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TIME-DEPENDENT FIRE BEHAVIOR OF AIRCRAFT CABIN MATERIALS

Clayton Huggett
U.S. Department of Commerce
National Bureau of Standards

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FINAL REPORT

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16. Abstract

In an aircraft cabin or other inhabited compartment, the early stages of fire growth are critical to life safety. During this period the rate of fire growth, as measured by the mass fuel consumption rate $\dot{m}$, can be represented approximately as a simple exponential function of time, $\dot{m} = \dot{m}_o e^{kt}$. The rates of development of hazard from temperature rise and smoke and gas accumulation can be related to $\dot{m}$. The growth constant k can be related to a small number of system parameters and fuel combustion properties. These properties are identified and laboratory methods for their measurement are suggested.

In a fire situation, the critical hazard (temperature, smoke or gas) can be considered to be the one which first reaches a limiting human tolerance level. This mode can be identified and the effects of changes in design and materials on the rate of critical hazard development can be estimated. The simple exponential growth model may provide a means of predicting relative hazard with reasonable accuracy.

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PREFACE

This study was carried out in the Center for Fire Research of the National Bureau of Standards, U.S. Department of Commerce, for the U.S. Department of Transportation, Federal Aviation Administration under Interagency Agreement DOT-FA76WAI-610.

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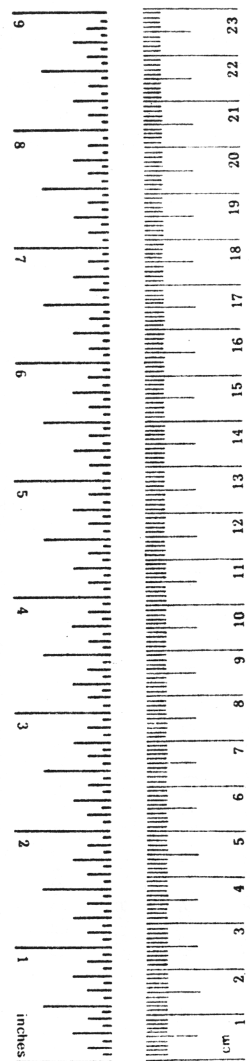
LIST OF ILLUSTRATIONS

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

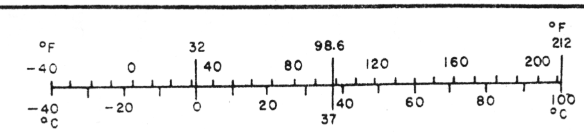
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

*1 in = 2.54 (exactly). For other exact conversions [illegible] see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. [illegible]



Approximate Conversions from Metric Measures

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



DEFINITION OF SYMBOLS

A	area (of burning fuel surface)
C_g	concentration of toxic gas
C_p	heat capacity of gas
$\overline{C}$	total thermal inertia of fire compartment
D	optical density of smoke
ΔH	heat of combustion of fuel
I	fire intensity (arbitrary scale)
k	fire growth constant (t^{-1})
L	optical path length
(MOD)	mass optical density (ref. 7)
m	mass of fuel
q	thermal energy
r_b	rate of regression of the burning surface
r_s	rate of flame spread over fuel surface
T	temperature
t	time
V	volume of fire compartment
v	volume of flame
α	gas generation coefficient
ε	combustion efficiency (ratio of heat release to heat of combustion of fuel consumed)
ρ	density of fuel

SUPERSCRIPTS

$\dot{}$	derivative with respect to time
"	per unit area
—	average value
*	critical value (human tolerance limit)

SUBSCRIPTS

o	zero time (arbitrary)
i	ignition or i the fuel element
s	smoke
g	toxic gas

INTRODUCTION

PURPOSE.

The purpose of this study was to investigate the concept of time-dependent fire behavior of aircraft cabin materials as applied to a methodology that would relate the rate of development of hazard from products of combustion of materials in an enclosure to laboratory measurable material properties and environmental parameters.

BACKGROUND.

Federal Aviation Administration (FAA) rules now cover the flammability characteristics of materials approved for use in air carrier cabin interiors [1]. The FAA has recently proposed regulations to limit the smoke production properties of aircraft interior materials [2] and has suggested the need for a similar standard to control toxic gas emission [3]. The ultimate goal is to provide a fire-safe environment for aircraft passengers, considering all aspects of the fire safety problem. In the area of material specifications these include, in addition to smoke and gas production, such combustion characteristics as ease of ignition, flame spread rate, rate of heat release, and flash fire potential. Ideally, these would be covered by a single test method or a combination of tests which would measure the suitability of a particular material for a specific cabin application. Such a comprehensive approach has not yet been developed; this work represents an effort to move in this direction. This study explores means of integrating related hazard parameters such as smoke, high temperature, and toxic gas formation in a single criterion and combining intrinsic material properties with fire growth characteristic to provide a measure of the rate of development of hazard.

Most unwanted fires, if unperturbed by outside intervention, show a characteristic pattern of growth from a small ignition source to an ultimate size determined only by the availability of fuel or oxygen, followed by a period of decay leading to extinction. Various stages in this growth process are of significance in the control of fires and the limitation of loss. These stages are commonly designated as "times." Some of these are determined by the progress of the fire, such as the time to develop a critical smoke level or toxic gas concentration, the time to flashover, or the time of structural failure. Others are determined by the response of various control systems, such as the time of detection, the time of activation of a fire extinguishing system, the time of evacuation, or the time of arrival of the fire department. In general, the extent of loss will depend on the relative sequence of events on these two time scales.

In the case of a fire in an aircraft cabin where the occupants are initially located within the fire compartment, the critical survival-escape time can be considered to be the time at which an intolerable hazard condition (temperature, smoke, toxic gas, oxygen concentration, etc.) is reached on the one hand, and the duration of evacuation period on the other. Clearly, conditions will be fatal when the point of flashover is reached. So from the standpoint of life safety, we will be concerned only with the period of fire growth from ignition to flashover. The post-flashover fire may be significant in causing structural failure but does not affect the hazard to life in the present case.

Despite this time dependent nature of the development of hazard, many fire test methods operate in a quasi-steady mode. The test specimen is exposed to a square wave energy input to determine a material property of the specimen. Even when the test method embodies a time dependent concept, the results are used in building codes and standards in the form of integrated, non-time-dependent, material properties (flame spread index, specific optical density, heat of combustion, char length, etc.). Building codes and standards do give some slight recognition to time dependence through the use of time ratings on structural components. The FAA has recently sponsored research and development studies to relate time dependent fire phenomena such as rates of smoke and toxic gas production to a "time to escape."

PRESENT STATUS OF TEST METHODS.

For some time, combustion characteristics of materials have been measured separately in small scale tests. These tests are convenient to produce data, but integration and extrapolation of these data to predict the behavior of the material on the larger scale of an actual fire situation of interest is awkward and generally unreliable.

At the other extreme, full-scale tests are certainly within our present technical capabilities. Unquestionably they produce an appropriate evaluation of materials in any given situation. However, they would be costly for routine material evaluation and prohibitively expensive for hazard assessment where many combinations of materials, enclosures, environmental conditions, and ignition sources are of interest. Moreover, they provide little predictive capability to guide design and material development.

As an alternative approach to the pure full-scale experimental technique, one could attempt to calculate the detailed fire growth information obtainable from full-scale tests by utilizing mathematical models and laboratory scale material test data. Work on a computer program (DACFIR) to perform fire growth calculations for the interior of wide-bodied commercial aircraft cabins is underway at the University of Dayton Research Institute under the sponsorship of Federal Aviation Administration [4]. The output of DACFIR is a detailed description of the fire spread, smoke density, and gas concentration in the aircraft cabin as a function of time from the given initial fire situation. To produce the detailed evaluation of fire growth approximately 50 pieces of laboratory test data must be supplied to the program for each material involved in the cabin fire. Material properties are determined in laboratory scale experiments using the Ohio State University rate of heat release calorimeter and other recognized test equipment [5]. It appears probable that any calculation scheme used to compute the details of fire growth in an enclosure will be lengthy and require a large amount of input data.

One purpose of any predictive enclosure fire growth scheme is to establish the relative fire time-hazards expected from the presence of various materials or design features in the enclosure. For this purpose it may not be necessary to calculate the pattern of fire growth in detail, but only to calculate the change in growth rate relative to some standard configuration when changes are made in design or materials. Thus any such scheme could be used to answer basic questions, e.g., would the fire hazard in an aircraft be increased or decreased if a given change in seat covering material were made?

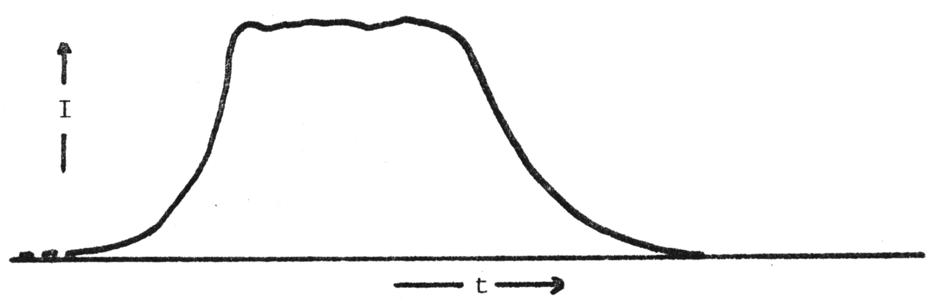
The impetus for this approach was the concept that relative fire hazard of materials, as in the example of seat cover material given above, could be resolved without the calculation of detailed fire growth. Rational application of some detailed enclosure fire growth techniques would allow one to greatly simplify the calculations involved in the hazard assessment, i.e., detailed fire growth methodology would be altered to stress simplicity of assessment and easier utility of the results.

