JPL PUBLICATION 78-86

Application of the Relative Energy Release Criteria to Enclosure Fire Testing

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January 1, 1978

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Space Administration

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract No. NAS7-100

DEFINITION OF SYMBOLS

A_f	fuel surface area
F_m	initial fuel mass
F_o	fuel mass actually consumed or burned at time t_o
ΔH	heat of combustion (fuel)
m	fuel mass loss (time dependent)
$\mathring{m}$	time rate of fuel mass loss, i.e., dm/dt
n	oxygen fraction burned in enclosure
$\mathring{Q}$	heat release rate
$\mathring{Q}_m$	maximum heat release rate that occurs at time t_m
$\mathring{Q}_s$	heat release rate during flame spread
$\mathring{Q}_f$	fuel surface (area) controlled heat release rate
$\mathring{Q}_v$	ventilation controlled heat release rate
$(\mathring{Q}/A)$	heat release rate per unit (fuel) area, a material property
Q_e	total heat released by complete combustion of air (oxygen) in enclosure
Q_{fm}	total heat released by fuel
Q_m	maximum value of heat release that occurs at time τ_m
R	fuel burning rate (constant dm/dt taken over some portion of the fire)
T	gas temperature in enclosure
T_i	initial or ambient gas temperature prior to fire
ΔT	change in gas temperature above T_i or $T - T_i$
t	time

t_m	time in which $\mathring{Q}_m$ occurs (Fig. 8)
τ_m	time at which Q_m occurs (Fig. 8)
t_f	time at which intersection of fuel surface limit and enclosure limit occurs
t_o	time (duration) of fire, or idealized fire time (Appendix A) also, intersection of ventilation limit with fuel load limit when $\mathring{Q}_f$ $\mathring{Q}_v$, or intersection of fuel surface limit with fuel load limit when $\mathring{Q}_v < \mathring{Q}_f$
Δt_v	idealized time increment for ventilation control, $t_o - t_f$ (Appendix A)
Δt_f	idealized fire time t_o when fire is fuel surface limited (Appendix A)
V_e	enclosure volume
$\mathring{V}$	ventilation rate, volume rate of air flow

ABSTRACT

The Relative Energy Release Criteria (RERC) are a first step towards formulating a unified concept that can be applied to the development of fires in enclosures. The five criteria place upper bounds on the rate and amount of energy released during a fire. They are independent, calculated readily, and may be applied generally to any enclosure regardless of size. They are useful in pretest planning and for interpreting experimental data.

In this report, data from several specific fire test programs have been examined to evaluate the potential use of RERC to provide test planning guidelines. The RERC were compared with experimental data obtained in full-scale enclosures by Stanford Research Institute and Lawrence Livermore Laboratory. These results confirm that in general the RERC do identify the proper limiting constraints on enclosure fire development and determine the bounds of the fire development envelope. Plotting actual fire data against the RERC reveals new valid insights into fire behavior and reveals the controlling constraints in fire development. Also, in this report, the RERC were calculated and plotted for several descriptions of full-scale fires in various aircraft compartments.

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SECTION I

INTRODUCTION

The development of fires in enclosures is a highly complex and variable process. In many cases the data from experimental fires, especially those performed on a model scale, can be correlated successfully. However, there has been great difficulty applying these correlations to other model fire data, full-scale experimental fires, and fire hazard analysis of existing enclosures. The root of this difficulty is the large number of interacting parameters that determine the course of fire development in enclosures. It is not simple to identify which parameters dominate at various stages of the fire. Thus, it would be highly desirable to have available a fire modeling approach that could be applied to the body of existing experimental data and to the analysis of new fire hazard situations as well. A unifying concept to accomplish this has been proposed by Coulbert (Refs. 1 and 19).

Coulbert has defined a set of five "Relative Energy Release Criteria" (RERC) that place bounds or constraints on the probable course of fire development without recourse to detailed heat balances of the enclosure. The RERC are constraints on the rate and amount of energy released during a fire; they are independent and have fixed numerical values. Nominal values for the RERC are readily calculated from known fuel, enclosure, and ventilation specifications, and using information available in the literature. They can be calculated for any enclosure in a general way. In their present form they are not used to predict the detailed and instantaneous history of a fire. Rather, when all are plotted in a single chart of energy release rate versus time, they are used to define the approximate fire development envelope. The RERC reveal which phases of the fire development would be in control during the major or critical portions of the fire. Relative changes of one or more constraints by a factor of two or three may be evaluated readily by intuitive reasoning.

To date the RERC approach has not yet been used to plan an actual series of enclosure test fires. It is the purpose of this report to demonstrate the use and application of the RERC, to test their validity and thereby reveal any shortcomings, and to offer recommendations concerning their application to enclosure fire modeling and the design of experiments. Several specific enclosure fire test programs have been examined to evaluate the potential use of the RERC to provide test planning guidelines. In several of the cases, where tests have been planned, but data have not yet been obtained, various fire scenarios may be envisioned using the RERC approach.

SECTION II

THE RELATIVE ENERGY RELEASE CRITERIA (RERC)

A. BACKGROUND AND DESCRIPTION

A vast body of literature exists on the theory of and experiments with enclosure fires; most of the results concern small-scale or model fires. Sophisticated analyses of discrete phases of fire development, e.g., ignition and flame spread, have been developed extensively using the principles of combustion physics and chemistry and thermal technology. However, a global approach that places the entire fire history in perspective has been lacking. There has not been a unifying concept that is meaningful for designing tests, understanding the results, and making extrapolations to differing fire conditions.

In recent decades the loss of life and property in enclosure fires of many types, e.g., commercial vehicles, aircraft, shipboard compartments, public and private facilities, has become an increasingly serious problem. Intensive research is being conducted on fire-resistant materials, structural design to minimize fire hazard and yet permit rapid evacuation and ease of fire fighting, and early-warning and fire-quench systems. Clearly, a systematic technique for predicting fire development under a wide variety of conditions and scale sizes is needed. Definition and application of the RERC is an initial attempt to meet this need. Basically, it is a systems analysis approach that can be refined to any degree warranted. The refinement process will require a blending of knowledge of several disciplines of the physical sciences and technology, as well as the life sciences.

B. DEFINITION OF THE CRITERIA

The five energy release constraints on fire development in an enclosure may be 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 proceeded, changes in fuel area and other fuel characteristics would alter this rate as the fuel supply diminished.

(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 and the fuel load limit.

(4) Enclosure Volume

A constraint on total energy release in the enclosure would be due to the depletion of the initial oxygen supply if ventilation were limited, as in a closed room or sealed compartment.

(5) Fuel Load.

The second constraint on total energy release is the total fuel load.

Methods for estimating and calculating nominal values of the RERC for simple but common situations were presented by Coulbert (Refs. 1 and 19), and will not be repeated in detail here. The approach was to calculate values for the RERC using experimental and empirical information available in the literature. In the case of wood cribs, for example, a maximum rate of burning R for optimum conditions and adequate ventilation is selected for use in the calculation of the ventilation limit. Clearly, this value could be revised downward, if desired, because, in a given wood crib experiment, this maximum R may never be achieved and would not remain constant over the whole duration of the fire. Nevertheless, it represents an upper bound and can therefore be considered an independent parameter.

The most tenuous of the RERC, and perhaps the most difficult to calculate, is the flame spread rate. This constraint is operative during the early stages of a fire. Although much of past fire research has been devoted to the physics of flame spread, it is difficult to generalize the results to any but the most simple cases. Thus, in a real enclosure with multiple fire loads of complex shape it may not be possible a priori to calculate the flame spread rate constraint. This is especially true because the early fire development will depend on the source, size, and location of the ignition. However, bounds on the flame spread rate might be determined by examining a large body of experimental data that cover a variety of conditions and fuels.

Interpretations of the RERC in different forms and further discussion on their use and limitations are given in Appendix A and Appendix B respectively.

SECTION III

APPLICATIONS TO REAL AND POTENTIAL ENCLOSURE FIRES

In this report, nominal RERC have been determined for specific cases and compared with experimental results obtained from full-scale enclosure fires: extensive experiments conducted by Stanford Research Institute and some experiments performed by Lawrence Livermore Laboratory. In both cases, a roughly cubical enclosure was used with forced ventilation, but the enclosure volume in the two sets of experiments differed by a factor of 3.3. With regard to forced ventilation, the ventilation limit is calculated as the heat released per unit flow of air into the enclosure. This differs from the calculation of vent limits for natural ventilation (open windows and/or doors) as outlined by Coulbert (Ref. 1), where the flow is determined by the vent geometry.

The primary and most useful experimental data for comparison with the appropriate RERC is the fuel weight loss measured as a function of time. By differentiating such curves to determine dm/dt it is possible to calculate the time history of thermal energy release rate $\mathring{Q} = \mathring{m}\Delta H$ by using the heat of combustion of the fuel. The time rate of fuel weight loss may not reflect the true energy release rate because evaporation and pyrolysis products may not be completely burned and may pass out of the system or recondense. As calculated herein, $\mathring{Q}$ represents an upper bound on the actual energy release rate, which may be somewhat lower especially during the early and, perhaps, the very late stages of the fire.

Also examined in terms of RERC were NASA cargo bay and lavatory descriptions (aircraft) and the Lockheed aircraft compartment descriptions. Although experminetal data were obtained in the NASA cargo bay and lavatory tests, the data were not in a form suitable for direct comparison with the calculated RERC.

A. STANFORD RESEARCH INSTITUTE EXPERIMENTS

1. Description

Stanford Research Institute (SRI) has performed numerous experiments in sealed enclosures of four different sizes that had volumes in the approximate ratio of 1:8:100:1000. The largest enclosure had a volume of 1050 ft^3 and dimensions 10 ft × 13 ft × 8 ft high. A variety of liquid and solid fuels and a series of fuel loads were tested. Burning rates (weight loss), total heat release, spatial and temporal heat fluxes (radiometers and thermocouples), gas compositions, and flame geometries were measured. The results and discussion of these experiments were given in Part 1 of an unpublished SRI report (Ref. 2), and will not be discussed further herein.

Part 2 of their work (in preparation) concerns experiments using forced ventilation in the 1050 ft^3 enclosure. Two liquid and two solid fuels were tested: methanol (MeOH), JP4, wood cribs, and rubber tires. The fuels were placed in a pan located centrally in the enclosure and about 2 ft above the floor. A load cell was used to measure fuel weight loss. In the case of rubber tires, tire fragments or sections were piled into a pyramid about 3 ft across at the base. In all cases the fuel load was about 15 kg (33 to 35 lb). Rapid start was provided by igniting a small portion of JP4 with a paper wick using a remotely activated electric-arc igniter. Four vent patterns were used with four different ventilation rates.

Ray Alger of SRI kindly has made available the preliminary data, in graphical form, of the weight of fuel burned as a function of time, and also heat fluxes measured at several locations in the enclosure as a function of time. This data has been examined and analyzed at JPL with reference to the calculated RERC.

2. RERC for SRI Experiments

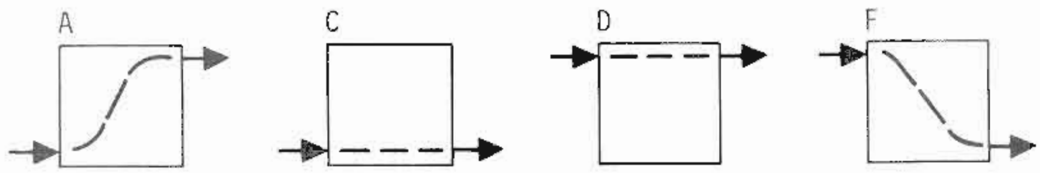
A summary of the fire parameters and the associated RERC are given in Table 3-1; no attempt was made to calculate the flame spread rates for these experiments because the spread times were very small compared to the total burn times. The fuel surface area limits were calculated assuming a heat release per unit area of 2400 kW/m^2 and 284 kW/m^2 for JP4 and MeOH respectively (Ref. 3). Because the surface area of the wood cribs was unknown, a maximum burning rate of $R \simeq 2.2$ kg/min was assumed, as obtained for an initial fuel load of 15 kg from an empirical result given by Thomas (Ref. 3) for well-ventilated wood cribs. The fuel surface limit for the rubber tires was not determined; based on data to be presented later it appears that $\mathring{Q}_f$ for the tires was about 100 kW, or less. The heats of combustion given in Table 1 were taken from Ref. 2, Part 1; these quantities represent low heating values for the liquid fuels and high heating values for the solid fuels. Fuel load limits were calculated from $Q_{fm} = F_m \Delta H$ and are valid as upper limits assuming that all the fuel is expended by combustion.

Excepting the flame spread rates and the fuel surface limit for rubber tires, the RERC are plotted in Fig. 3-1 in a log-log plot of $\mathring{Q}$ versus time; ventilation limits for the four experimental ventilation rates are shown. The curve labeled $Q_e/2$ represents the enclosure limit if only one-half of the initial oxygen in the room was consumed. Theoretically, the ventilation limit comes into play only after the experimental curves, to be shown later, cross the enclosure limit. The RERC, in their present form, do not take into account several factors (Appendix B); among these is the effect of a particular ventilation pattern.

Table 3-1. SRI Enclosure Fire Experiments and RERC

Experimental Conditions

Constant Room Volume: V_e = 1050 ft^3
Four Ventilation Rates: 71, 154, 237, 348 ft^3/min
Four Ventilation Patterns: A, C, D, F



Four Types of Fuel: load ∿ 15 kg = 33 lb

(Liquid) MeOH and JP4: 36-in. diam. pools
(Solid) { Wood Cribs: 3/4-in. square sticks
Rubber Tire Segments: pyramid piles

Basic Data: fuel weight loss with time
heat flux data (radiometers)
(no gas temperature or composition)

RERC

Flame Spread Rates: (Not calculated)

Ventilation Limit: $\mathring{Q}_v$

$\mathring{Q}_v$ = 115 kW for 71 cfm
= 250 kW for 154 cfm
= 390 kW for 237 cfm
= 570 kW for 348 cfm

Enclosure Volume:

Q_e = 1720 kW-min
$Q_e/2$ = 860 kW-min

Fuel Limits:

	Fuel Surface Limit $\mathring{Q}_f$, kW	Heat of Combustion ΔH, (kW-min)/kg	Fuel Load Q_{fm}, kW-min
Wood Cribs	640	308	4,600
MeOH Pools	187	297	4,400
JP4 Pools	1600	736	11,000
Rubber Tires	—	234	3,500

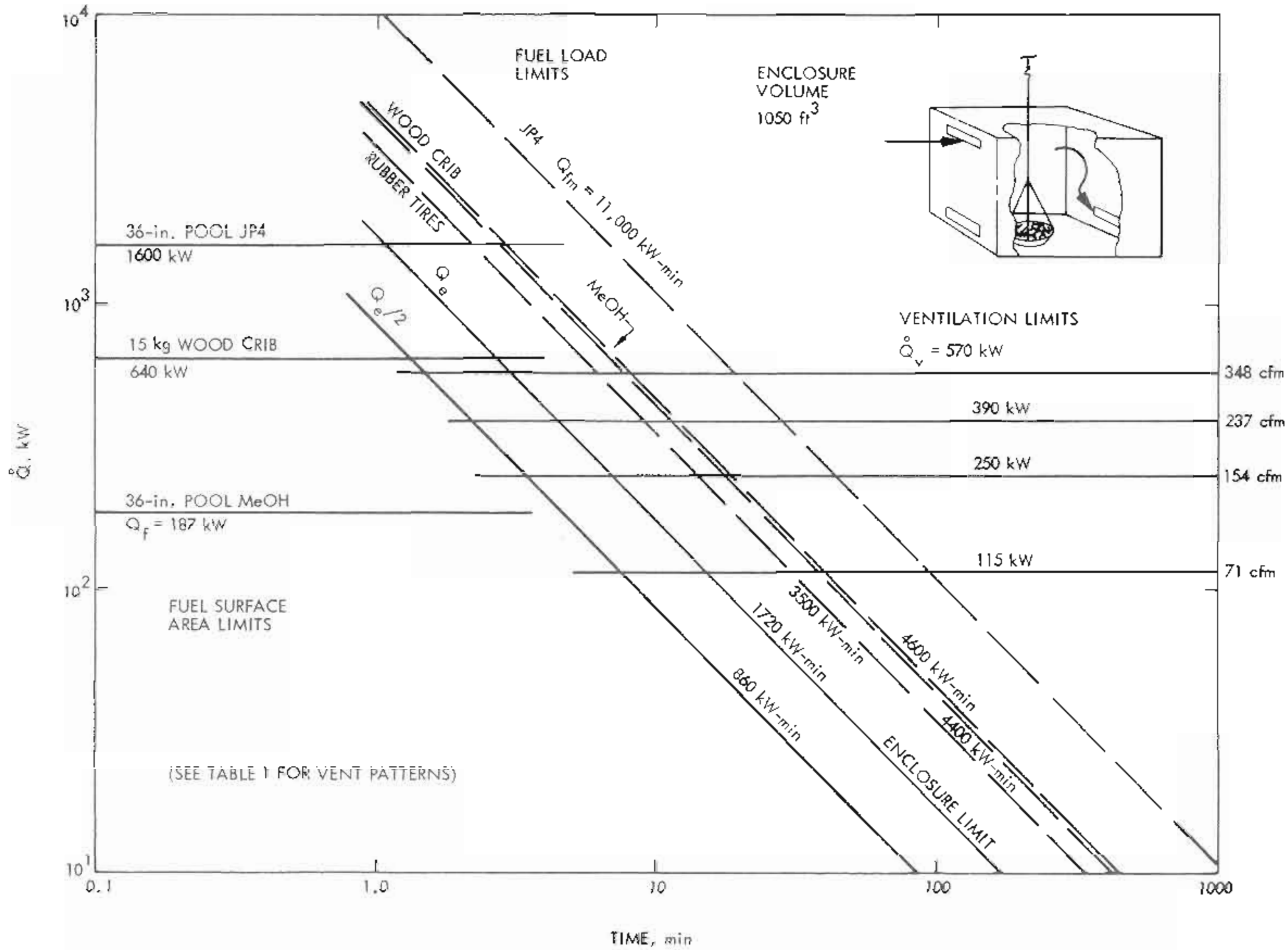


Figure 3-1. Relative Energy Release Criteria (RERC) for SRI Experiments

Assuming that adequate circulation exists in the enclosure to ensure complete combustion of the entire fuel load, several general observations are possible from Fig. 3-1.

(1) Wood cribs and JP4 fuels could be ventilation controlled for all experimental ventilation rates that were tested.

(2) Methanol, with the exception of the lowest ventilation rate, should be fuel surface area controlled.

(3) It is likely that the rubber tire fires were fuel surface controlled for all ventilation rates because the heat release rate data was below the minimum ventilation rate $\mathring{Q}_V$ in all cases.

(4) For the ventilation controlled fires, the absolute duration of time that the fire is ventilation controlled should increase as the ventilation rate decreases.

As will be seen later, these idealizations were not satisfied entirely. Reasons include poor combustion, failure to achieve complete burning of the entire fuel load, and the effects of ventilation pattern.

In Table 3-2 are listed the experiments and conditions for which data from SRI was available for analysis. Included are some gross observations on the fires that include the occurrence of oscillations in energy release rate, the approximate duration of the fire as determined either from dm/dt = 0 or cessation of data, and the fraction of fuel expended.

Oscillations in burning were common, especially with the solid fuels. The rubber tires oscillated in most of their tests apparently because of smoldering combustion, and only about half the fuel was expended during the fires. Wood cribs apparently burned rather well, but there was some residue of unburned material. Methanol burned well with vent patterns A and C, but poorly with pattern F and, at low ventilation rates, poorly with pattern D. The shortest burning times were obtained with JP4, which apparently burned quickly and with great intensity at first, but tended to die out prematurely. Note the relatively small amounts of JP4 that were expended. In a discussion with SRI, it was learned that in the JP4 fires, the flame was frequently observed to leave the fuel pan and move about as if seeking oxygen. Although the initial fuel load was the same in all of the tests (approximately 15 kg), the amounts of fuel expended varied greatly, so that the overall test results should not be compared on the basis of initial fuel load.

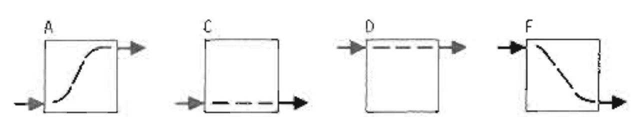
From just the results of Table 3-2 it can be observed that the vent patterns had significant influence on the fire development. It appears that the vent patterns affected the liquid fuel fires more than the solid fuel fires. This may be related partly to the relative densities of the combustion products and their time histories.

