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Naval Shipboard Fire Risk Criteria - Berthing Compartment Fire Study and Fire Performance Guidelines

B. T. Lee and W. J. Parker

Center for Fire Research
Institute for Applied Technology
National Bureau of Standards
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Final Report

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Ship Damage Prevention and Control
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Edward O. Vetter, *Under Secretary*
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

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NOMENCLATURE

A	floor area
A_B	potential bulkhead area contributing to the fire
A_i	burning area of i-th combustible
A_o	potential overhead area contributing to the fire
A_u	area of heated surface in upper part of compartment
B	mass burning rate
B_s	mass burning rate required to consume all of the incoming air
C	heat capacity
C_o	heat capacity at ambient temperature
D	density of ambient air
f	ratio of effective radiating area to the area of the heater surface, A_u, in the upper part of the compartment
F_s	flame spread factor
h	height of doorway
I_s	flame spread index
K	thermal conductivity
L	effective heat transfer coefficient equal to ratio of heat losses per unit area and the temperature rise, $(T_g - T_o)$
L_c	heat loss coefficient by conduction
L_R	heat loss coefficient by radiation
Q	net heat of combustion of burning materials
$\dot{q}_i$	heat release rate per unit area of i-th combustible
$\dot{q}_m$	maximum one minute averaged rate of heat release per unit area of material
t	time
T_g	temperature of the hot air in the upper part of compartment
T_o	ambient temperature of air
T_s	temperature of hot surfaces in upper portion of compartment
V	Volume
$\dot{V}$	Volumetric flow rate of incoming air
w	width of doorway

X thickness of walls and ceiling

ε emissivity of surface

θ^* characteristic temperature rise of air in upper part of room

$$\theta^* = QB_s/DC_o\dot{V}$$

σ Stefan-Boltzmann constant

ρ density of material

SI CONVERSION UNITS

In view of the present accepted engineering practice in this country, common U.S. Units of measurement have been used throughout this report. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measurements which gave official status to the metric SI system of units in 1960, we assist the readers interested in making use of the coherent system of SI units by giving conversion factors applicable to the U.S. units used in this report.

Length

1 in = 0.0254 meter
1 ft = 0.3048 meter

Mass

1 lb = 0.4536 kilogram

Temperature

Temperature in °F = 9/5 (temperature in °C) + 32 °F

Energy

1 Btu = 1054.6 joules

Power

1 Btu/s = 1054.6 watts

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BERTHING COMPARTMENT FIRE STUDY AND FIRE PERFORMANCE GUIDELINES

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Abstract

Judicious application of shipboard materials and choice of compartment furnishings can significantly reduce the threat of serious fire on board ship. Unfortunately, the fire performance of materials is currently difficult to ascertain from laboratory fire tests on the materials. Full size and quarter-scale compartment fires in conjunction with an analytical treatment were performed to obtain an improved understanding of the relationships between the laboratory fire test assessment and the observed behavior of materials in actual fires. The compartment fire experiments indicated that the temperature of the hot air layer below the ceiling is a suitable quantitative measure of the level of fire buildup in a compartment. When this temperature exceeds 700 °C there is sufficient radiation from the hot air layer and the heated upper surfaces to cause ignition of all combustible materials in the compartment. For a 3 x 3 x 2.1 m (10 x 10 x 7 ft) space lined with asbestos millboard having a 0.69 x 1.9 m (27 x 75 in) open doorway, a heat production rate of about 72 kW/m^2 ($6.3 Btu/s/ft^2$) of deck area is enough to attain this condition. Fires in some bunk configurations alone could exceed this critical rate of heat generation. Ventilation and its points of application were found to be very important considerations. Observations of the fire scenarios in the compartment tests along with an empirical and analytical analysis of fire growth in compartment spaces have resulted in an improved application of the fire test ratings. Consequently more rational design rules for fire safe material usage have been developed taking into account the ignitability, flame spread, rate of heat release, potential heat and smoke generation potential of materials. The study also indicated the practicality of using quarter-scale fire tests for studying fire performance in full size compartments.

1. INTRODUCTION

An accidental fire represents a potential major hazard to which a Naval ship is in constant danger of exposure. Effective ship design and damage control features permit most shipboard fires to be quickly brought under control with minimal property loss and little threat to the life safety of the crew. One of the most important elements of ship design is the judicious selection of materials for the ship's interior finish and choice of compartment furnishings to minimize the spread of fire, generation of smoke and gaseous combustion products, and the amount of additional fuel contributed to an on-going fire. The present Navy fire performance requirements given in MIL. STD 1623 for interior finish materials and furnishings [1][1] provided a significant improvement in the selection of fire safe materials. This military standard offered laboratory fire test limits on the surface flammability and smoke potential of many categories of materials. Unfortunately, the fire performance of materials is presently difficult to assess solely on the basis of laboratory tests.

[1] Numbers in brackets refer to the literature references listed at the end of this paper.

Ideally, the fire behavior of any one material or group of materials should be evaluated along with the room and its furnishings so that the combination will have a low probability of full involvement in the event of an accidental ignition. Prerequisite to this approach is a better understanding of the fluid dynamic, thermal, physical and chemical factors important in controlling the growth and spread of fire and combustion products within compartments. Concurrent with the need for fuller understanding of the fire phenomena is an improved interpretation and application of present test methods and/or better laboratory test methods which can provide meaningful correlation with fire buildup in the compartment. Some progress has been made in this direction with the on-going research on room fire growth at the Bureau of Standards [2]. In the latter study a variety of wall and ceiling panels in a full-scale room corner has been exposed to a wood crib fire to evaluate their contribution to room fire buildup. The results of these fire tests were compared with laboratory tests of the ignitability, flame spread, rate of heat release and smoke generation potential of the materials.