A simple two parameter exponential fire growth model is developed in this work. It is shown how this simple model could be used to calculate the relative fire hazard, including smoke and gas production from various materials, once the two parameters of the model are determined. Necessary laboratory measurable material properties are identified and the relationship between these properties and fire growth rate and hazard development are outlined.

DISCUSSION

EXPONENTIAL FIRE GROWTH MODEL.

Most fires in compartments follow a similar pattern of development. Starting from a small ignition source, the fire increases in intensity (I) as the flames spread to involve fresh fuel surfaces. When all exposed fuel surfaces are involved (termed flashover) further growth is restricted and the intensity of the fire may be limited by the rate at which oxygen is supplied. After a period of relatively steady burning fuel elements will begin to become consumed, the burning surface will decrease, and the fire will decay and ultimately be extinguished as shown in the sketch below.



For our present purpose we are concerned only with the period of growth up to flashover.

Huggett [6] has discussed fire growth in closed chambers, and found the rate of fire growth to be exponential in time. It is convenient to represent the intensity of the fire by the mass rate of fuel consumption, since this is an easily measured experimental quantity.

The mass burning rate of a fire in an enclosure can be represented by

1) $\dot{m} = \dot{m}_o \, e^{kt}$

Note: For definition of symbols - see page viii.

In equation 1, $\dot{m}_o$ is the initial burning rate of the material as the result of an ignition at time t = 0 and k is the growth factor for the fire which depends on the geometry of the system and the combustion characteristics of the fuel element(s). It will be noted that 1/k is the time necessary for $\dot{m}$ to increase by a factor e = 2.72.

Knowing the rate of fuel consumption $\dot{m}$, estimates of other fire parameters such as the rate of energy release ($\dot{q}$), the rate of increase of smoke density per unit path length ($\dot{D}/L$), the rate of increase of the concentration of specific combustion gases ($\dot{C}g$), and the rate of temperature rise ($\dot{T}$) can be made. The simplest constructions for these quantities involve the burning rate $\dot{m}$, heat of combustion ΔH, combustion efficiency ε, Seader's mass optical smoke density (MOD) [7], a gas generation coefficient α, the compartment volume V, and the total thermal inertia of the system ($\bar{C}$).

2) $$\dot{q} = \Delta H \ \varepsilon \dot{m}$$

3) $$\dot{D}_s/L = \frac{(MOD)}{V} \dot{m}$$

4) $$\dot{C}_g = \frac{\alpha}{V} \dot{m}$$

5) $$\dot{T} = \dot{q}/\bar{C} = \frac{\Delta H \varepsilon}{\bar{C}} \dot{m}$$

The total mass consumption at time t is given by:

6) $$\Delta m = \int_o^t \dot{m} \, dt = \frac{\dot{m}_o}{k} \left(e^{kt} - 1 \right)$$

Similar expressions hold for the total heat release and smoke and gas production. In a closed chamber such as an aircraft cabin, the average optical density or gas concentration can be found at any time t. In a ventilated compartment, appropriate corrections must be made for the loss of smoke and gas from the compartment.

The average temperature in the compartment at time t is

$$7) \qquad \bar{T} = \Delta q/\bar{C} = \frac{1}{C} \int_0^t \dot{q} \, dt$$

Again, corrections can be made for the flow of hot gases and other heat losses from the compartment.

An expression for the fuel consumption rate in the compartment for the case of a single item burning as the result of a single ignition would be

$$1) \qquad \dot{m} = \dot{m}_o e^{kt}$$

as discussed earlier. For multiple fuel elements,

$$8) \qquad \dot{m} = \sum_i \dot{m}_i$$

For multiple ignitions at various times (t_i) on different fuel elements in the enclosure the situation becomes more complicated. The total burning rate may be represented as:

$$9) \qquad \dot{m} = \dot{m}_o e^{kt} + \sum_i (\dot{m}_o)_i e^{k_t (t-t_i)}$$

IGNITION.

Measurement of the mass fuel consumption rate at two times t_1 and t_2 during the growth phase of a fire will permit estimation of the growth constant, k.

$$10) \qquad k = ln (\dot{m}_2/\dot{m}_1) \Big/ (t_2-t_1)$$

This tells us nothing, however, about the origin of the fire, i.e., the time of ignition or the size of the ignition source. If the ignition time is known, as in a laboratory test, a value of $\dot{m}_o$ can be obtained by extrapolating to $t = 0$. In many real fires the precise time of ignition and even the ignition source may be unknown. In principle, the fire could have been growing for a very long period of time from a very small initial energy source. This can occur in the case of spontaneous ignition due to self-heating in certain well insulated systems [8]. In most practical situations, however, it is recognized that the ignition source must be of finite size such that the rate of energy production through combustion is greater than the rate of energy dissipation to the surround.

It is apparent that the size of the ignition source will determine the value of $\dot{m}_o$ but it should have no effect on the growth constant k or the subsequent development of the fire. Thus the "time to flashover" (or the time to reach any arbitrary level of fire intensity) depends on the ignition source and is not a measure of the hazard potential of the fire configuration. The growth constant, on the other hand, is independent of the ignition source and provides a measure of the rate of hazard development that is characteristic of the fire situation.

BURNING OF A SINGLE FUEL ELEMENT.

The mass burning rate of a single fuel element can obviously be represented as

$$11) \qquad \dot{m} = \dot{m}'' A_t = \rho A_t r_b$$

where ρ is the fuel density, A_t is the area of the surface which is burning at time t and r_b is the linear rate of regression of the fuel surface. For a fire spreading from a small ignition source, A_t will be determined by the rate of surface flame spread, r_s. Thus for central ignition on a horizontal surface

$$A_t = \pi r_s^2 t^2 \tag{12}$$

and

$$\dot{m} = \pi r_b r_s^2 t^2 \tag{13}$$

The flame spread rate will depend on orientation of the fuel surface, but for the initial period of fire growth simple geometric models should suffice.

A more serious difficulty arises because both r_b and r_s are functions of the energy flux to the surface of the fuel. The effect of radiant flux on flame spread rate has been studied by Kashiwagi [9] and by Fernandez-Pello [10], while Tewarson [11] has measured the rate of burning of plastics as a function of incident radiation intensity. The latter has found the burning rate increases linearly with increase in radiant flux over the flux range of practical interest. Radiant energy transfer calculations in real fires are extremely complex due to temperature and concentration gradients and geometric complexity. For our present purpose we will make the simplifying assumption that the radiant flux can be related to the average temperature in the compartment as given by equation 7 while the convective flux to the burning surface of the fuel is constant. Then the total flux per unit area of burning surface is

$$\dot{q}'' = a + b \overline{T}^4 \tag{14}$$

Thus in principle both r_b and r_s can be related to $\dot{m}$.

<u>EXPERIMENTAL EVIDENCE — FIRE GROWTH MODEL VS ACTUAL FIRES.</u>

To judge the degree to which the above model resembles actual fires a number of burning rate histories for full-scale tests available in the literature will be presented. Also the results of a modest experimental program carried out at NBS to judge the sensitivity of the fire growth to the intensity of ignition will be discussed.

The exponential model of fire growth was proposed by Huggett in his analysis of fires within closed vessels. The measure of fire intensity was chosen as the rate of pressure rise within the chamber. The exponential growth model follows immediately from the assumption that the rate of increase of flame volume (v) is proportional to the flame volume, $\frac{dv}{dt} = kv$. All of the complications of fire spread rate within the chamber depending on the source of ignition, materials used, fuel arrangement, and initial values of pressure, temperature, and composition of the chamber atmosphere are lumped into the growth factor k. Available data from the Apollo spacecraft fire (figure 1) for the rate of pressure rise within the craft (proportional to the heat release rate from the fire) clearly shows that the exponential growth model is satisfactory. The model does not provide a means of calculating k without experiment. The value of the growth factor, however, is easily calculated from data like that shown in figure 1. For the Apollo spacecraft fire the growth constant was $k = 0.2$ sec^{-1} indicating that the fire more than doubled in intensity every five seconds.

The initial atmosphere of pure oxygen at slightly above atmospheric pressure undoubtedly contributed to the rapid growth of this fire. Fires with similar fuel loads burning in air can be expected to develop more slowly. In most compartment fires the presence of vents will prevent pressure build-up and allow the escape of hot combustion products, thus further slowing the rate of fire growth.

