle will start and go from start to finish. This continues until all available information is processed by the computer. A plan, routine or set of instructions for solving a problem on a computer.

Pyrolysis	The process by which a complex solid is thermally decomposed into a single solid or liquid(s) and ultimately into gases. A chemical change brought about by the action of heat.
Radiation	The transmission of energy (heat, light) through space. Example: the intense heat built up on the ceiling during a compartment fire transmits (radiation) heat to the floor and can cause items on the floor to ignite.
Richardson Number	A dimensionless number used in studying the stratified flow of multilayer systems.
Routine	A set of coded instructions arranged in proper sequence to direct the computer to perform a desired operation or series of operations.
Scale Model (Full Scale Model)	A full size replica of a room or compartment on which fire tests are performed in order to study compartment fire behavior. Full scale test data is used for evaluating mathematical fire models designed to predict compartment fire development.
Scaled Model	A reduced-sized replica of a particular compartment to be used in the study of fire growth and of its effect on the surroundings in a particular fire scenario. Reduced-size fire experiments have the advantages of ease of operation and lower cost. They have the disadvantage of being unable to maintain complete dynamic similarity. Scaled models are used to obtain empirical data for computer fire models.
Smoke	Small condensed drops of liquid or solid particles suspended in the atmosphere which result from incomplete combustion and the complex process of pyrolysis (pyrolysis products).

Smoldering	Smoldering is the burning of a solid in a flameless mode, usually resulting from ignition by a low temperature source which is applied over a long length of time. Smoldering is characterized by a relatively low temperature, absence of visible flame, slow spread rate and the production of smoke and gas.
Streamline	A line which is everywhere parallel to the direction of fluid flow at a given time.
Subprogram or Subroutine	A part of a larger program that can be compiled independently.
Thermal Discontinuity	During the combustion process in a compartment, the height of the imaginary boundary separating the lower layer of cool gases (air) from the upper layer of hot gases (combustion products).

1. INTRODUCTION

The Office of the Secretary of Transportation, in its role of overviewing and coordinating departmental transportation fire safety efforts, has tasked the Transportation Systems Center to conduct several studies assessing the present status of transportation fire safety. This report presents the results of a study that reviews the present state-of-the-art in fire modeling and identifies fire modeling research efforts which are applicable to transportation vehicles. Six mathematical fire models have been selected for review and discussion. Each of these models has either been developed specifically for the prediction of fire development in transportation vehicles or is suitable for application to transportation vehicles.

Currently, there is much interest in fire modeling techniques for the practical evaluation of potential fire hazards. This interest is a natural consequence of (1) the rising national concern with consumer related fire safety problems; (2) recent advances in understanding fire phenomena; and (3) the realization that full scale fire tests are frequently too cumbersome and expensive for analyzing the wide variety of potential fire hazards. In theory, mathematical fire models would be an efficient, cost-effective supplement to fire testing. The ideal model would be capable of predicting fire behavior and smoke and toxic gas emissions. A mathematical model could also be used as an effective tool in the design of transportation vehicles and in the study of the burning behavior of the materials used in their construction.

Sections 2 and 3 of this report provide a brief overview of fire dynamics and fire modeling. Section 4 discusses, in detail, the six mathematical models, while Section 5 presents the conclusions of the applications of mathematical fire models to transportation vehicles. Appendix A lists the Centers of Transportation Related Fire Modeling Research; Appendix B contains a bibliography of fire modeling literature.

2. FIRE DYNAMICS*

The following discussion is designed to provide the reader with a basic understanding of the dynamics of a fire. For a more detailed discussion, the reader is referred to the current literature on combustion theory and technology.

Fire research studies may be classified into four broad stages or areas: ignition, fire growth and propagation, fire detection, and fire containment and extinguishment. Many inherent phenomena or elements exist within each of these stages.

Much of the transportation fire research conducted to date has been directed at the fire growth and propagation stage. This research has been directed at the development and application of new and improved vehicle construction materials and vehicle configurations intended to minimize fire growth or propagation. The effectiveness of these new or improved materials and vehicle configurations in minimizing the effects of fire is determined by a series of standardized laboratory tests. Quite often the number and complexity of these tests requires the expenditure of large sums of money.

The application of mathematical analysis methods to the fire growth and propagation phase was identified several years ago as a possible means of complementing the test program and, in some instances, allowing the number of tests to be reduced. During the past several years advances in the understanding of fires have resulted in the development of many mathematical models designed to analyze and predict fire growth and propagation. A knowledge of fire dynamics, supplemented with experimental data from real and computer fire models, should prove to be an invaluable tool to apply to fire prevention, containment, and extinguishment techniques.

There are many interacting phenomena involved in the developing fire. Our inability to separate and study each

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*References 2,3,6,7,8,9,10

phenomenon clearly illustrates the complexity of fire dynamics. Fire development phenomena include such items as ignition, pyrolysis, smoldering, rate of burning, flame spread, movement of smoke, fuel composition, flashover, and extinguishment. In order to predict fire behavior using a computer model, each stage of development must be considered and must be characterized by thermodynamics, heat transfer, and fluid dynamics.

2.1 IGNITION

Ignition, the first stage or event in the history of a fire, can be described as the bringing together of an energy source (heat) and a combustible material (fuel) in the presence of an oxodizing atmosphere (air/oxygen) so that a self-sustaining exothermic reaction occurs. The energy source transfers its heat to the fuel material by convection, conduction, or radiation. Ignition of the combustible material will depend upon the strength of the energy source and the length of time the energy source is applied to the material (fuel). The ease of ignition will also depend upon the chemical composition or thermal properties of the fuel material and upon the conformation and texture of the fuel material. A flat surface material will not ignite as readily as a creviced material because heat is held in the crevices and more effective heat transfer results.

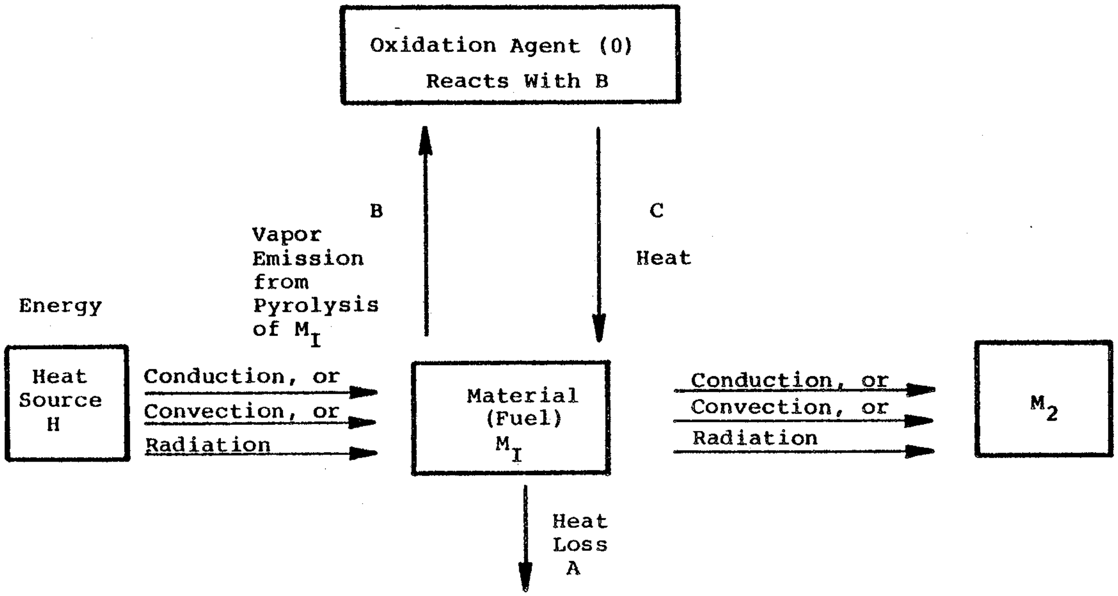
Whenever a solid fuel material ignites, it first decomposes into simpler solids and liquids, and, ultimately, into gases. This phenomenon is known as pyrolysis. It is very difficult to measure the rate of pyrolysis because of the complex chemical and physical reactions involved in the burning of most solids. The flammability of liquid fuel materials is measured by evaporation rather than pyrolysis. The applicable tests are flash point and fire point. The decomposition products (simple solids and gases) resulting from pyrolysis are oxidized by the air (oxygen) and result in the production of heat. The combination of the heat from this oxidation process and the heat from the existing energy source then serves to cause further pyrolysis. This reaction, shown in Figure 2-1, continues until the gaseous layer of the emitted decomposition products reaches the ignition temperature at which time the material then begins to smolder or flame. Smoldering occurs at relatively low temperatures and is accompanied by the production of smoke and gas in the absence of a flame. On the other hand, flaming combustion occurs with visible flames, intense heat, and rapid growth.

The burn process does not take place directly on the surface of the material. It has been observed on a vertical surface that a thin layer of gas exists between the fuel and the flame (Figure 2-2) and consists of the gaseous products of pyrolysis emitted from the fuel material. These combustible gases nourish the flames which radiate heat or impinge on other materials (fuels) in the compartment. When this occurs, the shape of the flame and its heat transfer characteristics are modified, and the movement of gases resulting from these flames becomes turbulent instead of smooth.

To summarize, the heat from the ignition source, the heat of oxidation of the pyrolysis products, plus an ample supply of oxygen on a combustible material completes the ignition scenario.

2.2 FIRE GROWTH

Many factors affect fire growth. Some of the environmental factors to be considered include: the size and combustibility of the enclosure; the location of the objects within the enclosure; the number of vents or openings in the enclosure; the location of the fire within the enclosure; and the oxygen or air supply. The flames from the initial ignition feed back heat to the burning material (fuel), heat other fuels within the compartment, and impinge on adjacent objects. The heat released by the flames expands the gases and adjacent air. These hot gases consist of the combustion products of the burning fuel material



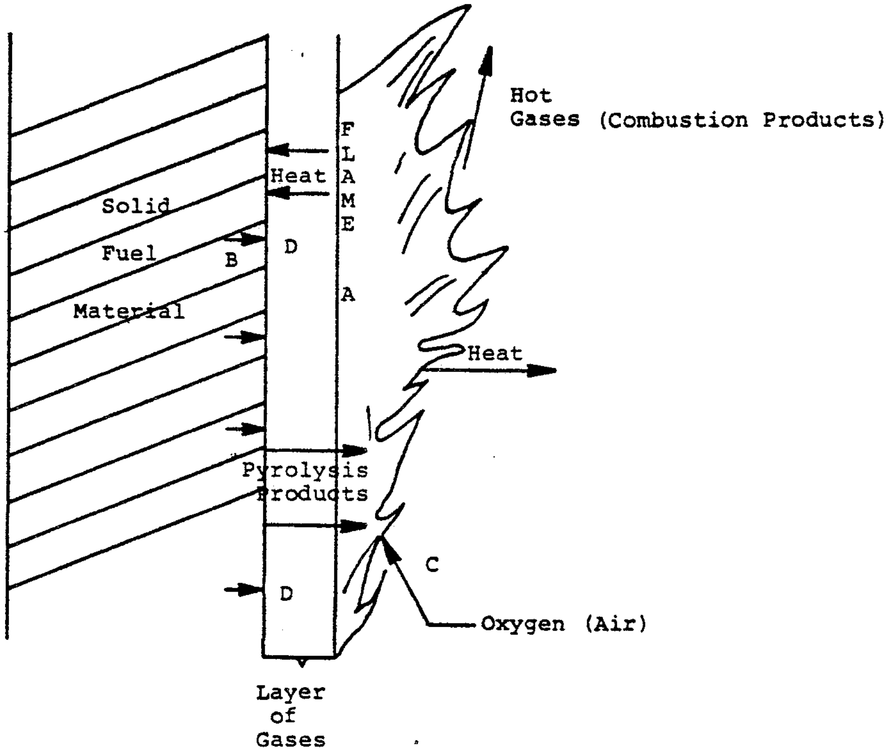
If A>C Pyrolysis Ceases

If A<C Combustion Continues

If M is Cooled
If H is Removed
If Oxygen Supply is Reduced
} Combustion Ceases

A - Heat Loss
B - Pyrolysis products
C - Heat Emitted, a Result of Oxidation
M_1 - First Material to Ignite
M_2 - Second Material to Ignite

FIGURE 2-1. ELEMENTS OF A FIRE SCENARIO



Notes: A. The flame covers the surface but does not touch the surface.

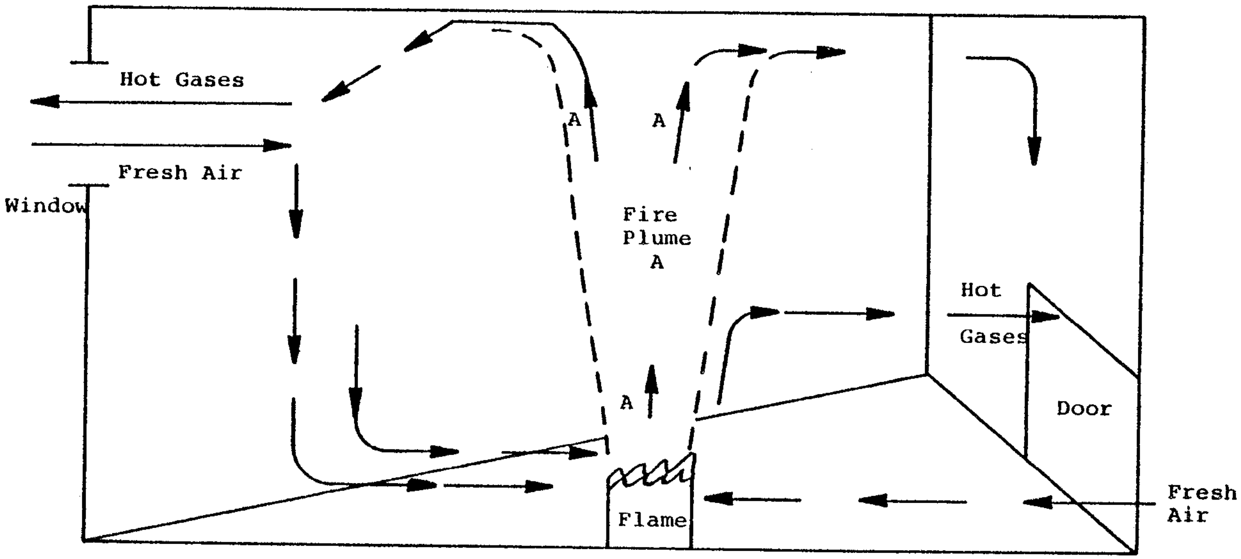
B. The fuel material surface is heated by the flame and pyrolyzes to emit combustible gases.

C. The emitted gases mix with the oxygen (air) which is fed to the flame by convection and the oxygen (air)/ pyrolysis gas mixture nourishes the flame.

D. There is no oxygen near the surface of the fuel, just a thin layer of pyrolysis products.

FIGURE 2-2. PROCESS OF COMBUSTION ON A VERTICAL WALL (smoke, toxic gases, pyrolysis products) and rise in a plume as shown in Figure 2-3. Fresh air is drawn to the fire by convection. Should a fire occur in a room with no openings, the supply of oxygen would soon diminish, and the fire would be extinguished. In reality, slight air leakage is usually sufficient to support a fire. The buoyancy effect of the hot gases results in the formation of a hot gaseous layer at the compartment ceiling, heating the ceiling and radiating heat to the other objects (fuels) in the compartment. When the hot layer reaches vents or openings in the room or compartment, the hot air flows out and cooler air comes in with the fresh source of oxygen needed to continue the burning process. Other items in the compartment may absorb energy from the flame by radiation, convection, or conduction. As these items increase in temperature, the pyrolysis process will begin, and finally they will ignite. In full scale fires, flame radiation is the dominant heat transfer mechanism. Many changes take place after the ignition of second and subsequential items, including radiation reinforcement, increased and redirected air motion, increased air temperature, and decreased air supply. The presence of sufficient fuel and oxygen may allow the fire to grow to the point that the heat from the fire and the hot gas layer at the ceiling causes the overall heat input to grow exponentially. This exponential heat input can produce a flashover which occurs when all the uninvolved fuel elements rapidly pyrolyze, and the entire compartment becomes involved in the fire. Flashover is generally defined as the rapid transition from a localized fire to total fire involvement. Prior to flashover, there is often a large flame extension across the ceiling. This flame, often mistaken for flashover, does not sustain itself but adds more heat to the unignited combustible products near the ceiling.