Table 3-2. SRI Enclosure Fires With Ventilation - Gross Observations

		Wood Cribs			MeOH			JP4			Rubber Tires		
Vent Pattern	Vent Flow, cfm	Oscillations Occurred	Approx. Fire Duration, min	Approx. Fuel Expended F_o/F_m	Oscillations Occurred	Approx. Fire Duration, min	Approx. Fuel Expended F_o/F_m	Oscillations Occurred	Approx. Fire Duration, min	Approx. Fuel Expended F_o/F_m	Oscillations Occurred	Approx. Fire Duration, min	Approx. Fuel Expended F_o/F_m
A	71	—	—	—	Yes	30	1.0	No	4	0.12	[illegible]	[illegible]	[illegible]
	154	—	—	—	No	25	1.0	—	—	—	[illegible]	[illegible]	[illegible]
	237	—	—	—	No	20	1.0	—	—	—	[illegible]	60	[illegible]
	348	—	—	—	No	28	1.0	—	—	—	No	50	0.63
C	71	Yes	85	0.93	Yes	45	0.92	No	>10	0.09	Yes	70	0.47
	[illegible]	[illegible]	50	[illegible]	[illegible]	45	[illegible]	Yes	10	[illegible]	[illegible]	70	[illegible]
	[illegible]	Yes	25	0.94	[illegible]	30	[illegible]	Yes	30	[illegible]	Yes	60	[illegible]
	348	—	—	—	No	24	1.0	Yes	>10	0.27	No	50	0.55
D	71	Yes	55	0.87	No	5	0.13	Yes	10	0.10	?	?	0.17?
	154	No	45	0.86	Yes	10	0.23	—	—	—	—	—	—
	237	Yes	40	0.93	Yes	27	0.80	No	2.5	0.07	[illegible]	?	0.5?
	348	No	30	0.94	No	28	0.89	No	2.5	0.09	No	50	0.6?
F	71	Yes	85	0.90	No	5.5	0.16	No	2	0.05	—	—	—
	154	Yes	55	0.88	—	—	—	—	—	—	Yes	[illegible]	0.43?
	237	Yes	50	0.93	No	5	0.12	No	2	0.05	Yes	?	0.52?
	348	No	40	0.90	Yes	20	0.50	No	2	0.07	Yes	50	0.50?

— NO DATA

VENT PATTERNS



3. Examples

Select examples of $\dot{Q}$ derived from the SRI data are plotted together with the appropriate RERC in Figs. 3-2 through 3-7. Figures 3-2 and 3-3 for wood cribs, and Figs. 3-4 and 3-5 for MeOH pools are plotted in standard coordinates. For clarity in these plots, only the enclosure limit corresponding to $Q_e/2$ is given, but the curve for Q_e is visualized easily. Figures 3-6 and 3-7 show two comparisons between the various fuels, in log-log coordinates.

The effects of ventilation rate for the wood cribs are shown for vent patterns C and D respectively in Figs. 3-2 and 3-3. In both figures there is a tendency for $\dot{Q}_m$ to occur prior to the enclosure limit for low ventilation rates and for $\dot{Q}_m$ to occur at a later time for higher ventilation rates. Note for wood cribs, however, that the fuel surface limit actually decreases with burn time because fuel area and composition change with time. The actual fire developments are well within the RERC limits; in fact, the tail-off or late stages of the fires are all roughly similar, well below the ventilation limits, and behave more like fuel surface limited fires. Clearly, the effects of increasing ventilation rate are minimal during the latter stages of the fires. Except for the lowest ventilation rate (71 cfm), there are no significant differences between vent patterns C and D. Apparently these vent patterns did not promote adequate enclosure circulation for the wood crib cases.

As discussed before, MeOH combustion should be fuel-surface-area limited except at the lowest ventilation rate. Results showing the effects of vent pattern are given in Figs. 3-4 and 3-5, each for a different ventilation rate. The results for pattern F in Fig. 3-4, though not shown, were virtually the same as for pattern D. At $\dot{V}$ = 71 cfm the fire for pattern D became extinguished quickly (Fig. 3-4). With pattern A, however, a significant time period occurred in which the ventilation limit was exceeded, which implies that the products of combustion were not completely burned. As noted in Appendix A, hot fires tend to occur when the fuel surface limit and the ventilation limit are approximately equal.

The results for MeOH at $\dot{V}$ = 348 cfm ventilation are shown in Fig. 3-5; as with wood cribs, there was a tendency for $\dot{Q}_m$ to occur at later times as the ventilation rate was increased. The similar burning trends for vent patterns A and C and the tail-off trends for patterns A, C, and D were all similar. All of these fires were fuel surface limited until the fuel was nearly depleted. The results for patterns A and C exceed the $\dot{Q}_f$ limit but there are several reasons why this can occur (Appendix A). Vent pattern F caused unusual burning oscillations and appears to be an anomalous case.

A comparison of the performance of the different fuels with vent pattern C is shown in Figs. 3-6 and 3-7, each for a different ventilation rate. The log-log coordinates tend to compress the curve shapes at large time. Typically, the JP4 flared early and died out quickly at low ventilation rate (Fig. 3-6), not exceeding any of the RERC limits. The rubber tires burned poorly for a long time and apparently became extinguished due to poor air circulation and poorly developed fire plumes; the wood crib and the MeOH pool both were ventilation limited and behaved accordingly.

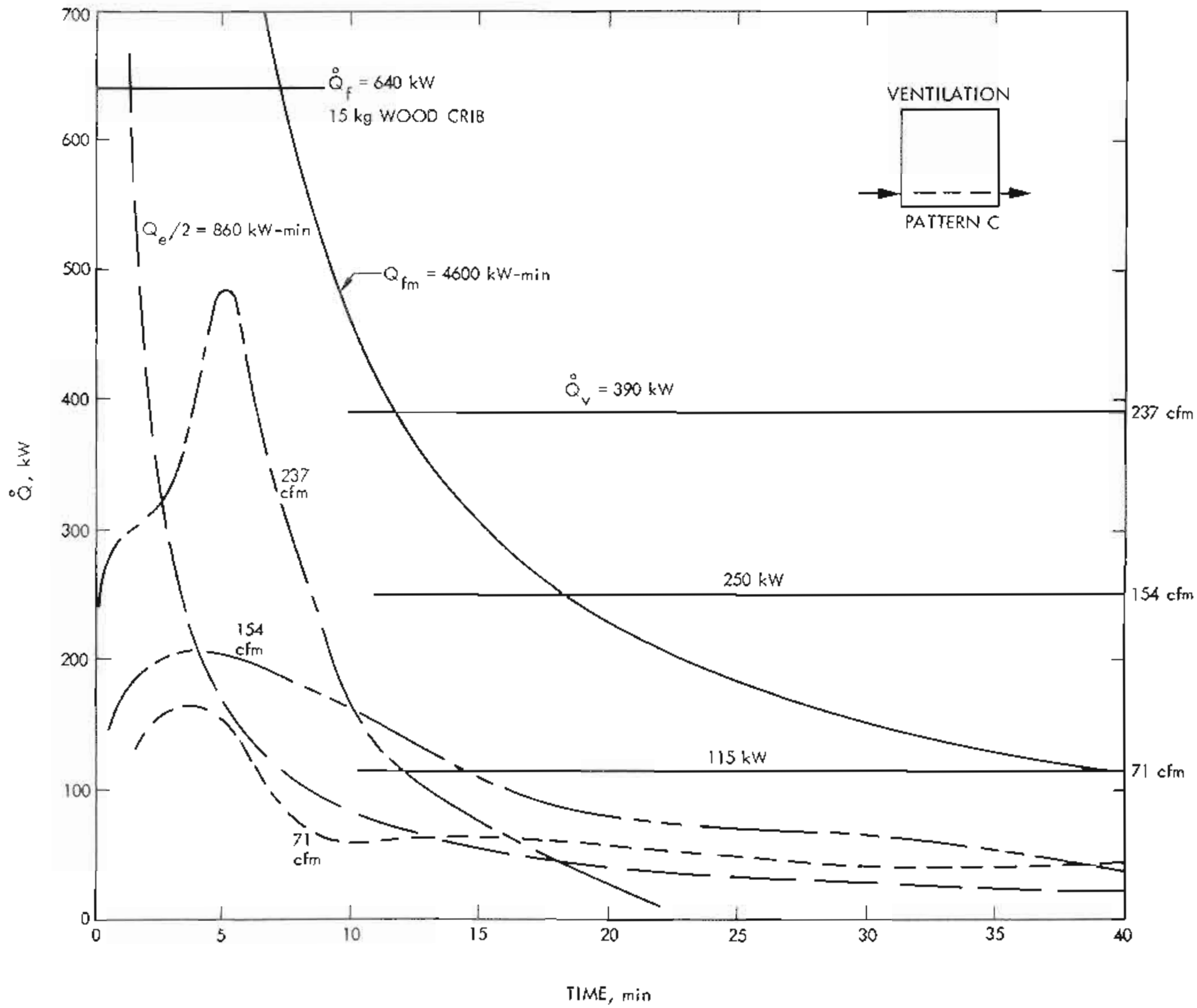


Figure 3-2. SRI Experimental Data Compared With RERC. Wood Cribs With Vent Pattern C at Three Ventilation Rates. Enclosure Volume of 1050 ft^3

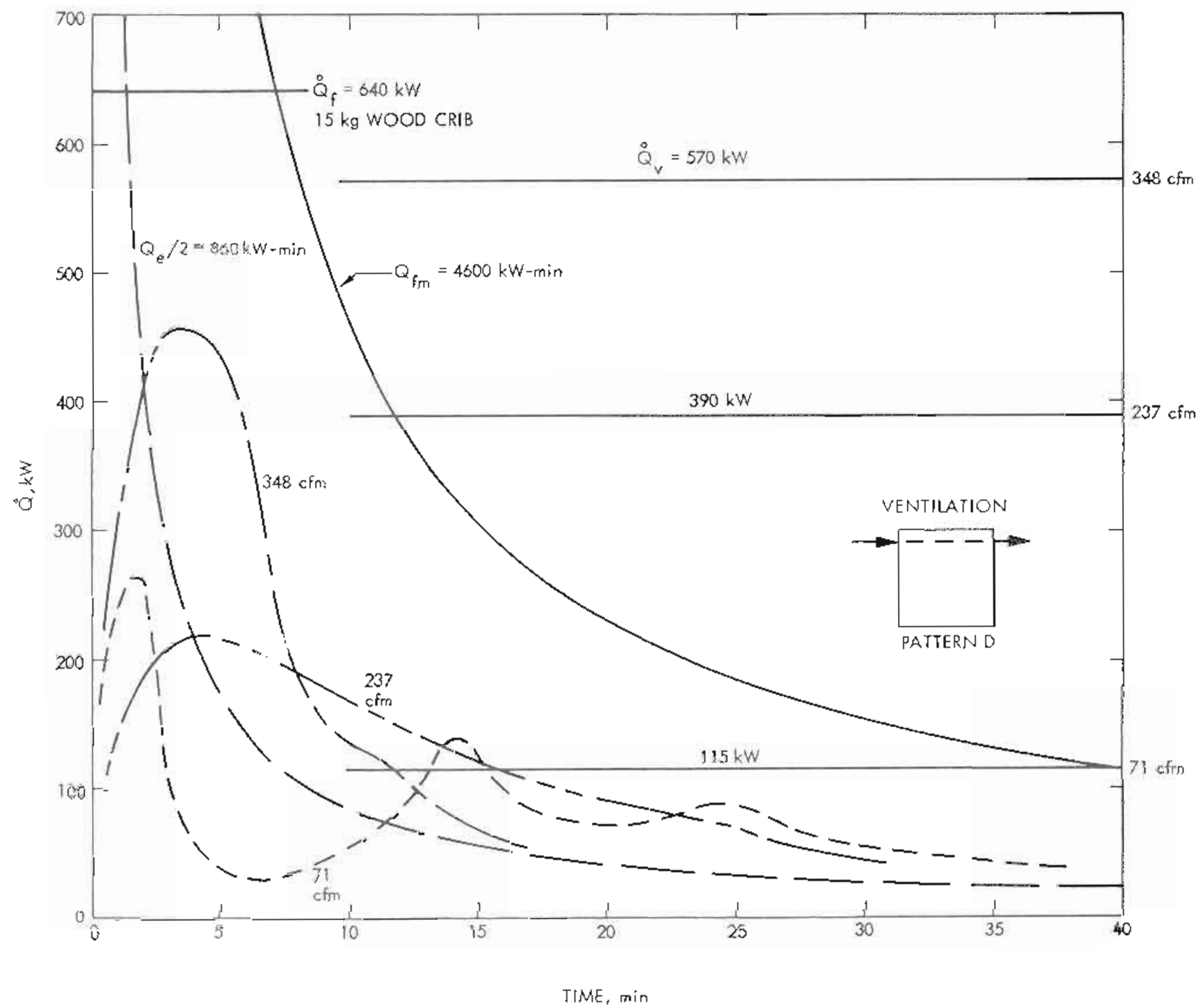


Figure 3-3. SRI Experimental Data Compared With RERC. Wood Cribs With Vent Pattern D at Three Ventilation Rates. Enclosure Volume of 1050 ft^3

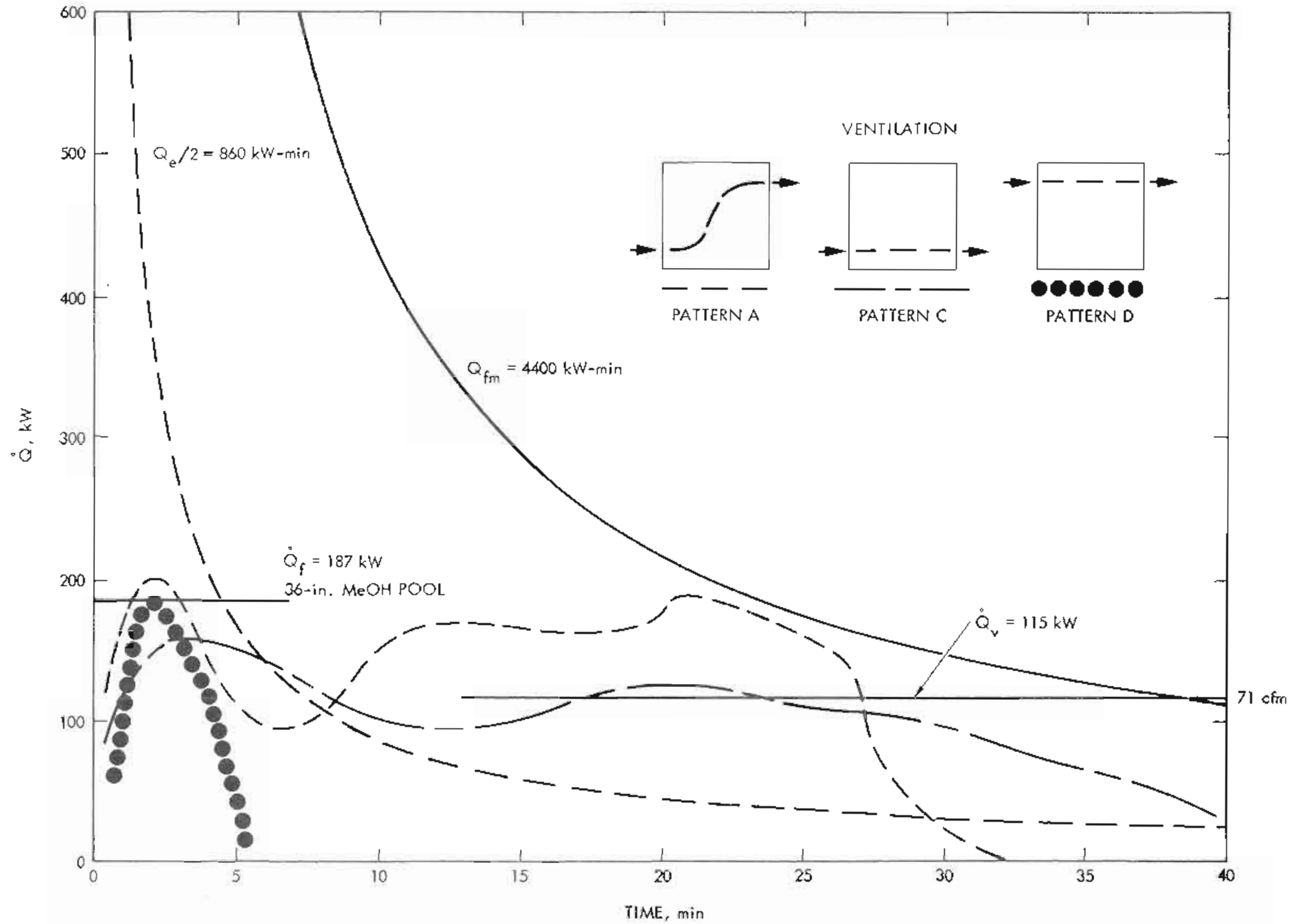


Figure 3-4. SRI Experimental Data Compared With RERC. Methanol Pools at a Ventilation Rate of 71 cfm With Three Ventilation Patterns. Enclosure Volume of 1050 ft^3

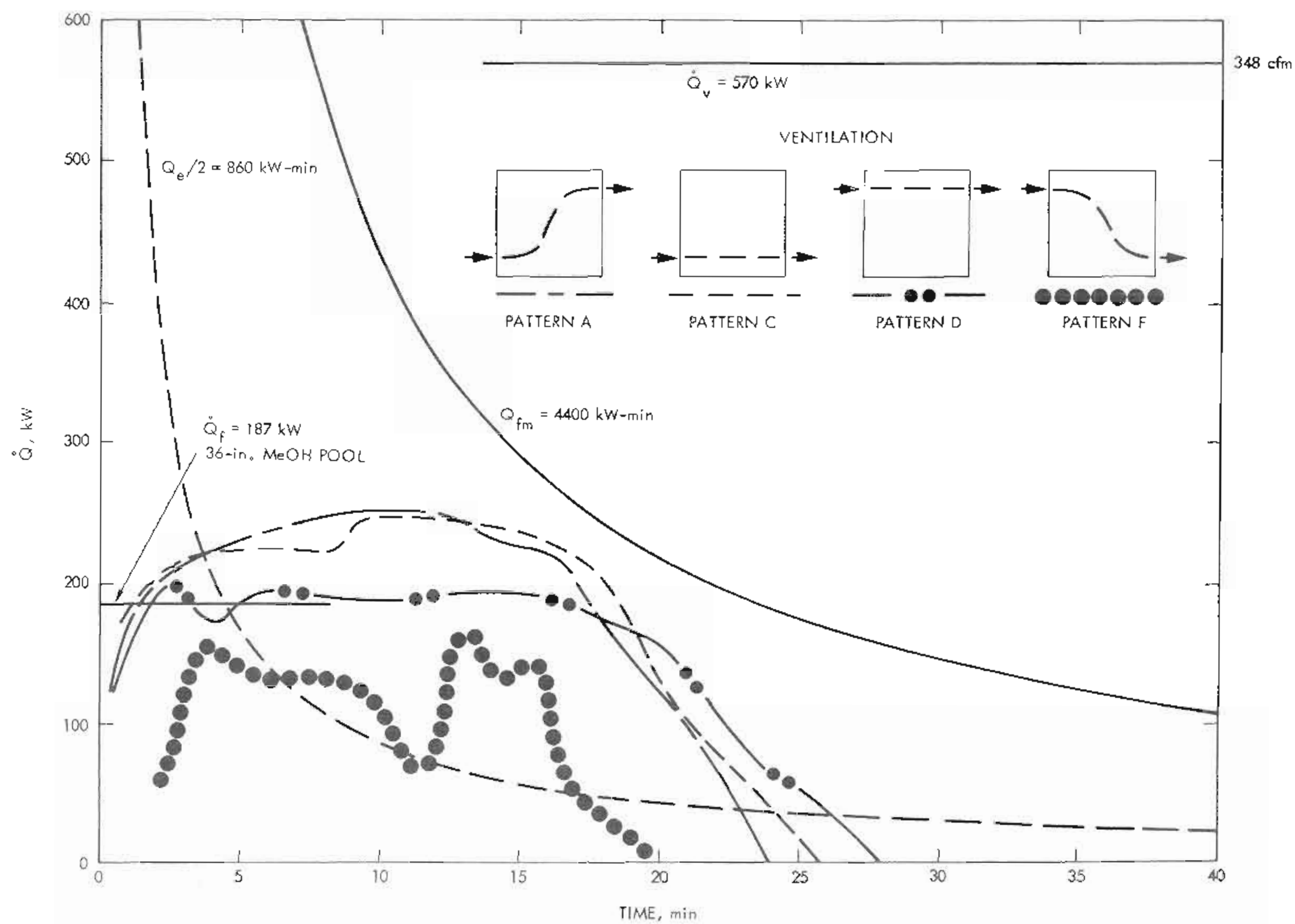


Figure 3-5. SRI Experimental Data Compared With RERC. Methanol Pools at a Ventilation Rate of 348 cfm With Four Ventilation Patterns. Enclosure Volume of 1050 ft^3