In recent years detailed measurements have been made of full-scale bedroom fires as part of the NSF/RANN Program in fire research. Weight loss measurements for a bed burning in a fully furnished 10 x 8 x 8 ft room are available [12] (figure 2). For this test the fire was started by a small match-like ignition on the bed mattress. The data in figure 2 show an exponential-like growth of the fire although deviations from a pure

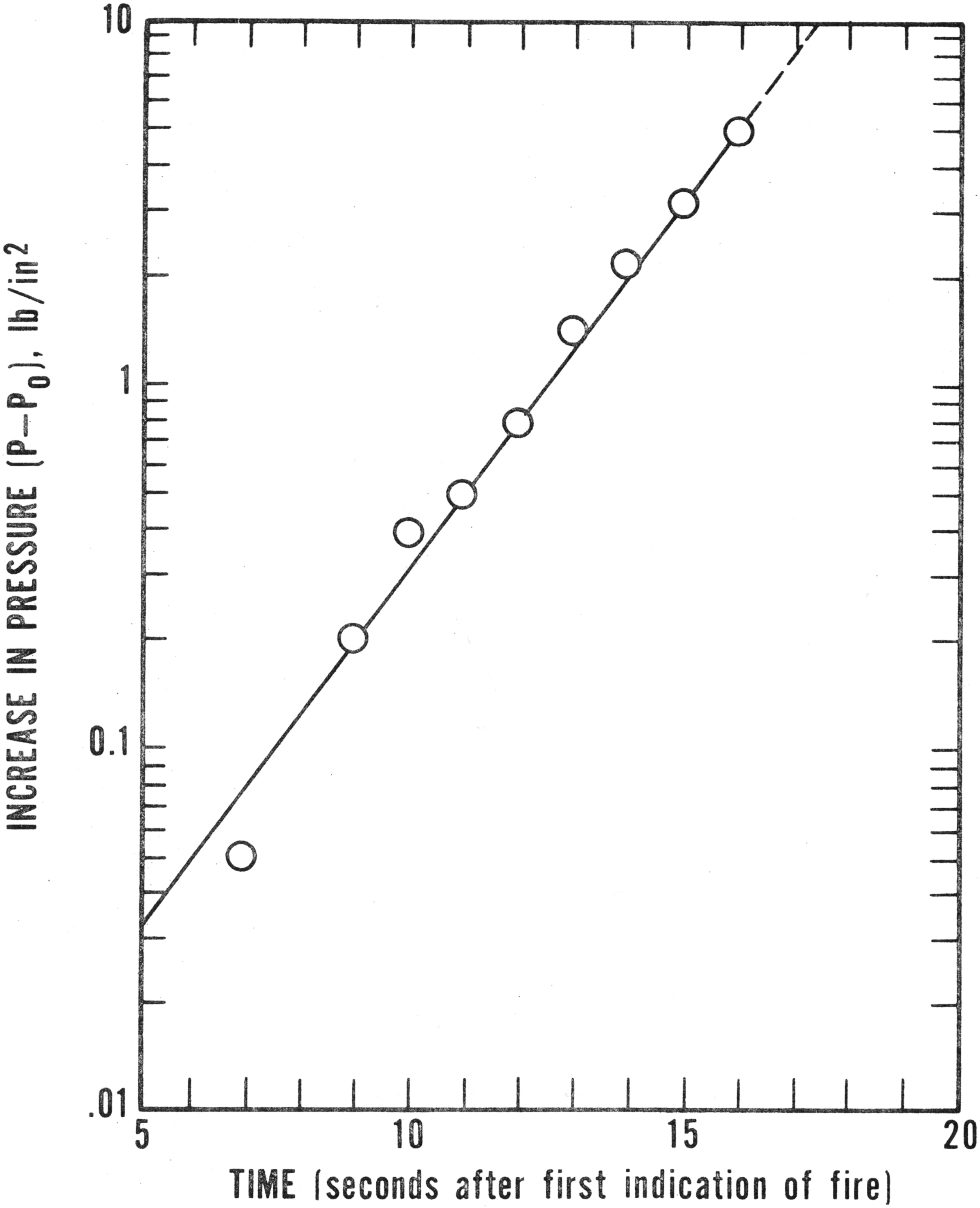


FIGURE 1. EXPONENTIAL GROWTH OF APOLLO SPACECRAFT FIRE (Ref. 6)

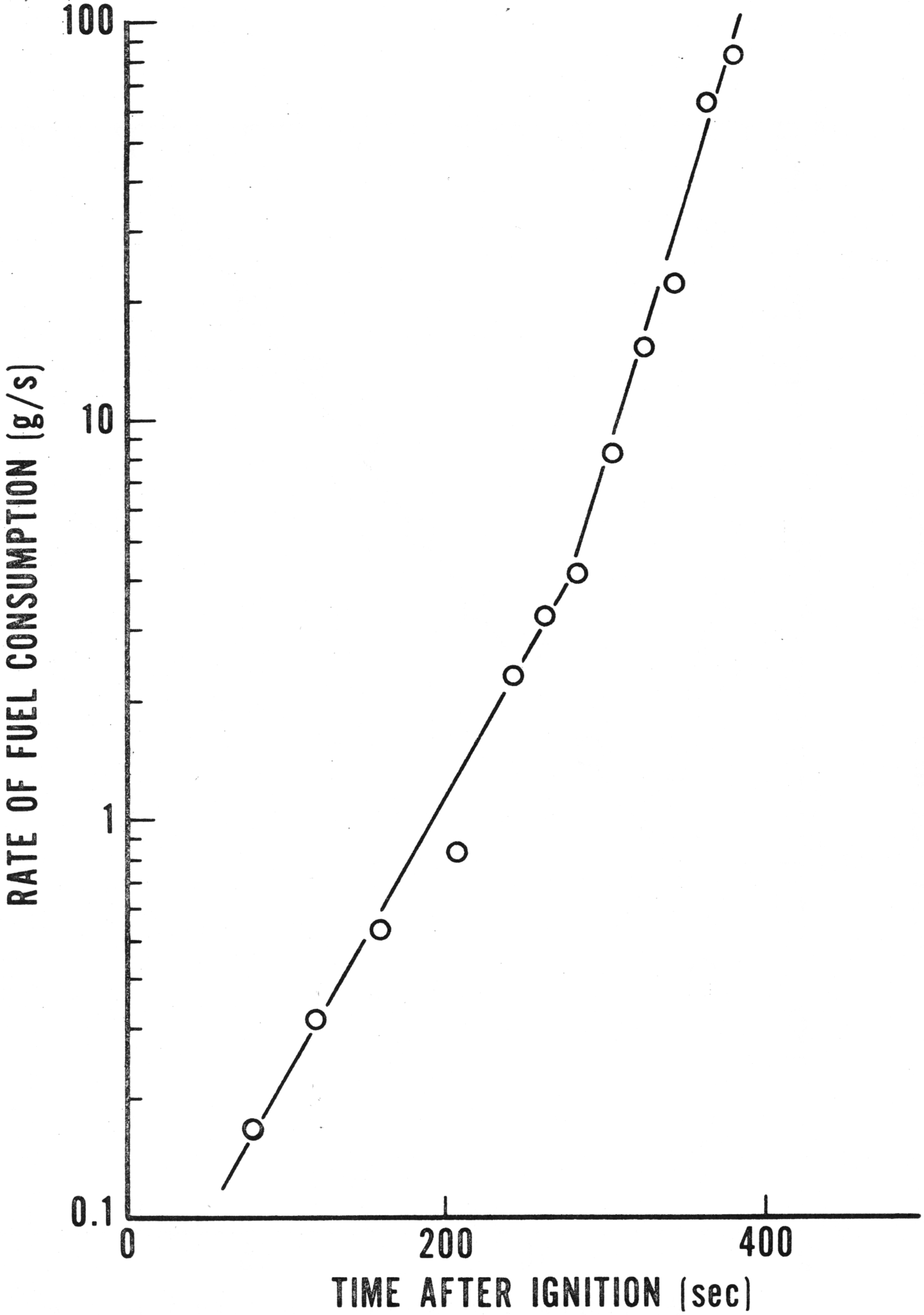


FIGURE 2. GROWTH OF BEDROOM FIRE (Ref. 12)

exponential can be seen. Again, as in the case of the spacecraft fire, a growth factor, in which all the intricate details of the fire spread are lumped, can be calculated from the test data. The line shown in figure 2 is for a growth factor $k = 0.022\ sec^{-1}$, indicating a growth rate 10 times slower than in the spacecraft fire.

In order to study the influence of the enclosure in the NSF/RANN Full-Scale Bedroom Test, Alpert, at Factory Mutual Research Corporation has performed burns of a bed similar to that used in the bedroom fire under a large laboratory hood. Figure 3 shows a comparison of weight loss data from the laboratory test, the bedroom test (also shown in figure 2), and the exponential function - exp (0.022 t). It should be noted that the laboratory data has been shifted by 100 seconds on the plot in figure 3. This shift in time base indicates a change in ignition source as discussed above and does not affect the interpretation of the growth constants for the fires.

