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Enclosure Fire Hazard Analysis Using Relative Energy Release Criteria

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ABSTRACT

A method for predicting the probable course of fire development in an enclosure is presented. This fire modeling approach uses a graphic plot of five fire development constraints, the Relative Energy Release Criteria (RERC), to bound the heat release rates in an enclosure as a function of time. The five RERC are (1) flame spread rate, (2) fuel surface area, (3) ventilation, (4) enclosure volume, and (5) total fuel load. They may be calculated versus time based on the specified or empirical conditions describing the specific enclosure, the fuel type and load, and the ventilation. The calculation of these five criteria, using the common basis of energy release rates versus time, provides a unifying framework for the utilization of available experimental data from all phases of fire development. The plot of these criteria reveals the probable fire development envelope and indicates which fire constraint will be controlling during a critical time period. Examples of RERC application to fire characterization and control and to hazard analysis are presented along with recommendations for the further development of the concept.

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SECTION I

INTRODUCTION

The complexity and variability of fire development in an enclosure is a common observation in both controlled experimental fires and accidental fires in rooms and compartments. A unique feature of enclosure fire development, often observed, is a sharp increase in fire intensity called flashover, at which point all combustible surfaces apparently become involved in the burning process. On the other hand, there may be an initial flare-up of highly combustible fuels followed by a sharp decrease in fire intensity. Alternatively, the fire could smolder, go out by itself, oscillate, or develop as a steady state fire until the fuel is exhausted. Each of these fire developments presents different types of personal and structural hazards. The complete development of the enclosure fire depends on the complex interaction of the fuel load characteristics, the enclosure geometry, and the ventilation parameters.

A considerable body of experimental data exists on different phases of general fire development such as flame spread rates (Refs. 1-10), wood and liquid combustion rates (Refs. 6, 11-14), and ventilation-controlled burning rates (Refs. 11, 15). However, a problem exists in applying these laboratory test data to the complex room fire situation. Small-scale tests do not appear to scale reliably, and full-scale prototype fires have been required to investigate the above-mentioned complexities (Refs. 16-22). These tests become very expensive when the great variety of enclosures of interest is considered, ranging from habitable rooms and compartments in homes, aircraft, ships, and transit vehicles to storage and cargo compartments in many shapes and sizes.

This study addresses the question, "Is there a unifying concept or fire modeling approach which can tie together the extensive body of experimental data for direct application to such practical fire hazard situations in enclosures?" The result of this study is the definition of a set of five Relative Energy Release Criteria (RERC) which provides a means of predicting the probable course of fire development in any enclosure. These five criteria are five constraints on the rate and amount of energy released in an enclosure during a fire. It is intended that these criteria utilize existing fire data and modeling studies for each fire phase and combine them in a coherent manner in order to predict the bounds of overall fire development and associated dynamic characteristics as a function of time from ignition to fuel exhaustion. Calculating the RERC prior to a fire and defining the fire development envelope (even approximately) for a given enclosure and fire load reveal which phase of the fire development would be controlling during the major or critical portion of the fire. The fire development envelope, thus defined, would indicate which phase of fire development (e.g., spread or ventilation control) would need more accurate input information to predict the course of the fire or which fire control or suppression method would be most effective during the critical phase of the fire.

Published enclosure fire data (Ref. 23) indicate that two fires having similar heat release and temperature characteristics could present entirely different hazards depending on whether the fire development is fuel or ventilation controlled. Furthermore, if people are present in the enclosure at the beginning of the fire, the critical time scale, the desirable ventilation criteria, and the nature of the hazard due to smoke and heat would be quite different than for fire situations where structural damage and fire containment would be the primary concern.

Another area of application of the RERC is in the evaluation of proposed fire test facilities and methods. For instance, if passenger seats are being burned in a test facility enclosure to evaluate maximum rates of seat burning and smoke release, one would have to ensure that the test fire is not ventilation controlled. This specific problem has been recognized in studying the small-scale simulation of room fires (Refs. 24, 25), door areas of the small-scale enclosures were deliberately made large relative to the rest of the enclosure due to the nature of the scaling relationships for the ventilation factor $AH^{1/2}$.

In this report the RERC are defined, the calculation method is presented, and the validity range is discussed. The RERC may be readily calculated as outlined and used to put potential fire hazards in better perspective. Also, the RERC may possibly be used to define the validity ranges of current testing and analysis methods. Examples of the application of RERC to different enclosures are presented using existing published data.

SECTION II

RELATIVE ENERGY RELEASE CRITERIA

It is common practice when publishing test results of fire progress in an enclosure to present air temperatures and fuel mass loss rates as a function of time (Refs. 16, 17, 26, 27). In the modeling approach presented here, however, energy release becomes the central parameter for fire characterization. The test time periods of interest have varied widely. In several reports on the analytical and experimental modeling of gas temperatures versus time in enclosures (Refs. 28-30), the assumption was made that the fires would be well developed and ventilation controlled (with a constant rate of heat release), and that the periods of interest for assessing potential damage to primary structure were many minutes or hours long. By contrast, the prototype room fire tests conducted by Factory Mutual Research (Ref. 19), Battelle (Ref. 18), and Georgia Institute of Technology (Ref. 31) were not ventilation controlled during the periods of interest, and the tests were terminated after burning times of 8 to 30 minutes. The initial progress of these fires during the period of interest and the rate of fire buildup as indicated by room gas temperatures were markedly influenced by the ignition method and location as well as by the fire load characteristics. The fact that widely differing time scales may be of interest can be readily seen in aircraft cabin fires. In a fire following a survivable crash, the critical time period may be the first 2 to 5 minutes, and toxic gas and smoke may be the critical hazards to the escaping passengers; in a similar aircraft during flight, a fire in a cargo bay or lavatory may require containment of heat and smoke over a period of many minutes until the fire can be extinguished or until the aircraft can make a safe landing.

In considering the above wide range of enclosure fire hazards and time scales, one might ask if these situations have anything in common. Can any coherent fire development description fit all these cases? After review of the data from many fire test programs, it has been found to be possible to define a simplified mathematical model for each of the basic constraints operating on a fire after ignition, all based on the common frame of reference of energy release rate $\dot{Q}$ as a function of time t.

It is further anticipated that the corresponding enclosure temperatures, heat fluxes, smoke densities, and toxic gas concentrations would also be directly related to the rates of energy release as a function of time. Thus, the energy release parameters would become unifying factors for characterizing all aspects of the fire hazard and possibly the focal point for improved fire testing and scaling method developments.

A. DEFINITION OF THE CRITERIA

The five energy release constraints on fire development in an enclosure are defined in terms of three constraints on the rate of energy release and two constraints on the total energy released.

(1) Flame Spread Rate. Initially the rate of energy release is controlled by the rate of fire spread or the flame spread velocity.

(2) Fuel Surface Area Limit. A second constraint on energy release rate is reached when the flame has spread to involve the total fuel surface. If not constrained by available air, the fire would burn at a heat release rate proportional to the exposed fuel area. As burning proceeds, changes in fuel area and other fuel characteristics alter the heat release rate as the fuel supply diminishes.

(3) Ventilation Limit. A third constraint on energy release rate is encountered when the combustion becomes ventilation controlled. While the fire is ventilation controlled, the rate of energy release in the enclosure is independent of the fuel surface limit.

(4) Enclosure Volume. A constraint on total energy release in the enclosure is due to the depletion of the initial oxygen supply if ventilation is limited, as in a closed room or sealed compartment.

(5) Fuel Load. The fifth constraint is the total fuel load.

These five fire development constraints are called RERC because numerical approximations of their values can be readily calculated, and they can be represented graphically as shown in Figure 2-1. Using the initial graphical representation of the RERC, one can assess the potential importance of each constraint and review the adequacy of the values calculated. The relative effect of changes in the fire constraints can be estimated. Questions can be answered, such as whether factor-of-two changes in flame spread rate, fuel surface area, room volume, or ventilation openings would appreciably affect the fire development rate.