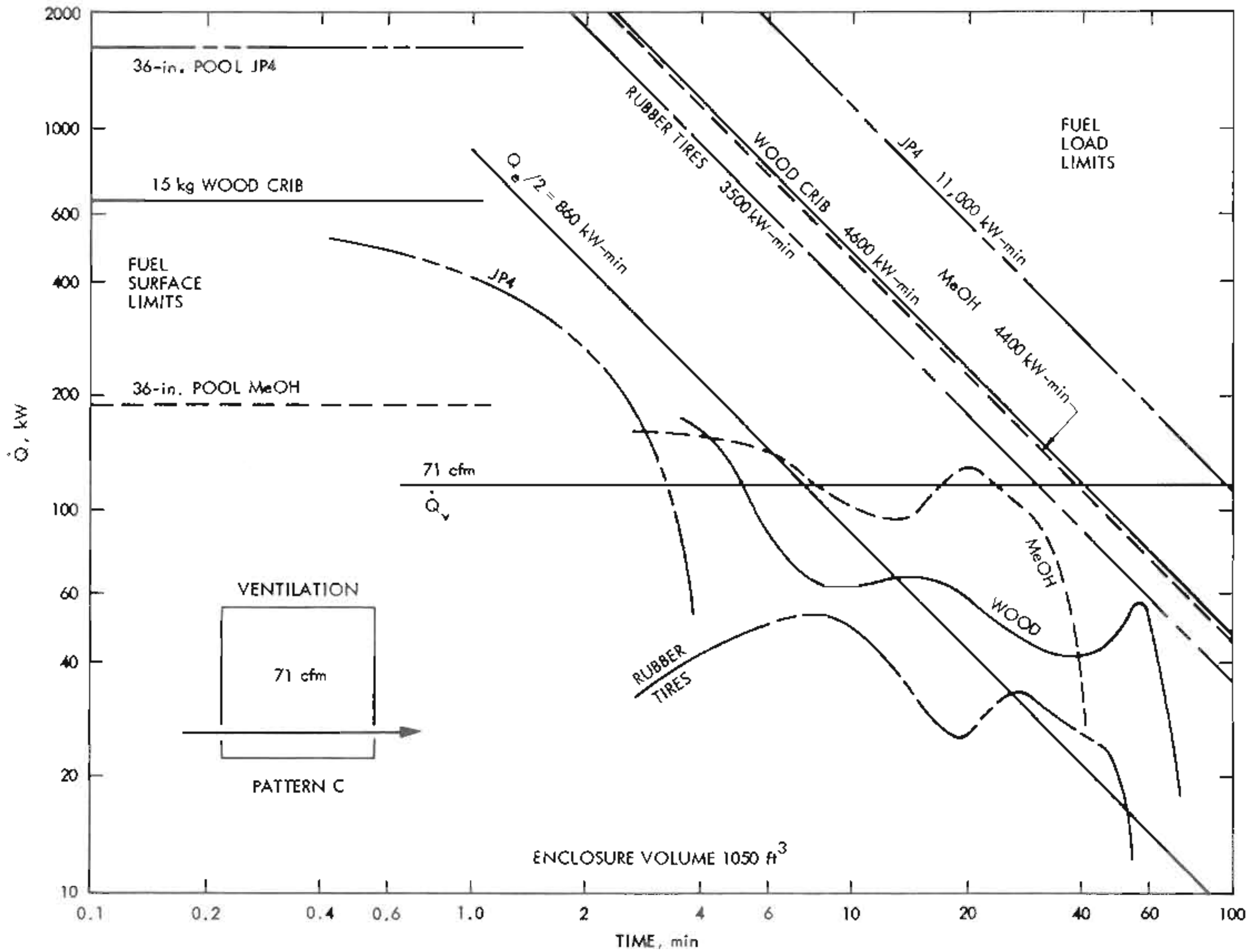


Figure 3-6. SRI Experimental Data Compared With RERC. Four Fuels With Vent Pattern C at a Ventilation Rate of 71 cfm

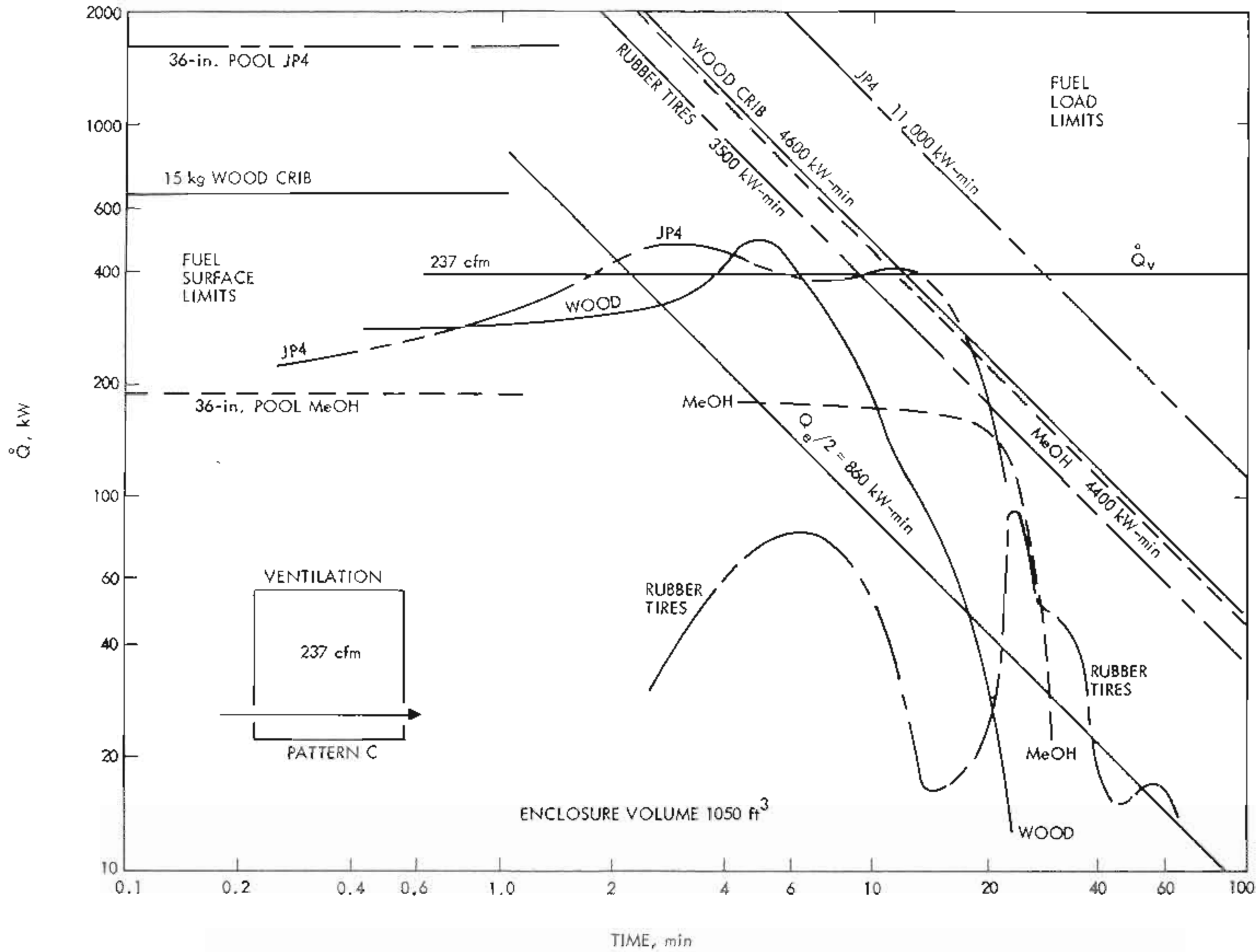


Figure 3-7. SRI Experimental Data Compared With RERC. Four Fuels With Vent Pattern C at a Ventilation Rate of 237 cfm

Figure 3-7 shows the fuel comparison at $\overset{\circ}{V}$ = 237 cfm. The wood crib and the JP4 both were ventilation limited and the MeOH was fuel surface limited, as expected. At this ventilation rate, the rubber tires produced a large flare-up at about 25 minutes into the test and then slowly died out. The early peak in the rubber tire curve probably occurred as a result of the fuel surface area limit.

The average heat release rate during an enclosure fire should be roughly proportional to the maximum heat release rate, $\overset{\circ}{Q}_m$. The average heat release rate is based on the <u>actual</u> fuel expended, not the initial fuel load, and is calculated from the total heat release divided by the time of duration of the fire t_o. The test of this hypothesis for the SRI experimental data is shown in Fig. 3-8. The correlation between $F_o \Delta H/t_o$ and $\overset{\circ}{Q}_m$ is reasonably good and is almost independent of both the ventilation rate and the vent pattern, but not the class of fuel. The trends show the expected proportionality for both the liquid fuels and the solid fuels. The liquid fuel trend, however, is somewhat higher than the solid fuel trend (shaded regions, Fig. 3-8). For the liquid fuels, the average heat release rates were approximately two-thirds of the maximum heat release rates. The corresponding value for the solid fuels was approximately 0.4.

Alternatively, Fig. 3-8 indicates that for an equivalent average heat release rate the solid fuels yielded higher values of the maximum heat release rate than did the liquid fuels. It is not known whether the results of Fig. 3-8 represent a universal property of enclosure fires, or whether these results are peculiar only to the SRI experiments.

The relatively consistent correlation shown in Fig. 3-8 was the motivation for seeking a further correlation involving the "fire times", i.e., the times of occurrence of $\overset{\circ}{Q}_m$ and Q_m (t_m and τ_m in Fig. 3-9). It was expected that the ratio $t_m/\tau_{m_o} \leq 1$ might correlate with an appropriate heat release ratio, e.g., $\overset{\circ}{Q}_m t_m/Q_m$. This proved to be true too, as shown in Fig. 3-10. Again, the correlation is nearly independent of both the ventilation rate and the vent pattern, and seemingly is independent of the class of fuel as well. The correlation, which is nonlinear, is quite good except for several anomalous points. Of the five anomalous points, three were related to the highly variable rubber tire fires; the other two (wood crib and MeOH pool) occurred with vent pattern F.

The results of Fig. 3-10 are interesting but the utility of the plot is not clear. If three of the four parameters were known, or could be predicted, then the fourth parameter could be determined. At present, the RERC are not designed to obtain accurate predictions of the four parameters.

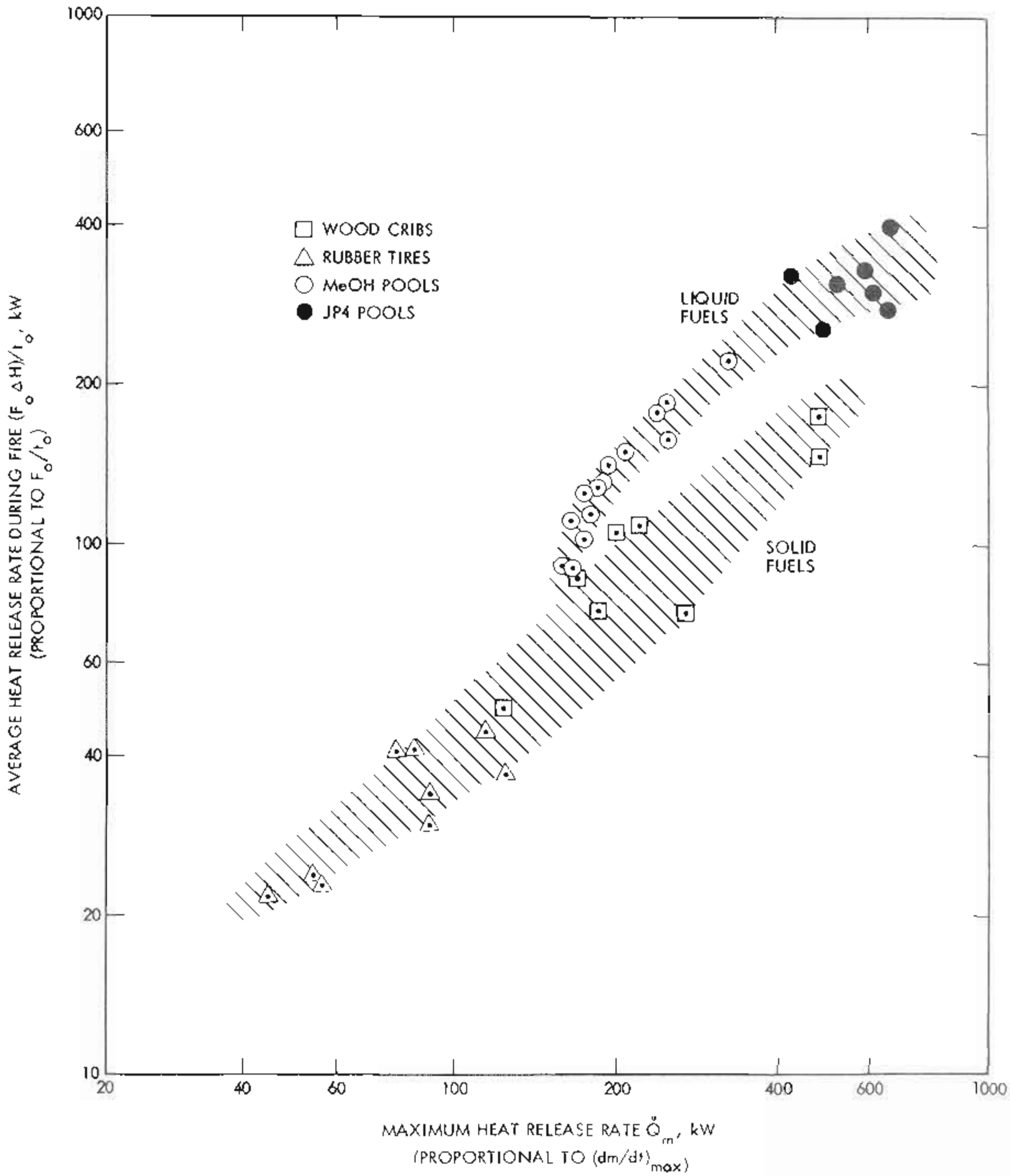


Figure 3-8. SRI Data: Relation Between Average and Maximum Heat Release Rate During Fires

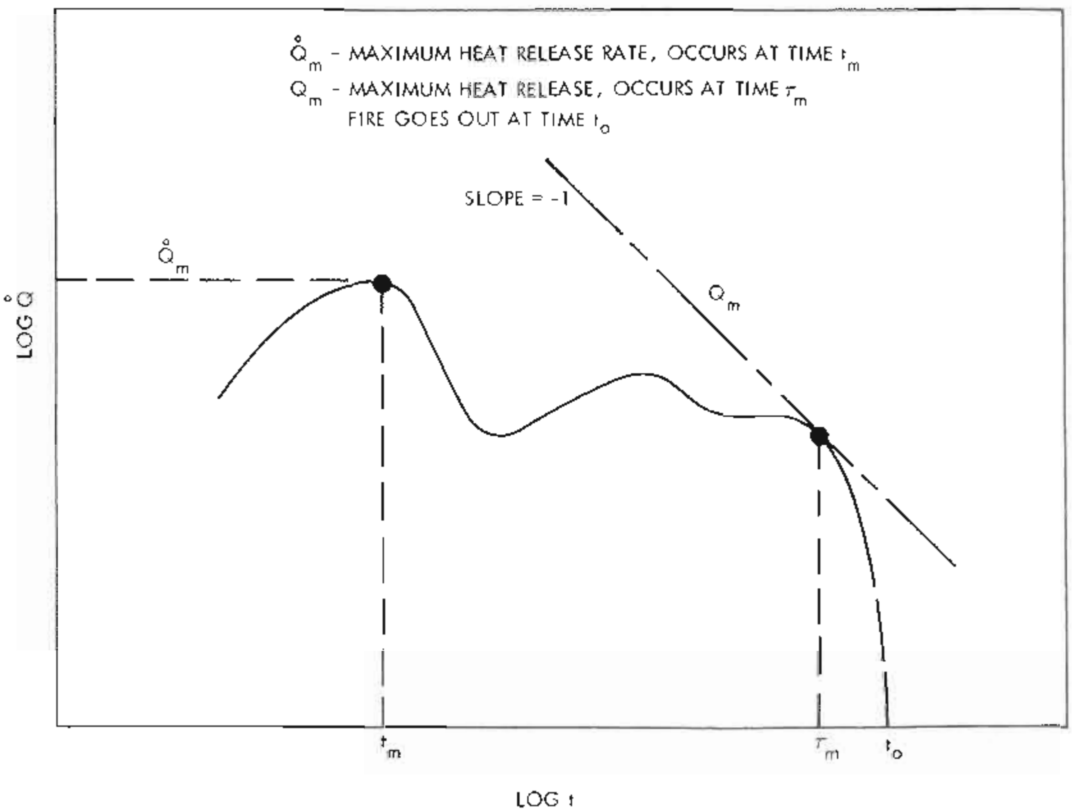


Figure 3-9. Definitions for a Typical Enclosure Fire

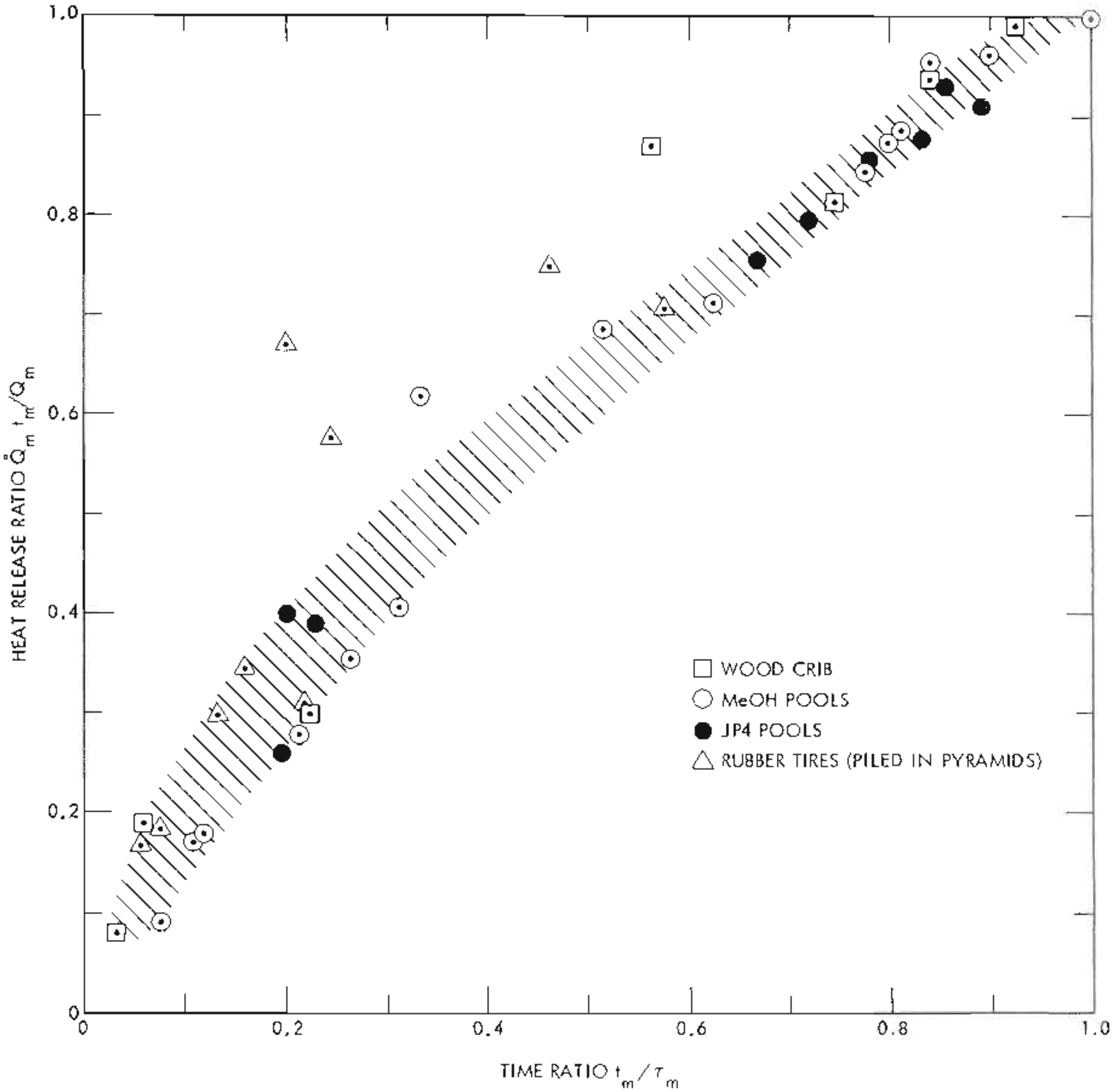


Figure 3-10. SRI Data: Heat Release Ratio vs Time Ratio (see Fig. 3-9)

Using the RERC, it is possible to predict, roughly, the fire duration. For ventilation limited fires the maximum expected value of t_o is obtained from the intersection of the $\dot{Q}_v$ and Q_{fm} limits, and $\dot{Q}_f$ is used similarly for fuel surface limited fires. Such an interpretation for "ideal" fire duration is presented in Appendix A (Fig. A-3). This prediction was compared with the approximate fire duration times obtained in the SRI experiments (Table 3-1), and the results are given in Fig. A-4 of Appendix A.