The growth constant for each of these fires, as determined from the period of initial fire growth, appears to agree well with the value $k = 0.022\ sec^{-1}$. Noticeable enhancement of the enclosure fire, because of heat feedback from the hot smoke layer in the room, begins at about 350 seconds after ignition while the fire in the open appears to fall off slightly from the exponential growth curve. Up until this time the fires are similar. For the purpose of hazard evaluation, it is the early stages of the fire that are of interest. These data suggest that the growth factor calculated for the early stages of fire growth may be insensitive to the presence of the enclosure. This is not unexpected since interactions between the fire and the compartment configuration (ventilation, radiation, etc.) will only become important when the fire products occupy a significant fraction of the compartment volume. For the time period in which the enclosure has no important influence on the fire, growth constants calculated for data from laboratory mock-up burns could be used with confidence in numerical models of the build-up of smoke and gases in any enclosure. Alpert's bed mock-up was an exact

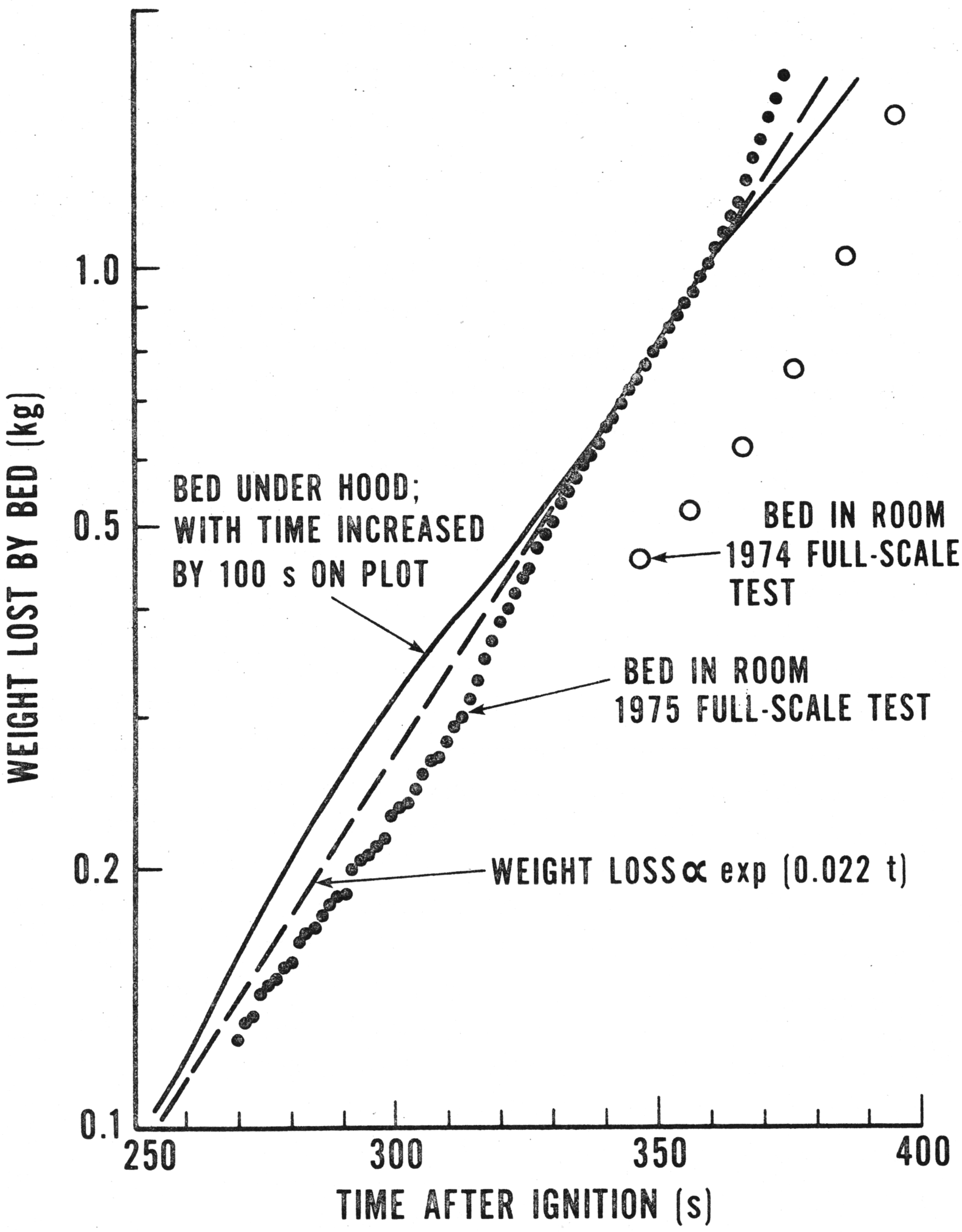


FIGURE 3. COMPARISON OF WEIGHT LOSS DATA - BED FIRES (Ref. 12).

copy of the bed used in the full-scale test except for the headboard. Other work related to this bed burn is the program of mattress burns carried out by Pagni, et al., [13]. Their tests did not involve a bed mock-up, but simply a square sample of mattress material with covering sheet. The materials used for the tests were however essentially identical with those used in Alpert's mock-up. Pagni and Clow recorded an exponential increase in the burning rate of the mattress ($\dot{m} \approx \exp[0.024\ t]$) with time for the first 125 seconds after ignition. This agrees well with Alpert's data for an entire bed. After this time, however, the burning rate fails to maintain its exponential growth, and seems to increase linearly ($\dot{m} \approx 0.02\ t$) for the remaining 65 seconds of mattress test burn. The primary difference between the tests was the absence of a folded top sheet in Pagni and Clow's test. In Alpert's test the folded sheet became involved in the fire at about 125 seconds into the test. In addition, the pillow in Alpert's bed mock-up became involved at 236 seconds. It appears that both of these subsequent ignitions help to sustain the exponential growth of Alpert's fire.

The comparison of these two tests points out the intricate fire details that result in the apparent exponential fire growth. Experiments on the burning of plastic parsons tables at NBS show a similar behavior. The mass burning rate increases exponentially during the early stages of burning but the growth constant decreases at later times as the fuel surfaces become completely involved in the fire (figure 4). It appears that fire growth on single fuel elements can be represented by a simple exponential function of time during the early stages of fire but the growth constant tends to decrease as the fire grows. Therefore, the apparent exponential growth of enclosure fires is intimately related to the sequential ignition of separate fuel elements by the primary fire.

FIRE GROWTH VS IGNITION INTENSITY — EXPONENTIAL MODEL.

The ease of manipulation in the exponential model presented in the first section of "Discussion" is in part due to the fact that the growth

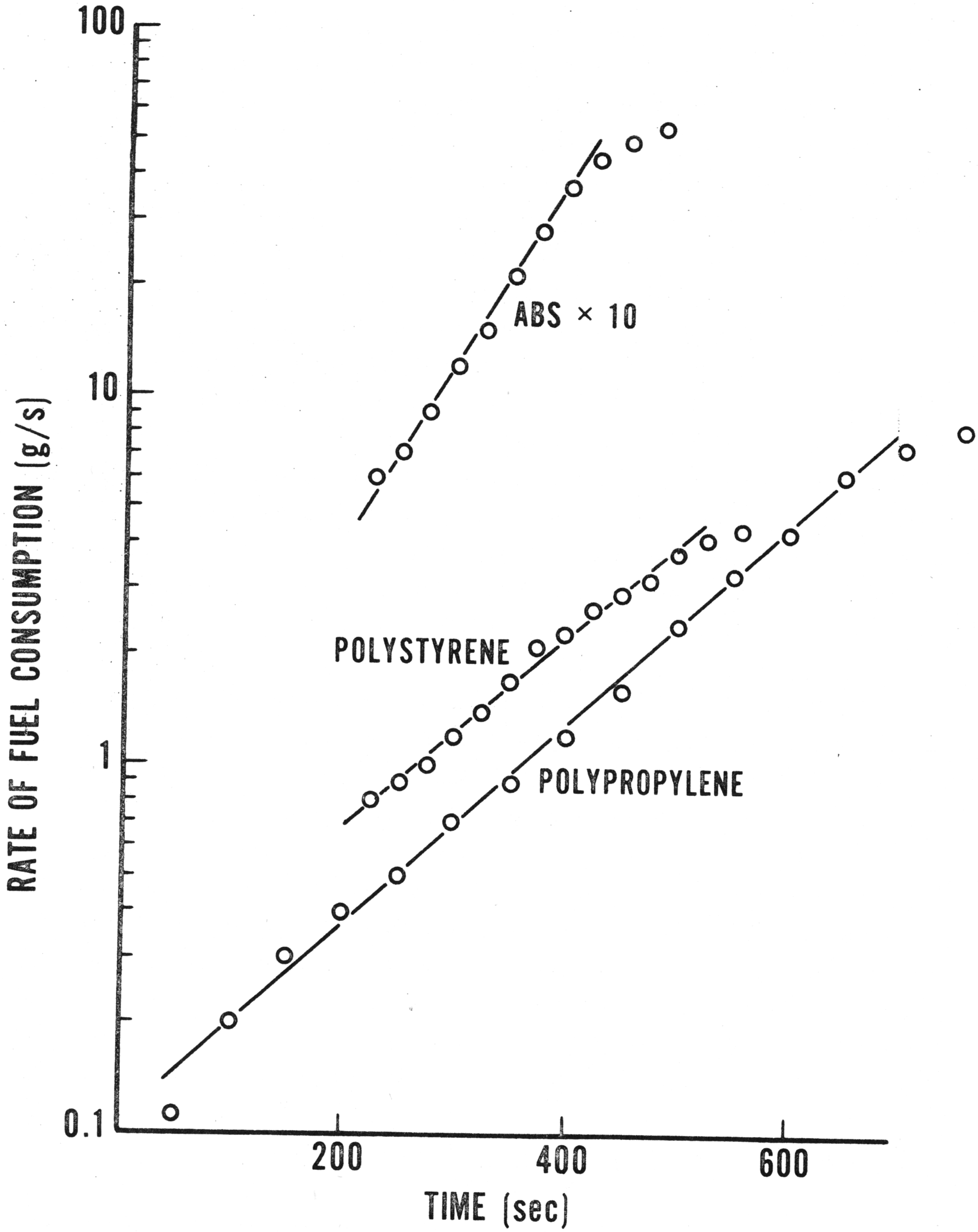


FIGURE 4. RATE OF BURNING OF PLASTIC PARSON TABLES (Ref. 21).

factor, k, was assumed independent of ignition intensity. A modest test program was carried out at NBS to verify this assumption. As most of the experiments discussed to this point have been urethane dominated fires, tests with urethane and polymethyl methacrylate (PMMA) were run to accumulate comparative information on the growth rate of fires.