Those working intimately with a particular type of fire hazard (e.g., dwellings) or with a particular phase of fire development (e.g., fire spread) may question the validity or value of such a general approximation; but for specific applications, it is likely that the five criteria are in fact being applied (Refs. 25, 27, 28), either intuitively or specifically, although other physical quantities are also used. The most valuable application of this graphical representation may be to new situations (i.e., to make order-of-magnitude estimates) and to facilitate the application of available fire technology to new problem areas.

B. CALCULATING AND PLOTTING THE CRITERIA

The locations of the five constraint curves are independent of each other, and their relative positions define which particular energy release constraint will be controlling at a particular time of fire development. The simplified calculation of each criterion in terms of heat release rate Q versus time t is outlined below. Three types of

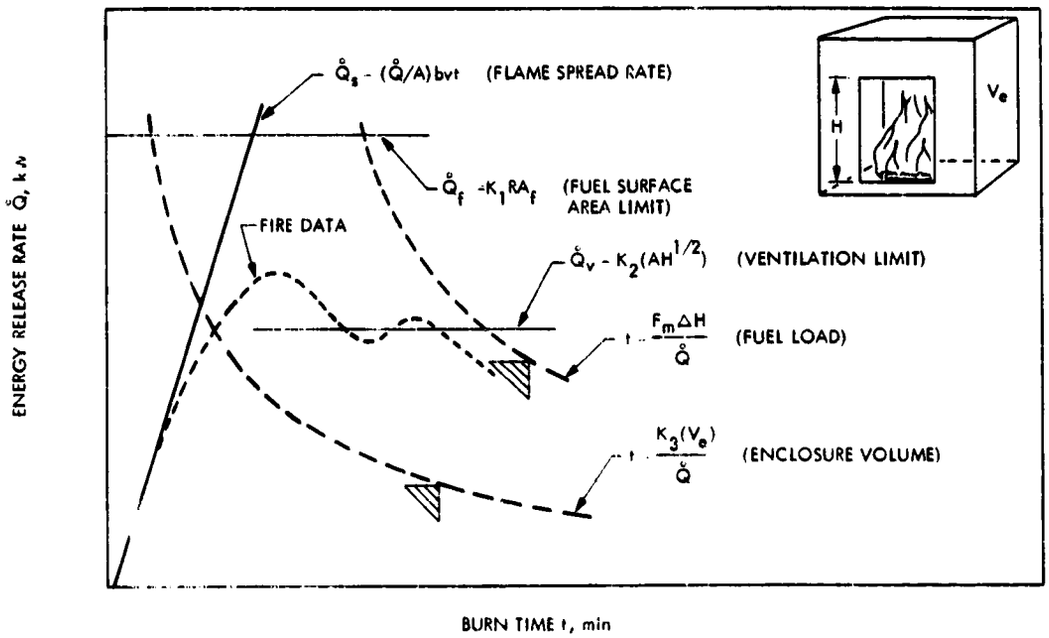

Figure 2-1. Relative Energy Release Criteria for Enclosure Fire Development

fire parameters are used in the calculation: (1) fuel characteristics, (2) enclosure geometry, and (3) ventilation factors. The calculation of temperatures, smoke densities, and toxic gas concentrations is discussed in Section III.

1. Flame Spread Rate

If, after ignition, the ignited portion of the surface continues to burn with a fixed rate of fuel consumption per unit area $\dot{Q}/A$ and the flame front advances at a constant rate, the increasing heat release rate in the enclosure would be

$$\dot{Q}_s = (\dot{Q}/A)bvt$$

where b is the fire front length and v is the flame spread velocity. This simple expression may become complex in a detailed analysis because the heat release rate $\dot{Q}/A$, the flame front length b, and the spread velocity v may be complex functions of local geometry, environmental conditions, and time of burning. However, an initial estimate may be made using published experimental data on flame spread velocities over various fuels, including liquids (Ref. 32) and solids (Refs. 4, 7, 33), and heat release rate data such as obtained for wood cribs (Ref. 34), liquid fuels (Ref. 34), and a variety of solid materials. One direct experimental method used is the heat release rate calorimeter (Refs. 6, 12, 22), which provides data on $\dot{Q}/A$ as a function of time and radiant flux.

A simple extension of the above equation for heat release rate may be written to apply to a radial flame spread from an initial point ignition source.

$$\dot{Q}_s = (\dot{Q}/A)(\pi v^2 t^2)$$

If flame spread rate proves to be the critical fire phase, as it may in occupied enclosures, then specific full-scale prototype data may be required to define this criterion more accurately.

For the cases of multiple ignition sources or sequential ignition of different fuel surfaces, it may be possible to sum the energy release rates directly from two separate fires in the enclosure if the assumption is made that the fires are both adequately ventilated and not enhancing or hindering each other. For detailed analyses, this assumption can be assessed after the initial hazard analysis has been made to define the critical periods of interest.

2. Fuel Surface Area Limit

When the fire has spread to involve the total fuel surface, the fire would burn at a heat release rate $\dot{Q}_f$ proportional to the fuel surface area A_f if not constrained by available air. The clearest example of surface-limited heat release rates is that of liquid hydrocarbon pools, for which burning in terms of surface regression rate is nearly uniform

over the surface and, therefore, directly proportional to the pool area. As an upper bound, the constant value of the regression rate (~4.5 mm/min) is generally used for pools greater than 1-m diameter (Ref. 34). See Figure 2-2. For a pool of burning gasoline, the heat release rate may be expressed as

$$\frac{\dot{Q}_f}{A_f} = 2500 \text{ kW/m}^2$$

For wood arranged in cribs, a maximum heat release rate per unit area of exposed wood has been measured experimentally to be about

$$\frac{\dot{Q}_f}{A_f} = 100 \text{ kW/m}^2$$

Experimental values of heat release rates for different woods and crib arrangements vary from 50 to 200 kW/m^2 (Refs. 11, 34, 35).

Some limited data are available for solid materials such as timber (Ref. 35), particle board (Ref. 36), and plastics (Ref. 6), including data on heat release rate versus time and irradiation level. These data indicate that reasonable maximum values could be defined for most materials with a limited testing program. The heat release rate calorimeter (Refs. 6, 36, 37), with provision to also measure mass loss rate, may be a most useful test method for evaluating fuel-surface-limited burning rates.

A special case of fuel-surface-limited burning arises for carpet burning, where a carpet is defined as any thin combustible bed of fuel. If flame spreads across a carpet at a rate v and the <u>total</u> heat of combustion per unit area of the carpet is Q/A, then a combustion wave (ignition, combustion, extinction) can be visualized traveling across the carpet of width b such that the total heat release rate for rectilinear fire spread would be

$$\dot{Q}_s = (Q/A)bv$$

For radial spread from a point, the heat release rate during the time of uniform spread would be

$$\dot{Q}_s = 2\pi(Q/A)v^2t$$

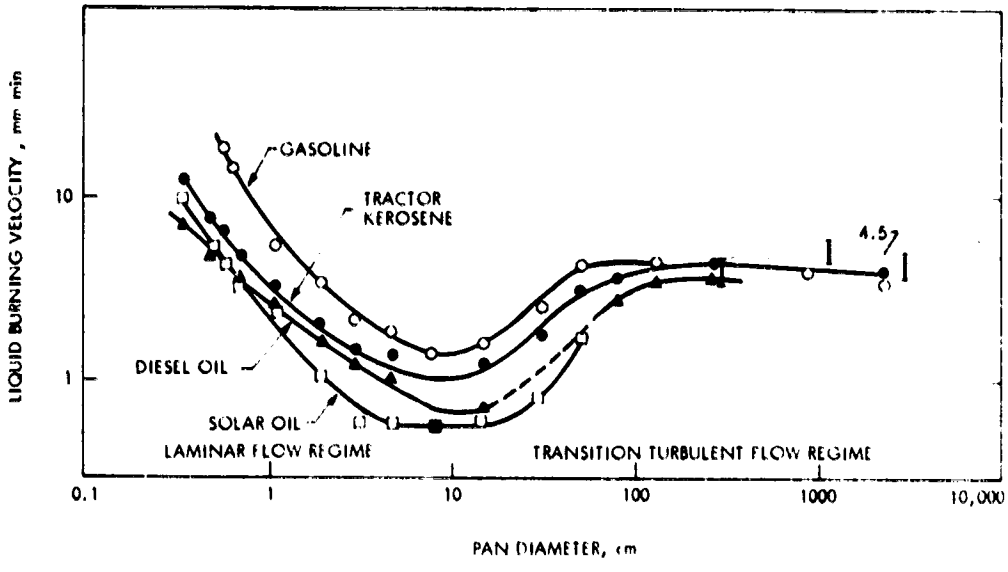

Figure 2-2. Burning Rates and Flame Heights of Liquid Fuel Fires

These simple expressions are not intended to describe the burning of a carpet accurately but rather to approximate the bounding values of heat release rate during the initial phase of the fire and to identify the controlling parameters.