All room fires do not necessarily reach flashover conditions. A localized fire may extinguish itself and not ignite a second item, or a slow burning fire may go from item to item without generating sufficient heat to produce rapid total



Notes: 1. Hot expanded gases rise in a gas plume (A) to the ceiling by convection. Hot expanded gases include smoke, toxic gases and all other pyrolysis products.

2. Convective forces carry cool air to the flame. As expanded hot gases reach door and window tops, they flow out of the compartment creating a low pressure in the compartment. A fresh cool air supply enters the compartment at lower levels of openings providing the fire with a new oxygen supply.

FIGURE 2-3. FIRE GROWTH

involvement. Flashover generally occurs in well ventilated compartments and is an important transition phase to study and understand.

Analytical fire models could possibly be used to aid in the understanding of compartment fire growth from the ignition phase to flashover.

3. MODELING*

Today, fire research in transportation is concerned primarily with the prevention of fire spread within a structure. This approach lends itself to the use of models to quantify the many phenomena associated with fire growth. There are two basic types of models: 1) experimental models of fires (full scale and small scale) and 2) mathematical models. This report addresses mathematical models, but a brief discussion of experimental modeling is presented to demonstrate its use in the research of fire phenomena and in the validation of mathematical models.

3.1 EXPERIMENTAL MODELING

Experimental modeling is a necessary step in developing an understanding of the fire performance of materials and assemblies. These experiments may be directed at the entire pre-flashover scenario or at a particular segment of fire growth. Experimental modeling may be conducted on either a full scale or a small scale (scaled) model.

Full scale models have the advantage of closely simulating an actual fire scenario, but they are expensive. Most research projects can not afford to use full scale models to test the validity of the obtained results. Other important factors to be considered in full scale modeling are the inherent hazards which make instrumentation, measurement, and observation very difficult.

The disadvantages of full scale models have necessitated the use of small scale models which attempt to maintain geometric and thermodynamic similarities of materials and assemblies found in real fire situations. Scaled models have the distinct advantages of low cost and ease of operation. Although scaled model fire scenarios have given good results, their capability, in terms of full scale fire prediction, remains uncertain because of the differences in fluid mechanics, heat exchange, and oxygen supply. Two types of scaled modeling techniques in use today are

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*References 1,4,6,7,11,12.

Froude (atmospheric) modeling and Pressure modeling. Both of these modeling techniques are based on the premise that fires can be regarded as diffusion flames and follow fluid dynamic scaling laws.

Although both of these methods have their advantages and disadvantages, Froude and Pressure Modeling are probably the most advanced of the scaled modeling techniques in current use.

Froude modeling is based on the premise that large fires are mainly controlled by turbulent free convection. Therefore, this type of modeling is quite successful in its application to turbulent fires as long as the scaling does not go below a certain size (large enough so viscous effects do not become important). Froude modeling has been used for the studies of smoke and heat movement of turbulent fires in enclosures. It is an advantageous method of scaled modeling because special experimental facilities and equipment are not necessary.

In Pressure Modeling, the ambient pressures are increased to adjust the buoyancy force to the reduced size of the model. By this method the burning rate is increased, and the increased pressure also helps to produce complete combustion.

Pressure modeling can be applied to both laminar and turbulent fires. It tends to be more general and more accurate than Froude Modeling. The chief disadvantages of pressure modeling are a special pressure vessel is required for the performance of fire tests and the thermal radiation is not modeled properly.

Data for testing mathematical models is derived from either full scale or scaled physical models.

The full scale and scaled models presently used in fire studies have not yet achieved the desired level of accomplishment. Since these models are used for testing the validity of mathematical models, the need for improved modeling techniques exists.

3.2 MATHEMATICAL MODELING

Using mathematical or computer models in describing fire development offers a cost efficient method for comparing candidate materials and compartment designs. This information enables one to predict rate of fire growth and production of smoke and toxic gases for combustible materials, thereby making possible the calculation of the time available before the compartment becomes uninhabitable. Mathematical modeling can serve a useful purpose in relating and analyzing many problems in fire safety.

There are three types of general fire models used in computer or mathematical modeling to describe the development of a fire in an enclosure:

1. Probabilistic models,
2. Modular (control volume) models [zone], and
3. Differential field equation models [field].

The probabilistic models describe the fire development as a sequence of events (ignition, flame spread, heat transfer, etc.) and consider the change from one event to the next in terms of probability of occurrence and time. These models make little use of the chemistry and physics involved in a compartment fire. Model inputs are provided by analytical and experimental informtion. At the present time, the probabilistic models are the most practical approach for decision making.

The Modular or Control Volume models divide a compartment into distinct control volumes (lower space, fire plume, hot upper layer, the ceiling and upper walls, the inert room). The modular type model relies strongly on the physics of the problem by concentrating on gas behavior within the enclosure. The control volumes are interrelated by means of mass and energy fluxes across their boundaries. Each control volume can also be an independent model and called a sub-model (or subroutine). These models view the entire field of a fire (as opposed to a single event in a fire, e.g., ignition) at any given time by describing the thermodynamic/fluid dynamic situation at that time.

The Differential Field Equation Models divide the enclosure into many finite volume elements. The proper differential conservation equations are used to calculate the exchanges of mass, momentum, and energy between these elements. As the fire progresses, the properties characterizing each small volume of gas are monitored in order to determine the properties of the field at that time. These models have a strong reliance on the physics of the fire problem. This emphasis should enable these models to yield the most detailed information on that part of the fire development modeled. The field equation models focus on the gas behavior within the compartment and are especially suitable for long, narrow compartments.

The application of these modeling techniques can help to expand our understanding of fire dynamics. Fire hazards and detection methods could also be assessed, new compartment configurations could be evaluated, and the impact of new materials on potential fire hazards could be determined. Once mathematical or computer models are corroborated with physical test data, these benefits may be derived without the expense of large scale testing.

A variety of mathematical models can be derived from the three general types described above. The following section presents an overview of six such models.

4. FIRE MODELS

This section presents a review and summary of the features of six mathematical models in use today. These models have possible applications in the simulation of transportation vehicle compartment fires. The models presented are strictly mathematical in nature and are directed at the fire growth and propagation stages of a fire in a compartment. Other modeling efforts have produced fire models which are not applicable to transportation vehicles but are relevant to the study of fire and fire systems. Appendix A lists the centers of fire research which include modeling as a part of their research activities. At the time of this review, the information available on foreign research efforts was limited, therefore, foreign modeling efforts are not included.

The extent of the review of each of the six models varies depending on the information available. In general, the basic model construction and features are presented along with the input data requirements and the type of output available. For a more detailed discussion of each model, the reader is referred to the literature listed in the Bibliography. Other models may presently exist or be in the development stage, but this review has been directed at existing mathematical models with possible application to transportation vehicle compartment fires.

4.1 DAYTON AIRCRAFT CABIN FIRE MODEL (DACFIR)*

The Dayton Aircraft Cabin Fire Model was developed for the Federal Aviation Administration's Systems Research and Development Service under the direction of C.D. MacArthur and J.B. Reeves at the University of Dayton Research Institute (UDRI). The original mathematical model, a computer simulation of a fire, was developed specifically to predict the smoke and toxic gas emissions from the burning materials in the cabin interior of a wide-body transport aircraft. DACFIR II is a modification of this model and allows for the computation of fires in standard width as well as

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*References 13,14,14,16

wide body aircraft. The model tracks the development of the fire and the atmospheric changes in the cabin with time.

4.1.1 DACFIR Features and Construction

The DACFIR computer simulation is a modular room fire model which divides the cabin into two zones. During a fire, a layer or zone of hot gases and smoke exists above a layer or zone of relatively cool air. The upper layer of hot combustion products will rise to the upper zone by natural buoyancy. The lower zone is assumed to have the cool uncontaminated air originally in the cabin and the air which enters the cabin during the fire.

This model considers only the burning of materials which are an intrinsic part of the inner cabin structure. In other words, it predicts fires which originate on, and propagate over, the fixed interior surface of the cabin. It does not consider materials which may be brought into the cabin.

The Dayton model has a unique method of simulating the cabin geometry and fire spread (element "gridscheme"). It divides the cabin surface into fuel squares or "elements." These "elements," which are six inches square, exist in any one of four primary states: uninvolved, smoldering, flaming, or charred. It is assumed that smoldering elements emit smoke and toxic gases; flaming elements emit heat, smoke, and toxic gases; uninvolved elements emit nothing since they are not yet affected; charred elements emit nothing since they are burned out. During the simulation of a fire there is a transition of elements from one state to another. This transition may occur by several mechanisms: creeping flame spread from burning elements to adjacent elements (conduction), contact and envelopment of non-burning elements from a near-by fire (conduction), and the transition from uninvolved to smoldering as a result of heat from a near-by fire (convection and/or radiation). The rates and times of transition, as well as the rate of the emission of heat, smoke and gases, are quantities supplied as input data from the program.

Laboratory tests, made on samples of cabin interior materials, are the source of these data.

A "surface" is a group of "elements" all in the same horizontal or vertical plane with identical properties. The model simulation of the cabin interior acknowledges 20 lining surfaces and nine seat groups, each seat group having seven surfaces. The program also recognizes seven groups of materials and assumes that all of these materials can emit one or more of nine toxic gases.

The rate at which a fire develops in these cabins is dependent upon the type of surface on which it develops, the surface orientation (horizontal or vertical), the type of material of the surface and the thermal conditions in the cabin. The DACFIR objective of predicting smoke and toxic gas emissions is accomplished in a two fold manner:

1. It predicts the amount of smoke, toxic gases, and heat released as a function of time by determining the area of the surfaces burning and the amount of smoke, toxic gases, and heat released per unit area per unit of time (fire development).

2. Once the above calculations are established, the rates of emission and the states of all the elements are used as input data to describe the cabin atmosphere by such parameters as temperature, visibility, and the gas dynamic relations of the cabin's two zones.

It should be noted that the basic flowcharts for DACFIR I and DACFIR II are the same. The modifications made on the original model are refinements of the model, rather than major structural changes. Refinements made on the original model include: the capability to simulate standard width aircraft; more flexibility in the model's description of cabin geometry; gas dynamics calculations which include oxygen depletion; forced ventilation effects and the effects of a circular cabin cross section; and a refinement of the radiation heat transfer computations.

A simplified flowchart of the computer program is shown in Figure 4-1. The program consists of a main program which provides the necessary controls to insure a logical sequence for the computations. Linked to this main program are subroutines. Each subroutine performs a specific function or set of computations. A description of the subroutines is given in Table 4-1.

The language of the program code is Fortran IV.

4.1.2 Input Data

The input data cards are prepared from three types of information:

1. Cabin geometry (Input G);
2. Material flammability properties (Input M); Data are obtained from laboratory flammability and toxicity tests of cabin interior materials. The laboratory data measurements are obtained from tests performed in the Ohio State University Combustion Analyzer and National Bureau of Standards (NBS) smoke chamber. This is the most voluminous part of program input.
3. Ignition conditions (Input O); This input contains the ignition source and program control variables. The program control variables include: integration step size, time step size for flame spread calculations, and output interval and maximum time for program run.

Other input data are inherent in the model and are based on theoretical principles and experimental data. Deriving fire dynamics data from theoretical principles would be the ideal situation, but fire science is not sufficiently advanced to predict fire behavior from theory alone. It is, therefore, necessary for fire modeling efforts to rely on both empirical and theoretical methods.

Tables 4-2, 4-3, and 4-4 illustrate what input data is necessary for each subroutine receiving its input from data input cards.

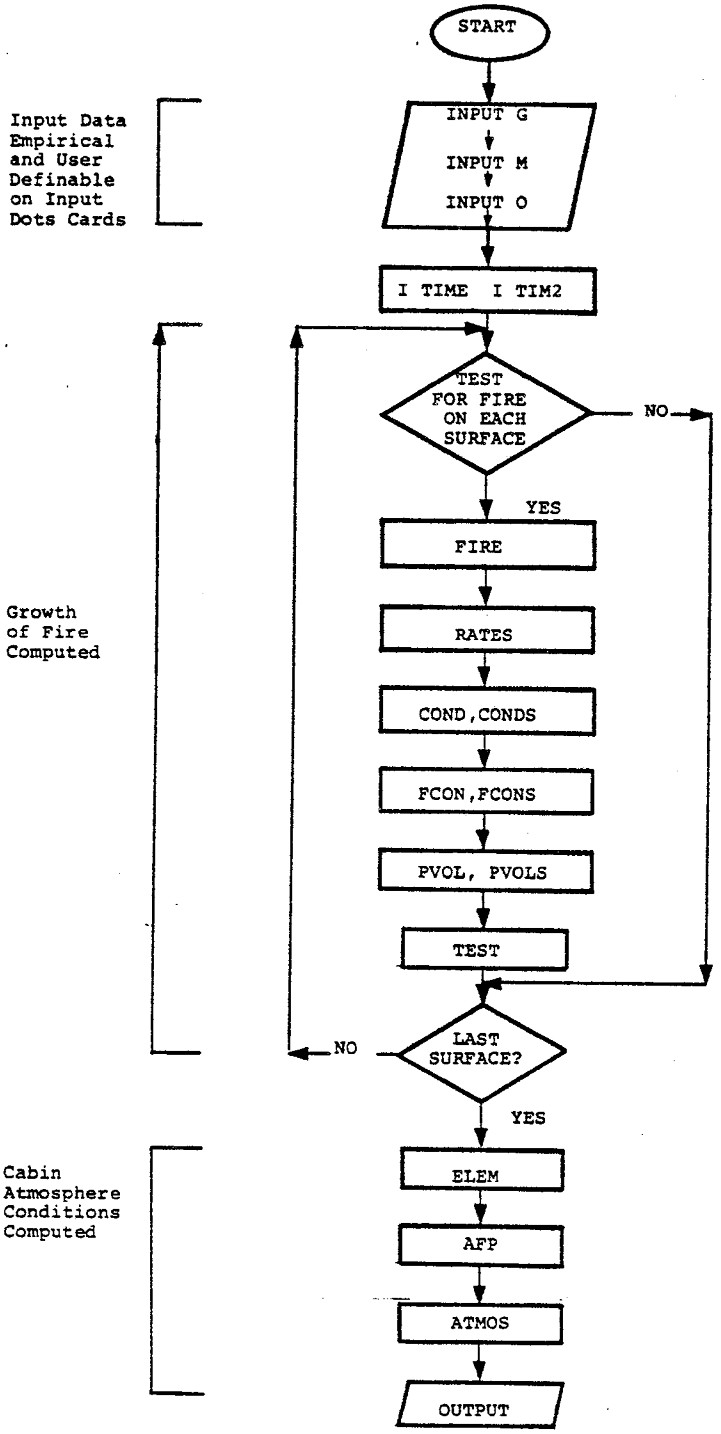

FIGURE 4-1. FLOWCHART OF THE DAYTON AIRCRAFT CABIN FIRE MODEL (DACFIR)

TABLE 4-1. SUBROUTINES - (DACFIR)

SUBROUTINE	FUNCTION OF SUBROUTINE
INPUT G	Reads data cards to establish basic conditions necessary for variables and defines those variables pertaining to the geometry of the cabin section
INPUT M	Reads all input data cards pertaining to the material properties of each surface
INPUT O	Reads all the data relating to the ignition source description
ITIME, ITIM2	ITIM2 is the time associated with the flame propagation computations. ITIME is the time associated with the cabin atmosphere computations
TEST FOR FIRE ON EACH SURFACE	Are there any flaming elements on the surface? If not, the flame growth computations are by-passed for this surface.
FIRE	Individual flaming surfaces are located, and their flame properties are computed.
RATES	Computes emission rates of heat, smoke and toxic gases; flame spread rates; and transition times as a function of heat flux
COND, CONDS	Computes flame spread by conduction
FCON, FCONS	Computes flame spread by flame contact
PVOL, PVOLS	New elements in the smoldering state are identified.
TEST	Determines if any flaming elements change to charred state and sums the emission rates for each fire.
LAST SURFACE?	Have all surfaces, both seat and lining surfaces been examined? In not, progress to the next surface.
ELEM	Updates the time counters and indicators associated with each element to identify element transitions from smoldering to charred states.
AFP	Determines the total number of flaming and smoldering elements and sums the emission rates.
ATMOS	Predicts cabin atmosphere conditions. Contains all of the equations describing the cabin atmosphere.
OUTPUT	Consists of the required print and format statements and controls to obtain the output data as reouired.