Three tests will be reported. In each a square slab of material was ignited in the center using methenamine tablets. In figure 5, weight loss data for two fires ignited with a single methenamine tablet in the center of the slab are shown. The urethane foam fire was on a 30 cm square slab, 10 cm thick. For the PMMA fire a 15 cm square slab, 1.75 cm thick was used. Each specimen was mounted on a load cell to record weight loss and burned in a large laboratory under a hood. As has been seen previously, for a single isolated fuel element fire the initial growth factor k is not sustained. The data for PMMA clearly shows an order of magnitude change in the value of the effective k as the test procedes. The values for PMMA growth constant are 2 or 3 orders of magnitude smaller than the value for the urethane test. Thus these data give one some perspective as to the range of values associated with the fire growth factor and the amount of change that can occur during a single fire.

To obtain some data on the effect of ignition intensity on the fire growth constant a second 15 cm square slab of PMMA was burned. In this test the equivalent of 9 methenamine tablets was used to ignite the slab in the center over a base area 9 times that covered by one pill. As before, weight loss measurements were made. In figure 6, the weight loss history from the 9 pill ignition test is compared to the PMMA fire ignited with 1 pill already discussed. The agreement between growth rate factors (relative slope of curves) calculated from either curve a few minutes after ignition is very good. The agreement in the growth of the fires can be illustrated better by shifting the data from the 9 pill ignition to a later time, thus adjusting for the more intense ignition by a shift in the curve as discussed in the section "Exponential Fire

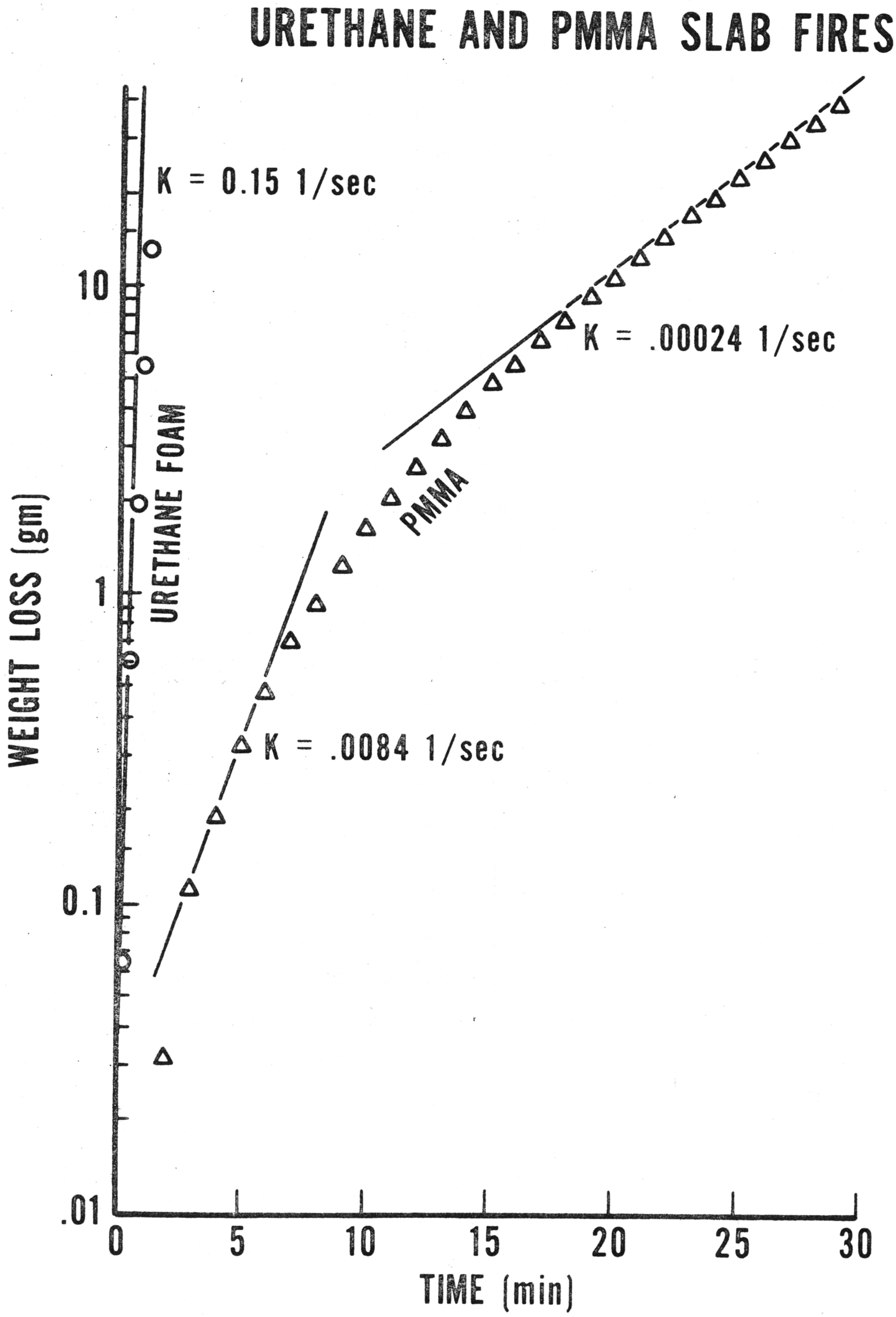


FIGURE 5. GROWTH OF POLYURETHANE FOAM AND POLYMETHYLMETHACRYLATE SLAB FIRES.