3. Ventilation Limit

The phenomenon of ventilation-controlled burning has been well analyzed both experimentally and analytically. Good correlation has been obtained between wood crib combustion rates R and a ventilation factor $AH^{1/2}$ where A is the vent opening area and H is the vertical height of the opening (Figure 2-1). The expression for wood burning rate,

$$\frac{R}{AH^{1/2}} = 6 \text{ kg/min m}^{-5/2}$$

appears to be well verified by both sets of data in Figure 2-3 (Refs. 11 and 34). Also, the rate of airflow into an enclosure in which a stratified layer of hot gas has been established can be calculated on the basis of density differences within the enclosure. A relationship for calculating the maximum airflow rate $\mathring{m}$ induced into the enclosure during the fire is (Ref. 38)

$$\mathring{m}_{air} = 0.145(C_g g^{1/2} AH^{1/2}) \text{ kg/s}$$

The theoretical amount of energy released by a given weight of air during the combustion of an organic fuel (i.e., C_xH_y) varies only slightly over a range of fuels and combustion conditions. Theoretical values of heat release per unit mass of air have been calculated for fuels with the hydrogen-to-carbon ratio ranging from 1 to 4 and for combustion products with the carbon-monoxide-to-carbon-dioxide ratio ranging from 0 to 0.7. The heat release calculated for these conditions varies between 45 and 48.3 kW-min per kilogram of air burned.

Based on a heat release for air of 48.3 kW-min per kilogram of air burned, which can apply equally to wood and to hydrocarbons, the heat release rate in the enclosure corresponding to this ventilation airflow rate for standard conditions can be written as

$$\mathring{Q}_v = 1580 \text{ AH}^{1/2} \text{ kW}$$

This heat release rate is nearly independent of the characteristics of the burning fuel and the enclosure geometry and varies little with the enclosure gas temperature if it is above 300°C.

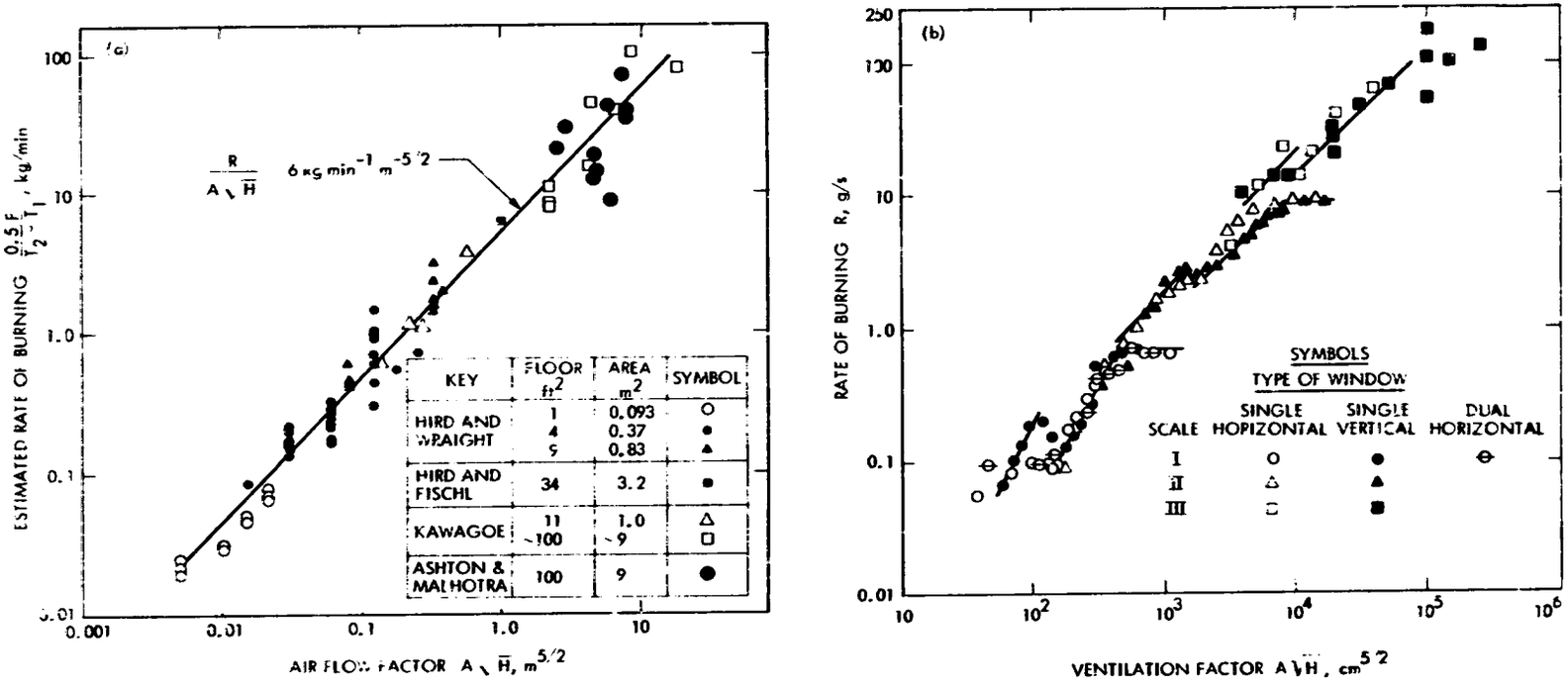

Figure 2-3. Ventilation-Controlled Wood Burning Rates (a) Burning Rate and Airflow (Ref. 34), (b) Burning Rate and Ventilation Factor for Three Enclosures (Ref. 11)

The ventilation factor $AH^{1/2}$ which defines the heat released in the enclosure as well as the airflow rate into the enclosure also facilitates calculation of quantities such as air velocities in the vent and air changes per minute. These latter quantities may be of interest in analyzing enclosures with forced ventilation in addition to natural ventilation.

For the forced ventilation case in which the air mass flow rate is known in kilograms per second, the ventilation limiting heat release rate $\mathring{Q}_v$ would be

$$\mathring{Q}_v = 2900\ \mathring{m}_{air}\ \text{kW}$$

4. Enclosure Volume

In a closed volume or sealed compartment, the total energy released by the fire is limited by combustion of the initially available oxygen supply. A buoyant air circulation pattern is established by the fire in the enclosure, and combustion continues until the air entrained in the flame zone becomes vitiated and depleted in oxygen concentration to a value below the lean combustion limit of the fuel. In experimental studies on sealed enclosure fires at Stanford Research Institute (Ref. 39), the oxygen concentration was found to change from an initial 21% to a final value of 11 to 15%. The value varied somewhat with fuel.

If all the oxygen in a given volume is consumed by the spreading flame, the total energy released per unit volume can be expressed approximately as

$$\frac{Q_e}{V_e} = \int_0^{t_e} \frac{\mathring{Q}dt}{V_e} = 58\ \frac{\text{kW-min}}{\text{m}^3} \qquad \text{(of air)}$$

based on an initial air density of 1.2 kg/m^3 and a heat release per kilogram of air equal to 48.3 kW-min.

A constraint curve for the enclosure volume criterion can be formed for the burning time t_e versus a uniform energy release rate $\mathring{Q}$ by the following equation:

$$t_e = \frac{58V_e}{\mathring{Q}_a}$$

where $58V_e$ is the maximum total energy which can be released by the initial volume of air in the enclosure and where $\mathring{Q}_a$ is the average release rate. The hyperbolic curve thus plotted represents a burning time constraint for a constant heat release rate if all the air is consumed. In practice, only about one-half of the oxygen in an unvented enclosure would be consumed; hence, the constraint becomes $Q_e/2$.