4. Discussion

From application to the SRI experimental enclosure fire data it is evident that the RERC approach does predict the maximum bounds of the fire development envelope and correctly identifies the limiting energy release limits and when they occur during a fire. Thus, the RERC should be useful for predicting the effects of changes — by factors large in comparison with unity — in the basic parameters, e.g., enclosure volume, fuel load, and surface area.

The RERC help to clarify poorly-burning fires of long duration in cases when the actual fire development everywhere is far removed from any of the limiting criteria. In such cases, intuitive deductions provide insight into the interactions of the constraints on one another and the effects of thermal feedback. For example, radiation feedback may have a large effect on the evaporation of liquid fuels, and a reduction in radiation feedback (due, say, to a high ceiling) may alter the vitiation of air entrained in the fire plume. Inhibited burning may develop, as apparently was the case for JP4. In the case of MeOH pools, burning rates higher than those for free-pool burning sometimes occurred. The explanation of this behavior lies probably in the interactive effects of increased radiation feedback (from stratified hot-gas layers) and enhanced air circulation, as compared to free pools.

The general value of the RERC is best exemplified by considering interpretation of the SRI data in their absence. Because the fire size, enclosure volume, and the heat release rate during ventilation control all interact markedly, the limiting or controlling parameters are difficult to identify from the data alone. Hence, extrapolation of the results to other values of enclosure volume or ventilation rates and fire size cannot be assessed with assurance. Even though different vent patterns produced unpredictably variable results, the RERC in general did bound all cases. The occasional departures were more easily interpreted in terms of the RERC themselves. By applying the RERC it was clear, for example, that changes in just the fuel load would have led to little change in the development of the pool fires, or that large increases in the ventilation rate would have had little effect on the MeOH and rubber tire fires.

The detailed effects of the different vent patterns, which are not predicted within the elemental RERC approach applied here, were not insignificant and thus are quite interesting. The air flow circulation variations induced by the different vent patterns with different fuels point to the importance of fluid dynamics in enclosure fires, as might be expected. Certain gross trends appear in the results despite the interactive effects of ventilation rate. These trends are summarized in Table 3-3 for each of the fuels.

Of the four ventilation patterns, pattern F in general was associated with the poorest burning. In the case of the liquid fuels (MeOH and JP4), fires with pattern F tended to die out relatively early; this tendency was also seen to some extent when pattern D was used. Apparently, the introduction of air at a location high compared to the fuel source prevents good mixing so that the local flow pattern to the fire is inhibited.

From fire testing and scaling of results the effects of vent flow may not become apparent if the room volume is large and the total fuel load is not adequate. The fuel surface limit must be much greater than the ventilation limit if the effect of ventilation flow is to be controlling in the steady state.

B. LAWRENCE LIVERMORE LABORATORY EXPERIMENTS

1. Description

The Lawrence Livermore Laboratory (LLL) has a full-scale fire-test facility that has been described in some detail by Gaskill, et al. (Ref. 4). The volume of the basic enclosure is 100 m^3 (3500 ft^3), which is a factor of 3.3 times larger than the SRI facility. Dimensions of the interior are 5.9 m × 4.0 m × 4.2 m high. There is provision for measuring gas temperature, heat flux, and optical density (smoke opacity) at various locations in the enclosure. Air is admitted through two intake dampers located in opposite sidewalls near to the floor, and ventilation is controlled and measured by a variable exhaust ducting system. Two exhaust ports are located centrally in one end wall, one near the floor and one near the ceiling. Thus, the vent pattern resembled a combination of vent patterns A and C in the SRI experiments. Gas sampling and composition are measured in the exhaust ports. Enclosure pressure is monitored by a transducer located in the roof. Fuel weight loss with time may be measured.

A series of test burns was conducted during the first half of 1976 to check out various elements of the system. Test Nos. 7 and 8 utilizing wood cribs are of special interest here because fuel weight loss data was obtained. The only real difference between these two tests, which herein are analyzed with reference to the appropriate RERC, was the ventilation rate. The ventilation rate for Test No. 7 was 500 l/sec (1060 cfm), and was twice the ventilation rate used in Test No. 8.

Table 3-3. Vent Pattern Trends — Gross Effects[a]

	Wood Cribs[b]	MeOH Pools	JP4 Pools	Rubber Tires
Highest $\mathring{Q}_m$	C & D	A	F	A
Highest Q_m	F	A	C	F
Lowest $\mathring{Q}_m$	F	D & F	C & D	Not Clear
Lowest Q_m	C & D	D & F	D & F	Not Clear
Absence of Oscillations	Not Clear	A	F	None

[a]See Table 1 for vent pattern descriptions

[b]Little or no data available for pattern A

Ignition of the Douglas fir wood cribs was by a remotely operated premixed natural gas flame that was kept burning throughout both tests. The flowrate of the natural gas was 100 l/min (3.5 cfm), which was small compared to the ventilation rates employed, and will be ignored herein. The wood cribs weighed approximately 195 kg (430 lb) and had dimensions of 36 in. × 48 in. × 32 in. high. The individual sticks were of square cross-section, 2 in. × 2 in.

2. RERC for LLL Experiments

A summary of the fire parameters and the associated RERC are given in Table 3-4. No attempt was made to calculate the flame spread rates for the two wood crib experiments, which differed only in the ventilation rates utilized. The ventilation limits and the enclosure limit were calculated in the same way as for the SRI experiments.

The fuel surface area limit was calculated in two ways. Based on a suggested average value of $\mathring{Q}_f/A_f$ = 100 kW/m^2 for wood (Ref. 1) and an estimated fuel surface area of 71.4 m^2 (for a crib containing 16 layers of sticks – alternate layers containing 9 and 12 sticks), $\mathring{Q}_f$ = 7140 kW. Based on the same method used for the SRI cribs and the results for maximum burning rate, and an initial crib weight of 195 kg (Ref. 3), $\mathring{Q}_f$ = 7440 kW. The latter value was used here, but the difference between the two estimates is not significant. A value of ΔH = 270 kW-min/kg was used for the heat of combustion of wood (Ref. 1); this is somewhat lower than the value used for the SRI experiments (Table 3-1).

3. Examples and Discussion

Excepting the flame spread rate, the RERC are plotted in Fig. 3-11 in a log-log plot of $\mathring{Q}$ versus time; ventilation limits for the two tests are shown. The curve $Q_e/2$ represents the enclosure limit if only one-half of the initial oxygen in the room was consumed. The RERC values for both tests should be ventilation limited. In fact, an increase in $\mathring{V}$ by a factor of four over the rate used in Test No. 7 would still result in a ventilation limited fire. Note, however, that in setting their test conditions, LLL assumed the fire would not be ventilation limited at a rate of 1060 cfm.

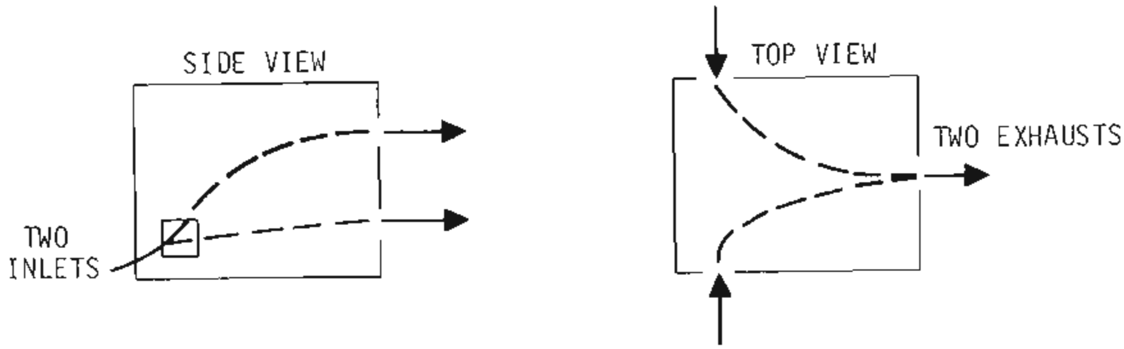
Values of experimental $\mathring{Q}$ were estimated from the fuel weight loss curves (to obtain $\mathring{m} = dm/dt$) and the heat of combustion. The values of $\mathring{m}$ were estimated from small plots (Ref. 4), and are not considered to be highly accurate. The derived heat release rate curves for the two tests are plotted in Fig. 3-11 together with the RERC. In Test No. 7, the fire was extinguished at about 16 min, at which time approximately 0.38 of the initial fuel had been consumed. In Test No. 8, the fire was extinguished at about 20 min, at which time approximately 0.47 of the initial fuel had been consumed. In both tests the fires had achieved maximum heat release rate at the time of extinguishment (Fig. 3-11). Translating the above results into the appropriate coordinates, it will be seen that the LLL test results of average heat release rates are in good agreement with the extrapolated SRI results shown in Fig. 3-8.

Table 3-4. LLL Enclosure Fire Experiments and RERC

Experimental Conditions

Constant Room Volume: $V_e = 100\ m^3 = 3500\ ft^3$
Two Ventilation Rates: 250 ℓ/sec (530 ft^3/min)
500 ℓ/sec (1060 ft^3/min)

Ventilation Pattern:



Type of Fuel: Load = 195 kg (430 lb)

Wood Crib: 2-in. square sticks
Overall Dimensions: 36-in. × 48-in. × 32-in. high

Basic Data: fuel weight loss with time
heat flux (radiometers)
gas temperature and composition
smoke opacity and particle size

RERC

Flame Spread Rates: (not calculated)

Ventilation Limits: $\mathring{Q}_v$

$\mathring{Q}_v$ = 1740 kW for 1060 cfm, Test No. 7
= 870 kW for 530 cfm, Test No. 8

Enclosure Volume: Q_e = 5800 kW-min
$Q_e/2$ = 2900 kW-min

Fuel Limits: heat of wood combustion ΔH = 270 kW-min per kg

Fuel Surface Area Limit: $\mathring{Q}_f$ = 7440 kW
Fuel Load: Q_{fm} = 52,400 kW-min

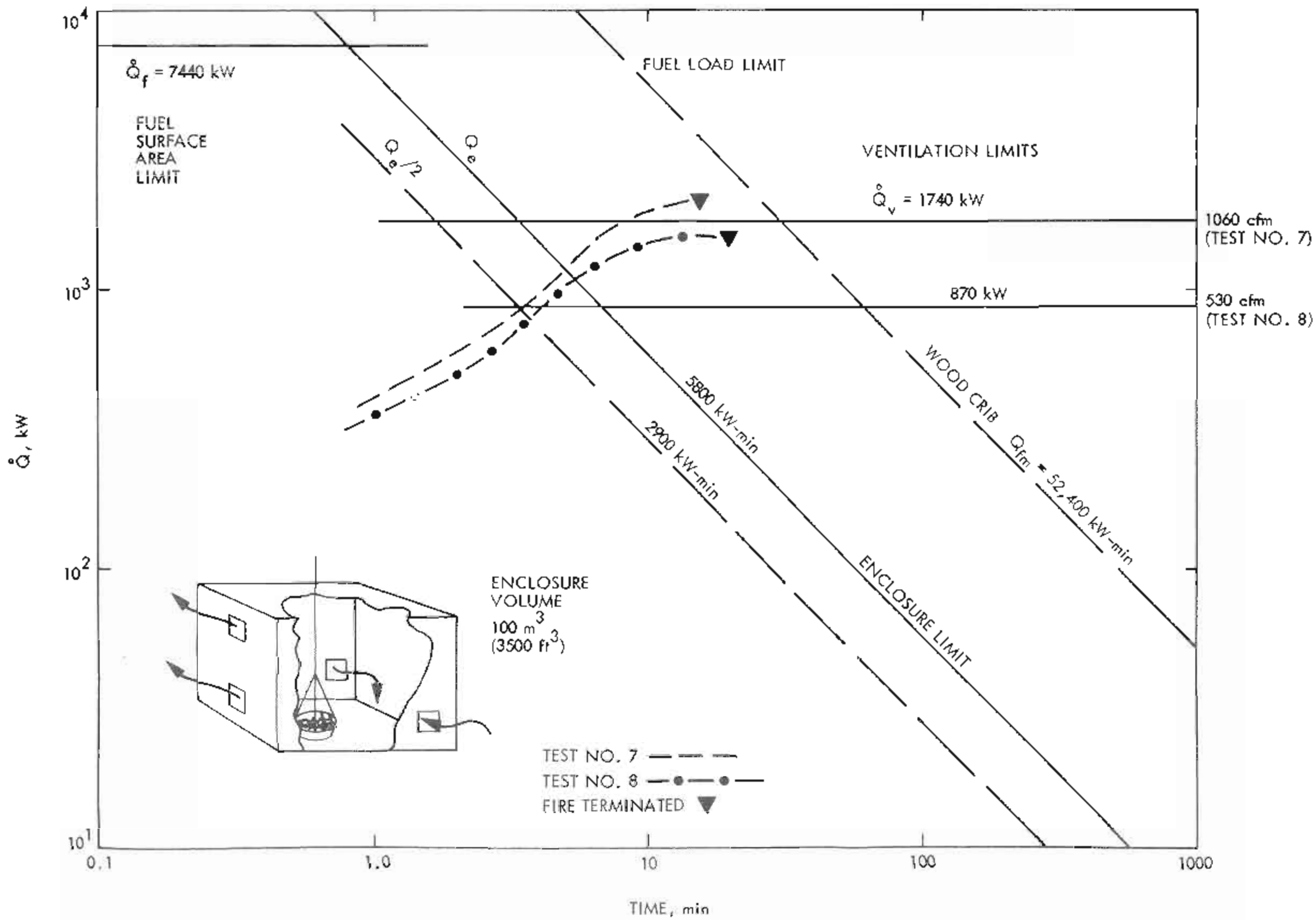


Figure 3-11. Relative Energy Release Criteria (RERC) for LLL Experiments and Results for Test No. 7 and Test No. 8

Both test fires crossed the enclosure limit curve and became ventilation controlled. Test No. 7 just did peak-out at extinguishment, at a $\overset{o}{Q}$ value slightly higher than the ventilation limit. Test No. 8, slightly past its $\overset{o}{Q}_m$, is considerably higher than its ventilation limit (see Appendix A). If left to burn, it appears that both test fires may have continued for another 15 to 20 min. No burning oscillations are evident in Fig. 3-11. It is interesting to conjecture that the fire in Test No. 8, had it continued, might have dipped sharply downwards and then oscillated about its ventilation limit. In any case, there is no behavior in Fig. 3-11 that invalidates the RERC approach significantly. A major conclusion is that initially the fires were flame-spread limited and finally approached a ventilation limit.

Also given (Ref. 4) are gas temperature histories at various locations in the enclosure and the oxygen fraction within the exhaust dust opening. Average gas temperatures above the fire were about 600°C and 400°C for Tests 7 and 8 respectively, confirming that there probably was excess volatilization of fuel. Towards the end of both fires, the oxygen fraction was about 0.05 (as compared to 0.21 for unburned air).

C. NASA CARGO BAY AND LAVATORY SIMULATION

1. Description

Research work has been sponsored by NASA to evaluate and improve the fire safety of aircraft interiors and has involved cooperative efforts with univeristies and commercial aircraft companies. The results of some full-scale fire tests on simulated aircraft cargo bays and lavatories have been reported (Ref. 5). There is a sharp contrast in these two aircraft compartments in terms of both size and shape (configuration). Lavatories are small, roughly square in cross-section, but relatively high. Cargo bays are large and very wide, and have relatively low ceilings.

The emphasis herein is on the cargo bay simulation tests even though the bulk of the reported data thus far concerns the lavatory simulation (Ref. 5). The main reason for this is that the information given for the lavatory test is not sufficient to calculate all of the RERC, e.g., the ventilation rate was not enumerated clearly (Ref. 5). The cargo bay test information is relatively complete in References 5 and 6, which contain essentially the same information. However, further discussion of the lavatory test results will be considered in Subsection III-D.

The simulated cargo compartment was representative of cargo compartments in wide-bodied jet aircraft such as the Lockheed L-1011, McDonnell-Douglas DC-9, DC-10, etc. The gross volume of the cargo bay was 2000 ft^3, with dimensions 13.6 ft × 26.7 ft × 5.6 ft high, but in the fire Test No. 1 approximately one-half the gross volume was occupied by simulated cargo and baggage. Provision was made for measuring gas and liner temperatures, heat flux, gas composition (near hot-gas outlet), and several smoke detectors were installed. Forced ventilation was induced by an exhaust fan to produce a ventilation rate of 703 ft^3/min. There was one inlet and one outlet, each of circular cross-section, and both were located near the floor and at opposite ends of the longest wall, and on opposite sides of the enclosure.

The simulated cargo (fuel) consisted of 270 cardboard cartons, 18 in. on each side, which were loosely filled with commercial packing material of various types. These cartons were stacked to form a rectangular volume 6 boxes wide, by 15 boxes long, by 3 boxes high. A remotely operated electric igniter was used to ignite oil-soaked rags in a topmost carton in roughly the center of the lateral cargo area.

In Test No. 1, which had a ventilation rate considered to be an unusually large value (Ref. 5), the ventilation was not shut-down upon initial smoke detection as is the usual practice. Test No. 2 (results as yet unreported) was designed to shut-down the ventilation, upon smoke detection, to a leakage rate of only 20 ft^3/min.

Test No. 1 was conducted in June of 1975 at the McDonnell-Douglas Sacramento Test Center. The fire, which was localized, migrated towards the inlet opening. The fire was terminated at about 14 min by flooding the simulated cargo bay with CO_2, and the cargo bay door was opened. The cartons were all scorched black but were otherwise undamaged except those few that were exposed to direct flame. The entire cargo (on a skid) was then extracted and moved to open air, whereupon it reignited and burned vigorously for a long period of time. Inspection of the cargo bay interior revealed two burn-throughs in the ceiling liner near the air inlet location.

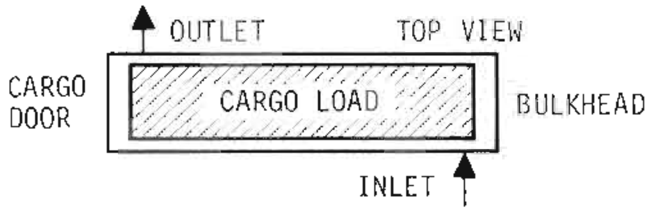
2. RERC Applied to Test No. 1

A summary of the fire parameters and the estimated RERC are given in Table 3-5. No attempt was made to calculate the flame spread rate; it might have been anticipated, however, that the fire would migrate across the carton stack down towards the air inlet opening because of the relatively small ventilation rate. The ventilation rate, though unusually large for an aircraft cargo bay, was small for the enclosure volume and fuel load. It is likely that the circulation pattern in the enclosure was generally poor.

Table 3-5. NASA Cargo Bay Simulation and RERC

Experimental Conditions

Gross Enclosure Volume: V_e = 2000 ft^3 (56.6 m^3)
Ventilation Rate: 703 ft^3/min (19.8 m^3/min)
Ventilation Pattern: one inlet, one outlet (opposite ends)



Fuel (Cargo) Description:

270 Cardboard (cubical) cartons, 18 in. on a side
cartons stacked 3-ft high by 6-ft wide by 15-ft long
cartons loosely filled with packing materials
total weight of cartons ∿ 729 lb
weight of contents ∿ 1000 lb

Basic Data: gas and liner temperatures (various locations)
heat flux (calorimeters, various locations)
gas composition near outlet
smoke detectors

Estimated RERC

Flame Spread Rate: (not calculated)

Ventilation Limit: $\overset{o}{Q}_v$ = 1150 kW for 703 cfm, Test No. 1

Gross Enclosure Volume: Q_e = 3280 kW-min

cargo load ∿ 50% gross volume, $Q_e/2$ = 1640 kW-min
$Q_e/4$ = 820 kW-min

Fuel Limits: assumed heat of combustion, all materials, was ΔH = 270 kW-min/kg

Fuel Surface Area Limit: $\overset{o}{Q}_f$ = 4500 kW

Fuel Load:		
	cartons alone	Q_{fm} = 89,000 kW-min
	carton contents	Q_{fm} = 123,000 kW-min
	total load	Q_{fm} = 212,000 kW-min

The ventilation limit and the enclosure limit (gross compartment volume) for Test No. 1 were calculated as before in this report. But in the present case, the limit $Q_e/2$ represents the more realistic enclosure limit because the cargo load occupied about 50 percent of the gross volume. The initial air sealed within the carboard cartons was here neglected as a contributing source for combustion because the cartons were well filled. Then, the limit $Q_e/4$ represents the effective enclosure limit if only one-half of the initial oxygen in the cargo bay was consumed.

An overall heat of combustion of 270 kW-min per kg was assumed as typical for wood, cellulose, and fiber materials. The fuel surface limit was calculated using a value of $\mathring{Q}_f/A_f$ = 100 kW/m^2, which is typical for wood or cellulose. The fuel surface area A_f was assumed to be the total exposed area of the cardboard carton stack exclusive of the floor contact area. In this case, A_f was 486 ft^2 (45.2 m^2). Initially this area would be valid but, as burning progressed, A_f would increase if the cartons burned through exposing the loosely packed contents.