TABLE 4-2. DATA CARD INPUT FOR SUBROUTINE INPUT G - (DACFIR)

INPUT G - Input relating to cabin geometry

a. Cabin section dimensions
b. Cabin sub-section dimensions
c. Number of lining surfaces

    (1) dimensions
    (2) location
    (3) orientation
    (4) material identification

d. Number of seat groups

    (1) dimensions
    (2) location
    (3) material identification

e. Number of passageways(doors)

    (1) dimensions
    (2) location

f. Element dimensions - set at 0.5 ft x 0.5 ft.

g. Specify "square" or "round" cabin cross section[1]

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[1] For gas dynamics calculations.

TABLE 4-3. DATA CARD INPUT FOR SUBROUTINE INPUT M - (DACFIR)

INPUT M - Material properties

Two types of INPUT M data:

1. Properties associated with the flaming combustion state of the material
   - a. Horizontal flame spread rate
   - b. Vertical upward flame spread rate
   - c. Vertical downward flame spread rate
   - d. Time to flame
   - e. Time to char from flaming state
   - f. Heat release rate per unit area
   - g. Smoke release rate per unit area
   - h. Toxic gas release rate per unit area
2. Properties associated with the smoldering combustion state of the material
   - a. Heat flux at which smoldering is induced in less than 20 seconds
   - b. Smoke release per unit area
   - c. Toxic gas release per unit area
   - d. Time to begin smoldering
   - e. Time to become charred from smoldering
   - f. Time to cease smoldering when the heat flux is reduced to zero.

TABLE 4-4. DATA CARD INPUT FOR SUBROUTINE INPUT O - (DACFIR)

INPUT O - Ignition Source Description

There are two methods by which ignition source may be described:

1. One or more fires of a given size ignite a material instantaneously. This material is the only fuel for continued burning. The method of ignition is not considered as part of the computations.

   a. Initial location of fire
   b. Initial size of fire
   c. Combustion parameters of original source materials[1]
      (1.) Two entrainment constants
      (2.) Adjusted heat of combustion
      (3.) Fuel vapor density
      (4.) Fuel vapor velocity at the base of the flame
      (5.) Fuel vapor temperature
      (6.) Stoichiometric oxygen to fuel mass ratio
   d. Smoke generation rates
   e. Toxic gas generation rates
   f. Heat generation rates

2. The ignition source fuel is superimposed on another material (fuel) surface. The fire involves both the ignition fuel and the material on which it is superimposed. This simulates the spill of a flammable material.

Input is as above with the following changes:

TABLE 4-4. DATA CARD INPUT FOR SUBROUTINE INPUT O (Continued)

a. Separate smoke, toxic gas and heat generation rates for each material in orter to calculate combined effects

b. Only four combustion parameters are used to describe the superimposed material 1.C(2), 1.C(3), 1.c(4) and 1.C(5).

c. All combustion parameters are used on the inner material.

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[1] The values for these parameters are not available for the polymeric materials used in aircraft. Values for these quantities have been estimated based on the available information from the fire research literature.

4.1.3 Output Data

The output of the DACFIR program is divided into two parts: one section describing the cabin atmosphere and another section containing flame spread data. The user has the capability of specifying the time interval of the output for both the cabin atmosphere vs. time and the flame spread vs. time. The quantity of output will vary according to the number of flaming and smoldering areas in existence at any particular time and also with the frequency of the outputs.

The user also has two output options:

1. The user may call for only a printed summary of the cabin atmosphere.
2. The user may call for a printout which includes: a cabin atmosphere summary, a list of elements in the burning or smoldering state, a summary of the flaming and smoldering areas by material type, and a graphic diagram of each surface showing the state of each element.

Table 4-5 presents further details about output data.

4.2 HARVARD COMPUTER FIRE CODE*

The Computer Fire Code, being developed at Harvard University under the direction of H.W. Emmons and H.E. Mitler, has the ultimate goal of predicting fire behavior in a structure of any size and complexity (n rooms with n vents, halls, stairways, etc.). Computer Fire Code V**, the latest available version of the Harvard model, is basically an improved version of Fire Code III. Although the program is indexed to permit consideration of a multi-room structure, its capabilities, at the present time, are limited to one rectangular shaped enclosure (divided into two zones) with five rectangular openings (doors or windows). At time zero, fire is ignitied on a horizontal surface, or a gas burner is turned on

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*References 17,18,19,20

**To be published, a tape for Fire Code V is available

TABLE 4-5. DACFIR DATA OUTPUT DETAILS

Output data given at time intervals selected by user

Cabin Atmosphere Summary

Upper Zone	Lower Zone
Zone Depth	Zone Depth
Gas Density	Gas Density
Gas Temperature	Gas Temperature
Material Surface Temperature	Material Surface Temperature
Heat Rate to Surface	Heat Rate Surface
Smoke Concentration	
Toxic Gas Concentration	
Oxygen Concentration	

Flame Spread Data

For Each Distinct Fire at Start of Flame Spread Calculation

Zone

Distance of Fire Base from Floor

Flame Height

Fire Base Area

Flame Volume's Base Radius

Conditions on All Surfaces at End of Flame Spread Calculations

Element State Summary

Smoldering

Flaming

Charred

Flaming & Smoldering Areas by Material Type

Material

Area Flame

Area Smoldering

within the enclosure. The fuel surface usually used in Fire Code V validation experiments is a slab of polyurethane foam. The room may contain any number of target objects, but at the present time there is an arbitrary limit of four.

4.2.1 Harvard Computer Fire Code Features and Construction

The basis for the prediction of the growth of a fire in this model is the recognition of the existence of separate interacting events which can be described quantitatively. This computer program is written in modular (zone) form. The burning fire is not modeled as a single complex three dimensional system but as a collection of interacting components which are grouped together in separate modules. This means that all separable functions, operations, or phenomena are computed in separate subroutines so that each subroutine is independent of the others. This method permits the addition of a new subroutine or the revision of an old one without changing the rest of the program. It, therefore, allows for several versions of a subroutine, each with varying degrees of precision. This system permits the users to run the program with whatever degree of accuracy or precision is needed for their purposes.

At present, computer Code V has more than 60 subroutines linked together in 13 files (a system for storing together functionally or conceptually related subroutines). Each of these 13 files functions in one of five modules of the model (Table 4-6). These five modules or categories constitute the organizational design of the Harvard Computer Fire Code. Figure 4-2 is a simplified flow diagram and organizational chart.

A brief description of each model or section of the computer program follows:

Control - The function of this section of the program is to regulate the general flow of the program, decide which numerical procedure to use, direct the use of the other sections, regulate output, decide at a specified time if a solution has been found, and decide when to stop the program.

TABLE 4-6. HARVARD COMPUTER FIRE CODE EXAMPLES OF SUBROUTINES WITHIN THE FILES AND MODULES IN WHICH FILES FUNCTION

FILE	DESCRIPTION	SUBROUTINES*	MODULE
C	Convention	CNVW, CNVL	Physics
D	Discovery	TIGN, NWSTAT	Physics
F	Fire	BFIR, PFIR, GFIR, HFIR	Physics
I	Input and Initialization	INIT, INPUT, INPUT3, RECAP, DISP, VERIFY, COPINP, ALTINP	Input/Output
L	Layer	LAYR, ABSRB1, ABSRB2, ABSRB3, EMSVTY	Physics
M	Main Program	FRCD, BLOCK, EXTRAP, NUMER, DELTAT, RESETI	Control
N	Numerical	JACB, NWTN, DECOMP, SOLVE, MSLV, SING DECOMP, CONV	Numerics
P	Plume	PLUM, PLHT	Physics
R	Radiation	RDNO, RNPO, RNLO, RNWO, RNLH, RNLV, RNFF, RDNP, RDNW, RDNL	Physics
S	Interfacing	CALS, SETI, SETJ, MAPS	Interface
T	Temperature	TMPF, TMPW, TMPO01, TMPO02	Physics
V	Ventilation	VENT, FLOW	Physics
W	Output	WRIT, DEBUG, LIST, WRIT03, LOOKUP	Input/Output

*Subroutines - Usually labeled by letters suggestive of the process they describe

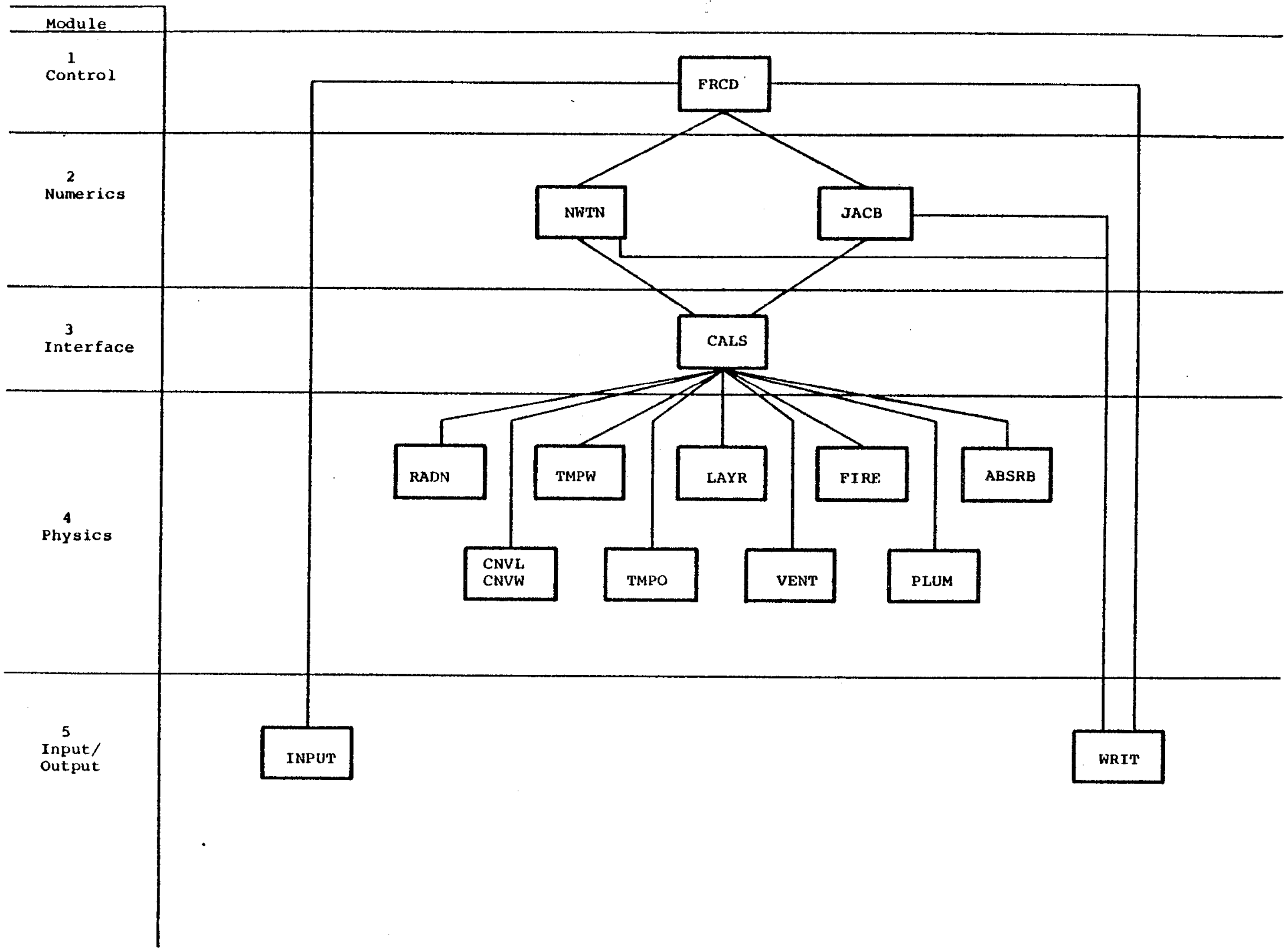


FIGURE 4-2. HARVARD COMPUTER FIRE CODE-ORGANIZATIONAL CHART[5]

Numerics - This section directs all numerical calculations.

The computer program is designed to predict the progress of a fire by solving a set of equations with the variable necessary to describe fire behavior. The differential equations are of the first order in time and of the simplest form. Conversely, most of the algebraic relations are nonlinear and often quite complex.

There are three numerical programs available for solving simultaneously the subprograms of the computer code at each time step. Each numerical program varies in its ability to solve the problem. If the problem cannot be solved by the simplest method, the program proceeds to the next method. If all three methods fail, the time step is halved, and the methods are tried again (Jacobi method, Newton method, Fast Newton method). In other words, there is reiteration of the problem until convergence.

Interface - This section of the computer model calls for the physical subroutines and organizes the data arrays.

For a variety of reasons, numerical calculations are best done if all variables are of comparable magnitude. This fire prediction model may have variables ranging in physical magnitude from 10^7 to 10^{-9} in the same equation. These values are scaled to magnitudes of order unity and are rescaled before output.

Interface also eliminates variables which are having no effect on the calculation because they are too small or because they are not changing and thereby act as constants.

Physics - All the subroutines which describe the fire dynamics are included in this module. For most of the physical processes, there are alternative subroutines available. These alternative subroutines may contain modifications or additional physics.