The intersection of a flame spread limit curve of $\mathring{Q}_s$ with this enclosure burning time curve would give the approximate duration for a fire if it has a linearly increasing heat release rate ($\mathring{Q}_s$ versus t) in a sealed enclosure of volume V_e. This result is because the area under the $\mathring{Q}_s$ curve up to the intersection with the enclosure curve is equal to one-half of the value of $58V_e$.

Correspondingly for fires of constant energy release in a sealed enclosure, the burning duration is approximately one-half of the time defined by the equation above. For ventilated compartments, the relative locations on the RERC plot of the flame spread curve $\mathring{Q}_s$, the enclosure volume curve $Q_e/2$, and the ventilation factor curve $\mathring{Q}_v$ indicates whether the fire intensity would be affected by the initial air supply prior to becoming ventilation limited.

5. Fuel Load

The fuel load in an enclosure includes the furniture, the stored items, and the combustible wall coverings as well as transient items carried in by a room's occupants. Some materials do not burn and contribute to the energy released until the fire intensity is quite high. Nevertheless, the total fuel load can be defined as the summation of the heats of combustion of all the potential fuels in the enclosure. The course of fire development may be complex, but the limiting value of total heat released Q will be related to the fuel load $F_m\Delta H$ by the expression

$$Q = \int_0^{t_e} \mathring{Q}dt = F_m\Delta H$$

where t_e is the fire duration, F_m the fuel mass, and ΔH the effective low heat of combustion per unit mass of fuel.

A constraint curve for the fuel load criterion can be formed for a fire duration t_e versus a uniform energy release rate, $\mathring{Q}_a$ which is expressed by the following equation:

$$t_e = F_m\Delta H/\mathring{Q}_a$$

where $F_m\Delta H$ is the total energy release of the fuel load.

SECTION III

FIRE CHARACTERIZATION

Defining the RERC for a specific enclosure description based on the foregoing simplified quantitative relationships gives considerable insight into the probable course of fire development in terms of heat release rate versus time. However, the problem of predicting temperatures, smoke densities, and toxic gas concentrations remains; and in terms of material response and human hazards, these are the fire characteristics of most importance.

The proposed approach to predicting these fire characteristics is to use the RERC to describe an idealized fire model for which limiting values of temperatures, smoke densities, and toxic gas concentrations can be calculated. This approach to fire characterization provides a framework and a set of coherent relationships for comparing data from different enclosure fires and different phases of development in the same fire. Also, it is often useful in the analysis of experimental data to form dimensionless parameters or ratios comparing experimental measurements with ideal or reference values of a variable. The following values of fire characteristics may prove useful in the formation of such dimensionless parameters.

A. TEMPERATURE

For the enclosure fire, one ideal temperature which may be defined is a "mixed mean adiabatic air temperature" T_m. This is the volume-average gas temperature which would occur in the enclosure if all the heat released is absorbed by the initial volume of enclosure air at constant pressure (neglecting the fuel heat capacity and heat losses to the surroundings). This temperature rise may be calculated as

$$\Delta T_m = \frac{\int_0^{t_e} \dot{Q}\,dt}{c\rho V_e}$$

where $\dot{Q}$ is the heat release rate in the enclosure prior to the induction of ventilation airflow, c and ρ are the specific heat and air density, and V_e is the enclosure air volume. It is apparent, of course, that actual air temperatures in the enclosure are also a function of stratification, heat losses to the surroundings, and induced air dilution. However, in the initial stages of a fire, most of the heat is used to heat the air, and initial heat losses from the enclosure are small. Thus, one could gain some insight into the initial rate of air temperature rise and the effect of enclosure volume (e.g., test scale) on air temperature increase. The formulation of a temperature stratification function (describing vertical temperature variation) and a heat transport function (describing initial heat loss to walls) when combined with the ΔT_m values could yield a better approximation of the temperature distribution in an

occupied enclosure such as an aircraft cabin during the time period prior to people evacuation.

Application of the ΔT_m also provides an evaluation of fire scaling effects in geometrically similar enclosure fire tests. The following example will demonstrate these scaling effects.

Consider three geometrically similar enclosure fires with length scale ratios of 1.0, 2.0, and 3.0 (Figure 3-1). The fuel bed is postulated as a rectangular slab on the floor of the enclosure with a linear flame spread velocity v of 0.2 m/min and constant value of heat release flux $\dot{Q}/A$ of 395 kW/m^2. These are material properties and are independent of scale in this model.

If each fuel bed is ignited along one edge, the time to reach the opposite edge t_s would be linearly related to the enclosure scale. In this example, the fire would burn across the fuel bed in Enclosure I in 5 minutes, II in 10 minutes, and III in 15 minutes. The same time scale relationship would be true if the fire is started in one corner or at a point in the center of the fuel bed. The value of the mixed mean adiabatic temperature rise ΔT_m may be calculated for the spreading fire in the three enclosures as

$$\Delta T_m = \frac{\int_0^{t_s} \dot{Q}dt}{c\rho V_e} = \frac{(\dot{Q}/A)bvt_s^2}{2c\rho V_e} \qquad \text{(for edge ignition)}$$

The temperature-versus-time-scale relationships for the cases of radial flame spread (e.g., point ignition) and for a constant heat release rate (e.g., pan of gasoline) have also been calculated using the heat release rates defined in the previous section. In each case, the time to reach a specific temperature is linearly related to the enclosure scale, with air temperatures rising faster in small enclosures. The average air temperature T_m in the enclosure reached at a given phase of fire development (such as t_s) would be the same. These initial temperature calculations may not be applicable to or valid for temperature values much above 300° or 400°C because of heat losses and ventilation effects, but these lower temperatures are in the range of concern for human tolerance to heat.

Published data and analysis methods are available for determining temperatures in enclosures during fully developed, ventilation-controlled burning (Refs. 28, 30, 34). These temperatures usually vary between 900° and 1200°C and are primarily a function of the ventilation factor $AH^{1/2}$ as well as time and wall materials. It is anticipated that the temperature distribution in an enclosure as a function of time can be bounded and characterized by an appropriate combination of the calculated ΔT_m values (Figure 3-1) and the calculated ventilation-controlled temperature values as available from existing analysis methods. This aspect of