The fuel load limit was considered to consist of two portions, the cardboard cartons alone, and their contents. The mass or weight of the cardboard cartons was calculated using a value (measured at JPL) of 0.2 lb/ft^2 of cardboard area, a value typical of cartons of the size employed in Test No. 1. Assuming the contents had an average nominal specific weight of 1.1 lb/ft^3, the fuel load limit for just the carton contents is calculated knowing the total carton interior volume, which was 911 ft^3. The total fuel load limit is then the sum of the two components mentioned.

Excepting the flame spread rate, the estimated RERC are plotted in Fig. 3-12 in a log-log plot of $\mathring{Q}$ versus time. It is evident that accurate values of the fuel limits, especially the fuel load limit, are not needed because a factor of two change would not change the fire control situation. It is evident by examining the RERC that the cargo bay fire would be ventilation limited provided the energy release rate curve crossed the enclosure limit. However, fuel weight loss was not measured during Test No. 1, so that the actual $\mathring{Q}$ development history is unknown.

A conjectured fire history is sketched as the dashed curve in Fig. 3-12; the curve is believed to be accurate for $\mathring{Q}$ within a factor of two for time greater than 1 minute. Basis for the curve was established by examining the various fire data (Refs. 5 and 6). Peak heat flux over the fire occurred in less than 2 min and the maximum heat flux over the test was about 4.5 kW/ft^2. Assuming, conservatively, that heat flux was transferred to the entire wall and ceiling area of the cargo bay early in the fire, a maximum $\mathring{Q}$ of less than 3000 kW would be realized. At four minutes into the fire the oxygen concentration had dropped to one-half its initial value and at 10 min virtually all the oxygen (measured near the outlet) had been consumed. The fire was terminated at approximately 14 min.

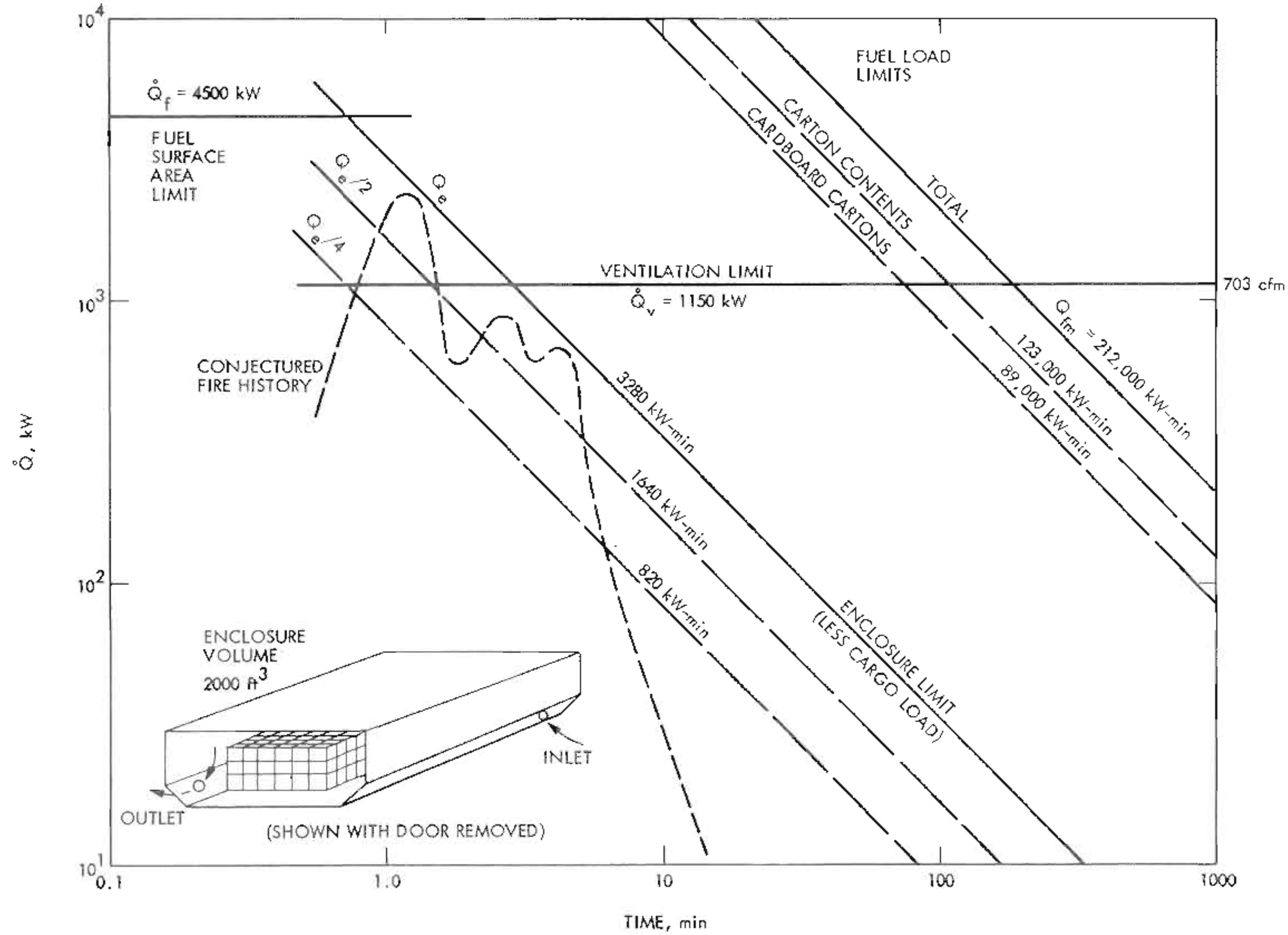


Figure 3-12. Relative Energy Release Criteria (RERC) for NASA Cargo Bay Simulation and Conjectured Fire History for Test No. 1

If the conjectured fire history is correct, then the fire barely exceeded the $Q_e/2$ enclosure limit. At most, the fire might have been ventilation controlled for just a few minutes prior to termination. It is evident that if more oxygen had been supplied the fire could have burned for several hours before becoming fuel-load limited.

3. Discussion

A low-level fire of the type that occurred in Test No. 1 nevertheless poses a considerable hazard potential. If, for some reason, a person entered the cargo bay during an undetected fire that had been burning or smoldering for some minutes, the low oxygen levels and high carbon monoxide and methane levels (Refs. 5 and 6) might quickly prove lethal.

The events that occurred following Test No. 1, when the cargo load was removed, indicate, too, the potential hazard of a suddenly increased air supply. This can be visualized from the RERC (Fig. 3-12). An increase in ventilation rate by a factor of three or four might cause a hotter fire of large extent, which achieved $\dot{Q}_m$ somewhat later and then became ventilation controlled. Several scenarios for increased ventilation come to mind: (1) opening the cargo door (which might cause a flash fire), (2) a wall burn-through that would communicate with another compartment, with the cabin ventilation supply, or with outside air, (3) a heat-generated internal explosion that would blow out a portion of the wall, or (4) a wall or bulkhead rupture that might occur during a crash or forced landing.

The projected Test No. 2, to shut-down the ventilation upon smoke detection, is interesting but is valid only for sealed compartments. An equally meaningful test would be to introduce deliberately an increased ventilation later in the fire, by opening the cargo door, removing the bulkhead, or otherwise exposing the fire to a fresh air supply.

D. LOCKHEED FIRE MANAGEMENT REPORT

1. Description

Reference 7 is a feasibility investigation and tradeoff analysis of two different approaches to increase aircraft fire safety: (1) an integrated fire management system incorporating fire detection, monitoring, and suppression, and (2) application of improved nonmetallic materials with greater fire resistance and lower production of hazardous pyrolysis products.

The analysis was performed for a hypothetical wide-bodied jet transport such as the L-1011 and DC-10. The aircraft was subdivided into its natural compartments (Fig. 3-13), which are described in great detail (Ref. 7). Because the individual compartment volumes, ventilation rates, and (potential) fuel descriptions (interior materials) are all listed, the information given in Ref. 7 lends itself readily to the calculation of RERC. A breakdown of the materials, including individual weights and exposed surface areas, is given for each compartment or zone. Some zones have two possible ventilation rates, normal or minimum, and other zones have no forced ventilation provided (attic and service centers.

2. RERC for Various Aircraft Compartments

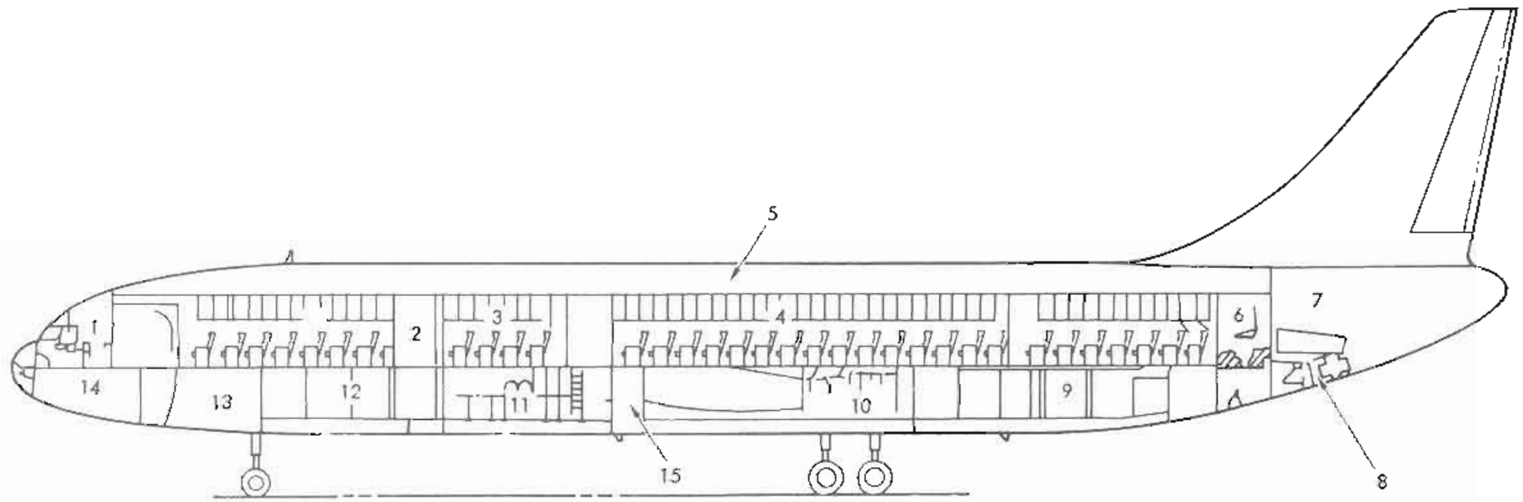
A summary of the nominal RERC is given in Table 3-6, which, in addition, lists the volume of each zone or compartment. No attempt was made to calculate flame spread rates because these would be highly dependent on too many circumstances difficult to define. The enclosure limits and the ventilation limits were calculated in the usual way. The fuel limits given in Table 3-6 are sums for each zone, i.e., based on the total fuel surface area and fuel weights as listed in Ref. 7. Because most of the aircraft interior materials are polymeric, an effective heat of combustion of ΔH = 500 kW-min/kg was used for all materials.

A series of tables (Ref. 7) lists a complete materials description by weight and exposed surface area. Many materials were employed: epoxy, phenolic, and polyester resins and glass laminates, vinyl laminates of various kinds, thermo-formed and -molded polycarbonates, polyurethane foam, polyamides, and a variety of fabrics - Kelvar, Nomex, wool, rayon, etc. In addition there were various insulations, and also metallic components. Note that there were 2 forward lavatories and 5 aft lavatories (Fig. 3-13).

Representative plots of the RERC for 7 of the 15 zones are shown in Figs. 3-14 through 3-20. In the case of the fuel surface limits and fuel load limits, a partial breakdown of the actual materials is indicated in these charts, and the total as well (see numbered curves and legends). To simplify the plots and reduce the number of curves in each chart, the materials were regrouped into larger subsets than given originally (Ref. 7). It will be noted that the nature of the potential fuel (interior surfaces and furnishings) is such that there is a strong relationship between surface areas and masses of material, so that $\mathring{Q}_f$ and Q_{fm} are not independent. This follows, of course, because most of the materials are deployed in flat, thin panels and wall and floor coverings.

COMPARTMENT ZONES			
1.	FLIGHT STATION	9.	AFT CARGO
2.	FWD LAVATORIES (2)	*10.	MLG, HYD SER CENTER (MULTICOMPARTMENTS)
3.	FIRST CLASS CABIN	11.	LOWER GALLEY
4.	COACH CABIN	12.	FWD CARGO
5.	ATTIC	*13.	NLG, ECS SERVICE CENTER (MULTICOMPARTMENTS)
6.	AFT LAVATORIES (5)	14.	AVIONICS SERVICE CENTER
*7.	AFTERBODY, EXCEPT APU	15.	ELECTRICAL SERVICE CENTER
*8.	APU COMPARTMENT		

* NOT PRESSURIZED



DESIGNATION OF FUSELAGE ZONES TO BE ANALYZED

Figure 3-13. Definition of Compartment Zones in a Hypothetical Wide-Bodied Aircraft (Reproduced from Ref. 7)

Table 3-6. Lockheed Fire Management Report — RERC for the Various Zones of a Hypothetical Aircraft

Zone	Description	Volume, ft^3	Fuel Surface Area Limit Q_f, kW	Ventilation Limit Q_v, kW Normal	Ventilation Limit Q_v, kW Minimum	Enclosure Limit Q_e, kW-min	Fuel Load Limit Q_{fm}, kW-min
1	Flight Station	400	15,540	655	410	655	43,830
2	Forward Lavatories	70 (each)	2,100	50	50	115	15,310
3	First Class Cabin	7,000	128,520	2460	855	11,480	794,970
4	Coach Class Cabin	10,000	183,600	6560	2280	16,400	1,135,670
5	Attic	4,000	225,870	0	0	6,560	205,440
6	Aft Lavatories	70 (each)	2,100	50	50	115	15,310
7	Afterbody (except APU)	2,100	—	3445	3445	3,445	—
8	APU Compartment	NA[b]	NA	NA	NA	NA	NA
9	Cargo Compartment (2), Aft	2,300	33,090	16	16	3,770	95,050
10	MLG, Hyd. Service Center	700	—	1150	1150	1,150	—
11	Lower Galley	1,400	21,380	655	0	2,295	123,720
12	Cargo Compartment, Fwd	1,600	23,020	16	16	2,625	66,120
13	NLG, ECS Service Center	1,000	—	0	0	1,640	—
14	Avionics Service Center	600	14,720	1970	0	985	25,200
15	Electrical Service Center	400	9,820	985	0	656	16,800

[a]Fuel limits given are sum totals for each compartment.

[b]NA - Not applicable.

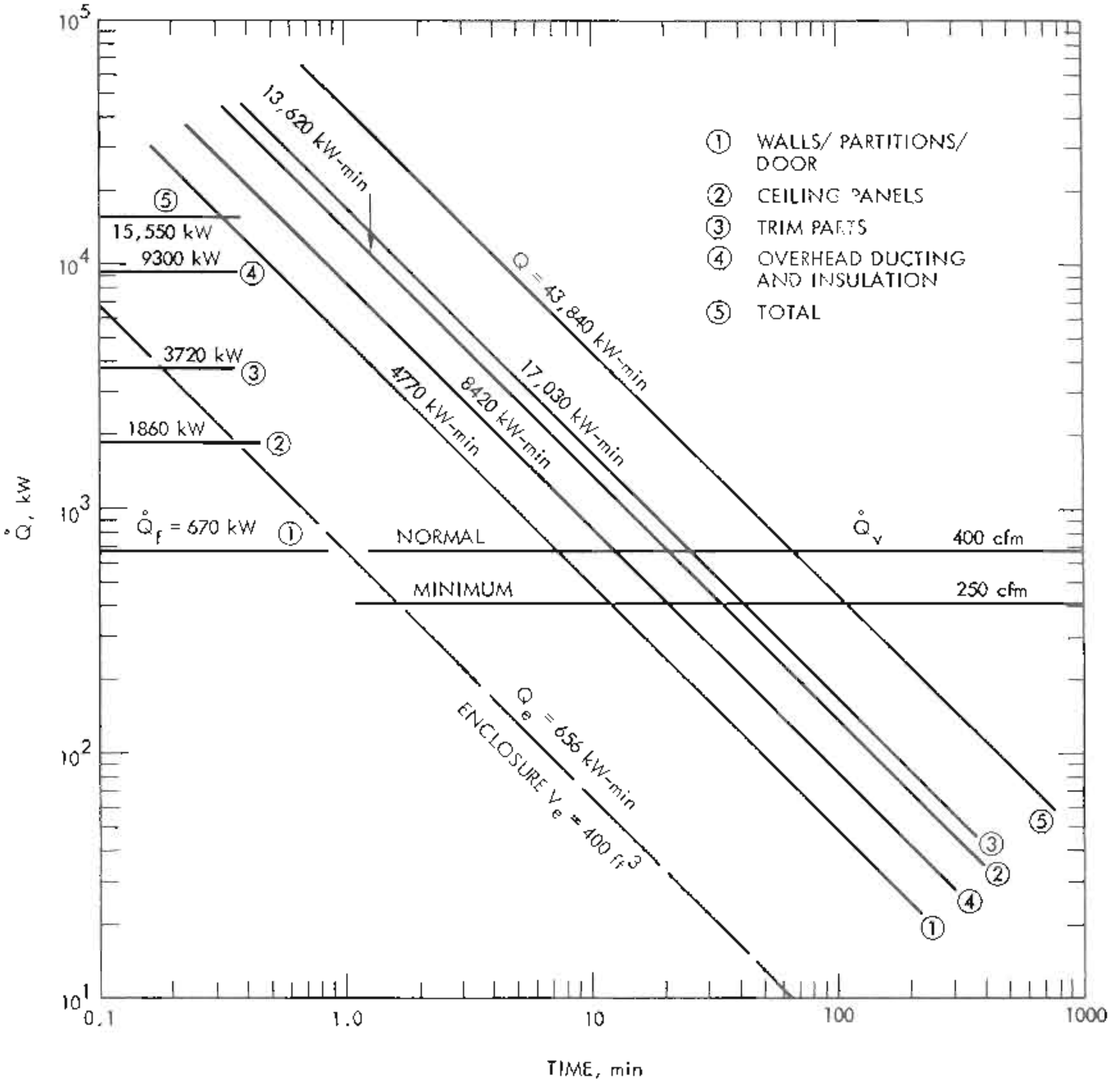


Figure 3-14. RERC for Hypothetical Aircraft
(Zone 1: Flight Station)

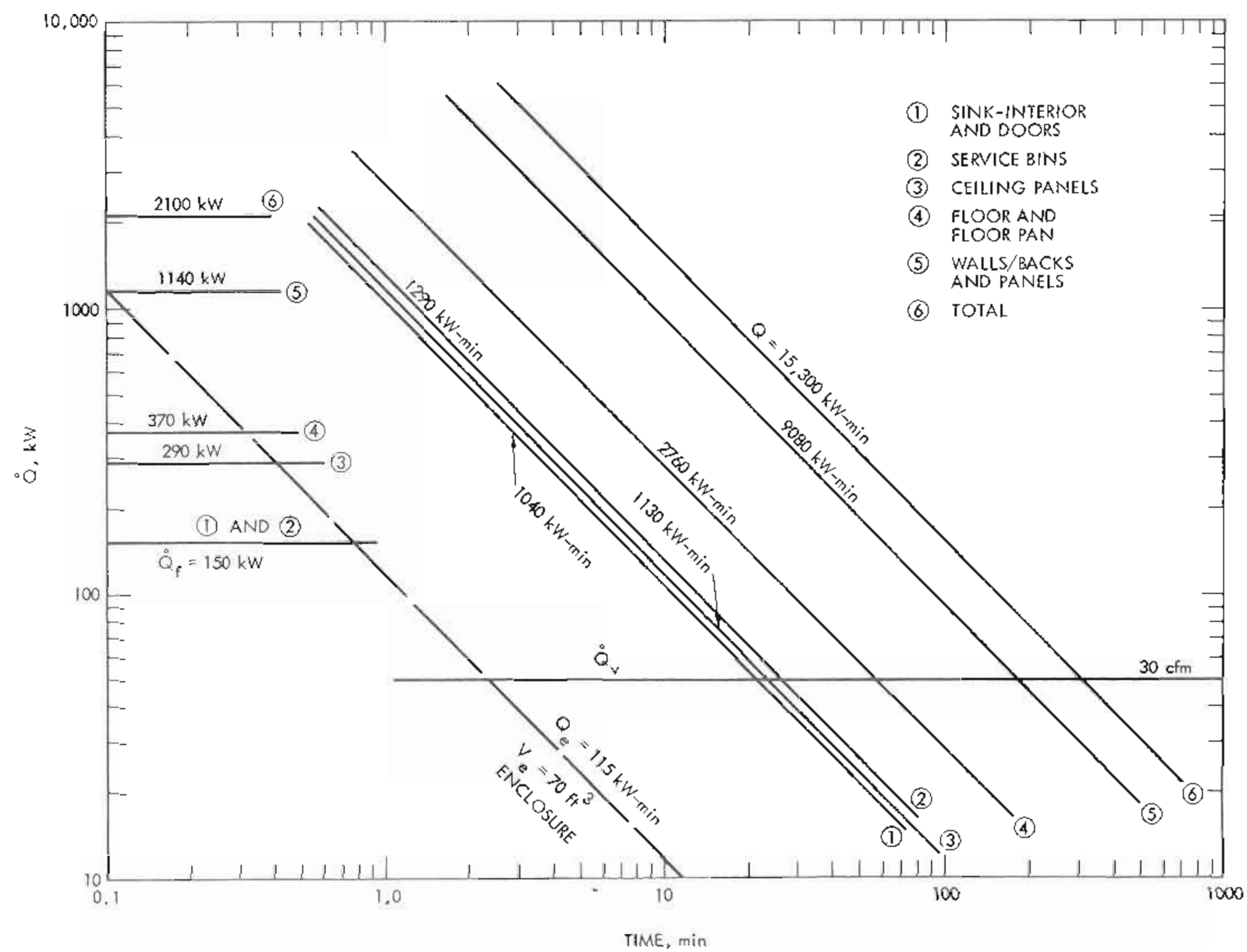


Figure 3-15. RERC for Hypothetical Aircraft (Zone 2: Single Lavatory)