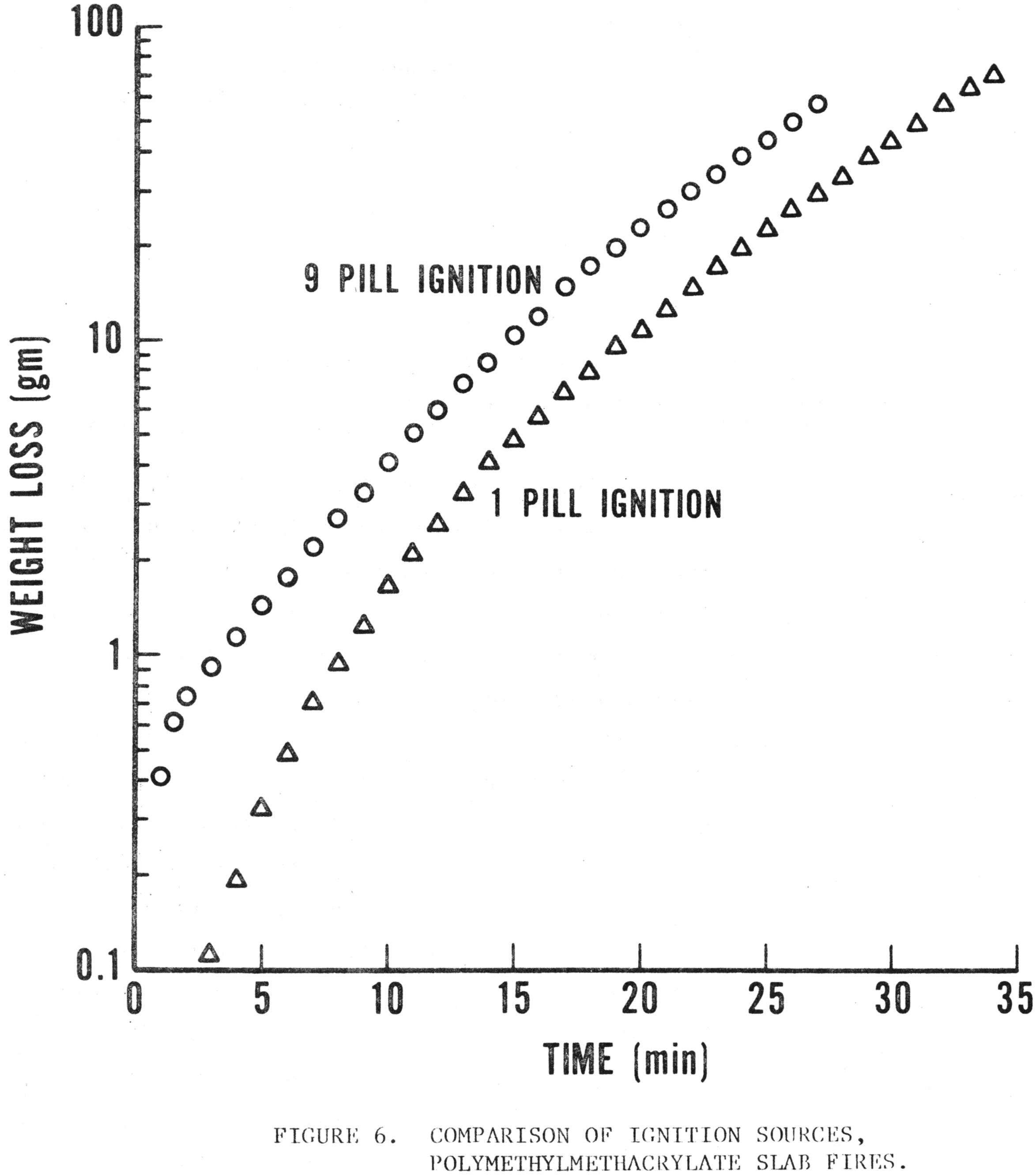


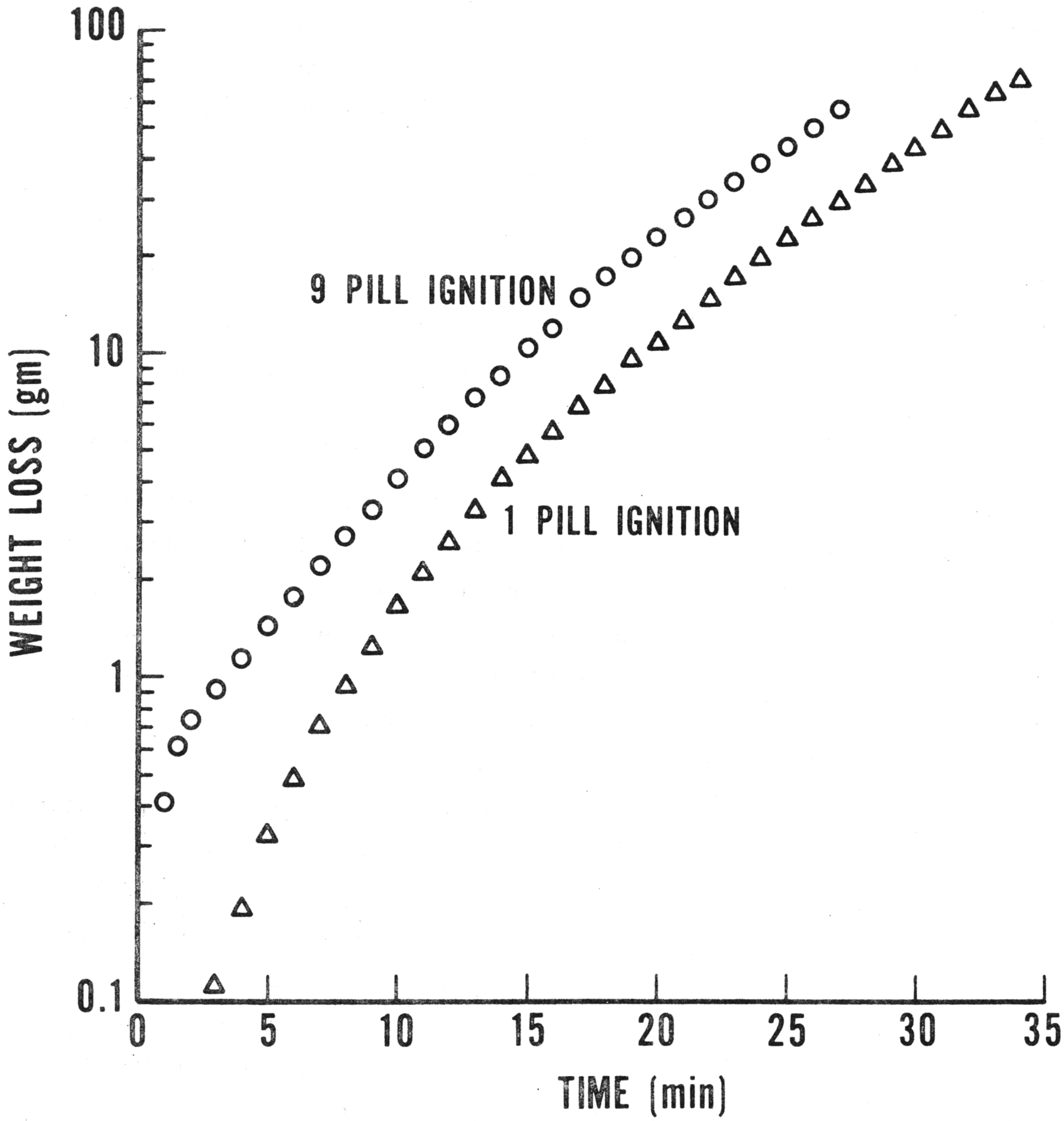
FIGURE 6. COMPARISON OF IGNITION SOURCES, POLYMETHYLMETHACRYLATE SLAB FIRES.

Growth Model." In figure 7, the time base of the 9 pill ignition data has been shifted to match that of the 1 pill ignition at the time of 1 gram weight loss. The agreement in the character of the growth is now obvious. Even though the two fires did not grow in a simple exponential fashion with time, the effective growth rate factor determined from either set of data will be the same. Through these simple experiments some evidence has been presented to verify the assumption of insensitivity of fire growth rate factor to ignition intensity, which is an important point in determining the usefulness of the exponential fire growth model.

DEDUCTIONS FROM EXPERIMENTS.

Several deductions can be drawn from the collection of experimental data presented above. Some caution is in order in reviewing these deductions, as many are interpretations based on a single test.

First, as seen in the case of the spacecraft fire and the full-scale bedroom fire, the exponential model of fire growth is an adequate fit to experimental data for the early stages of enclosure fires. Second, mattress fire data collected by Alpert and Pagni suggests that ignition of additional fuel items in the enclosure by the primary fire is necessary in order to maintain exponential fire growth. The absence of additional fuel elements in the simple single fuel element fire prevents the sustaining of the initial growth rate. Single element fires suggest a continual decrease in effective growth rate factor, k, with time from ignition. This observation requires modifications in the pursuit of the originally envisioned hazard analysis that was based on the determination of a single growth factor k appropriate to the fire spread on a single slab of material in an enclosure. Ease of mathematical manipulation offered by using exponential functions, and the fact that each exponential data fit only involves the determination of two parameters are strong reasons to encourage their use. In most cases an accurate representation of the data may be obtained by using 2 or 3 exponential fits, each applying to a separate time intervals during the fire.



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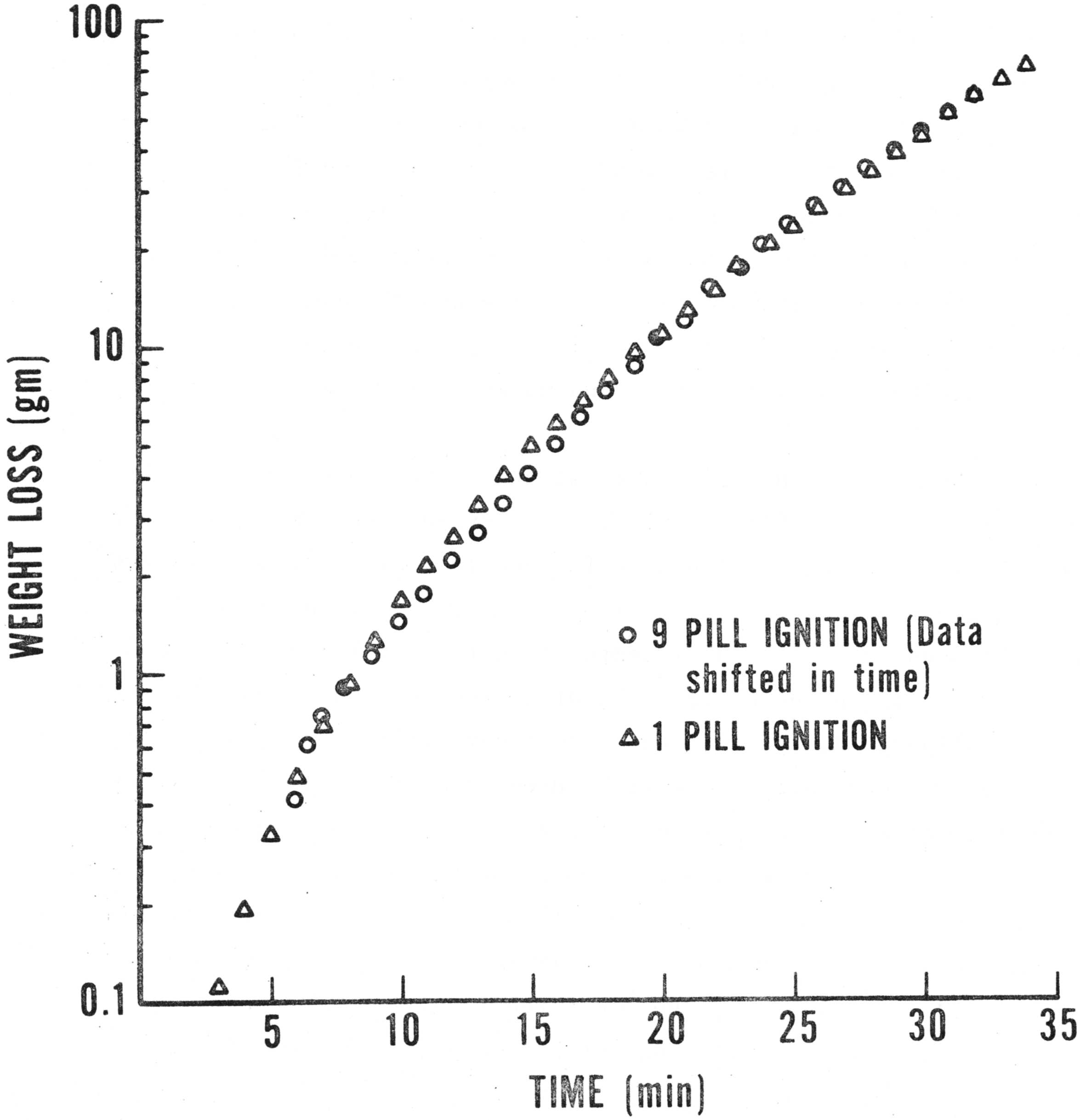