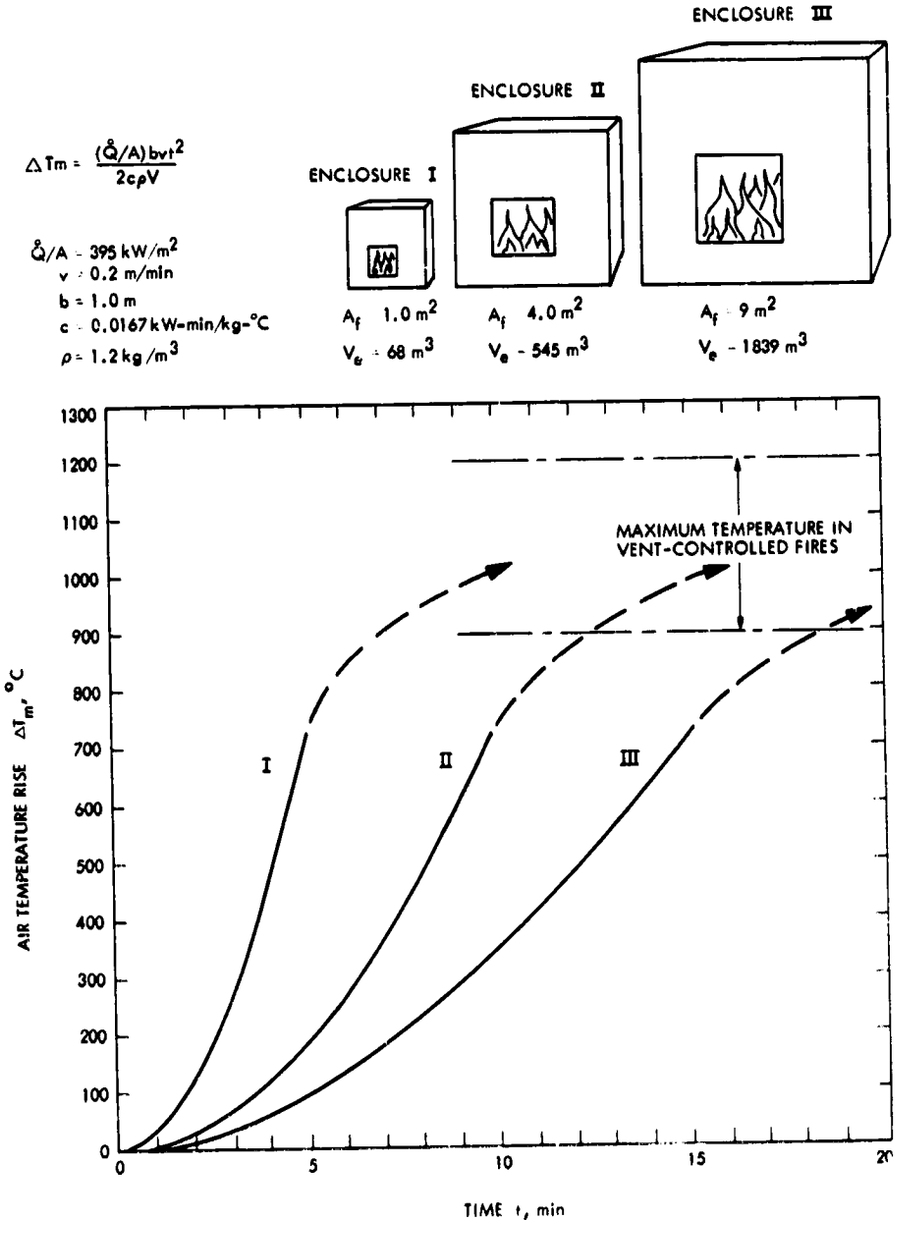

Figure 3-1. Calculated Mixed Mean Adiabatic Air Temperature Rise in Three Geometrically Similar Enclosure Fires

fire characterization requires further investigation, as does the possible relationship between a suitably modified T_m value and the flashover phenomenon.

B. SMOKE AND TOXIC GASES

The quantity of smoke and toxic gas released during burning may be treated in a manner similar to the above analysis for temperatures. The quantities of smoke and toxic gases released per unit mass of fuel are subject to a wide range of variability. However, they tend to be uniquely related to each phase of fire development. For example, during initial fire spread, the fuel tends to be cold and there is excess ventilation, which would yield specific gas and smoke evolution characteristics. During a period of ventilation-controlled burning, the fuel would be heated by feedback from the hot trapped gases and there would be a shortage of air. The volatile product and smoke yield for this situation may possibly be directly related to the ratio between the potential heat release rate $\mathring{Q}_f$ as defined by the fuel surface area and the vent-controlled heat release rate defined by the induced air supply $\mathring{Q}_f/\mathring{Q}_v$, both of which can be calculated regardless of which constraint is controlling.

The fraction smoke yield (designated as Γ) of several fuel materials, in terms of solid and condensible liquid products, has been measured (Refs. 40, 41) and falls in the range of 10 to 30% of the mass of fuel consumed.

As defined by Seader and Chien (Ref. 40), the mass optical density MOD may be a useful experimental correlating parameter which would be directly related to the mass rate of burning during a particular phase of burning. It is defined by the relation

$$\text{MOD} = \frac{D_s A_f}{m} = \frac{V_e}{mL} \log_{10}\left(\frac{I_o}{I}\right)$$

where D_s is the smoke-specific optical density determined in a National Bureau of Standards smoke chamber, m is the fuel mass loss, L is the light beam length (or visual path), and I_o/I is the reciprocal of light transmittance (e.g., for 25% light transmitted, the value of I_o/I would be 4.0).

The fuel mass loss in this case is the same mass loss measured in a fuel combustion experiment to measure heat release. Therefore, the initial rate of smoke generation can be related directly to the rate of heat release $\mathring{Q}_s$ if both are proportional to the rate of mass loss $\mathring{m}$ during burning. That is, the total mass of smoke is related to the burning rate and heat release rate by

$$\frac{\text{smoke mass}}{\Gamma} = \int \mathring{m}\,dt = \frac{\int \mathring{Q}\,dt}{\Delta H}$$

If the mass of smoke released in the enclosure is uniformly distributed prior to dilution by induced air and if an applicable experimental value of MOD is available for the fuel of interest, then the average light transmission in the enclosure as a function of time can be calculated from the above relationships as follows:

$$\log \frac{I_o}{I} = \text{MOD} \frac{L}{V_e} \int_0^t \mathring{m} dt$$

Although this idealized value does not exist in general, the effects of varying heat release rate, enclosure volume, path length, and smoke fraction can be assessed. The application of an appropriate stratification factor would yield more realistic estimates of smoke distribution as a function of time during the initial fire spread phase along with the estimate of air temperature rise.

The value of toxic gas concentration could be treated in a similar manner during the initial fire spread phase. If the combustion or pyrolysis of a given mass of fuel yields a known weight of toxic product (such as CO or HCl), its average concentration is proportional to the total mass of fuel consumed $\int \mathring{m} dt$ and inversely proportional to the enclosure volume V_e. Again, it is anticipated that during ventilation-controlled burning the ratio of the ventilation factor to the fuel area can uniquely control the toxic gas yield, composition, and distribution.

The complex relationships and feedback functions which would exist in an enclosure among fuel composition, flame spread rates, air temperatures, time, and the heat release functions are the subject of continuing study. However, it is believed that these idealized fire characterization relationships can provide a coherent unifying framework for integrating experimental data from a variety of material tests and prototype enclosure fires.

SECTION IV

HAZARD ANALYSIS AND FIRE CONTROL

Two general categories of fire hazards are the hazards to humans and the hazards to materials and structures. In general, humans are more sensitive and easily damaged than structures. However, people can usually be evacuated from the fire vicinity in a short time and without the fire necessarily being under control.

Fire control may include containment within the enclosure as well as extinguishment. This often includes appropriately controlling and altering the enclosure ventilation, either to gain access to the fire or to exclude air and prevent fire, smoke, or toxic gas from spreading to adjacent areas.

Calculating and plotting the RERC can assist in characterizing the fire hazards and assessing the effects of various fire control options during the applicable time periods of interest. In one sense, this analysis approach does not add anything new to existing fire technology since it relies on existing data, testing methods, and fire control techniques to provide answers. However, this analysis approach provides a unifying framework for data presentation and graphically relates the different phases of potential fire development, making it possible to apply data from a variety of sources to both familiar and new fire situations as well as to make preliminary hazard assessments and define the need for more specific data and testing techniques.

Two examples of the application of the RERC are presented and discussed to demonstrate their application to existing data and to hypothetical situations.

A. EXPERIMENTAL FIRES IN ENCLOSURES (EXAMPLE 1)

Two well-documented studies of experimental fires in enclosures are presented by Tewarson (Factory Mutual Research) in References 12 and 23. Data are included for three fuels: wood, ethyl alcohol, and paraffin oil. These investigations were undertaken to study the generation of smoke and toxic products under various conditions with the ultimate objective of establishing appropriate scaling parameters for building and laboratory enclosure fires.