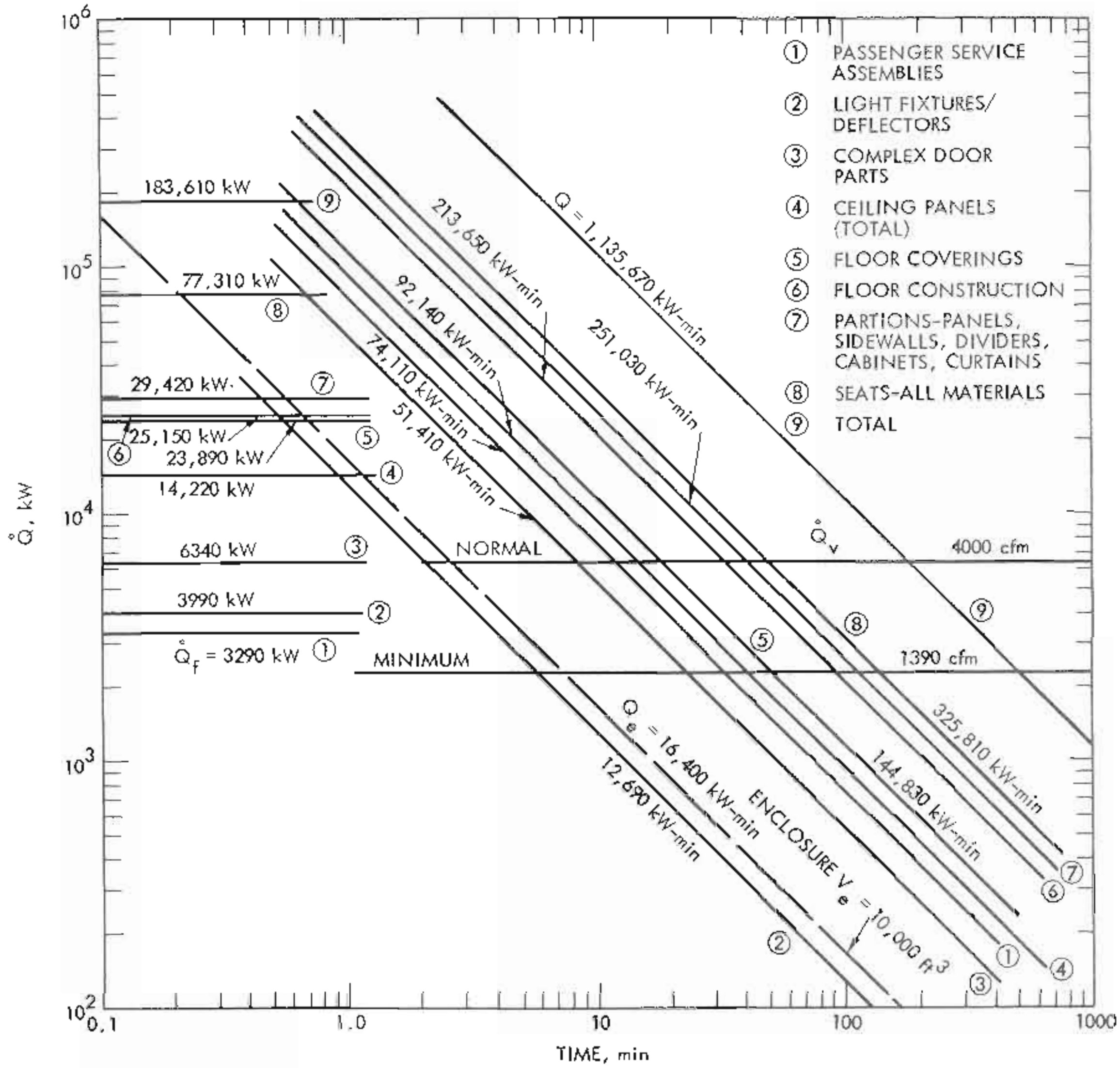


Figure 3-16. RERC for Hypothetical Aircraft
(Zone 4: Coach Cabin)

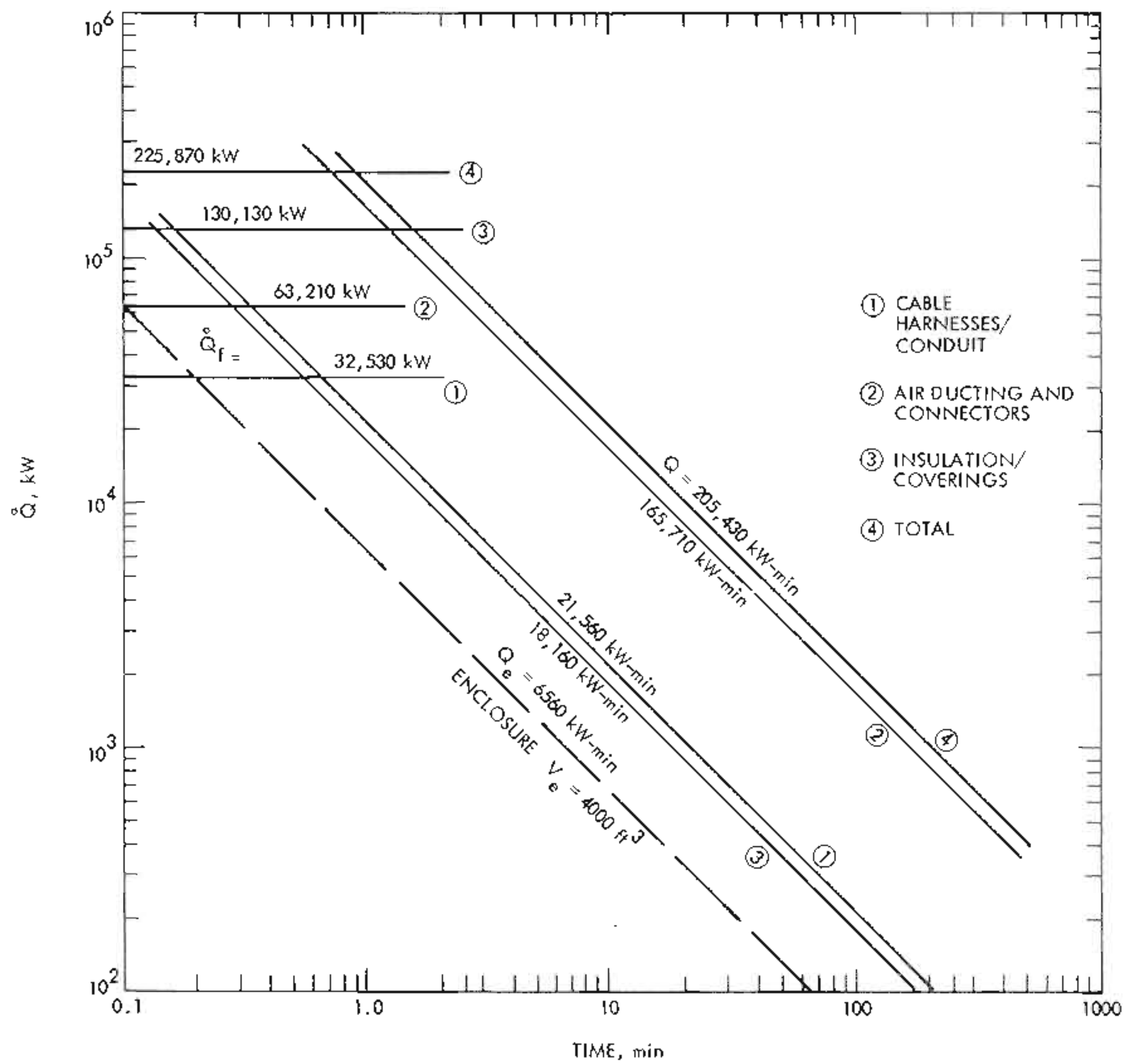


Figure 3-17. RERC for Hypothetical Aircraft (Zone 5: Attic Area Without Ventilation)

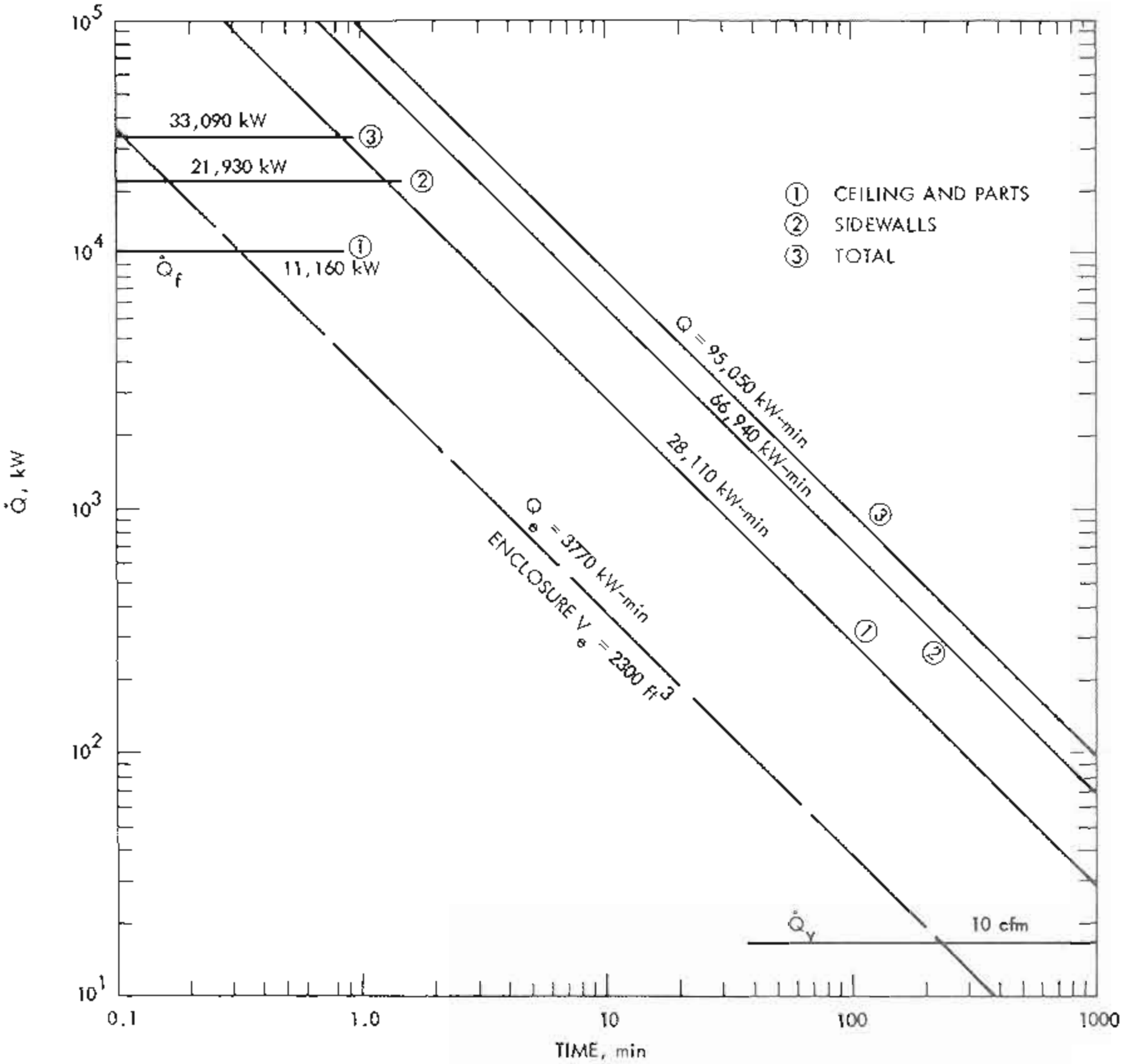


Figure 3-18. RERC for Hypothetical Aircraft (Zone 9: Aft Cargo Compartment)

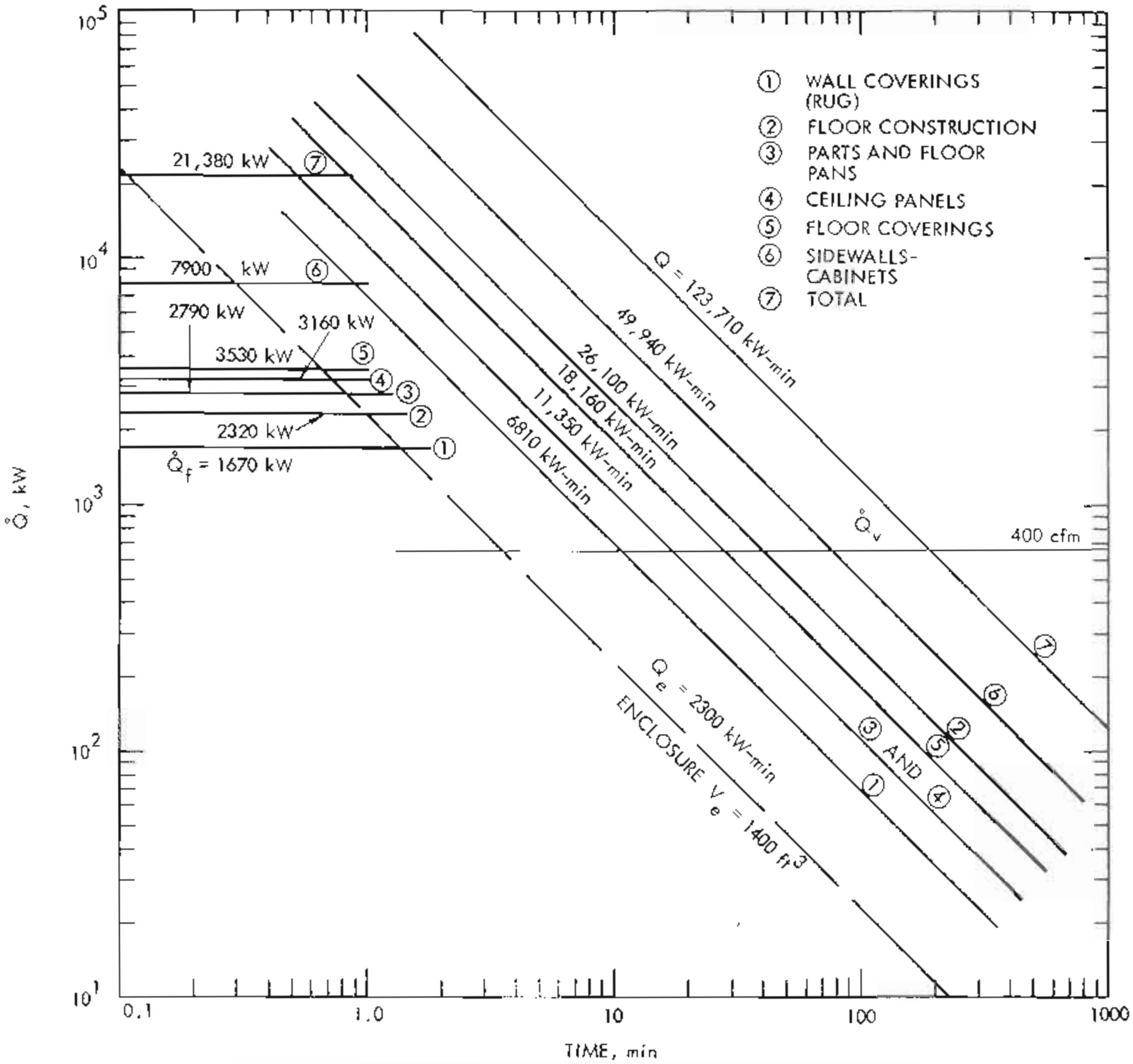


Figure 3-19. RERC for Hypothetical Aircraft (Zone 11: Lower Galley)

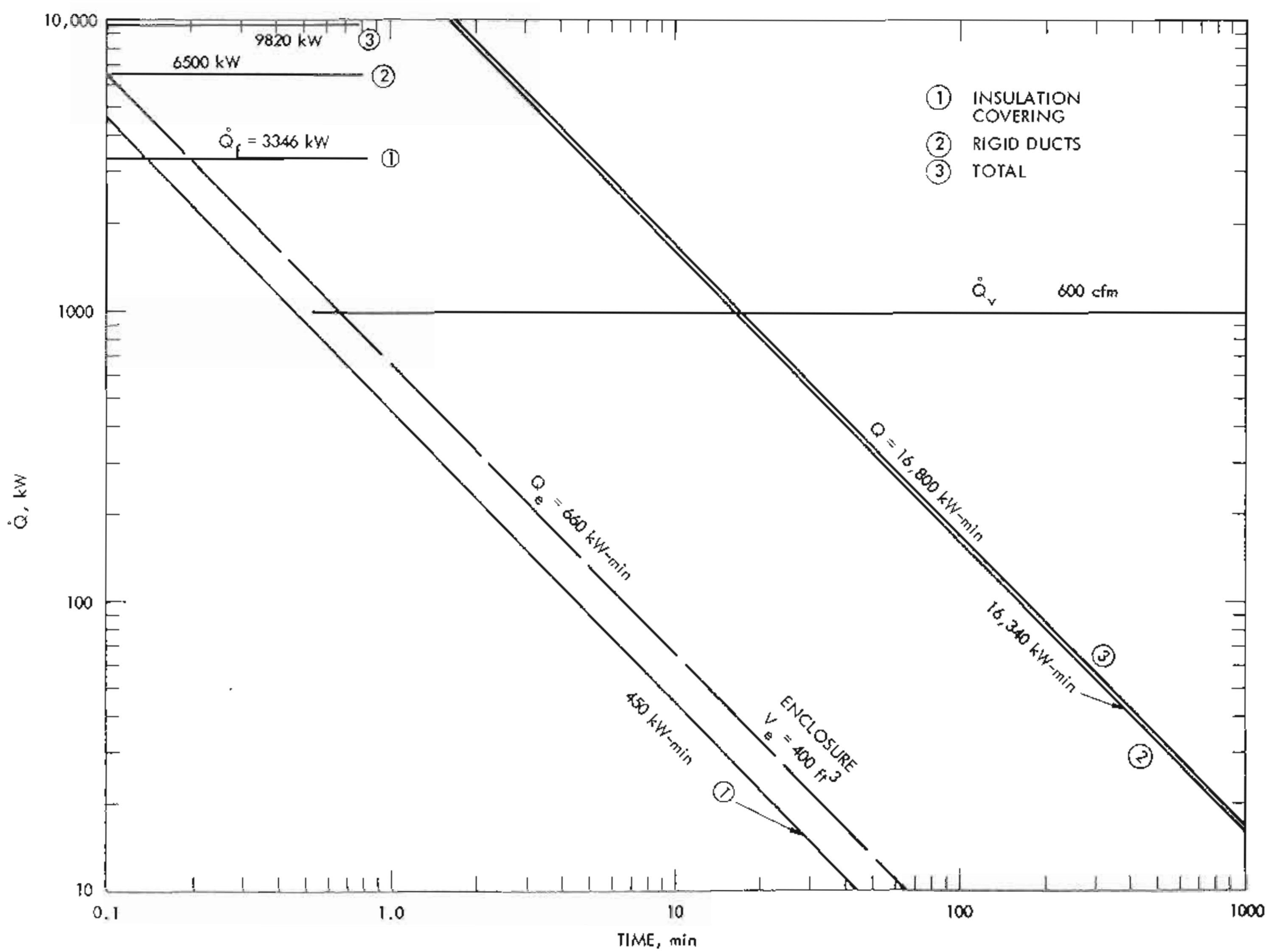


Figure 3-20. RERC for Hypothetical Aircraft (Zone 15: Electrical Service Center)

It is evident from Figs. 3-14 through 3-20 that most fires in the compartments of the hypothetical aircraft would be ventilation limited if burn-throughs into other compartments did not occur and there was no access to additional oxygen from sources other than the stated ventilation. For example, in Fig. 3-14 (Zone 1), the enclosure limit and the ventilation limit cross at a time of about 1 minute. It is unlikely that a fire could spread fast enough and far enough to become fuel-surface limited in lesser periods of time. In general, the fuel limits are both large and unlikely to become limiting factors in most of the aircraft compartments. This is true even if, in most of the zones depicted, the lowest fuel limits had happened to be the fire-involved surfaces.