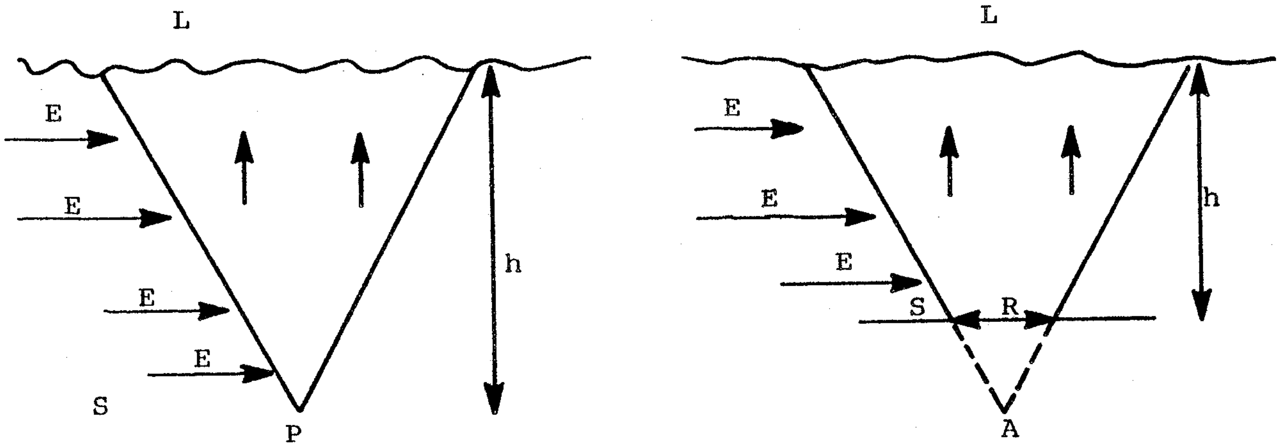
4.2.2 Physical Calculations and Processes

4.2.2.1 Fire - Fire subroutines take into account three events: the size and burning rate of the fire; the rate of growth of the fire; and the amount of heat given off by the flame. All of the data and information used in the calculations of these subroutines are derived from empirical data, since the information can not be derived theoretically. The location of the point of ignition is arbitrary, without exception. The program cannot, as yet, consider the growth of a fire adjacent to a wall, an edge, or a corner. The production of combustion products is also calculated here.

4.2.2.2 The Plume - Many attempts have been made to adequately describe the turbulent buoyant plume rising from a fire. This model uses a "virtual point source" or an area source plume rather than a point source plume (Figure 4-3). The virtual point source seems to be a more realistic approach than a point source which assumes that the energy release occurs at a point on the fuel surface. The virtual point source or area source assumes the energy release is from an area equal to the area of the burning surface.

The mass and energy transferred from the fire to the layer by way of the plume is assumed to be instantaneous.

4.2.2.3 The Hot Layer - The plume is assumed to end at a flat horizontal interface with the hot layer. It is also assumed that there is complete and instant mixing of hot gases in the upper layer so the density, temperature, and optical properties are uniform throughout this hot layer. As the hot gases accumulate, they produce a layer of increasing depth to the point where the layer falls below the top of the vent (door or window) and allows the hot gases to flow out. The mass of the hot layer is increased through the plume as the fire burns and is decreased by the flow of gases through the vent. The energy of the hot layer is increased by energy input from the plume and is



Point Source Plume

Area Source Plume
(Virtual Point Source)

E - Air which will be entrained by the plume, heated by the fire and pass through the plume to the upper layer
L - Upper layer
h - Height of plume
p - Point source, all heat release occurs here
A - Virtual point source
R - Area of fire
S - Fire surface

FIGURE 4-3. HARVARD COMPUTER FIRE CODE - PLUME MODELS USED FOR PLUME SUBROUTINE CALCULATIONS decreased by conduction losses to the ceiling and upper walls, to other objects in the room, and by flow out the vent.

The Harvard Model does not consider the possibility of combustion in the hot layer.

Harvard Fire Code V has the capability of calculating smoke (particulate matter and gaseous hydrocarbons), CO_2 (carbon dioxide), CO (carbon monoxide), O_2 (oxygen), and H_2O (water) concentrations.

4.2.2.4 The Vent - At the present time five flow regimes are included in the vent calculations:

Regime 1 - Cold air is pushed out of the vent.

Regime 2 - Both cold and hot gases flow out of the vent. The fire growth during this regime is so rapid that hot and cold gases are forced out the vent by the buoyant flow and by the expansion of gases.

Regime 3 - Hot gases flow out the upper portion of the vent, and cold gases flow in the lower portion. This regime prevails most of the time.

Regime 4 - "Choked flow" occurs when the hot outflow and the cold inflow have reached their maximum. Therefore, the magnitude of the fire is essentially controlled by the size of the vent, since the vent size determines the amount of oxygen or cold flow entering the enclosure.

Regime 5 - Only hot gases flow out of the vent. The VENT routine calculates the correct mass flow rates through all the vents in the room by one general expression independent of the prevailing regime.

The mass and energy changes occurring in the room are also calculated.

4.2.2.5 Heat Transfer by Radiation - The radiation to and from up to 5 objects within the compartment is computed along with the heat loss rate from the hot layer and the plume. At the present time, these subroutines calculate the radiative transfer or flux from the walls, hot layer, and flames to the target.

4.2.2.6 Heat Transfer by Convection - This calculates the convective heat transfer or heat loss from the hot gas layer to the walls and ceiling (extended ceiling). It is assumed the "extended ceiling" has a uniform temperature where it comes in contact with the layer and that the layer has the same temperature throughout.

4.2.2.7 Heating of the Walls and the Target - These physical subroutines calculate the temperature and state of the walls and targets at any given time. All objects or targets are considered to be in one of ten states: (1) cold-not invloved; (2) heating but not pyrolyzing; (3) pyrolyzing but not burning; (4) smoldering; (5) flaming: a. growing fire, b. pool or ignited fire, c. gas burner; states (6) and (7) not yet identified; (8) burning charcoal; (9) extinguished; and (10) burned out. The state of an object may change during the execution of the program.

The Harvard Computer Fire Code program is written in Fortran. A simplified flowchart is shown in Figure 4-4.

4.2.3 Input Data

This section of the computer program controls the input materials of the program.

4.2.3.1 Input - Input data are entered into the computer program through the keyboard in an interactive manner or by the batch mode which is also available. The user must know or anticipate the questions the program will ask and have the answers ready.

The data entered as input must be in Systeme International (SI) units. Input items include:

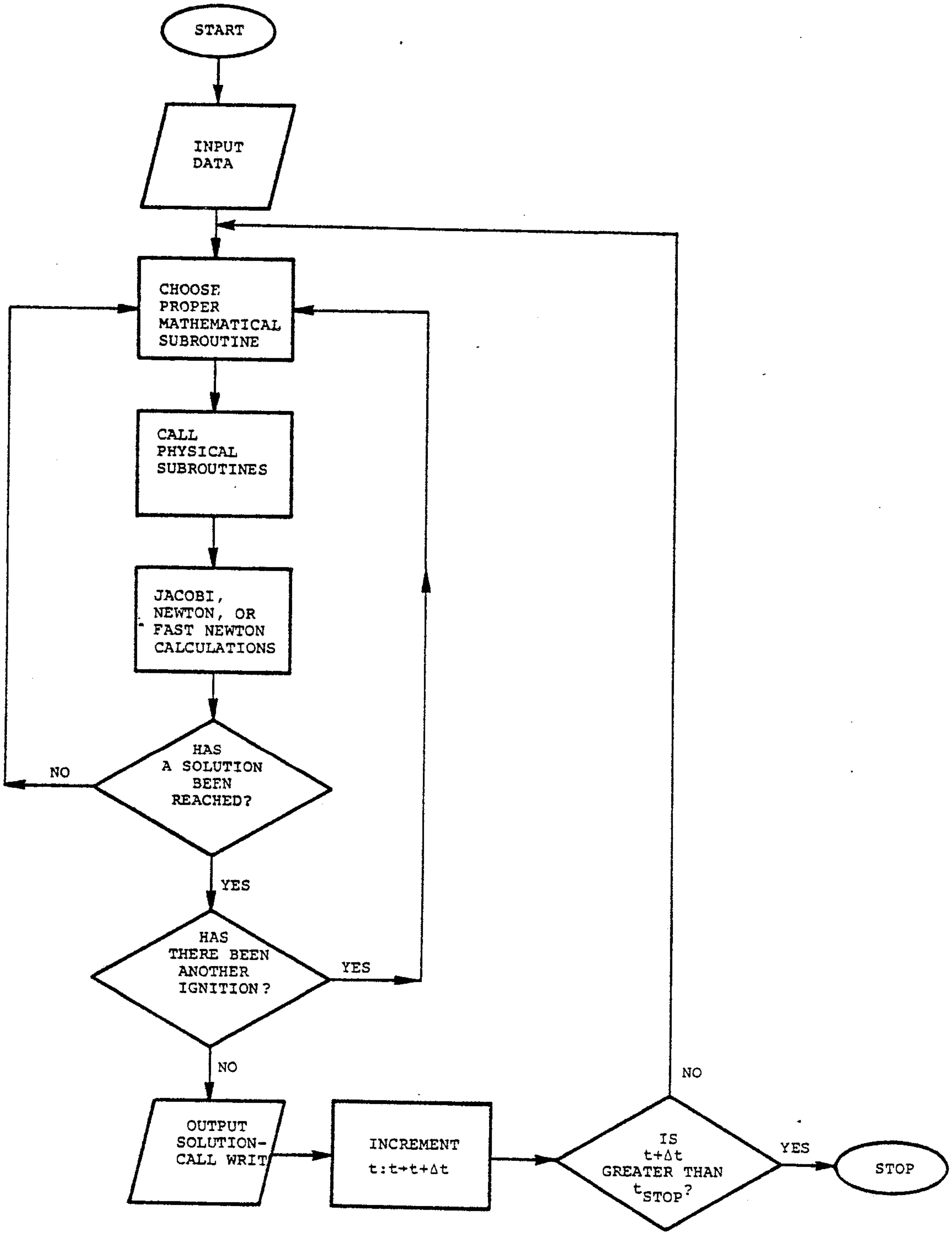


FIGURE 4-4. HARVARD COMPUTER FIRE CODE - SIMPLIFIED FLOWCHART

1. Room Geometry (The user has the option of a standard room, or he may enter his own figures.);
2. Physical constants and material parameters for walls and objects;
3. Ignition point and target (located by the Cartesian coordinate system);
4. Maximum burning radius for each object;
5. Desired length of the run (The standard run is 500 seconds long); and
6. Output requirements.

4.2.4 Output Data

Currently, there are two formats of output, user chosen. The output format selection is entered as an input item to the program. Format 1 is fixed and outputs almost all the calculated variables. When there is a change in the vent-flow regime or when a new object ignites, it is indicated in both formats.

A third format should be available so that the user can choose which variables are to be in the output. The two formats are:

1. Format 1 - Long Form - Output is shown every 20 seconds after the first output, which is given at two seconds. Other interval choices may be made.

   Format 1 outputs include the following information:

   (a) Time from ignition,

   (b) Number of iterations to obtain convergence,

   (c) Total number of iterations taken from start,

   (d) Total number of time steps taken by time t, and

   (e) A table of physical variables grouped as they relate to: vent, object, plume, fire, inside wall, and outside wall.

2. Format 2 - Short Form - Output is shown every 50 seconds unless otherwise specified during input. Format 2 outputs include the following information:
   - (a) The time, t
   - (b) Values of 8 physical variables at time, t. The choice of variables is made by the user. If the user makes no choice, there is a default set.
   - (c) The number of variables in the program at time, t,
   - (d) The largest relative error after convergence,
   - (e) Which of the three numerical programs is being used for the current calculation.

4.3 ILLINOIS INSTITUTE OF TECHNOLOGY RESEARCH INSTITUTE FIRE MODEL*

The Illinois Institute of Technology Research Institute (IITRI) was given a grant by the National Bureau of Standards for the development of a mathematical model to simulate the initiation and growth of a room fire from ignition to flashover. It was believed this model would present fire development characteristics in terms of probabilities of occurrence (probability of spread to a second item, probability of flashover within a certain post-ignition time, etc.). The original concept of this model was to divide the fire into a series of independent events with the expectation of predicting the transition from one event to the next. It was quickly determined that fire development within an enclosure must be viewed not as a series of sequences but as a single event, characterized by thermodynamics, heat transfer, and fluid dynamics. The same phenomena exist and control the fire at each stage of fire development.

4.3.1 RFIRES - Features and Construction

The model developed by IITRI "RFIRES", under the direction of Thomas Waterman and Ronald Pape, predicts the response of a room to the burning action of the major burning items in

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*References 5, 11, 21, 22.

the room. The room or enclosure contains up to ten furniture items in various positions within the room. The model views the furniture items as solid rectangular boxes with four sides and a top, all surfaces being parallel to the room walls or the floor. The boxes ignited at the start burn on top and burn down like a candle until the combustible contents of the box disappears. The box fire is considered terminated when all the combustible mass of the box is consumed.

A new ignition occurs when a box (furniture) surface exceeds its critical ignition temperature. When this temperature is reached, flaming combustion is assumed to begin. RFIRES uses the critical ignition temperature to predict new ignitions or fire spread. The IITRI model includes the prediction of smoke and toxic gas concentrations in both the upper and lower zones of the compartment. Smoke particle and toxic gas generation data used for this model are obtained primarily from the NBS smoke chamber.

Fire plumes are assumed to be cylindrical in shape, with the fire spreading radially from the center of the box from which it is considered to have initiated. The fire grows radially at a constant velocity until the circle area equals the box top area. Flame spread velocity is not constant, but it is treated as such in order to simplify calculations.

Ignition by flame impingement is also possible. The model assumes the flames diverge at a 10° angle from the base of the plume. If a plume touches an adjacent box, the box is ignited. The user makes the decision if this type of ignition is to be included in the program.

The RFIRES computer model is a modular (zone) type simulation. The enclosure is divided into two control volumes: the hot upper layer and the cool lower layer separate at the height of thermal discontinuity. This height changes as the fire progresses.

Full scale validation experiments have been the basis for many modifications in the original program. Several simple models were incorporated into the program to account for the combustion of residual fuel in the upper spaces of the room, and a subroutine was developed to predict smoke and gas concentrations as a function of time.

Several observations and conclusions based on many test cases have been made about the RFIRES code:

1. The first major fuel item burning determines room fire burning behavior.

2. The combustion of residual fuel and the amount of oxygen in the upper spaces of the room are important and must be considered.

3. The thermal response of the ceiling can have a strong effect on the fire growth and, therefore, the thermophysical properties of the ceiling used in the calculations must be accurate.

4. Nonburning items in the lower space of the room are heated by both radiative heat flux from the upper layer and flames in the lower layer.

5. Plume air entrainment is important in predicting the upper layer gas temperature and the thermal discontinuity height. For simplification, RFIRES uses a plume model with a constant entrainment coefficient, even though it has been shown that the entrainment coefficient changes as the flame grows.

A simplified flowchart of the RFIRES code is depicted in Figure 4-5.

4.3.2 Subroutines and the Main Program

4.3.2.1 Main Program - The main program begins with the reading of the input data and establishes the necessary conditions for the use of this data. Other functions of the main program

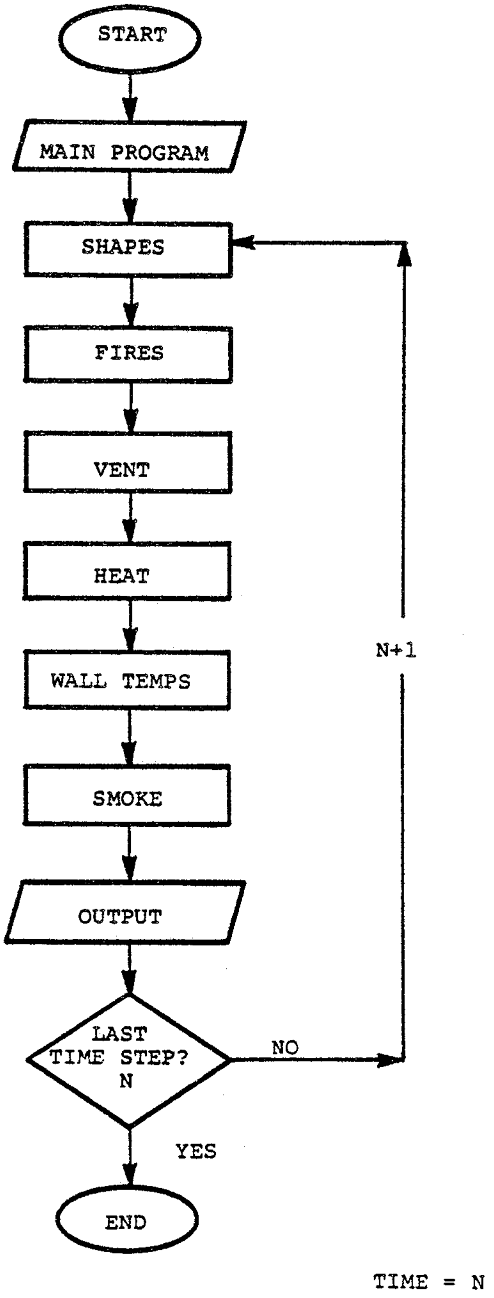

FIGURE 4-5. RFIRES CODE - SIMPLIFIED FLOWCHART

include: organizing the entry to the different subroutines, controlling the time frames for output readings, and printing the program output. The remaining part of the main program is involved with estimating the box (furniture) wall temperatures for the prediction of new ignitions.