Tewarson's values of enclosure volume, fuel characteristics, and ventilation factors have been used to calculate the five RERC values and to plot them for one wood crib fire as shown in Figure 4-1. Heat release and fire spread rates for the wood cribs were estimated from the given fuel mass values and from maximum equivalent burning rate data from Reference 34, which provides applicable data on crib burning characteristics. The experimental burning rate-versus-time data, which appear to have a cyclic characteristic (Ref. 23), are plotted in Figure 4-1 as heat release rate $\dot{Q}$ using a heat of combustion for wood of 270 kW-min/kg. The value used for flame spread rate through the crib is probably the least

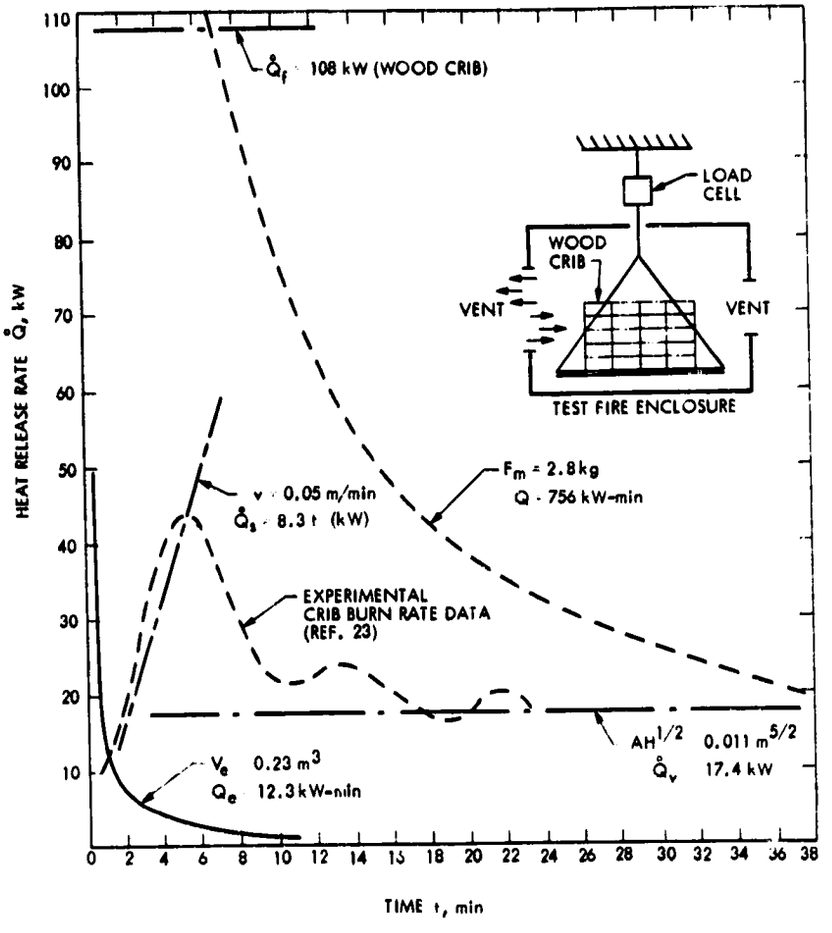

Figure 4-1. Enclosure Fire Wood Burning Rate-Time Profile From Factory Mutual Research Experiments (Ref. 23) Compared With Calculated Values of Relative Energy Release Criteria

accurate of the criteria shown because the details of the wood crib configuration were not given.

Examination of the graphical RERC presentation in Figure 4-1 reveals several fire characteristics which are verified by the background data included in the Factory Mutual paper. Light is also shed on one possible mechanism of fire periodicity. The most notable characteristic of the crib burn rate curve shown is that it initially exceeds the ventilation limit criteria $\mathring{Q}_V$. However, this result is consistent with the manner in which the crib was ignited with acetone-soaked cotton balls placed at the bottom of the crib. The RERC plot indicates that the crib was not completely aflame when the ventilation constraint was reached. Because the crib was ignited from the bottom, the heat released by the lower crib material heated and pyrolyzed the upper crib material, releasing unburned volatiles. Thus, the excess heat release indicated by the experimental weight-loss rate curve represents combustible gases evolved which would exit the enclosure unburned and probably burn outside where additional air is available. This is consistent with the discussion and gas composition data in Tewarson's report and with the large value of the ratio $\mathring{Q}_f/\mathring{Q}_V$. Examination of data for the other conditions of fire load and ventilation reveals several cases for which the total fire load F_m is insufficient to establish ventilation-controlled burning even though the fuel surface area may have been adequate.

A possible explanation of the cyclic characteristic in Figure 4-1 is the gradual reduction in flame and air temperatures due to the buildup of a fuel-rich condition in the enclosure with an excess volatile gas outflow. The consequent reduction in induced air and hence reduction in heat release rate, along with the net reduction in material available for volatilization, would cause a decrease in both mass loss rate and fire intensity. As the volatile gas outflow decreases, an increase in induced air and higher consequent flame temperatures can cause an increase in burning rate again and another burn cycle. The value of the $\mathring{Q}$ burn rate curve remaining above the $\mathring{Q}_V$ criteria curve would indicate continuing excess volatilization. For other fuel loads, different crib configurations, and different points of ignition, one might expect different burning rate-versus-time profiles.

The Factory Mutual data also confirm the expectation that maximum enclosure temperatures would result as the ra $\mathring{Q}_f/\mathring{Q}_V$ approaches a value of 1.0 (Ref. 30).

The location of the enclosure volume constraint Q_c in Figure 4-1 indicates such a small initial volume of air available in the enclosure that the apparent excess heat release rate cannot be attributed to its combustion.

B. HYPOTHETICAL ROOM FIRE (EXAMPLE 2)

The enclosure described in Figure 4-2 represents several possible enclosures and variations thereof. It might be visualized as a living room, an aircraft cabin, a transit vehicle, or a storage compartment. The sketch has been simplified, but several added complexities (e.g.,

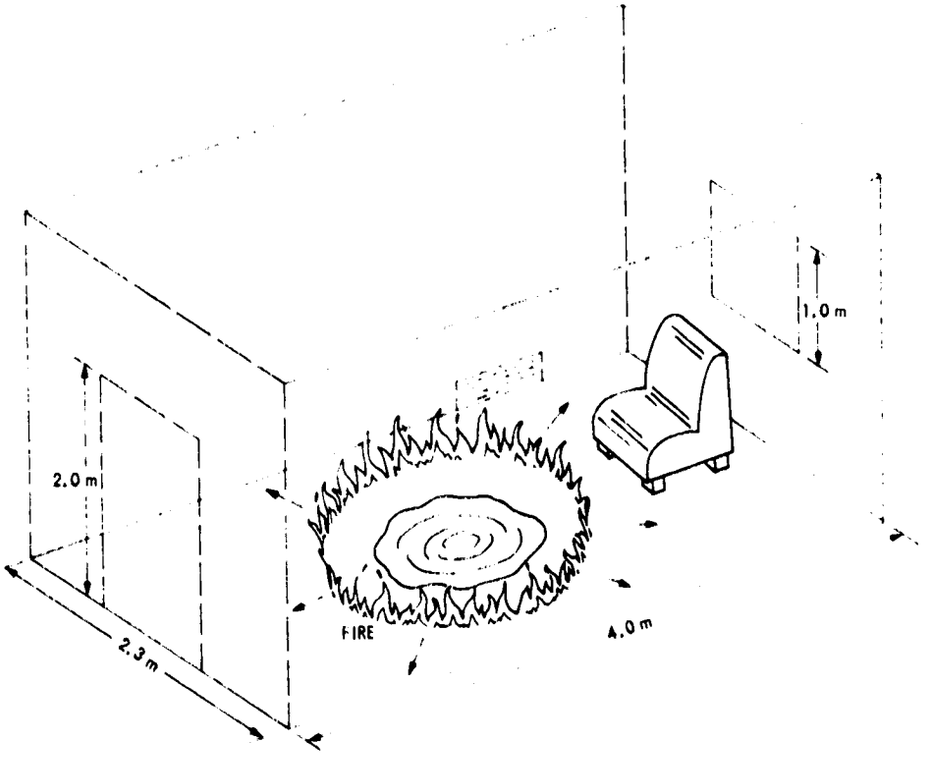

Figure 4-2. Relative Energy Release Criteria (Example 2)

more seats or spilled gasoline) may be evaluated directly using the PLRC as calculated and plotted in Figure 4-3.