FIGURE 7. COMPARISON OF IGNITION SOURCES, POLYMETHYLMETHACRYLATE SLAB FIRES. TIME BASE SHIFTED TO SHOW SIMILARITY OF FIRE GROWTH RATE.

INTEGRATION OF HAZARDS.

In this section, a method to integrate temperature, smoke, and toxic gas hazard values will be developed using an exponential model for fire growth. For all of the calculations to follow, the burning rate of the fire as a function of time is assumed to be a known function of measurable properties of the system. Therefore, the major road block to the application of the hazard assessment schemes to be presented is a reliable, simple method to estimate the enclosure fire growth rate. Lacking this complete model, it still appears possible to estimate relative changes in hazard due to changes in design and material from limited data.

Through experiment, it has been demonstrated that the exponential fire growth model is applicable in the closed, oxygen rich atmosphere of the space capsule fire and for the open full-scale bedroom fire where gases flow in and out of the enclosure freely. A method of integrating combustion hazards that depends on temperature rise or the accumulation of smoke or gases in an enclosure will, of course, depend on how the enclosure is configured and ventilated. The non-ventilated system is the easiest case to deal with and will be used as a first illustration of the development of an integration of hazards. The cases in which flow of gases in and out of the enclosure occurs during the fire is significantly more complicated to analyze. A simplified model with uniform airflow, which may be more appropriate to the aircraft fire situation than the closed vessel case, will also be presented to give some perspective to the overall problem of developing integrated hazards from material properties through mathematical fire modeling.

CABIN FIRE WITHOUT VENTILATION.

The integrated hazards value for temperature, smoke, and gases is based on determining the time needed for conditions in an enclosure to reach a predetermined level of untenability. Depending on the material, temperature, smoke, or one of many hazardous gases may be the limiting quantity in determining the time to reach a hazardous condition. As discussed above, the rates of temperature rise and of smoke and gas accumulation can be estimated from the mass burning rate, $\dot{m}$, and the times needed to reach hazardous conditions due to each of these parameters may be developed independently.

Consider a situation in which the time (t^*_g) to reach a hazardous concentration of a combustion gas (C^*_g) only depends on the burning rate ($\dot{m}$), the volume of the enclosure (V) and the quantity of the combustion gas evolved from a unit mass of burned material (α). Similarly, the time (t^*_s) to reach a hazardous level of accumulated smoke (D/L)* will only depend on $\dot{m}$, V, and (MOD), and the time to reach a hazardous temperature (T*) will depend on $\dot{m}$, $\overline{C}$, ΔH and ε.

One fire that meets these requirements is a fire in an aircraft cabin of volume V, in which a single material is burning at a rate $\dot{m} = \dot{m}_o e^{kt}$. The cabin will be closed. Mixing of gases and smoke within the cabin is assumed to be uniform and immediate. It follows that the mass of fuel consumed from the time of ignition t = 0 to an arbitrary time t will be

15) $$\Delta m = \int_o^t \dot{m}\, dt = \frac{\dot{m}_o}{k} (e^{kt} - 1)$$

In the closed cabin, gases and smoke will accumulate in time to the following concentration

16) $$C_g = \int_o^t \dot{C}_g\, dt = \frac{\alpha \dot{m}_o}{V\, k} (e^{kt} - 1)$$

17) $$(D/L) = \int_o^t (\dot{D}/L)\, dt = \frac{(MOD)\, \dot{m}_o}{V\, k} (e^{kt} - 1)$$

and the temperature will be

$$18)\quad T = T_o + \Delta T = T_o + \frac{1}{\overline{C}}\int_o^t \dot{q}\, dt = T_o + \frac{\Delta H \varepsilon}{\overline{C}}\frac{\dot{m}_o}{k}(e^{kt} - 1)$$

The times to reach hazardous conditions can be calculated from the equations above:

$$19)\qquad t^*_g = \frac{1}{k}\, ln\left(\frac{C^*_g\, V\, k}{\alpha\, \dot{m}_o} + 1\right)$$

$$20)\qquad t^*_s = \frac{1}{k}\, ln\left(\frac{(D/L)^*\, V\, k}{(MOD)\, \dot{m}_o} + 1\right)$$

$$21)\qquad t^*_T = \frac{1}{k}\, ln\left(\frac{(T^* - T_o)\, \overline{C}\, k}{\Delta\, H\, \varepsilon\, \dot{m}_o} + 1\right)$$

One may set the various hazard potential values of a material as equal to the reciprocals of these times

$$22)\qquad h_g = \frac{1}{t^*_g} = k/ln\left(\frac{C_g{*}\, V\, k}{\alpha\, \dot{m}_o} + 1\right)$$

$$23)\qquad h_s = \frac{1}{t^*_s} = k/ln\left(\frac{(D/L)^*\, V\, k}{(MOD)\, \dot{m}_o} + 1\right)$$

$$24)\qquad h_T = \frac{1}{t^*_T} = k/ln\left(\frac{(T^* - T_o)\, \overline{C}\, k}{\Delta\, H\, \varepsilon\, \dot{m}_o} + 1\right)$$

The critical hazard value for the material would be the greatest of the three (the smallest escape time). Depending on the material, either temperature, smoke, or a toxic gas may be the limiting hazard for a material in a particular situation. Thus the concept of integrating hazards does not imply a combination of various hazard parameters by some mathematical formula, but rather a determination of which parameter will be controlling in a given situation.

The selection of appropriate critical hazard levels T^*, C_g^* and $(D/L)^*$, is beyond the scope of this study. These questions have been discussed extensively elsewhere. Given suitable values for these quantities, the procedures outlined above offer an approach for estimating the relative times at which critical levels of the various hazard parameters may be reached, identifying the critical hazard mode, and predicting the effects of changes in design and materials on the rate of development of hazard.

CABIN FIRE WITH CONSTANT VENTILATION.

Slightly more complicated to model than the closed cabin fire is the fire in a cabin with constant ventilation. Even though the resulting hazards value will be more complicated to evaluate, its use may be justified because the model is more realistic.

In concept, we will consider the case of a single material fire burning at rate $\dot{m} = \dot{m}_o e^{kt}$ in a cabin of volume V, with air circulating through the cabin at a constant rate $\dot{m}_{air}$. The mixing of the gases and smoke within the cabin will be assumed uniform and immediate. As in the closed cabin the mass of fuel consumed in time t is

25) $$\Delta m = \frac{\dot{m}_o}{k} (e^{kt} - 1)$$

There is no reason to believe that $\dot{m}_o$ and k will maintain the same numerical values in this case compared to the non-ventilated cabin fire. The temperature and concentration of combustion gases and smoke within the cabin as a function of time must be calculated from the differential equations. For simplicity the mean density of the gases within the cabin will be assumed constant and equal to air.

26) $$\alpha \dot{m}_o e^{kt} - \frac{\dot{m}_{air}}{\rho_{air}} C_g = V \frac{dC_g}{dt}$$

27) $$(MOD)\ \dot{m}_o e^{kt} - \frac{\dot{m}_{air}}{\rho_{air}} (D/L) = V \frac{d(D/L)}{dt}$$

28) $$\Delta H\ \varepsilon\ \dot{m}_o{}^{kt} - \dot{m}_{air} C_p (T-T_o) = \overline{C} \frac{dT}{dt}$$

The initial conditions are zero concentrations of smoke and combustion gases in the cabin and $T = T_o$ at the time of fire ignition, $(t = 0)$.