4.3.2.2 Shapes - This subroutine computes all the radiative interchange areas between surfaces or box walls. These box walls are either parallel or perpendicular. The transmitting box wall is considered to be at a uniform temperature. All possible radiative interchanges are calculated and stored for use later in the program.

4.3.2.3 Fires - This subroutine which is the driver for the program estimates volatilization rates, pyrolysis areas, box burned masses, and box height (assumes a candle type burning) for each burning item (box) in each time step. The model reports volatilization or pyrolysis and pyrolysis area as a function of time. The pyrolysis rate provided at each time step is either interpolated directly from experimental input data or computed by one of three simple relations. The relation used is dependent on the type of furniture item burning.

4.3.2.4 Vent - The primary purpose of this subroutine is to predict the rate of air entrainment into fire plumes and the height of the thermal discontinuity. VENT is a model of the gas flow inside the enclosure, and it also determines the gas flow carried through the plume to the upper spaces, the visible flame height, the height of the natural buoyancy plane at the door, the hot gas volume, and the upper wall and ceiling area "wetted" by the hot gas layer.

The three major relations which describe the flow of gases through the enclosure are: (1) air entrained by the plume, (2) the flow of products out of the door, and (3) the flow of air in through the door.

4.3.2.5 Heat - This subroutine conducts an energy balance on the plumes, the hot layer, and the hot upper walls and ceiling by computing the plume temperatures, the average temperature of the hot gas layer, and the average ceiling temperature.

4.3.2.6 Wall Temps - This transient model is incorporated into the main program in order to predict the temperature of the non-burning surfaces. Since the critical temperature of any surface determines when that surface will ignite, this subroutine is also capable of predicting new ignitions.

4.3.2.7 Smoke - This subroutine predicts smoke and toxic gas concentration in the upper and lower gas layers. These concentrations are reported as mass concentrations of smoke particles and attenuation coefficient. The attenuation coefficient is a measure of thermal capacity or thermal emissivity of the gases within the zone. Values for this subroutine are obtained from experimental data generated primarily in NBS smoke density chambers.

4.3.3 Input Data

Input data is entered into the main program on input data cards using English units. This input includes: a collection of empirical data about burning behavior (combustible mass, ignition temperature, flame spread velocity, heat of combustion, toxic product information), room geometry information, information about the furniture (number of pieces and arrangements), probability curves, and physical constants.

4.3.4 Output Data

The output is printed by the main program at the time intervals specified by the user.

The model predicts the response of the room to the furniture volitalization rate provided as input. It predicts, at any given time:

1. Average upper layer temperature,

2. Ceiling temperature,
3. Thermal discontinuity height,
4. Floor or target incident heat flux and temperature, and
5. Flame height.

For different applications other outputs, such as rate of air entrainment, obscuration due to smoke, and CO concentration, have been generated.

In recent work done for NBS, the RFIRES code was exercised to evaluate parameter sensitivities. A summary of these results* provides a sampling of the type of output that can be provided by this code.

4.4 OHIO STATE UNIVERSITY**

The Release Rate model of a compartment fire was developed at Ohio State University under the leadership of Dr. Edwin E. Smith. This simple, easy-to-use model provides the user with comparative information about materials in a real fire system. Release Rate data about each material within the fire system is necessary for the operation of this model.

Release Rate data is empirically derived information from release rate tests to determine the rates of heat, smoke, and gas emissions from materials during their burning process. The release rate tests do not simulate a real fire but test the fire behavior of material under controlled conditions. The fire behavior observed during a release rate test includes: flame travel rate, time to ignition, heat and smoke release rates, and total heat and smoke released. The Release Rate model simulates a real fire system using release rate data about the materials within the fire system.

In an identical compartment, fire systems will behave differently because the release rate characteristics of the materials within the compartment are different. By using the Release Rate

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*Reference 22.
**References 23, 34.

model, the rate of heat, smoke and gas emission from a fire in a compartment can be predicted, making it possible for the model to predict how much time will elapse before a hazardous condition will exist in the compartment.

If the release rate characteristics of materials are known, comparative information about these materials is easily acquired with this model. The model can effectively compare the fire performance of these materials in a real fire system.

Much of the research for the Release Rate model was sponsored by the Product Research Committee, the American Iron and Steel Institute, and the Transit Development Corporation. For a more detailed description of Dr. Smith's Release Rate model the reader is referred to a forthcoming report to be published in 1981 for the American Public Transit Association.

4.4.1 Release Rate Model- Features and Construction

The Ohio State Release Rate model consists of a main program and several subroutines which perform the calculations necessary to produce the output information. Table 4-7 lists each subroutine and gives a brief description of its function.

Differences in the combustibility of materials cause them to emit different amounts of smoke and heat in a real fire system. This model uses release rate data to solve a simple mass and energy balance equation in order to determine the smoke and heat emitted by fire in compartments furnished with different materials. The mass and energy balance equation used for this purpose is illustrated in Figure 4-6.

In the construction of this Release Rate model describing fire development in a compartment several assumptions were made:

1. This is a two layer model.
2. The venting rate is a function of the upper layer temperature and the rate of temperature rise.
3. All heat released by the fire goes to the upper layer.

TABLE 4-7. OHIO STATE RELEASE RATE MODEL SUBROUTINES AND FUNCTIONS

SUBROUTINE	FUNCTION
Main	Controls program flow and storage of subroutine calculations
Compartment	Calculates temperature and smoke concentration in the compartment
Wall	Calculates smoke and heat release by the wall and heat loss into the wall
Surface Temperature	Calculates surface temperatures throughout compartment
Emissivity	Calculates concentration of smoke particles in upper layer
Release Rate	Calculates total heat and smoke release
Burner Release	Calculation referring to heat and smoke release rates of initial burner (source)
Flame Travel Rate	Calculates flame travel rates in real fire system.

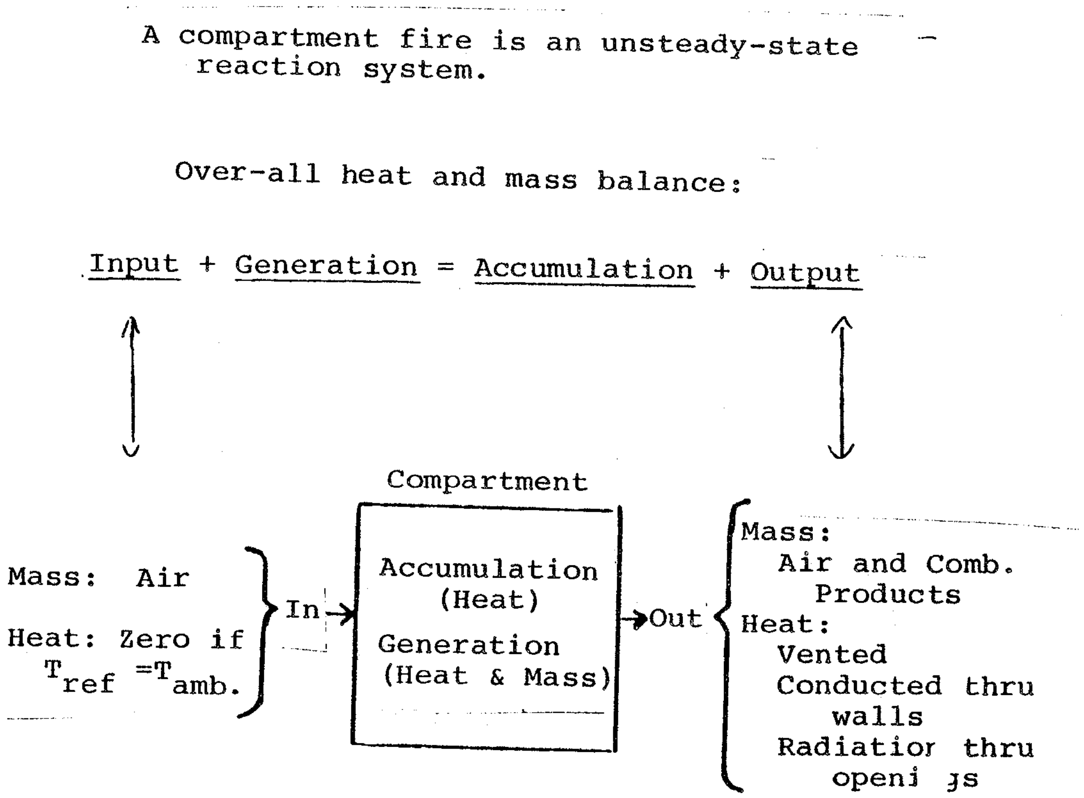

FIGURE 4-6. OHIO STATE RELEASE RATE MODEL - HEAT AND MASS BALANCE ON A COMPARTMENT

4. All the combustible gases released by the fire will burn within the compartment.

5. Pre-flashover conditions exist in the compartment.

The initiating fire source may be of any size or type. The fire may or may not spread to adjacent objects depending upon the "ignitability" of those objects and the size and intensity of the initiating fire. The rate at which the flame spreads and the rate of heat release are determined by the combustibility characteristics of the adjacent materials.

The Ohio State model, programmed in Fortran IV, is a two layer model of a rectangular compartment with one opening-door or window. The compartment contains objects which burn and propagate along their horizontal or vertical surfaces. Flame spread for this model is by contact and not radiation. A simplified flowchart of this model is shown in Figure 4-7.

Full scale validation tests for the Release Rate model were made at the Upjohn Company's D.S. Gilmore Laboatories in North Haven, Connecticut as part of PRC Project No. RP-76-U-4, and at Ohio State University as part of an American Public Transit Association (APTA) project.

4.4.2 Input Data

Empirically derived release rate data on all materials within the compartment are required in order to use this model. Some of the necessary inputs for a model run include:

1. Release rate data - all materials within the compartment,
2. Initial conditions within the compartment,
3. Constant values,
4. Flame travel rates - all materials within the compartment,
5. Output options - time increment of calculations, desired output information, time of run completion,
6. Room geometry - dimensions of room, objects in room, door or window dimensions,

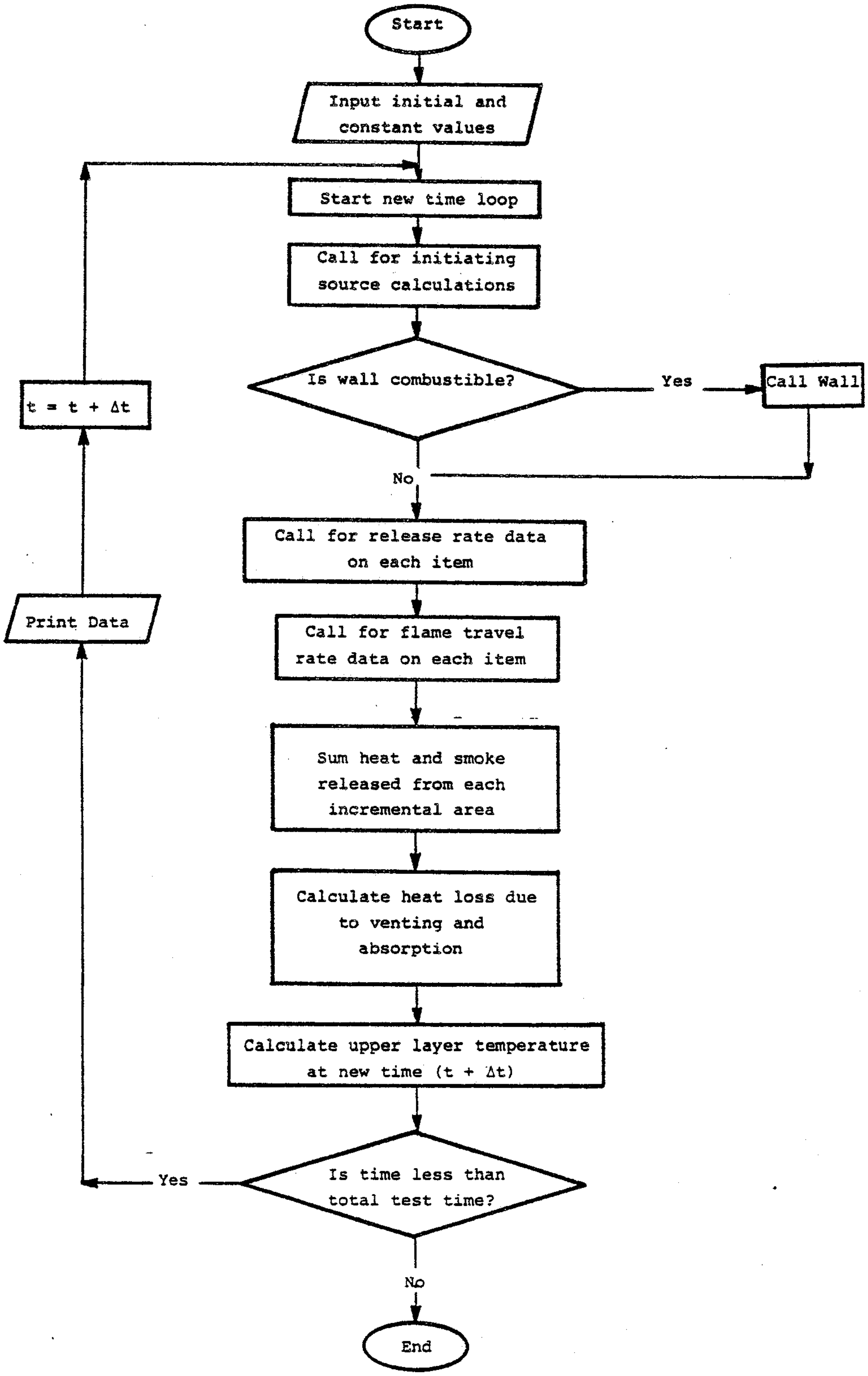

FIGURE 4-7. OHIO STATE RELEASE RATE MODEL FLOWCHART

7. Thermal properties of wall, floor, and ceiling, and
8. Fire source data - size, intensity, and heat release data.

4.4.3 Output Data

Output is in the form of numerical data on a line printer. Output can be given at any time increment as specified in the input data. Outputs may include at time, t:

1. Rate of heat, smoke and gas released from each incremental area involved,
2. Total heat, smoke, and gas released,
3. Heat output through the opening,
4. Heat absorbed by the walls and ceiling,
5. Thickness of the upper layer,
6. Temperature of the upper layer,
7. Temperature of the floor,
8. Temperature of the walls and ceiling,
9. Mass flow rates,
10. Plume temperatures,
11. Amount of surface involved,
12. Smoke concentration, and
13. Run time.

4.5 NATIONAL BUREAU OF STANDARDS (NBS)*

The NBS Center for Fire Research, in its study of fire modeling, sponsors research for the development of mathematical models, and performs in-house research on all aspects of fire modeling. In addition, under the direction of Dr. Robert S. Levine, NBS has organized the Ad Hoc Working Group on Mathematical Fire Modeling, a group of scientists in the fire modeling field that coordinate

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*References 12, 25, 26.

work being done on mathematical fire models, facilitate the use and understanding of mathematical models, and determine the research necessary to improve these models.