For the purpose of illustrating several fire development phenomena, somewhat arbitrary values of the fire parameters and material properties have been postulated. The burning characteristics of the seat have been simulated for a 21-kg wood crib (Ref. 34). Thus, the following parameters have been defined for this example:

Enclosure Parameters

Room dimensions = 4.0 x 2.3 x 3 m

Enclosure volume V_e = 27.6 m^3

Total energy released $Q_e = 58V_e$ = 1600 kW-min

Air $c = 0.017 \frac{\text{kW-min}}{\text{kg-}^\circ\text{C}}$, ρ = 1.2 kg/m^3

Fuel Parameters

(1) Carpet

Dimensions = 4.0 x 2.3m

Area A_f = 9.2 m^2

Fuel mass per surface area F_m/A_f = 1.5 kg/m^2

Flame spread rate v = 0.12 m/min

Heat release rate $\dot{Q}/A$ = 100 kW/m^2

Fuel mass F_m = (1.5)(9.2) = 13.8 kg

Heat of combustion ΔH = 270 kW-min/kg

Fuel load ΔHF_m = 3726 kW-min

(2) Seat (equivalent wood crib, Ref. 27)

Fuel mass F_m = 21 kg

Maximum burning rate R = 3 kg/min

Maximum heat release rate $\dot{Q} = \Delta HR$ = (3)(270) = 810 kW

Fuel load per seat ΔHF_m = 5670 kW-min

(3) Gasoline Pool

Pool burning $\dot{Q}$ = 2500 kW/m^2

Fuel load ΔHF_m = 566 kW-min

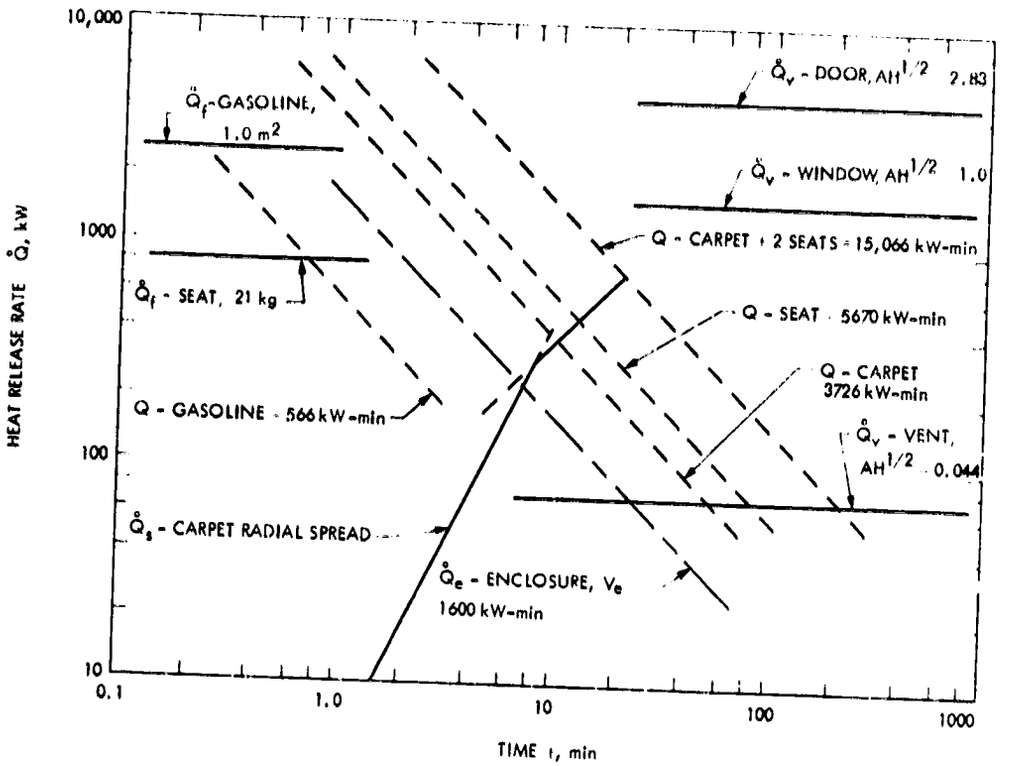

Figure 4-3. Relative Energy Release Criteria Graphical Presentation for Hypothetical Room Fire (Example 2) With Alternate Fuels and Ventilation Options

Ventilation Factors $AH^{1/2}$

(1) Door

Dimensions = 2.0 x 1.0 m

$AH^{1/2} = (2)(1)(2^{1/2}) = 2.83\ m^{5/2}$, $\mathring{Q}_v = 4471$ kW

(2) Window

Dimensions = 1.0 x 1.0 m

$AH^{1/2} = 1.0\ m^{5/2}$, $\mathring{Q}_v = 1580$ kW

(3) Small vent

Dimensions = 0.2 x 0.5 m

$AH^{1/2} = 0.044\ m^{5/2}$, $\mathring{Q}_v = 69.5$ kW

The RERC for this example have been plotted using log-log coordinates to allow consideration of a wider range of parameter values.

If the fire is ignited at a point in the center of the carpet and spreads radially, the initial spread-limited heat release rate is

$$\mathring{Q}_s = (\mathring{Q}/A)\pi v^2 t^2$$

or

$$\mathring{Q}_s = (100)(\pi)(0.12)^2 t^2 = 4.52t^2 \text{ kW}$$

Since the fuel mass per unit area of the carpet is limited to 1.5 kg/m^2, the maximum total heat release per unit area Q/A would be limited to 405 kW-min/m^2. As the flame continues to spread, it becomes limited by the expression

$$\mathring{Q}_s = 2\pi(Q/A)v^2 t = 36.6t$$

These two limits and their intersection are shown in Figure 4-3. The intersection of the two heat release rate limits occurs at 8.1 minutes.

The value of the mixed mean adiabatic temperature rise ΔT_m can be calculated as described previously. It may be more useful to calculate the time at which ΔT_m would exceed some specified value, such as 300°C, which would be based on the temperature rise equation for flame radial spread over the carpet alone.

$$\Delta T_m = \frac{(\mathring{Q}/A)\pi v^2 t^3}{3c\rho V_e} \quad \text{or } 3.21t^3$$

or the time to reach 300°C

$$t_{300} = \left(\frac{300}{3.21}\right)^{1/3} = 4.54 \text{ min}$$

The relative effect of changes in heat release rate, flame spread velocity, or enclosure volume may be estimated from the above expression.

The enclosure volume criterion curve is plotted from the expression

$$\mathring{Q} = \frac{58V_e}{t} \text{ kW}$$

On the log-log coordinates, this curve is a line through $\mathring{Q}$ = 1600 kW at t = 1.0 min with a negative slope of 1.0. In a similar manner, the fuel load curves may be added to the graph as shown. The fuel load curves for the carpet alone, for one seat, and for the carpet plus two seats have been plotted. The fuel surface-limited heat release rate curves for the seat (wood crib) and for a gasoline pool have been plotted as unit values on the left side of the figure; the values can be summed as appropriate.

The ventilation limit curves for the door, window, and vent have been plotted on the right-hand side of the figure based on the expression for ventilation-controlled heat release rate

$$\mathring{Q}_v = 1580AH^{1/2} \text{ kW}$$

The five RERC plotted in the manner presented in Figure 4-3 may now be used to evaluate several fire scenarios and fire control options. A number of preliminary observations are outlined below. These are based on greatly simplified assumptions as noted. Complexities and sophistication may be added as the critical fire phase is identified and as available data warrant.

(1) For the carpet alone burning, room ventilation would not affect the fire spread and heat release for the first 7 minutes because of the adequate initial air supply. Therefore, opening the door to gain access or escape would not alter the fire intensity. Closing off all ventilation would not alter the fire progress until after the first 7 minutes.

(2) For the carpet and one seat fully involved with ventilation provided only by the open window, the maximum heat release

rate would remain fuel surface controlled; hence, heat release would not be altered by further increase in ventilation. If the seat becomes fully involved within 1 minute after ignition, it would burn for about 7 minutes or less at the maximum heat release rate.

(3) For burning gasoline spread over a 1 m^2 area the fire becomes ventilation controlled by window-only ventilation. If the door is also opened, fire intensity in the enclosure would increase; with the door closed and the window open, vaporized unburned gasoline would exit the window resulting in flames outside the enclosure.

(4) The fire due to any combination of fuels which is ventilated only by a small opening ($AH^{1/2} = 0.044$) would develop until it encountered the enclosure volume constraint, and then it would reduce in intensity to the heat release rate determined by the ventilation limit ($\dot{Q}_v = 69.5$ kW). However, excess volatiles would probably cause either fire oscillation or flaming outside the enclosure. The duration of the fire would be approximated by the intersection of the vent limit curve with the appropriate fuel load curves. For the carpet plus two seats, the burning time could extend over 3 hours.