The above equations cannot be solved explicitly for the time to reach a hazardous condition, t_T*, t_s*, or t_g*. Solutions for the temperature and the concentration of any combustion gas or smoke as a function of time can be obtained. They are

29) $$C_g = \frac{\alpha \dot{m}_o}{\frac{\dot{m}_{air}}{\rho_{air}} + V k} \left[e^{kt} - e^{-\frac{\dot{m}_{air}}{V \rho_{air}} t} \right]$$

30) $$(D/L) = \frac{(MOD)\ \dot{m}_o}{\frac{\dot{m}_{air}}{\rho_{air}} + Vk} \left[e^{kt} - e^{-\frac{\dot{m}_{air}}{V\rho_{air}} t} \right]$$

$$T-T_o = \frac{\Delta H \, \varepsilon \, \dot{m}_o}{\dot{m}_{air} C_p + \bar{C} k} \left[e^{kt} - e^{-\frac{\dot{m}_{air} C_p}{\bar{C}} t} \right] \tag{31}$$

The addition of a simple uniform flow of air through the aircraft cabin has complicated the solution of the problem to the extent that numerical means are necessary to calculate the time to reach a hazardous level of smoke or combustion products. For long times after ignition, the second term in the parenthesis can be neglected with respect to the first. Here a long time is defined as

$$t > 3 \frac{V \rho_{air}}{\dot{m}_{air}} \tag{32}$$

Since, for an airplane cabin $\frac{V \rho_{air}}{\dot{m}_{air}}$ is approximately 5 min, the approximation would be of little interest in this study where the safe exit time is relatively short.

It should be clear that the addition of more realistic assumptions concerning the distribution of smoke or gases within the cabin will result in increasing the complexity of the solution, thus increasing the need for numerical evaluation and decreasing the utility of the solution for the purpose of establishing acceptable performance.

MEASUREMENT OF PROPERTIES

We have proposed that the initial stages of fire growth in a compartment (the time critical to the safety of the occupants) should be predictable, to the degree of approximation useful in establishing practical standards, from a relatively few parameters of the system and laboratory measurable properties of the principal fuels. In this section we discuss the quantities necessary to predict performance and the methods by which they may be estimated.

SYSTEM PROPERTIES

The following parameters of the fire system appear to be a minimum set necessary to make approximate prediction of fire growth and hazard development in a compartment.

V. The volume of the compartment. It is assumed that in an inhabited compartment the ratios of height to width to length will fall within current design limits. Extreme geometries will present special problem.

L The optical path length. This may be taken as the distance an occupant would have to travel to reach an exit.

$\overline{C}$ The effective heat capacity or thermal inertia of the system. This will be largely determined by the area and thermophysical properties of the compartment lining materials and furnishings.

$\dot{m}_{air}$ The ventilation rate. This may be due to forced ventilation or to natural ventilation in the case of a compartment with openings to the exterior.

$\dot{m}_o$ An arbitrary parameter related to the ignition conditions of the fire. A suitable value can be estimated from simple experiments, but the exact choice of value will not affect the calculation of the relative rates of hazard development since all three hazard parameters are linearly related to $\dot{m}_o$.

MATERIAL PROPERTIES

ρ The fuel density

ΔH_c The heat of combustion of the fuel, determined by standard calorimetric techniques

ε The combustion efficiency, the fraction of the theoretical heat of combustion released in the fire. A method of determining ε for textile materials is given by Yeh and Birky [14]. The various rate of heat release calorimeters under development such as the Ohio State (5] or NBS [15] calorimeter, if modified to permit simultaneous determination of weight loss, would be suitable for the measurement of for heavier fuels. A method based on the measurement of oxygen consumption, under development by Sennsenig and Parker (16], appears particularly promising.

r_s The flame spread rate. Methods of measuring flame spread rates as a function of orientation and energy flux have been described by Kashiwagi [9] and by Fernandez-Pello [10].

r_b The linear burning rate. The burning rates of a number of materials, as a function of surface energy flux, have been measured by Tewarson [11]. The method appears suitable for this study.

(MOD) The mass optical density. Seader [7] has described modifications to the Smoke Density Chamber [17] which permit the determination of (MOD). Two values will be required, one for smoldering combustion and another for flaming combustion.

α The gas generation coefficient. If the combustion toxicology of a material can be characterized by the quantity of one or a few gases generated during burning, standard analytical methods such as those used by Spurgeon [18] can be used to determine α. However, the complexity of the product mixture, lack of knowledge of the intrinsic toxicity of many of the components, and the possibilities for interaction make it desirable to use a biological assay for the estimation of α. This problem has been discussed by Birky [19]. A number of procedures are under development for the purpose, such as that of Smith [20], and could readily be adapted to the present requirements.

CONCLUSIONS

1. The rate of growth of fire in a compartment during its early stages, the critical time with respect to the safety of the occupants, can be approximated by a simple exponential in time.

2. A small number of system parameters and laboratory measurable fuel properties are identified as necessary for the estimation of the rate of fire growth.

3. The rates of development of hazardous conditions in a compartment due to temperature rise, smoke accumulation, and toxic gas production can all be related, through simplified mathematical equations, to the rate of fire growth as measured by the mass fuel consumption rate.

4. The time at which a burning enclosure becomes untenable due to high temperature, smoke, or gas can be estimated and the shortest of these times then defines the critical hazard parameter for a given system.

5. The exponential fire growth model can provide a simple mathematical technique for estimating the relative rates of hazard development for different materials systems and comparing the effects of changes in material and design on the rate of hazard development.

6. Laboratory methods are available or under development to provide the necessary materials combustion properties data.

7. For fires involving a single fuel element, the simple exponential model of fire growth is not adequate as the value of the growth constant decreases with increasing fire size.

8. The simple exponential growth model may provide a means of predicting relative hazard of different materials in a manner to allow their respective merits to be tentatively assessed. Further elaboration of the model to increase its accuracy is possible at the cost of increased complexity.

9. The relationship of the effective exponential constant for fire growth to the material properties and geometric factors needs further elucidation.

REFERENCES

[1] DOT, Federal Aviation Administration, Airworthiness Standards: Transport Category Airplanes, Federal Aviation Regulations, Vol. III, Part 25, Transmittal 10, effective May 1, 1972.

[2] DOT, Federal Aviation Administration, Flight Standards Service, Transport Category Airplanes, Smoke Emission from Compartment Interior Materials, Notice of Proposed Rule Making, Federal Register, Vol. 40, p. 6505, February 12, 1975.

[3] DOT, Federal Aviation Administration, Flight Standards Service, Compartment Interior Materials: Toxic Gas Emission, Proposed Standards, Advance Notice of Proposed Rule Making, Federal Register, Vol. 39, p. 45044, December 30, 1974.

[4] Reeves, J. B., and MacArthus, D.C., Dayton Aircraft Cabin Fire Model, Vol 1 - Basic Mathematical Model, Vol. 2 - Laboratory Test Program, Report No. FAA-RD-76-120, I & II, Final Report, June 1976.

[5] Smith, E. E., Measuring Rates of Heat, Smoke, and Toxic Gas Release, Fire Technology, 8, 237 (1972).

[6] Huggett, C., Combustion Processes in the Aerospace Environment, Aerospace Medicine, 40, 1176 (1969).

[7] Seader, J. D. and Chien, W. P., Mass Optical Density as a Correlating Parameter for the NBS Smoke Density Chamber, J. Fire & Flammability, 5, 151 (1974).

[8] Gross, D., and Robertson, A. F., Self-Ignition Temperature of Materials from Kinetic Reaction Data,J. Res. NBS, 61, 413 (1958).

[9] Kashiwagi, T., "A Study of Flame Spread over Porous Materials under External Radiation Fluxes," Fifteenth Symposium (International) on Combustion, The Combustion Institute, 255-265 (1974).

[10] Fernandez-Pello, A. C., Fire Spread over Vertical Fuel Surfaces Under the Influence of Externally Applied Thermal Radiation, Harvard University, Home Fire Project Technical Report No. 19, January 1977.

[11] Tewarson, A. and Pion, R. F., Flammability of Plastic - I. Burning Intensity, Combustion Flame, 26, 85 (1970).

[12] "First, Second and Third Full-Scale Bedroom Fire Tests of the Home Fire Project," FMRC Serial No. 21011.4-6, Technical Reports, RC74-T-31 (1974), RC75-T-31 (1975), RC-B-48 (1975).

[13] Pagni, P. J., Claw, K. H., Heffner, G., and Bard, S., Observations on the Burning of Urethane Mattresses Western States Section of the Combustion Institute Paper No. 76-35, October 1976

[14] Birky, M. M., and Yeh, K-N, Calorimetric Study of Flammable Fabrics I. Instrumentation and Measurements, J. App. Poly. Sci., 17, 239 (1973).

[15] Parker, W. J. and Long, M. E., Development of a Heat Release Rate Calorimeter at NBS, Ignition, Heat Release, and Noncombustibility of Materials, ASTM STP 502, p. 135 (1972).

[16] Sensenig, D., and Parker, W. J., Report in Preparation, National Bureau of Standards.

[17] Standard Test Method for Smoke Generated by Solid Materials, NFPA 258, National Fire Protection Association, Boston, Ma.

[18] Spurgeon, J. C., Speitel, L. C. and Feher, R. E., Thermal Decomposition Products of Aircraft Interior Materials, Report No. FAA-RD-77-20, Final Report, April 1977.

[19] Birky, M. M., Review of Smoke and Toxic Gas Hazards in Fire Environment, International Symposium, Fire Safety of Combustible Materials, University of Edinburgh, October 1975.

[20] Smith, P., Material Toxicology Evaluation by Direct Animal Exposure, International Symposium on Toxicology and Physiology of Combustion Products, University of Utah, March 1976.

[21] Davis, S., unpublished data, National Bureau of Standards.