Because of the broad scope of their work at NBS, its scientists have extensive experience in all phases of fire modeling research, including mathematical fire model development and validation. The Quasi-Steady model, now being developed at NBS, is the model most applicable to the compartments used in transportation vehicles. The model is so named because transient effects on the fire system are not considered. This model has evolved from previous research efforts by NBS scientists, including Dr. J.A. Rockett and Dr. B.J. McCaffrey, and is being further developed under the direction of Dr. James G. Quintiere of NBS. The development of this model is part of a three-objective study at NBS:

1. To provide a means of determining the behavior of cellular plastics in real fire situations,
2. To determine experimentally what effect fires of varying size, fuel type, and ventilation conditions will have on the compartment fire variables (temperature, heat flux, burning rate, air flow rate), and
3. To develop a mathematical model, using the collected data for validation, which will predict room fire conditions as a function of fuel type, quantity of fuel, and room geometry.

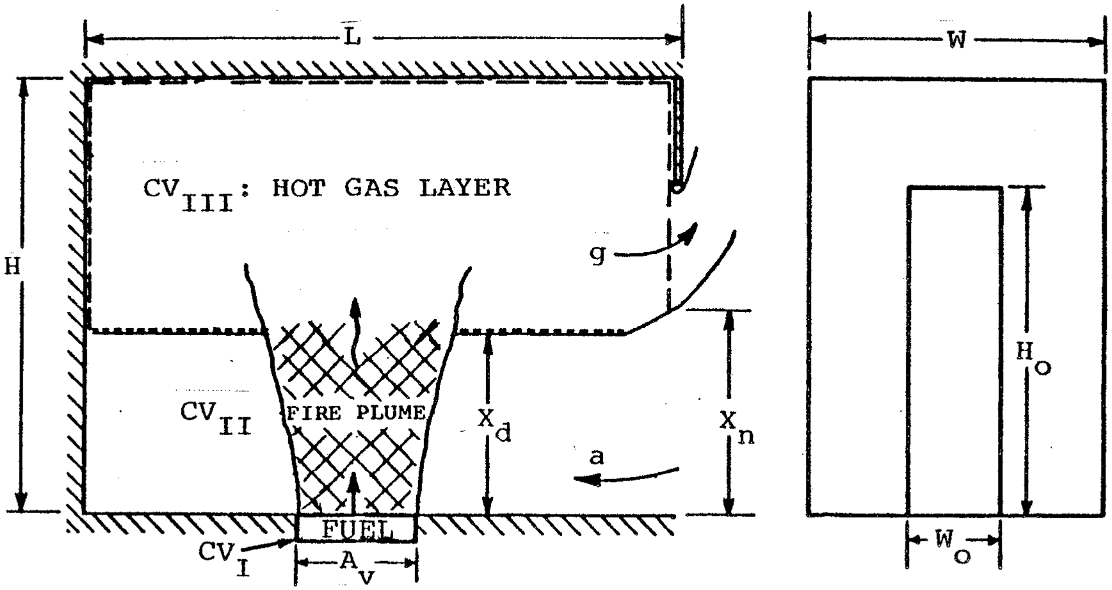
The NBS Quasi-Steady model does not consider time as a parameter nor does it predict fire growth. It predicts the "critical" values of fuel area and door size necessary to promote fire growth and the thermal conditions which would make the room intolerable. In other words, the model is designed to predict "what will happen" under specified conditions rather than "when a critical event will occur." However, NBS has recently embarked on an effort to develop a time-dependent model using verified subprograms from other models.

4.5.1 Quasi- Steady Model- Features and Construction

The NBS Quasi-Steady model describes the development of a wood or plastic crib fire in a rectangular compartment with one opening (doorway). In order to describe the progress of the fire, the compartment is divided into three homogeneous zones or control volumes (Figure 4-8). Mass and energy conservation equations (Table 4-8) are solved as the means of describing the existing conditions in each zone and the interface between zones. The three zones or control volumes include: 1) the plume and upper layer of hot gases, 2) the lower layer of cooler gases, and 3) the fuel.

The model has two distinguishing features:

1. The lower layer is heated by the natural mixing process between the upper and lower layers. As air enters the doorway, it entrains some of the hot gases from the upper layer, thereby causing the temperature of the lower layer to rise. The hot combustion product gases, entrained by the entering fresh air, also diminish the amount of oxygen in the lower layer. The reduced oxygen concentration in the lower layer caused by this mixing process, as well as the radiation feedback from the enclosure, affect the pyrolysis rate within the compartment. The fuel pyrolysis calculation for this model includes both the effect of radiation enhancement and the counter effect of oxygen reduction.
2. The calculations have been simplified to seven nonlinear algebraic equations (Table 4-8) in seven unknowns. This unique feature is accomplished by expressing all dependent variables (Table 4-9) in terms of the independent variables of the seven governing equations. All the dependent variables of these seven equations are calculated in the program subroutines. Each of the seven governing equations expresses a conservation law applied to a control volume or interface (Table 4-8).



CV_I - Fuel

CV_{II} - Lower layer, bounded by thermal discontinuity plane, walls and floor

CV_{III} - Upper layer, includes plume, bounded by walls, ceiling, thermal discontinuity plane and fuel surface.

a - Air entering compartment through doorway

g - Hot gases (combustion products) leaving compartment through doorway

X_d - Height of thermal discontinuity

X_n - Height of neutral plane

H - Height of compartment

L - Length of compartment

W - Width of compartment

H_o - Height of doorway

W_o - Width of doorway

FIGURE 4-8. NBS QUASI-STEADY MODEL CONTROL VOLUMES AND ROOM GEOMETRY

TABLE 4-8. NBS QUASI-STEADY MODEL - SEVEN GOVERNING EQUATIONS

EQUATION	CONTROL VOLUME OR INTERFACE
Conservation of Mass	Plume and Upper Layer
Conservation of Mass	Lower Layer
Conservation of Energy	Plume and Upper Layer
Conservation of Energy	Lower Layer
Conservation of Energy	Upper Layer Solid/Gas Interface
Conservation of Energy	Lower Layer Solid/Gas Interface
Fuel Pyrolysis	Fuel

The structure of the quasi-steady model is illustrated by the simplified flowchart in Figure 4-9. The main program controls the flow and the storage information. The computer program includes many subroutines to solve the seven governing equations which, in the process, call for subroutines to solve for the dependent variables (Table 4-9) necessary for the governing equation solution. There is also a subroutine designed to solve nonlinear algebraic equations.

At this time, convergence over all desirable ranges is not achieved by this model, but results compared to the experimental values studied are judged fair to good.

Because the transient effects are not included, the model is considered a Quasi-Steady model. The time rate of change of mass and energy within each zone are ignored. This limitation of the model could be remedied by some mathematical changes.

More information about this model is available in Reference 12.

4.5.2 Input Data

The input parameters of the model consist of both constants and variables. This information is provided by the user and may vary according to his needs and objectives.

The input parameters necessary to execute the NBS computer program are listed in Table 4-10.

4.5.3 Output Data

Output consists of the seven independent variables listed in Table 4-11, plus any dependent variables which may be desired by the user.

TABLE 4-9. NBS QUASI-STEADY MODEL - DEPENDENT VARIABLES - SUBROUTINES

Air Flow Rate
Rate of Entrainment Between Layers
Upper Layer Gas Emissivity
Radiant Flux to Upper Surfaces
Radiant Flux Out of Doorway
Radiant Flux Between Upper and Lower Layers
Convective Flux to Upper Surfaces
Radiant Flux to Lower Surfaces
Oxygen Mass Concentration, Upper Layer
Oxygen Mass Concentration, Lower Layer
Incident Radiant Flux to Crib Sides
Incident Radiant Flux to Crib Top
Incident Radiant Flux to Floor Target

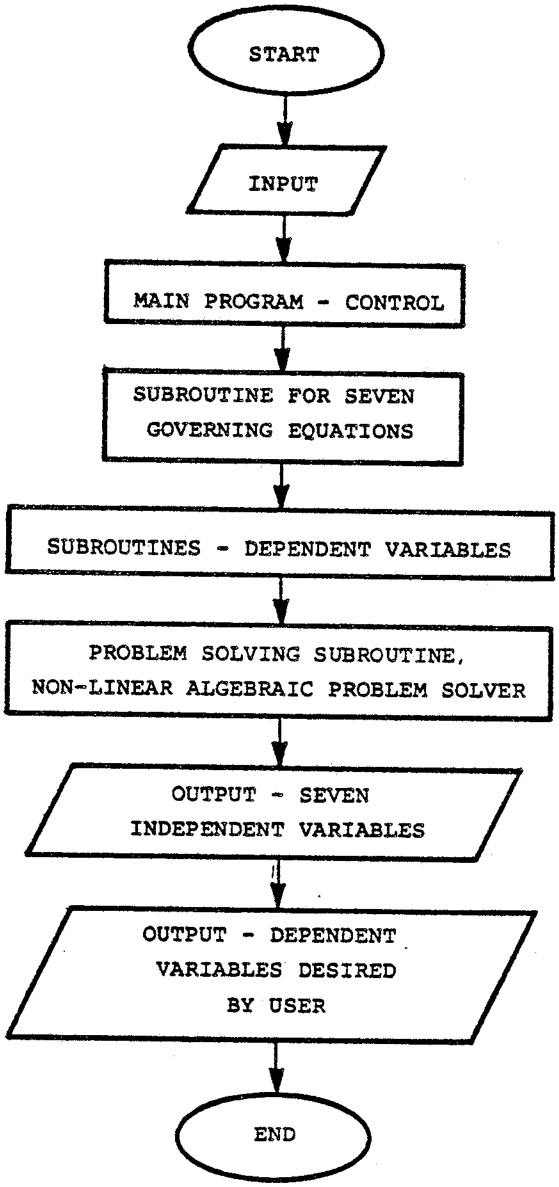


FIGURE 4-9. FLOWCHART OF NBS QUASI-STEADY MODEL

TABLE 4-10. NBS QUASI-STEADY MODEL INPUT PARAMETERS

PHYSICAL PROPERTIES

- Gravitational Acceleration
- Stefan-Boltzmann Constant
- Air Density
- Air Temperature
- Specific Heat of Air

ROOM GEOMETRY

- Room Height, Width and Length
- Doorway Height and Width

CRIB GEOMETRY

- Number of Cribs
- Free Burn Pyrolysis Rate Per Unit Area
- Stick Length and Thickness
- Number of Sticks Per Layer
- Number of Layers

FUEL PROPERTIES

- Mass Air to Fuel Ratio
- Effective Heat of Combustion
- Fraction of Energy Radiated from Flame
- Effective Heat of Vaporization
- Char Fraction
- Flame Absorption Coefficient
- Effective Flame Temperature
- Mass of (single) Crib

TABLE 4-11. NBS QUASI-STEADY MODEL OUTPUT

Height of Neutral Plane
Height of Thermal Discontinuity
Upper Layer Gas Temperature
Lower Layer Gas Temperature
Upper Layer Surface Temperature
Lower Layer Surface Temperature
Fuel Pyrolysis Rate

4.6 UNIVERSITY OF NOTRE DAME*

UNDSAFE University of Notre Dame Smoke and Fire in Enclosures is a computer code developed by the Fire Research Group of Notre Dame's Department of Aerospace and Mechanical Engineering. The group is currently under the direction of Drs. K.T. Yang, J.R. Lloyd and A.M. Kanury. The numerical code development was carried out under grants from the National Science Foundation and the Center for Fire Research of the National Bureau of Standards. It is designed to predict quantitatively the spread of fire and smoke in enclosures of various designs.

UNDSAFE has been specialized and made public in two user versions, UNDSAFE I and UNDSAFE II. UNDSAFE II is an updated version of UNDSAFE I. It maintains all the capabilities of UNDSAFE I but has incorporated many refinements and improvements which make UNDSAFE I obsolete. This report discusses the specialized UNDSAFE II code and provides an indication of the capabilities of the general UNDSAFE code.

UNDSAFE II predicts the spread of fire and smoke due to a volumetric heat source in a two dimensional enclosure by describing flow, temperature, and pressure fields. The objective of this computer code is to provide detailed predictions of the changes in flow, pressure, and temperature as functions of the enclosure geometry; heat source location, extent, and strength; thermal boundary conditions at the floor and ceiling; soot concentration distribution; and the distributions of water and carbon dioxide. This objective is accomplished with the use of computer distribution curves and computer contour plots.

This numerical computer code has been used successfully in simulating several of the experimental cases studied in the small corridor facilities at the National Bureau of Standards' Center for Fire Research and at the University of Notre Dame.

4.6.1 UNDSAFE II - Features and Construction

The Notre Dame Model is designed for a rectangular enclosure

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*Reference 27

with a right-side doorway and a free boundary region outside this doorway. The free boundary region is added because the air flow behavior outside the doorway may affect the air flow inside the compartment. Flow, temperature, and pressure conditions in the free boundary region can be predicted and compared directly with experimental data. The room has a height, H, a length, L and a doorway of height, D. A volumetric heat source of strength, Q, simulates a floor fire which may vary in location, strength, and extent. The free boundary region dimensions are dependent on the dimensions of the enclosure (Figure 4-10).

UNDSAFE II utilizes a grid cell system to describe the compartment interior. The number of vertical square grid cells in fixed at 20, therefore, the size of each cell is determined by the height of the enclosure (height divided by 20 gives the x or y axis dimension since each grid cell is square). The number of horizontal cells must be a multiple of the x or y dimension of the grid cell, so that all grid cells in the compartment are a square. The extended free boundary region has an extension of fifteen grid cells in the x-direction, and it extends five grid cells up from the ceiling and five grid cells down from the floor in the y-direction. This gives the free boundary region a dimension of 3/2 H by 3/4 H (Figure 4-10).

The mathematical procedure for solving the problems in UNDSAFE II involves the use of differential field equations and corresponding finite difference equations. The subroutines written into the code are designed to solve these mathematical problems (Table 4-12). UNDSAFE II has a feature which provides communication between the user and the computer. Two additional subroutines, not included in the computer code, allow the user to terminate the program or to find out how much computer time remains. These two subroutines [QUIT(MM) and TLEFT(IT)] are written in assembly language and are, therefore, not included in the program. The user has the option to use them, ignore them, or replace them with the user's own subroutines.