Various heat-release-rate time profiles could be approximated by summing individual heat-release-rate profiles if the sequences of ignition and flame spread rates could be approximated. Using the criteria in Figure 4-3 and a postulated heat release profile for a single seat (such as could be measured in a laboratory test), a number of fire scenarios may be examined. Figure 4-4 presents one potential fire development profile based on the following postulates:

(1) The fire is initiated at one end of the enclosure by 1 liter of gasoline spilled over a 1 m^2 area and ignited.

(2) The enclosure ventilation is one window.

(3) Two seats, side by side, are located with the side of the first seat at 1.5 m from the spilled gasoline.

(4) The total fuel load consists of the gasoline, carpet, and two seats; $\Delta HF_m = 15{,}632$ kW-min $= \int \dot{Q} dt$

(5) The carpet burning rate after the flame spreads to the wall becomes constant as it burns the length of the room:

$$\dot{Q} = (Q/A)bv = 175 \text{ kW}$$

Examination of the composite fire development profile in Figure 4-4 indicates that with the window open the fire would always be fuel surface controlled. The initial flash fire due to the 1 liter of gasoline would last less than 1 minute and would not be ventilation limited because the

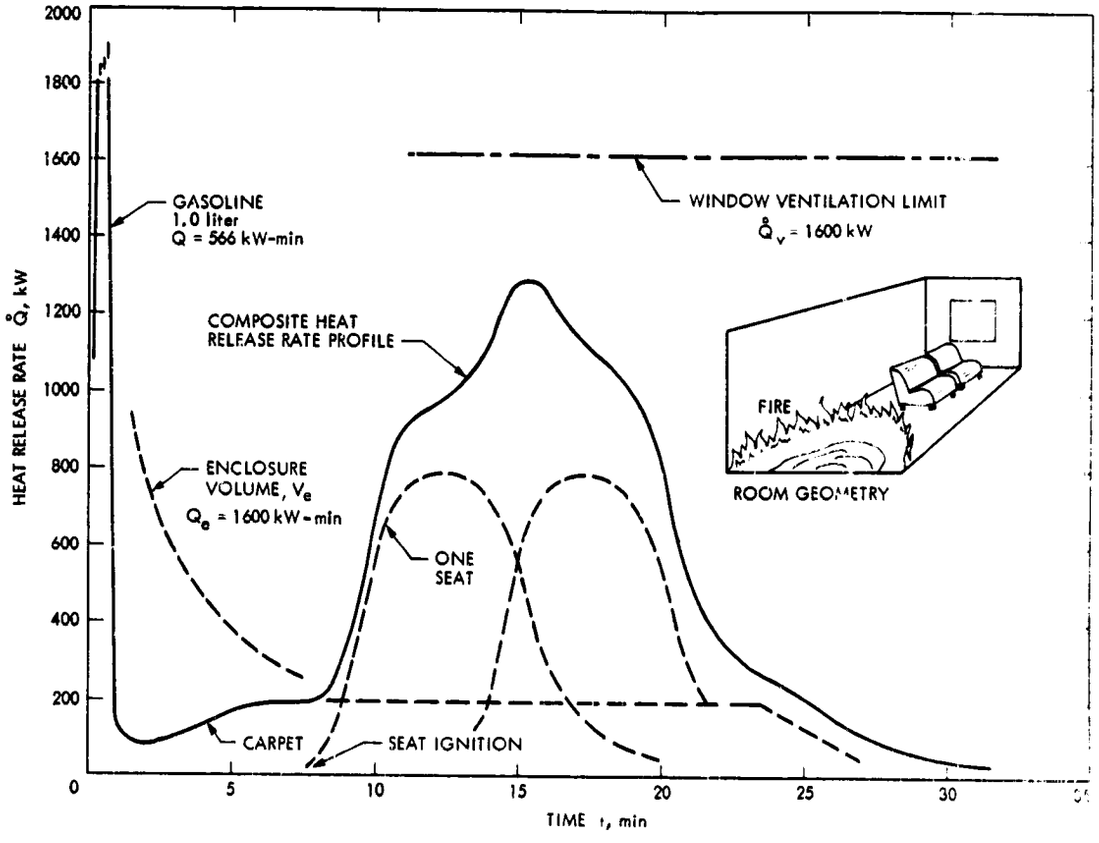

Figure 4-4. Hypothetical Room Fire Development Profile (Example 2)

gasoline fuel load (Q = 566 kW-min) is much less than half the enclosure volume limit (Q_e = 1600 kW-min). The calculated mixed mean adiabatic air temperature rise ΔT_m would be approximately 1000°C within a few seconds due to the gasoline. This is consistent with an almost explosive effect in the room if 1 liter of gasoline is spilled on the carpet and ignited. After the first minute, the fire would reduce to burning at a relatively low heat release rate until the seats ignite. If the air temperature is being monitored in an actual fire of this type, one would expect an initial air temperature surge followed by a marked reduction due to heat losses and a subsequent steady rise in air temperature with continued carpet and seat burning. This type of fire response has been reported for several test fire situations (Refs. 17, 18, 34).

SECTION V

CONCLUSIONS

V. CONCLUSIONS

This report presents an enclosure fire modeling approach based on the graphic presentation of five relative energy release criteria (RERC) which individually constrain the rate and the total amount of energy released during the course of an enclosure fire. This fire analysis approach does not replace or supersede existing fire analyses but provides a coherent unifying framework or common base for relating and integrating available data and analyses for different fire phases.

In this analytical approach, simplified definitions are presented for fire characterization parameters and their interrelationships which control the fire development and the consequent gas temperatures, smoke densities, and toxic gas concentrations.

The effects of heat transport phenomena, fluid flow patterns, complex interactions, and feedback effects have not been considered in detail. These effects have been investigated by others for specific fire situations, and in some cases their results may be used directly in the present modeling approach.

This modeling approach is adaptable to computer programming; the real complexities may be included when warranted and feasible.

The types of fire test data and material properties which may be of most value in predicting fire development are suggested. A heat release rate calorimeter with the capability of also measuring mass loss rate, toxic gases, and smoke production from materials and components having irregular geometry could be used to provide data for application to a wide variety of complex enclosures and fire loads.

This analytical approach can be directly used in its present form to assess the validity of assumptions made in current full-scale test methods. With further development, better estimates for temperatures, smoke densities, and toxic gas concentrations would be possible. Other fire phenomena such as flashover and periodicity may also yield to more complete analysis using this modeling approach.

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SECTION VII

NOMENCLATURE

A	= Ventilation opening area, m^2
A_f	= Fuel surface area, m^2
b	= Flame front length, m
c	= Specific heat at constant pressure, kW-min/kg-°C
D_s	= Smoke specific density
F_m	= Fuel mass, kg
g	= Gravitational constant, 9.8 m/s^2
H	= Vertical dimension of ventilation opening, m
ΔH	= Heat of combustion, kW-min/kg
I_o/I	= Radiant intensity ratio
K_1, K_2, K_3	= Proportionality factors in consistent units
L	= Optical path length, m
m	= Fuel mass loss, kg
$\mathring{m}_{air}$	= Mass flow of air, kg/s
Q	= Total heat released, kW/min
Q_e	= Total heat released by complete combustion of air in enclosure, kW-min
Q/A	= Total heat released by complete combustion of unit area of fuel carpet; a material property, kW-min/m^2
$\mathring{Q}$	= Heat release rate, kW
$\mathring{Q}_a$	= Average rate of heat release, kW
$\mathring{Q}_f$	= Fuel surface-controlled heat release rate, kW
$\mathring{Q}_s$	= Heat release rate during flame spreading, kW
$\mathring{Q}_v$	= Ventilation-controlled heat release rate, kW
$\mathring{Q}/A$	= Heat release rate per unit area; a material property, kW/m^2

R	= Fuel burning rate, kg/min
T	= Temperature, °C
ΔT_m	= Mixed mean adiabatic temperature rise, °C
t	= Burning time, min
t_e	= Fire duration, min
t_s	= Time for fire to spread to total fuel surface, min
V_e	= Enclosure volume, m^3
v	= Flame spread velocity, m/min
Γ	= Fraction of fuel evolved as smoke
ρ	= Air density, kg/m^3

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