Actually, because hot, longer-duration fires would be required to cause rapid fire spread and engulfment, it is likely that "ideally" set fires in most of the compartments would be enclosure limited, i.e., the fires would burn poorly and tend to smolder and die out before the ventilation had much effect. The danger to human life would probably be more in terms of smoke and toxic fumes inhalation, and suffocation. On the other hand, it is important to consider, in each case, in each compartment, the relative hazards arising from a sudden and massive increase in the available oxygen supply. The case of an aircraft crash with fuselage rupture, and concomitant liquid fuel spill and potential explosion, is not included in the aircraft-specific RERC shown in Figs. 3-14 through 3-20. In such cases, the evacuation time would become a dominant factor and the influence of high fire-resistant materials, and early-warning smoke and fire-detection systems might be minimal.

Therefore, it is clear that a proper distinction must be made between the objectives of model or full-scale fire tests and the hypothetical fire scenarios that might be envisioned. In the former case, realistic bounds can be established on fires in a controlled setting; in the later case the RERC would require modification to include other contingencies.

3. Discussion

Numerous fire scenarios for the hypothetical aircraft may be envisioned. To be considered on the one hand are the compartment(s) of involvement, the source and location of the fire inception within the compartment, and whether or not the fire remained undetected and appropriate countermeasures had been taken, e.g., compartment sealed and the ventilation reduced or terminated. On the other hand, there are the circumstances of the fire breakout and the passenger loading: ground fire in a motionless aircraft, in-flight fire, fire eruption following a crash for other reasons, ground collision of two aircraft, one or both of which may be moving, and in-flight collision of two aircraft.

Sources of ignition and potential hazards for all the compartments have been enumerated (Ref. 7). Clearly, an important aspect of any aircraft fire is the rate of fire spread, which has not been dealt with in any detail in the present report. Given the same materials of involvement, the early fire development history would depend to a large extent on whether the fire started on the floor, on a wall, or at the ceiling. Equally important would be the ventilation pattern, especially the local flow pattern at the fire. In slowly spreading fires, the enclosure volume and the ventilation rate and pattern probably would be the dominating and limiting factors, not the fuel surface area or amount of fuel available.

Two cases or zones of fire development are of special interest because full-scale tests have been conducted. These are the lavatory and cargo bay simulation tests discussed previously (Refs. 5 and 6). Both can be considered in the light of the compartment descriptions (Ref. 7) and the RERC given herein.

The gross enclosure volume was about the same in the lavatory compartment, 70 ft^3 in the description (Ref. 7), and 65 ft^3 in the fire simulation test (Ref. 5). In the description, the ventilation rate is $\mathring{V} = 30\ ft^3/min$; in the actual test, the ventilation rate appears to have been about twice that value, at least initially. In either case, the fire should be ventilation limited. The lavatory test fire was conducted using four plastic bags containing representative waste paper and plastic cups, which supplemented the construction materials already present. In a 30-minute test (Ref. 5), no burn-throughs occurred, but the lavatory interior was virtually destroyed. Average gas temperature near the ceiling exceeded 600°F throughout the test. With widespread involvement of the available fuel load and surface area in the actual test, it is clear from Fig. 3-15 that a long and rather hot fire would occur before the fuel load limitations were reached, provided the ventilation was adequate. In the actual test, however, the ventilating valve was closed when rapid fuel burning occurred in the lavatory. The production of toxic gases in the lavatory was considerable; time histories of these were given and were discussed in Ref. 5.

In the description of the cargo bay (Ref. 7) the enclosure volume for the cargo bay was 2300 ft^3 as compared to a value of 2000 ft^3 in a full-scale test (Refs. 5 and 6). In the description, the ventilation rate apparently was merely the leakage rate (only 10 ft^3/min). In the first test (Refs. 5 and 6), an unusually large ventilation rate of 703 ft^3/min was employed; even then the fire burned poorly. In planned Test No. 2 (Refs. 5 and 6), the ventilation rate would be cut to the leakage rate upon fire detection. Figure 3-18 indicates that such a fire would be enclosure limited for a long period of time if it continued to burn at all.

SECTION IV

VALUE OF THE RERC APPROACH

The Relative Energy Release Criteria do provide upper bounds on fire development in enclosures and indicate which factors are likely to be the limiting factors at various stages of the fire. Nominal values for the RERC are not difficult to calculate, have application to specific enclosures regardless of size or scale, and provide a nonambiguous, consistent, and generalized set of fire constraints. It is suggested that the RERC can be of considerable value in designing full-scale tests and interpreting the resulting experimental data.

In designing experimental tests, the RERC can be used to predict, at least roughly, whether the test objectives are likely to be compatible with the test results. For example, if ventilation limited fires are to be studied, then the fires should not be constrained by a fuel surface limit. If enclosure limits are to be studied, e.g., sealed compartments, then the test should not be constrained by a too-small fuel load. Alternatively, the RERC should be useful in data interpretation, especially when experimental fuel weight-loss curves all appear similar even though various fire parameters have been changed. When only limited experimental data are available, the probable effects of changes in the enclosure, fuel, and ventilation parameters may be estimated. The interaction of the various constraints is of interest and may be assessed through an RERC plot. For example, ventilation effects are not significant unless a fire development exceeds its enclosure limit.

Comparison of actual experimental data with the associated RERC can give valuable insights into a fire development and indicate which of the constraints require improved input values. In some cases, improved values of the RERC will follow directly from the experimental data. In cases where one or more of the nominal RERC are exceeded significantly for an appreciable duration of time, a close search for the cause may yield useful information. If the calculated RERC are essentially correct (and they may not be), then errors in measurements or in data analysis may be indicated. Otherwise, anomalies are present that require explanation or further testing. Such cases may occur during the period of peak fire intensity. Clues may be provided, for example, towards the separation of evaporation and volatilization effects from heat release per se, e.g., when volatiles can transport and burn elsewhere outside an enclosure and thus not participate in internal heat release.

SECTION V

CURRENT AND FUTURE WORK

Analysis of heat flux data should provide further insights and clues for comparison with established RERC. We are examining experimental heat flux data for some tests, e.g., the SRI data, to determine if they are compatible with RERC projections. The latter are estimated by assuming that heat release rates may be projected on a suitable control area, or the walls, in proximity to a fire plume. Estimates for radiation, reradiation, and turbulent convective heat transfer can be incorporated into this analysis. Results to date are incomplete and will not be reported here. It appears that the heat flux variations closely follow derived heat release rates, as might be expected.

Other hazards are of interest as well, such as smoke production and gas temperatures within an enclosure. It is expected that both of these quantities will scale in some way with the energy release rates, and that, therefore, they can be related to the RERC. One of the authors (Coulbert) already has initiated such studies. A main goal in the near future will be to produce a report that will propose full-scale fire test criteria and scaling effects, as based on the RERC approach, for use in the NASA FIREMEN sponsored test program.

It is increasingly evident that energy release and/or combustion oscillations are a common occurrence in enclosure fires. There exists no unified approach to the prediction of this phenomena that is generally useful. A simplified analytical model of an oscillating enclosure fire will therefore be formulated. The model would include such quantities as fuel volatilization rate, heat release rate, heat (radiation) feedback rate, and ventilation rate, all with simplified storage terms and appropriate feedback and transfer functions. Present systems analysis methodology is available for application to the prediction of the transient and periodic responses of complex electrical, mechanical, and fluid dynamic systems. An alternate approach is to use the rate differential equations themselves, e.g., see Ref. 8. The main task here would be to identify and characterize the appropriate systems elements and to develop means to define their dynamic interaction.

An overview of the relation between RERC and fire parameter characterization is given pictorially in Fig. 5-1.

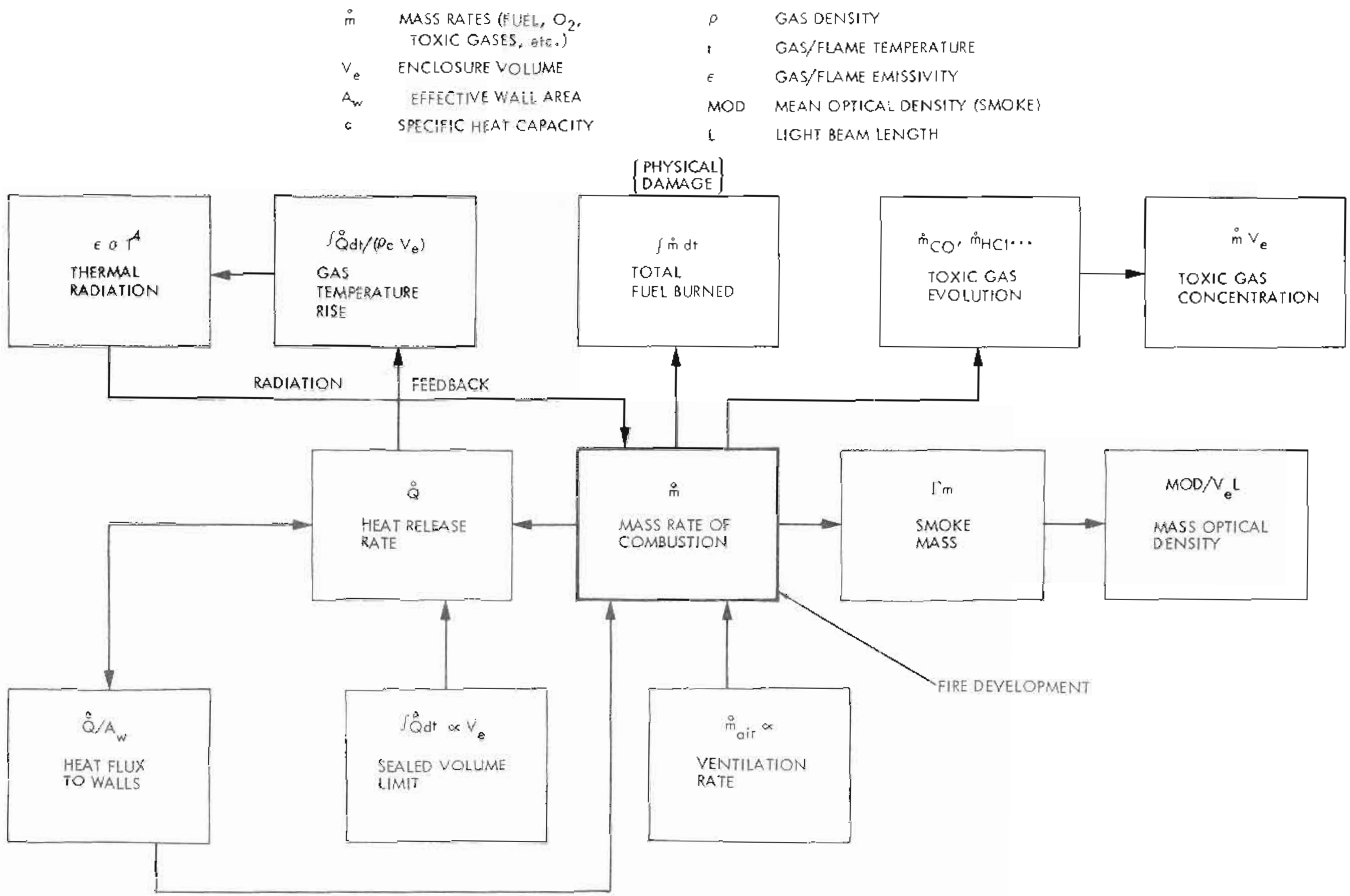


Figure 5-1. Overview of Fire Parameter Characterization

SECTION VI

COMMENTS ON FULL-SCALE TESTS IN AIRCRAFT COMPARTMENTS

The Boeing Airplane Company has kindly made available to JPL advance copies of reports describing plans for full-scale tests in aircraft fuselage sections (Refs. 9, 10, and 11). In this cooperative effort, which is partially sponsored by NASA, the overall goal is to define tests for ranking aircraft interior materials according to various "hazard" criteria, and ultimately to rank the candidate materials themselves. The effort integrates with the NASA FIREMEN program. The Boeing program has three principle phases: (1) design-fire (baseline) definition, (2) standard fire tests, and (3) test data correlation.

In Ref. 9 is described a series of laboratory tests for application to select materials of interest. Measurements and observations will include flame spread and heat release rates, oxygen index, smoke and toxic gas evolution, etc. Two baseline and 10 newly developed materials will be tested.

The objectives in Ref. 10 are to develop a "Design Fuel Fire" and a "Design Interior Fire Source" that can be used as a standard fire simulation for testing candidate materials in a controlled, known fire environment. These design fire definitions have application for post-crash fire conditions (with representative liquid fuel spill) and interior in-flight fire conditions respectively, and will be selected to produce a maximum thermal environment for cabin interior materials. After the "fire sources" have been defined, they will be tested further in short sections of a 737 aircraft to determine the effects of enclosure volume and ventilation rate.

Fuel pans located in the aircraft section will be used to burn at least 7 materials typical of in-flight fire situations. An instrumented calibration panel and other equipment will be used to characterize the fires (Ref. 10). Later, the thermal environments of the selected fire sources will be duplicated using a combination radiant heat source and liquid propane flame igniter.

In full-scale tests to be conducted in a 707 aircraft, the desired thermal environments will be duplicated using the calibration panel (Ref. 11). When the desired conditions are achieved, the calibration panel will be removed and replaced by a test panel of special construction. Special test panels 4 ft by 6 ft, curved to approximate a wall section of a typical aircraft, will be subjected to simulated postcrash fires and in-flight fires. The 2 baseline and the 10 newly developed materials mentioned in Ref. 9 thus will be tested by this methodology.

It is especially during Phase 1 of the Boeing test program, i.e., definition of the design fire sources, that application of the RERC approach might prove useful and fruitful. All the information necessary to calculate the RERC, including, perhaps, the flame spread rates, would or could be available. Pretest application of the RERC would reveal the most likely fire development constraints and could be used to reconcile the test objectives with the proposed full-scale tests. Posttest comparison with the experimental data would give insight into understanding the actual fire behavior. Not mentioned in Ref. 10 was the measurement of fuel weight loss as a function of time for the various test fuels. That information would be a valuable adjunct to the considerable body of measurements that is planned and, in fact, is needed for comparison with the RERC.

SECTION VII

RECOMMENDATIONS

It is recommended that the approach employing the Relative Energy Release Criteria (RERC) be applied to projected/planned enclosure fire tests for both full-scale and model situations. The RERC can be useful in reconciling planned test objectives with proposed tests, and in interpreting experimental data. The cost of full-scale fire tests (in particular) is high, so that use of the RERC is warranted to exclude unnecessary or ambiguous tests from a test program before the fact. The potential gain from the RERC approach is so much greater than the time and effort required to calculate and display them, that they should be an essential part of any planned fire test program.

To facilitate the application of RERC, using Ref. 1 as an initial guideline that can be extended as needed, several recommendations are in order:

(1) The enclosure and ventilation parameters should be defined fully. The enclosure configuration and dimensions should be given in addition to its volume. The ventilation should be described as natural or forced, and the dimensions and location of all vent openings should be detailed, i.e., the vent patterns should be given. All planned ventilation rates should be given.

(2) All fuel parameters should be described fully. This includes the type or class of test fuel(s), their heats of combustion (estimate if not known), the dimensions and geometrical configuration of the fuel, its spatial orientation, its exposed surface area and mass, and the location of all fuel sources within the test enclosure. The specification of the fuel load per unit area of floor area is not a very useful parameter and should be avoided.

(3) The source and type or means of ignition should not only be identified, but the heat of combustion and the mass flow rate of ignition fuels should be specified.

(4) The total fuel actually consumed in the experiments should be noted. After fire burn-out, or termination, the fuel mass residue should be measured before a water quench is used.

(5) Consistent units such as the international metric system should be used throughout.

Concerning the actual tests, measurements should include the fuel mass loss rates and the heat release rates.

It is recommended that the RERC be applied to more experimental data to further confirm their validity and to reveal where and how improvements can be made in the approach. Clearly, the effects of local ventilation pattern should be studied and incorporated into the present RERC. The approach should be broadened further to facilitate comparison with other parameters commonly measured, such as gas temperature and composition, heat flux, and smoke production. Such studies, as displayed in Fig. 5-1, are planned for the future.

SECTION VIII

CONCLUSIONS

It is concluded that the RERC approach is both valid and meaningful in bounding enclosure fire development and that it should be used (1) for experiment design and pretest planning, (2) for assessment of actual experimental data, (3) for establishing bounds on the course of fire development, and (4) for comparing different situations and test configurations in the absence of data. It is believed that the RERC approach may help to avoid inconsistencies between test objectives and proposed full-scale tests, and will minimize the possibility of ill-defined or repetitive tests. Thus, the RERC should be incorporated into any planned fire test programs.

From experimental data it is clear that the local ventilation flow pattern also can have a significant influence on enclosure fire development. This observation suggests that one worthwhile extension to the RERC approach would be provision for accommodating vent patterns. Another area of interest is oscillations in burning, a common occurrence in enclosure fires. At present there is no simple and convenient means for dealing with these oscillations. However, by comparing the RERC with fire data, it is sometimes possible from intuitive reasoning to predict when they might occur.

APPENDIX A

INTERPRETATION OF THE RELATIVE ENERGY RELEASE CRITERIA

Interpretation of the RERC is straightforward if it is kept in mind that their purpose is to place bounds or constraints on fire development and not to predict the detailed time history of the fire development itself. Coulbert has given explanations of the use of RERC by means of several illustrative examples (Refs. 1 and 19). The merits of the RERC approach are readily appreciated through familiarity gained by applying them to specific situations and comparing them to actual experimental results. It is worthwhile to explore reasons why the RERC may, on occasion, be exceeded. In cases of poor combustion and inhibited fire development, the intrinsic properties of the RERC in their present, initial form do not always facilitate ready explanations of the actual fire behavior.

A case of a ventilation controlled fire, for which $\mathring{Q}_f > \mathring{Q}_v$, is shown in Fig. A-1. By examining the RERC, a bounding envelope (illustrated by the solid symbols) for the fire development may be envisioned. Compared with this envelope is a curve typical of actual fire data. This curve will, in general, not rise as high as predicted by the flame spread rate, the enclosure, or the fuel surface limit, but it may exceed the ventilation rate limit briefly, oscillate about that limit, and then begin to die out as the fuel load limit is approached. If the fire development is very rapid, the enclosure limit may not have much initial effect until the total available oxygen becomes limited. If the actual fire development is much slower than predicted by the flame spread rate, the fire may begin to die out even before the enclosure limit is reached and may never approach the ventilation limit. For such fires only a portion of the available fuel may actually burn, and the theoretical fuel load limit is much greater than the effective limit, which would be further to the left than shown in Fig A-1.

In Fig. A-1, the envelope cut-off defined by intersection with the fuel load limit is idealized; the average $\mathring{Q}$ is actually less than that value defined by the intersection of the ventilation and fuel load limits for the idealized fire envelope. It is important to point out that any particular point on the theoretical Q_e and Q_{fm} curves denote an average value of the energy release over a time period specified by their absolute values. If, in a real fire development, the value of $\int \mathring{Q}\, dt$ for the same time period is substantially less than that for a corresponding theoretical average value, then the Q_e and Q_{fm} limit curves may be exceeded briefly. This, therefore, provides a mechanism for explaining instances where the enclosure limit or the fuel load limit may be exceeded, and this is not really a violation of the RERC.