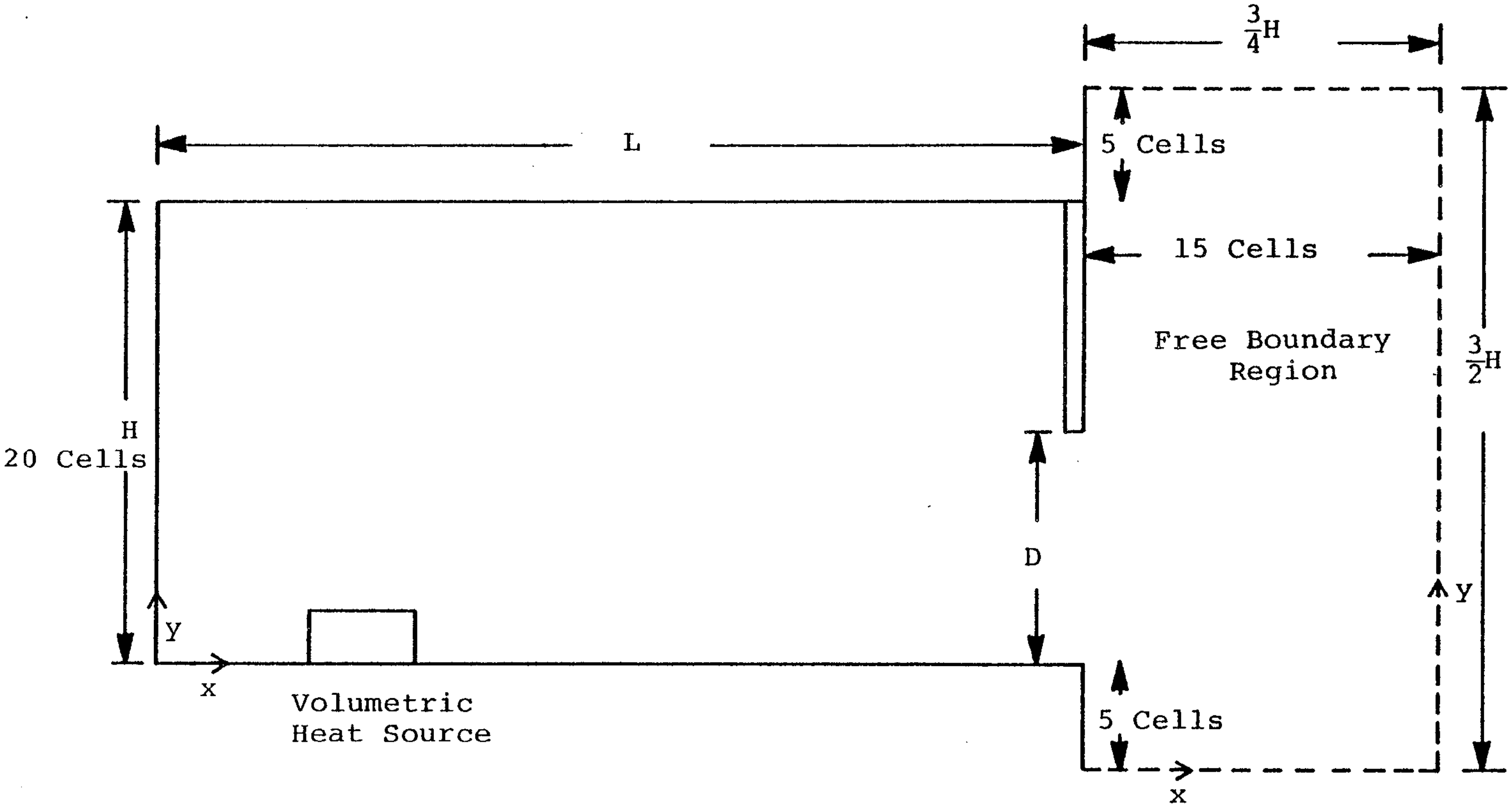

FIGURE 4-10. UNDSAFE ENCLOSURE GEOMETRY

TABLE 4-12. UNDSAFE SUBROUTINES

SUBROUTINE	FUNCTION
CALT	Numerical solution to energy equation for temperature variable
CALU	Numerical solution for a velocity component in x-direction
CALV	Numerical solution for a velocity component in y-direction
CALP	Calculation of pressure and velocity correction equations
MAP	Routine for plotting matrix contours of physical properties distributions
TRIDAG	Tridiagonal Matrix solution calculations
TRIDA	Tridiagonal Matrix solution calculations
TRIDAX	Tridiagonal Matrix solution calculations
TRIDAY	Tridiagonal Matrix solution calculations
RAD	Calculation of radiative energy flux equation
SUMM2	Computation of integrals by use of Trapezoidal Rule
GASRAD	Calculation of wall radiation flux due to gas radiation
CALVIS	Calculation of the eddy viscosity
SIMNR	Solution of two simultaneous equations for floor and ceiling temperatures - radiation involved
HSOOT	Calculation for soot radiation
PHI	Computation of quantity PHI used in gas radiation equations.

The buoyant turbulent flow problems in UNDSAFE II contain a large number of parameters. It is difficult to design the code so that all these parameters can be assigned by the user, thus some paramters must be preassigned. Too many preassigned or fixed parameters would cut down on program flexibility, so there are only six fixed parameters. UNDSAFE II still maintains a degree of flexibility because the six fixed parameters can readily be altered to suit the needs of the user.

It takes three to five hours of computer time to calculate as many as one thousand dimensionless steps in the execution of this program. This amount of computer time necessitates the deposition of intermediary results onto tapes or discs so that runs can be completed at different times.

UNDSAFE II, programmed in Fortran IV-HX Level 2.2, was developed on an IBM 370/158.

A simplified flowchart of the UNDSAFE program is illustrated in Figure 4-10.

4.6.2 Input Data

The input necessary to run UNDSAFE II is introduced into the computer by means of input data cards, discs, or tapes. If the program is being run for the first time, the computer gets its input information from input data cards. If the program is a continuation of a previous run, information is furnished to the computer by a disc or tape which contains the results of the calculations from the first part of that run. The first input into any program (KRUN) is an "option" input entered on an input data card specifically to inform the computer whether the run is a first or continuation run.

The required input for a computer run of the UNDSAFE code includes:

1. A starting point option,
2. Numeric data-room geometry and heat source information,

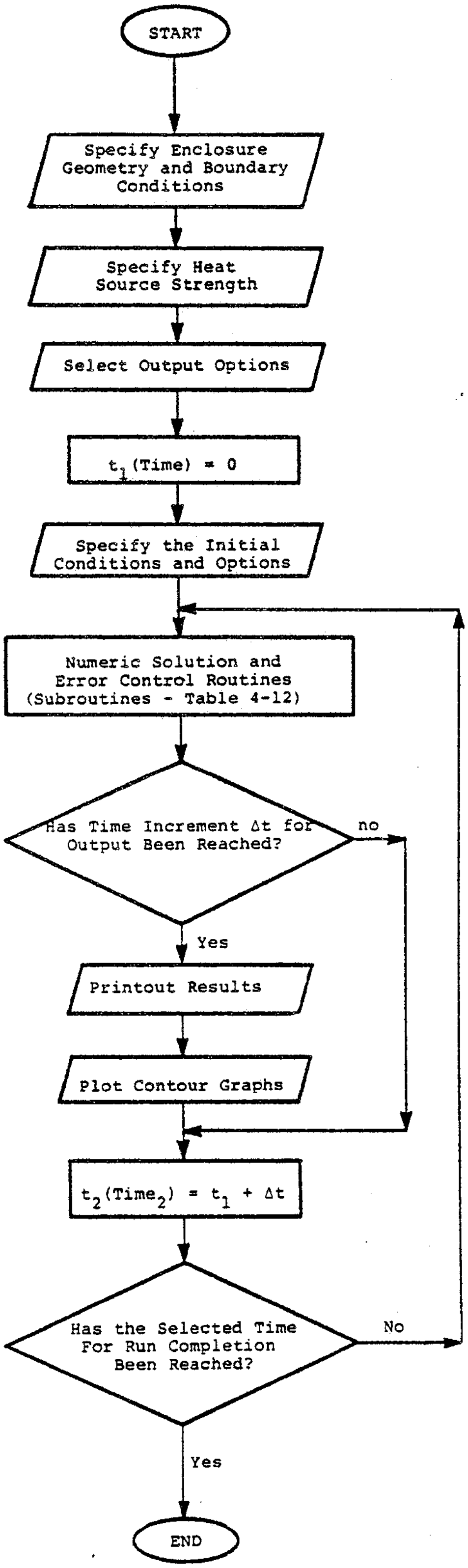

FIGURE 4-11. FLOWCHART OF UNDSAFE II

3. Output options,
4. Options concerning variations of thermal boundary conditions,
5. Options concerning the kind of radiation,
6. Spectral band information, and
7. Pollutant information.

Table 4-13 lists the code names for the inputs used in UNDSAFE II along with a brief explanation of each input.

4.6.3 Output Data

UNDSAFE II provides three output options (Table 4-13) which are determined as input. TMAX allows the user to select the time duration of the program run; TWRITE allows the user to select the number of seconds between each printout of output values (dependent variables); TTAPE is provided because of the lengthy time necessary to complete the mathematical calculations. This option gives the user the opportunity to continue a run which cannot be completed in the selected time. TTAPE records data specified by the user on tape or disc at time intervals specified by the user. Since the information on the tape or disc is not an integral part of UNDSAFE, a separate program called CALCOMP is used to plot data from the tape or disc.

It is possible for the user to eliminate any of these output modes.

UNDSAFE II prints out detailed results of calculations and compartment contour plots at time intervals preselected by the user. CALCOMP plotting is not an integral part of UNDSAFE, so a separate computer code is provided to plot the results from data on tape or disc. Table 4-14 indentifies the printed outputs of UNDSAFE and CALCOMP.

TABLE 4-13. UNDSAFE INPUT DATA AND OPTIONS

CODE	EXPLANATION
KRUN	User input option - starting point KRUN = 0 a first run calculation at time zero and no flow inside the room KRUN = 1 a continuation of a run and initial conditions are read from the tape or disk.
HD	Height of enclosure
MD	Length of the enclosure
ND	Height of the doorway
MC	Number of cells from the left wall to the left edge of the heat source
MS	Number of cells in the width of the heat source
NS	Number of cells in the height of the heat source
QD	Rate of heat release from the heat source
TMAX	User output option to select total time duration of the calculation
TWRITE	User output option - user designates number of seconds between the printing of all dependent variables
TTAPE	User output option - user specifies what data and how often this data will be recorded on tape or disk
KBOUND	User input option - thermal boundary conditions KBOUND = 1 Ceiling and floor are adiabatic; there is no radiation effect. KBOUND = 2 Ceiling and floor temperatures for all cells are given; there is no radiation effect. KBOUND = 3 Data on density, heat capacity, thermal conductivity and thickness of floor and ceiling must be provided; there is no radiation effect. KBOUND = 4 Floor and ceiling are black and adiabatic; radiation is considered; radiation options are specified in IJRAD.

TABLE 4-13. UNDSAFE INPUT DATA AND OPTIONS (CONT.)

CODE	EXPLANATION
IJRAD	User input option - type of radiation to be considered IJRAD = 1 Only soot radiation is considered; FV must be given (see below). IJRAD = 2 Only gaseous radiation is considered (Water and carbon dioxide are the only gases which this program accommodates.); WH2, WC2 and NB must be given, see below. IJRAD = 3 Soot and gaseous radiation effects are considered; FV, WH2, WC2 and NB must be given; overlapping bonds (NB) are not accounted for. IJRAD = 4 Only surface radiation is considered. IJRAD = 5 Same as IJRAD = 3 except overlapping bands are accounted for.
FV	Volumetric concentration of soot
WH2	Molar fraction of water vapor
WC2	Molar fraction of carbon dioxide
NB	Number of spectral bands - up to nine can be considered
IUSE(I)	User input option; index I corresponds to individual band IUSE(I) = T for active band IUSE(I) = F for inactive band Ex: IUSE(3) = T (means third band is active)

TABLE 4-14. UNDSAFE PRINTED OUTPUT

- I. UNDSAFE II
  - A. Numeric Results of Calculations
    - 1. Temperature
    - 2. Density
    - 3. Pressure
    - 4. Viscosity
    - 5. Richardson number
    - 6. Two velocity components
    - 7. Error source
  - B. Computer Contour Plots of the Compartment
    - 1. Density distribution
    - 2. Temperature distribution
    - 3. Pressure distribution
    - 4. Viscosity distribution
    - 5. Richardson number distribution
    - 6. Soot concentration distribution
- II. CALCOMP Plotting Outputs
    - 1. Velocity vector plot
    - 2. Velocity profile
    - 3. Temperature profile
    - 4. Isotherms
    - 5. Isobars
    - 6. Streamlines

5. CONCLUSIONS

The material presented in this report attempts to enhance the readers' understanding of the problems and complexities associated with fire modeling efforts and to impart the many benefits that may be derived from reliable modeling techniques. Discussions of full scale and scaled models, as well as descriptions of six mathematical computer models, have been presented. Each type of modeling may, to some degree, be applied to study the fire growth within a transportation vehicle occupant compartment. The applications of mathematical modeling as a tool in fire safety technology are far-reaching. At the present time however, it is far from a panacea, but the many advances attained since its inception make the objectives of mathematical modeling conceivably attainable.

5.1 FULL SCALE MODELING

Qualitative and quantitative information about the fire growth mechanism has been obtained from full scale room fire experiments, but sufficient data for a full and accurate qualitative or quantitative description of fire growth in a compartment has not been achieved. Although full scale experiments are the true fire scenario, this type of experiment is not ideal because the quantitative data for specific phenomena are often not readily obtainable and the preparation and execution of experiments are expensive and potentially dangerous.

5.2 SCALED MODELING

Scaled room fire experiments have been carried out with varying degrees of accuracy. They have been used successfully for some aspects of fire development. An experiment using a scaled model is relatively inexpensive, readily constructed and easily monitored. The serious drawback to scaled modeling is the inability of experimentors to proportionately scale down ventilation and radiation effects, as well as the plume or flame size. Since fire behavior is governed by the many complex interactions which occur inside the compartment, the scaled model compartment fires are somewhat limited in their application to real fire situations.

5.3 MATHEMATICAL MODELING

There are many applications for mathematical models in the study of fire because it is theoretically possible to represent fire growth and behavior by the solution of appropriate equations. These equations are designed to represent all of the fire phenomena and the interaction of these phenomena during the progress of a fire.

A mathematical model is useful only if it can accurately describe fire behavior in a real fire scenario. The equations used in the mathematical approach are only good if they are conceived with a correct understanding of the fire growth process; otherwise, they are not necessarily describing the fire scene being computed.

As research progresses and mathematical fire models are validated, the potential uses of these models will quickly be realized. Mathematical models can be used to predict fire hazards, to aid in the development of emergency procedures, to predict if flashover will occur, and to predict the type and quantity of toxic emissions from a fire. Some mathematical models could be used effectively in the design of fire safe transit vehicle compartments by comparing the arrangement of furnishings and the type of materials used in the construction of one compartment to the furnishings and materials of another compartment. Mathematical models could minimize the use and, therefore, the high cost of full scale models used in studies of the complex interactions which occur during a fire in a compartment. The application of modeling to fire growth as a possible tool in fire safety technology is obvious, but its actual use will ultimately depend upon the accuracy which this method can achieve and its cost.

The six models discussed in this report illustrate six different approaches to the mathematical modeling of fire growth. The final objectives and the theoretical assumptions of any model are the influencing factors in the construction of a computer model.

REFERENCES

1. DeRis, J., "Modeling Techniques for Prediction of Fires," Applied Polymer Symposium, No. 22, p. 185-193 (1973).

2. Emmons, H.W., "Fire and Fire Protection," Scientific American, 231(1), p. 21-27 (July 1974).

3. Grant, J., Editor, Hackh's Chemical Dictionary, Fourth Edition, McGraw-Hill Book Company (1969).

4. Levine, Robert S., "Mathematical Fire Modeling," Paper Presented at the National Symposium on Fire Safety Aspects of Polymeric Materials, Washington DC (June 7, 1977).

5. Pape, R., and T.E. Waterman, "Understanding and Modeling Pre-Flashover Compartment Fires," Design of Buildings for Fire Safety, ASTM STP 685, p. 106-138 (1979).

6. Sippl, C.J., and C.P. Sippl, Computer Dictionary, Second Edition, Howard W. Sams and Co., Inc., The Bobbs-Merrill Company, Inc. (1974).

7. Emmons, H.W., C.D. MacArthur and R. Pape, "The Status of Fire Modeling in the United States," Paper Presented at U.S. - Japan Panel on Fire Research - Premises" Mathematical Modeling (1979).

8. National Materials Advisory Board Report, Fire Safety Aspects of Polymeric Materials, Volume 4, Fire Dynamics and Scenarios, National Academy of Sciences, Publication NMAB 318-4 (1978).

9. National Materials Advisory Board Report, Fire Safety Aspects of Polymeric Materials, Volume 3, Smoke and Toxicity (Combustion Toxicology of Polymers) National Academy of Sciences, Publication NMBA 318-3 (1978).