In real fires it will not be uncommon that the maximum energy release rate exceeds either the fuel surface limit or the ventilation limit, depending on the particular time when that maximum (or peak) occurs. This is not in general to be explained by inaccurate estimates for those limits, though that too is possible. There are several reasons why these limits may be exceeded, especially if the peak occurs very early in the fire development. As mentioned previously, the values of $\mathring{Q}$ calculated from dm/dt for a real fire do not prove complete combustion and associated heat release; some of the fuel weight loss may reside in evaporation and/or pyrolization and will not then reflect

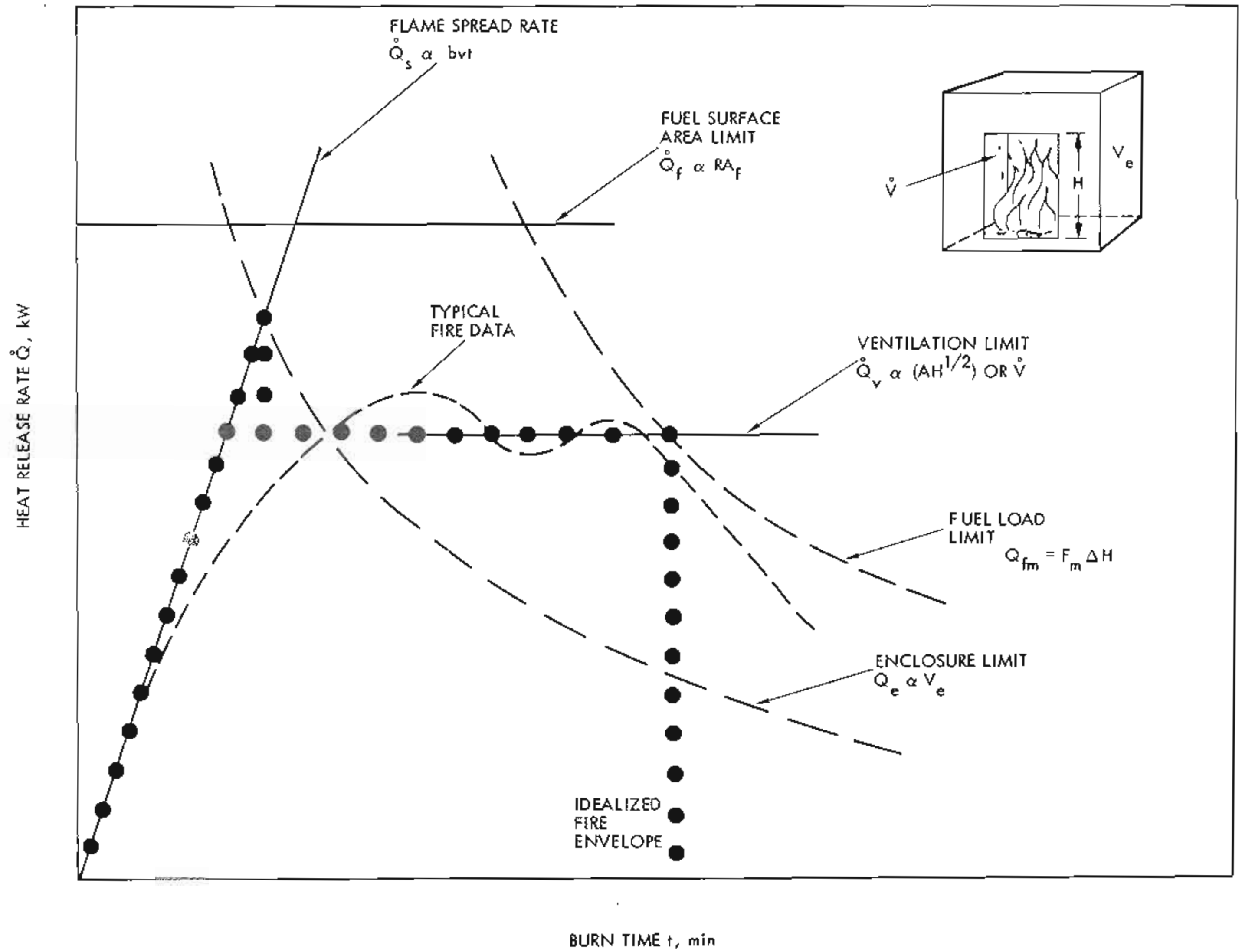


Figure A-1. RERC for Enclosure Fire Development complete burning of the volatiles within the enclosure. Thus the true $\mathring{Q}$ may be lower than the estimated $\mathring{Q}$. A rapidly developing intense fire also may reflect a temporary flare-up caused by ignition of the starting fuel (often, a secondary volatile liquid).

At present, the fuel surface area limit is calculated for a freely burning fuel or, at least, a well-ventilated fire. Enclosure fires may be more, or less, intense than free fires depending on radiation feedback, which may be significantly different in the two cases. Enclosures may inhibit the air circulation in natural ventilation or may augment it in forced ventilation cases with particular vent patterns. Burning rates for real enclosure fires have been observed to exceed the rates for comparable free fires (Refs. 12 and 13). Flashover may occur in enclosures when the flames approach ceiling height; the suddenly increased flame area provides greatly increased radiation feedback to the fire as compared to a free fire or an enclosure fire that has a very high ceiling (Ref. 12). In the case of thin layers of liquid fuel, increased burning rates may occur if the liquid achieves a boiling conditions (Ref. 14), which might lead to augmented mixing at the fuel surface.

An interesting case occurs when the fuel surface area limit and the ventilation limit are virtually identical. That this case provides a potential for optimum burning is suggested by some experimental data for wood cribs in model enclosure fires (Factory Mutual data)[1] (Refs. 13 and 15). In Fig. A-2 is plotted the gas temperature change as a function of $\mathring{Q}_f/\mathring{Q}_v$ calculated for the published data (Ref. 13). Initial ambient temperature was assumed to be 295 K (72°F). The hottest fires occurred when $\mathring{Q}_f/\mathring{Q}_v \sim 1$; fire intensity appears to decrease with increasing $\mathring{Q}_f/\mathring{Q}_v$. Based on $\mathring{Q}_m$ and Q_{fm}, there is some evidence that this effect occurred in the SRI data, especially in the case of wood cribs.

Ideally, if none of the RERC are exceeded and the fuel load burns entirely to extinction, it is possible to derive ideal "fire times" and durations from the RERC. This is done by analyzing the intersections of the various RERC, as shown in Fig. A-3 and defined as follows:

CURVE (1) : Intersection of fuel area limit with enclosure limit

$$nt_f = n\, Q_e/\mathring{Q}_f\,, \qquad 0.3 < n < 1.0$$

All oxygen consumed when $n = 1$

CURVE (2) : Intersection of vent limit with fuel load limit

$$t_o \sim Q_{fm}/\mathring{Q}_v \qquad \text{for } \mathring{Q}_f > \mathring{Q}_v$$

Duration of vent limit $\Delta t_v = t_o - nt_f$

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[1] This data was obtained from Factory Mutual Research Corporation, Norwood, Mass.

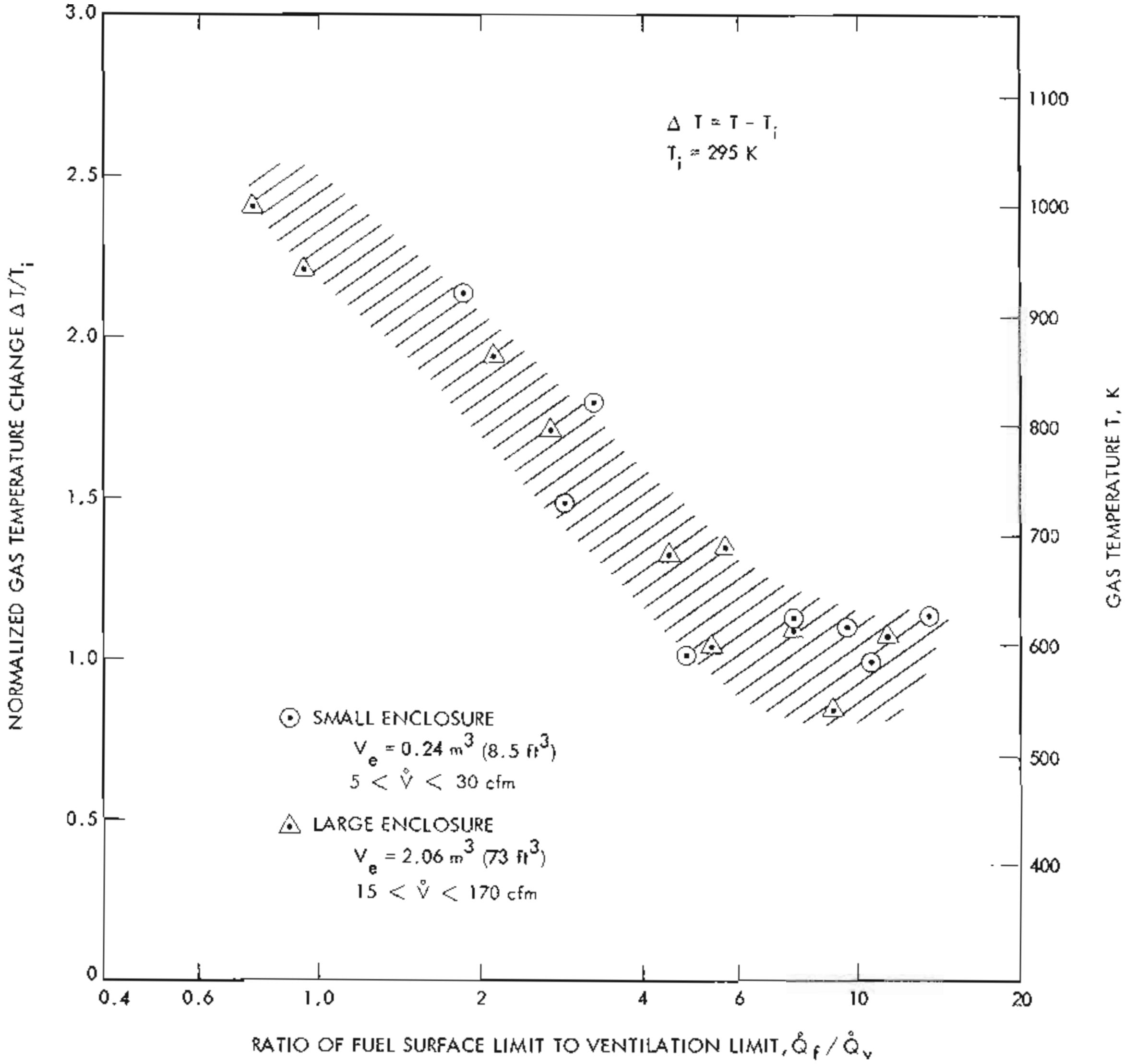

Figure A-2. Effect of the Ratio of Fuel Surface Limit to Ventilation Limit $\mathring{Q}_f/Q_v$ on the Gas Temperature Above Wood Crib Fires in Well-Ventilated Model Enclosures (Natural Ventilation). Selected Data for Well-Developed Fires from Ref. 13; $\mathring{Q}_f/\mathring{Q}_v$ Calculated by Methods Given in Ref. 1.

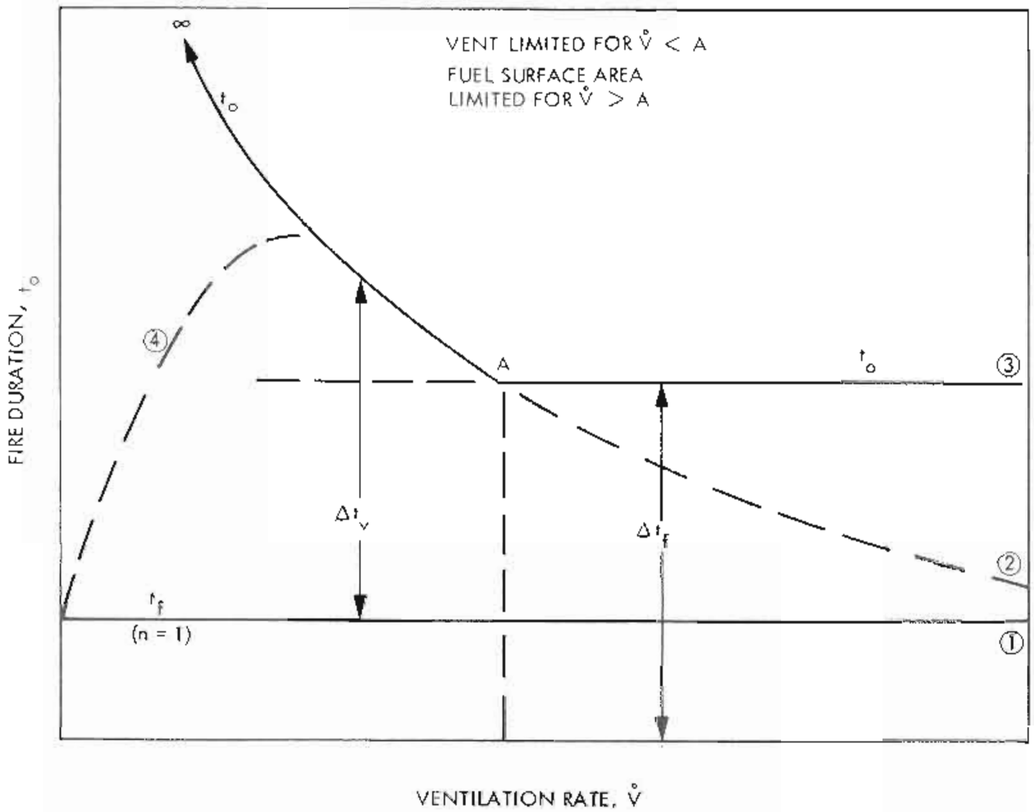

Figure A-3. Ideal Fire Duration and Other Fire Times as Derived from the RERC

CURVE ③ : Intersection of fuel area limit with fuel load limit

$$t_o \sim Q_{fm}/\mathring{Q}_f \quad \text{for } \mathring{Q}_v > \mathring{Q}_f$$

$$t_o = \Delta t_f$$

CURVE ④ : Real curve, since Δt_v must approach zero as $\mathring{V}$ approaches zero. Curve for this is unknown.

This figure has meaning only when the enclosure limit is exceeded, i.e., when $\mathring{Q}$ enters the region between Q_e and Q_{fm} in Fig. A-1. The idealization shown in Fig. A-3 is not expected to yield accurate information for real fires because the times of occurrence of t_m and τ_m (Fig. 3-9 of text) are usually not the same as t_f and t_o (Fig. A-3).

Data from Table 2 of the text (estimated fire duration) for the SRI data is compared in Fig. A-4 with the ideal duration limits derived from the RERC. In the case of fuel surface area limited fires, that is, for MeOH and the rubber tires, the agreement is reasonably good. The more variable ventilation controlled fires obviously are less predictable.

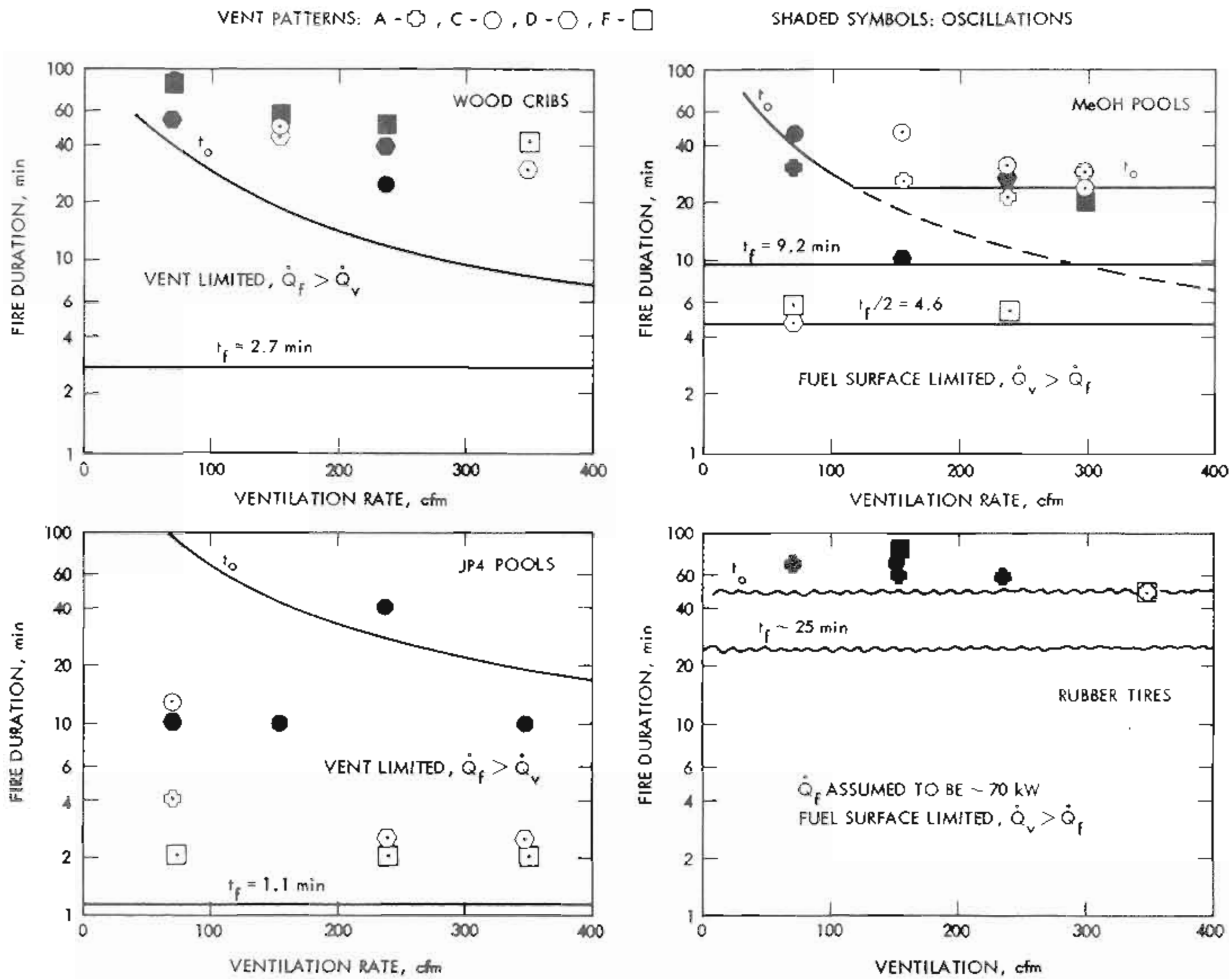

Figure A-4. Approximate Experimental Fire Duration Time for SRI Experiments Compared With Limits Derived From the RERC

APPENDIX B

DISCUSSION OF THE RELATIVE ENERGY RELEASE CRITERIA

The RERC in their present formulation do not account for several parameters and variables. Among these are:

(1) The shape of the enclosure in distinction to just its volume. Two enclosures of equal volume but greatly different shape, e.g., roughly cubical vs. tall and thin or low and narrow, might be expected to influence fire development differently. The height of an enclosure relative to the fuel surface area might have considerable influence on fire intensity and flashover.

(2) Vent pattern geometry. Clearly, different vent locations and geometry (distribution in enclosure and/or multiple openings) having the same size and area may cause different fire development.

(3) Fuel parameters such as geometry (shape) and location in the enclosure (near center, near wall, etc.) and location with respect to ventilation openings. The shape of the fuel will govern not only its exposed or total surface area, but also its radiant interchange between mutually viewing surfaces and the enclosure walls.

(4) Fuel flammability limits.

(5) Ignition source, e.g., the location in the enclosure, the type, and the extent of initial involvement.

(6) Radiation feedback, an important aspect of fire development and control. This, however, must be dealt with using heat balances, fire spread, flame geometry, gas layer stratification, etc., and is an exceedingly complex subject.

At present, the RERC are calculated as if each constraint influenced fire independently. This is an excellent assumption for predicting the nominal fire development envelope, but is not strictly true. For example, the fuel surface area and the fuel mass may be independent (such as fuel containers for liquid fuel having the same exposed surface area but different depths), may be weakly dependent for different shapes of the same material, or may be strongly dependent (such as geometrically similar wood cribs). The flame spread rate may be a function of the fuel geometry and mode of ignition, and may be related to fuel surface areas or masses in some cases. Also, it could be influenced by enclosure geometry and, in slowly developing fires, by the ventilation rate itself. The effective enclosure limit might be influenced weakly by the type of fuel and its flammability limits.

It remains to be determined which of the above factors, if analyzed, would enhance application of the basic RERC. Changes of 10 or 20 percent in RERC are really of little significance; of interest, however, are changes of the order of 50 or 100 percent. A change of the latter magnitude might alter which of the RERC controls the fire development during the fire's critical phase. The enclosure limit calculation is less straightforward than it appears because it is difficult a priori to estimate the amount of oxygen in the enclosure that will be consumed before the ventilation has an effect. Better bounds on the enclosure limit might be achieved through consideration of the fuel flammability limits.

The prediction of maximum energy release rate might be enhanced significantly by incorporating the enclosure shape into calculation of one or more of the RERC. As a first step, this might be done by studying the effect of flame height (which can be predicted for free fires knowing the fuel surface area and mass) as compared to the enclosure ceiling height. At present it is difficult to estimate from the RERC what the total energy release will be, or what the fire duration will be. This is true especially of slowly-developing, poorly-burning fires because the actual amount of fuel that is consumed cannot be predicted. Total energy release and fire duration may not be important considerations for early fire development and human hazard, but they do have bearing on property damage and fire-fighting. Any means for predicting the actual fuel consumption in advance, e.g., considering ventilation controlled fires, would lead to a great improvement in calculating the effective fuel load limit.

It is clear that with modest effort improvements in RERC, calculation could be achieved using available knowledge, if warranted. Two factors will be difficult to analyze: (1) the effects of vent pattern, because they determine in part the air and hot gas circulation within the enclosure and involve fluid mechanics in complex ways, and (2) the radiation and radiation feedback within the enclosure. During the development phase of an enclosure fire, these two factors may be interdependent. Recent examples of fluid mechanics related to enclosure fires with natural ventilation are the results of Harmathy (Ref. 16), and Prahl and Emmons (Ref. 17). Dayan and Tien have calculated the thermal radiation from cylindrical flames (Ref. 18).

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