10. Pape, R., Preflashover Room Fire Model: Parametric Sensitivity Analysis and Development of a Submodel for Burning Furniture Items, NBS-GCR-81-300 (January 1981).

11. Pape, R., "Preflashover Room Fire Model: Parametric Sensitivity Analysis and Development of a Submodel for Burning Furniture Items," Phase I Report, NBS Contract NB 79-SBCA-0068, p. 37-46 (September 7, 1979).

12. Quintiere, J.G., "Growth of Fire in Building Compartments," Fire Standards and Safety, ASTM STP 614, p. 131-167 (1977).

13. MacArthur, C.D. and J.F. Meyers, "Dayton Aircraft Cabin Fire Model Validation Phase I," Final Report, Federal Aviation Administration, Systems Research and Development Service, Report No. FAA-RD-78-57 (March 1978).

14. Reeves, J.B., "Dayton Aircraft Cabin Fire Model, Volume II - Laboratory Test Program," Final Report, Federal Aviation Administration, Systems Research and Development Service, Report No. FAA-RD-76-120, II (June 1976).

15. Reeves, J.B., and C.D. MacArthur, "Dayton Aircraft Cabin Fire Model, Volume I - Basic Mathematical Model," Final Report, Federal Aviation Administration, Systems Research and Development Service, Report No. FAA-RD-76-120, I (June 1976).

16. Kahut, P.M., "Dayton Aircraft Cabin Fire Model, Volume III - Computer Program User's Guide," Final Report, Federal Aviation Administration, Systems Research and Development Service, Report No. FAA-RD-76-120, III (June 1976).

17. Emmons, H.W., "Computer Fire Code II," Harvard University, Division of Applied Sciences, Home Fire Project, Technical Report No. 20 (January 1977).

18. Emmons, H.W., H.E. Mitler, and L.N. Trefethen, "Computer Fire Code III," Harvard University, Division of Applied Sciences, Home Fire Project, Technical Report No. 25 (January 1978).

19. Mitler, H.E., "Users' Guide for the Harvard Computer Fire Code," Harvard University, Division of Applied Sciences, Home Fire Project, Technical Report No. 37 (April 1979).

20. Mitler, H.E., "The Physical Basis for the Harvard Computer Fire Code," Harvard University, Division of Applied Sciences, Home Fire Project, Technical Report No. 34 (October 1978).

21. Pape, R., "Computer Simulation of Full Scale Room Fire Equipments," Quarterly Report, Products Research Committee, NBS, IITRI Project J6414 (June-August 1977).

22. Pape, R., Preflashover Room Fire Model: Parametric Sensitivity Analysis and Development of a Submodel for Burning Furniture Items, NBS-GCR-81-300 (January 1981).

23. Smith, Edwin E., "Evaluating the Performance of Cellular Plastics in Fire Systems," Final Report for Products Research Committee, Grant No. RP-75-1-36 (1979).

24. Smith, Edwin E., "Transit Vehicle Material Specification Using Release Rate Tests for Flammability and Smoke," Phase I Report, Final Report, Prepared for Transit Development Corporation, Report No. 14-5-76-1 (October 1976).

25. Quintiere, J.G., and B.J. McGaffrey, "The Burning of Wood and Plastic Cribs in an Enclosure," Volume I, NBS Report No. NBSIR 80-2054 Final Report (November 1980).

26. Quintiere, J.G., B.J. McCaffrey and K. DenBraven, "Experimental and Theoretical Analysis of Quasi-Steady Small-Scale Enclosure Fires," NBS Center for Fire Research, NBS Report No. NBSIR 78-1511 (October 1978).

27. Liu, V.K. and K.T. Yang, "UNDSAFE-II, A Computer Code for Buoyant Turbulent Flow in an Enclosure with Thermal Radiation," NBS Grant G7-9002, Department of Commerce, Report No. TR-79002-78-3 (July 15, 1978).

APPENDIX A

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National Aeronautics and Space Administration
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National Bureau of Standards
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National Engineering Laboratory
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Bureau of Mines
Pittsburgh Research Center
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Naval Research Laboratory
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APPENDIX B

BIBLIOGRAPHY

Alpert, R.L., "Pressure Modeling Transient Crib Fires," Paper 75-H1-6, American Society of Mechanical Engineers, San Francisco, CA (August 1975).

Bellan, J., L.H. Back et al., "Enclosure Fire Dynamics Model for Interior Cabin Fires," (Projection Slide Review), Jet Propulsion Laboratory, Pasadena, CA (March 1981)

Berl, W.G., Editor, <u>The Use of Models in Fire Research</u>, National Academy of Science-National Research Council, Washington, DC (1981).

Bricker, R.W., J.F. Kuminecz and C.D. MacArthur, "FAA-DACFIR Math Model Validation Test Plan," NASA Lyndon B. Johnson Space Center, Houston (May 1978).

Coulbert, C.D., "Enclosure Fire Hazard Analysis Using Relative Energy Release Criteria," JPL Publication 78-51, Jet Propulsion Laboratory, Pasadena, CA (December 1, 1978)

Croce, P.A., "Modeling of Vented Enclosure Fires," Presented at the Fall Meeting, Eastern Section, Combustion Institute, API, (November 1974).

De Ris, J., "Modeling Techniques for Prediction of Fires," Applied Polymer Symposium No. 22, p. 185-193 (1973).

De Ris, J., A.M. Kanury and M.C. Yuen, "Pressure Modeling of Fires," Fourteenth Symposium (International) on Combustion, The Combustion Institute, p. 1033-1044 (1973).

Emmons, H.W., "The Prediction of Fires in Buildings," Proceedings 17 Symposium (International) on Combustion, Leeds, England (1978).

Emmons, H.W., "The Modeling of Fires," Second Joint Meeting, U.S.-Japan Panel on Fire Research and Safety, UNJR, Tokyo (1976).

Fang, J.B., "Measurement of the Behavior of Incidental Fires in a Compartment," NBSIR 75-679, National Bureau of Standards (March 1975).

Fang, J.B., "Analysis of the Behavior of a Freely Burning Fire," NBSIR 73-115. National Bureau of Standards, Washington, DC (February 1973).

Friedman, R., "Status of Mathematical Modeling of Fires," to be Presented at the First Specialists Meeting (International) of the Combustion Institute, University of Bordeaux, France (July 20-24, 1981).

Friedman, R., "Behavior of Fires in Compartments," Presented at International Symposium Fire Safety of Combustible Materials, Edinburgh, Scotland, p. 100-113 (October 15-17, 1975).

Gross, D. and J.N. Breese, "Experimental Fires in Enclosures, (Growth to Flashover)," CIB Cooperative Program (CIB2), NBS Report 10471, National Bureau of Standards, Washington, DC, (July 15, 1971).

Gross, D. and A.F. Robertson, "Experimental Fires in Enclosures," Tenth Symposium (International) on Combustion, The Combustion Institute, p. 931-942 (1965).

Hasemi, Y., "Numerical Simulation of the Natural Convection in Fire Compartment," Second Joint Meeting, U.S.-Japan Panel on Fire Research and Safety, Tokyo (October 19-22, 1976).

Heselden, A.I.M. and S.J. Melinek, "The Early Stages of Fire Growth in a Compartment," FR Note No. 1029, Fire Research Station, Borehamwood, England (Janaury 1975).

Heskestad, G., "Modeling of Enclosure Fires," Fourteenth Symposium (International) on Combustion, The Combustion Institute, p. 1021-1030 (1973).

Heskestad, G., "Physical Modeling of Fire," J. Fire and Flammability, 6, p. 253-273 (1972).

Hillenbrand, L.J. and J.A. Wray, "Full Scale Fire Programs to Evaluate New Furnishings and Textile Materials Utilized by the National Aeronautics and Space Administration," Contract No. NASW-1948, Battelle Columbus Laboratories (July 1973).

Hottel, H.C., "Use of Models in Fire Research," NAS-NRC Publication No. 786 (1961).

Kawagoe, K., "Fire Behavior in Rooms," Building Research Institute, Tokyo, BRI Report No. 27 (1958).

Knight, C., "Numerical Studies of Natural Connection in an Enclosure," Technical Report 15, Harvard University Division of Engineering and Applied Physics (1976).

Larson, D.W. and R. Viskanta, "Transient Combined Laminar Free Convection and Radiation in a Rectangular Enclosure," Journal of Fluid Mechanics, 78, p. 65-86 (November 1976).

Levine, R.S., "Mathematical Fire Modeling," Presented at the National Symposium on Fire Safety Aspects of Polymeric Materials, Washington, DC (June 7, 1977).

Levine, R.S., "Mathematical Modeling of Fires," NBSIR 80-2107, National Bureau of Standards, Washington, DC (September 1980).

Lloyd, J.R. and M.L. Doria, "Fire and Smoke Spread," Semi-Annual Progress Report, University of Notre Dame, South Bend, IN (May 1975).

Mitler, H.E., "Mathematical Modeling of Enclosure Fires," FMRC Technical Report No. 21011.7 (1976).

Modak, A.T. and R.L. Alpert, "Influence of Enclosures on Fire Growth Volume I: Guide to Test Data," FMRC-Harvard Home Fire Project, FMRC J.I. No. OAOR2.BU-8 (November 1977).

Pape, R. et al., "Preflashover Room Fire Model: Parametric Sensitivity Analysis and Development of a Submodel for Burning Furniture Items," Phase I Report, IITRI Projects J6485, (September, 1979).

Pape, R. et al., "Program Documentation and Users Guide, Semi-stochastic Approach to Predicting the Development of a Fire in a Room from Ignition to Flashover, RFIRES," IITRI for NBS, Grant 5-9018 (June 1976).

Pape, R. and T.E. Waterman, "Modification of the RFIRES Preflashover Room Fire Computer Model," IITRI Report, J6400 for NBS, (1977).

Pape, R. and T.E. Waterman, "Programs and Users Guide (Addendum), Semistochastic Approach to Predicting the Development of a Fire in a Room from Ignition to Flashover, RFIRES," IITRI for NBS, Grant 5-9018 (August 1976).

Pape, R. and T.E. Waterman, "RFIRES," IITRI, Report No. J6367 (1976).

Parker, W.J. and B.T. Lee, "A Small-Scale Enclosure for Characterizing the Fire Buildup Potential in a Room," NBSIR 75-710, National Bureau of Standards, Washington, DC (June 1975).

Parker, W.J. and B.T. Lee, "Fire Build-up in Reduced Size Enclosure," NBS Special Publication 411, National Bureau of Standards, Washington, DC, p. 139-153 (November 1974).

Quintiere, J.G., "Growth of Fire in Building Compartments," Fire Standards and Safety, ASTM-STP 614, p. 131-167 (1977).

Quintiere, J.G., "The Growth of Fire in Building Compartments," Paper Presented at the ASTM-NBS Symposium on Fire Standards and Safety, NBS, Gaithersburg, MD (April 5-6, 1976).

Quintiere, J.G., B.J. McCaffrey and T. Kashiwagi, "A Scaling Study of a Corridor Subject to a Room Fire," Combustion and Science Technology, 18, p. 1-19 (1978).

Quintiere, J.G., K. Steckler and B.J. McCaffrey," A Model to Predict the Conditions in a Room Subject to Crib Fires," to be Presented at the First Specialists Meeting (International) of the Combustion Institute, University of Bordeaux, France (July 20-24 1981)

Rockett, J.A., "Fire Induced Gas Flow in an Enclosure," Combustion Science and Technology, 12, p. 165-175 (1975).

Roschke, E.J. and C.D. Coulbert," Application of the Relative Energy Release Criteria to Enclosure Fire Testing," JPL Publication 78-86, Jet Propulsion Laboratory, Pasadena, CA (January 1, 1978)

Smith, E.E., "Relation of Performance Tests to Actual Fires," Fire Tech, 12 No. 1 (February 1976).

Smith, E.E., "Model for Evaluating Fire Hazard," Journal of Fire and Flammability, 5, p. 185-195 (July 1974).

Smith, E.E., "Measuring Rate of Heat, Smoke, and Toxic Gas Release," Fire Tech., 8 No. 3 (August 1972).

Smith, E.E. and M.J. Clark, "Model of the Developing Fire in a Compartment," ASHRAE Trans., 81, Part I p. 568-580 (1975).

Spalding, D.B., "Computer Modeling Techniques for Laminar and Turbulent Combustion," Proceedings of the 16th Symposium (International) on Combustion (August 1976).

Spalding, D.B., "The Art of Partial Modeling," Ninth Symposium (International) on Combustion. The Combustion Institute, p. 833-843 (1963).

Takeda, H. and I. Nakaya, "Small-Scale Model Fire in Enclosure Using Liquid Fuel - Effect of Ventilation Factor," Paper Presented at Second Joint Meeting of the U.S.-Japan Panel on Fire Research and Safety, UJNR, Tokyo (October 19-22, 1976).

Tanaka, T., "A Model on Fire Spread in Small Scale Buildings," 3rd Joint Meeting, U.S.-Japan Panel on Fire Research and Safety, UJNR, Washington, DC (1978).

Tanaka, T., "A Mathematical Model of a Compartment Fire," BRI Research Paper No. 70, Ministry of Construction, Japanese Government (February 1977).

Tanaka, T., "A Mathematical Model of a Compartment Fire," Building Research Institute of Japan, Second Joint Meeting U.S.-Japan Panel on Fire Research and Safety, UJNR, Tokyo (October 19-22, 1976).

Tewarson, A., "A Laboratory-Scale Test Method for the Measurement of Flammability Parameters," Final Technical Report, PRC Grant No. RP-75-1-33A (October 1977).

Thomas, P.H., "Theoretical Considerations of the Growth to Flashover of Compartment Fires," Fire Research Note 663, Joint Fire Research Organization, England (December 1967).

Thomas, P.H., A.J. Heselden and M. Law, "Fully Developed Compartment Fires - Two Kinds of Behavior," F.R. Technical Paper No. 18, Fire Research Station, Borehamwood, England (October 1967).

Trent, D.S. and J.R. Welty, "Numerical Computation of Convection Currents Induced by Fires and Other Sources of Buoyancy," WSCl 72-18 Battelle Pacific Northeast Laboratory, Richland, Washington (1972).

Waszeciak, P.H., "Large Scale Experimental Evaluation of Release Rate Model for Predicting Fire Hazard Development in Compartments Containing Cellular Plastics," Upjohn Company for PRC, Project RP-76-U-4, (1977).

Waterman, T.E., "Room Flashover - Model Studies," Fire Technology, 8, No. 4 (November 1972).

Waterman, T.E., "Scaled Room Flashover," Final Report, OCD WU 2534G, Office of Civil Defense, Washington, DC (April 1971).

Waterman, T.E., "Determination of Fire Conditions Supporting Room Flashover," Final Report, IITRI Project M6131, DASA 1886, Defense Atomic Support Agency (September 1966).

Waterman, T.E., and R. Pape, "A Study of the Development of Room Fires," IITRI, Final Report, J6367 for NBS, Appendix A (September 1976).

Yang, K.T., and L.C. Chang, "UNDSAFE-I A Computer Code for Buoyant Flow in an Enclosure," University of Notre Dame, Fire Research Group, Aerospace and Mechanical Engineering, Technical Report TR-79002-77-1, (March 1. 1977).

Zukoski, E.E., "Convective Flows Associated with Room Fires," Semi-Annual Progress Report, NSF GI 31892Xl, California Institute of Technology, Pasadena, California (June 1975).

Zukoski, E.E., and T. Kubota, "A Computer Model for Fluid Dynamic Aspects of a Transient Fire in a Two Room Structure," California Institute of Technology, NBS Grant No. 5-9004 (January 1978).

210 Copies