The shipboard fire research program for the Navy has also been designed to help fulfill the above needs. The project was structured in three phases. During the first phase of this project a review was made of the existing specifications for shipboard construction materials and the test methods used to determine fire performance. The survey indicated that a wide variety of tests were being used in conjunction with different criteria to evaluate materials designated for identical or similar usage.

A set of three standardized tests on surface flammability, fuel contribution and smoke generation were recommended to replace a variety of tests in the Navy's material specifications. Specifically, these tests were the ASTM E-162 radiant panel, the potential heat test, and the smoke density chamber. All of these tests had been developed previously at the Bureau. The acceptance criteria recommended for the tests depended on the designated usage of the material.

It was also indicated that ignitability and the rate of heat release were important in determining the potential fire hazards of materials and that the development of suitable laboratory test methods for these properties should be undertaken in the second phase of the program. Furthermore, tests should be conducted in full-scale compartments with selected lining materials whose fire properties would also be measured by these five tests. This would establish the ability of the laboratory tests and their associated acceptance levels to provide a valid measure of fire risk without excessive restrictions on the materials that could be used aboard ship. This information was included in the Phase I report [3].

An ease-of-ignition test, which measures the exposure time required for sustained ignition by flame contact, and a heat release rate calorimeter were developed and tested on a variety of materials under Phase II. Their operations have been described in progress reports [4,5].

Phase III, covered in this report, has had the following objectives:

(1) to determine the physical conditions and interior materials likely to lead to full fire involvement of a furnished compartment and potential spread to other shipboard areas, and

(2) to improve fire risk criteria for material usage on board ship.

This report describes the full-scale compartment fires and quarter-scale modeling of these fires and includes material ratings with the above five laboratory fire tests and their comparison with their contribution to fire growth observed in the compartment fires. A brief description of a new test being developed for evaluating the flammability of floor and deck coverings has also been included. In addition, a preliminary analytical method is given for predicting the fire hazard potential of full size furnished compartments. Starting with a basic heat balance for a compartment containing combustible furnishings and interior linings, the analysis section evaluates the rates of heat generated, absorbed and lost and establishes a method for calculating temperatures in the compartment. This assists in establishing a basis for fire safe guidelines for construction material usage. This report also includes improved fire risk criteria for material selection.

2. FACILITIES AND EXPERIMENTAL TESTS

2.1. Full Size Compartment Fires

The berthing compartment fire tests were conducted in a 3.1 x 3.1 m (10 x 10 ft) room having a 2.1 m (7 ft) drop ceiling and a 0.69 x 1.9 m (27 x 75 in) doorway, figure 1. The room was only one-half of the smallest size normally encountered aboard ship, but it was desirable to make this reduction in order to use the existing burnout room at NBS. The compartment was located within a large building, so that the effects of wind and temperature extremes were eliminated. Two walls were lined with 2.5 cm (one inch) fiberglass. The other sides were covered with 1.59 mm (1/16 in) decorative aluminum panels over 5.1 x 10.2 cm (2 x 4 in) steel studs 40.6 cm (16 in) apart. The decorative coatings on the aluminum were either vinyl or melamine. The deck was 0.64 cm (1/4 in) mild steel over a brick floor. A sliding door having a 0.093 m^2 (one foot square) exhaust port was used. In situations where the doorway was partially or fully opened, the exhaust port was closed. When the door was closed the exhaust port was open. Provisions for forced air ventilation into the compartment were available at a ceiling vent at the rear of the room and at terminals located at each bunk, figure 2. The total flow rate of this air was roughly 4.5 m^3/min (160 ft^3/min). A viewing port was also located on one wall.

In line with the reduction in compartment size the contents of the space was restricted to the needs of three crew members. These contents include a modular crew berth three high, and a large fully opened locker, figure 2. The latter was filled with 33 kg (72 pounds) of simulated clothing. The bedding for each crew member weighed 14.5 kg (32 pounds) and was in considerable disorder to promote a rapid growth of the fire, simulating worst case conditions. Table 1 lists the interior linings used in this study. Other furnishings such as the locker contents, bedding and clothes are indicated on table 2.

Measurements made to characterize the thermal environment in the compartment included ceiling and wall temperatures, vertical temperature profile down from the center of the ceiling, air temperature near the top of the doorway, radiation incident on the deck, air inflow velocity near the bottom of the doorway and the weight loss rate of the bedding. Auxiliary measurements to fully describe the fire included smoke obscuration, oxygen and carbon monoxide concentrations at the top of the doorway and inside the compartment. Temperatures were measured with 0.025 cm (0.010 in) diameter chromel-alumel thermocouples. The thermal radiation incident on the lower portion of the room was monitored with a water-cooled Gardon-type total heat flux gage. Crumpled up newsprint on the deck was also used to indicate if and when the irradiance was sufficient to ignite light combustible materials. A hot wire anemometer was used to measure the air inflow velocities. A chemical cell and infrared analyzer were used to record the oxygen and carbon monoxide, respectively. Weight loss, i.e., fuel depletion, in the berths was measured by suspending the three-man unit with an overhead pulley connected to a load cell transducer. The location of all instrumentation in the compartment is indicated in figure 1. Thirteen test arrangements were considered and are indicated in table 1.

Table 1. Compartment Fire Tests

Model Test*	Full-Scale Test	Lining Variable	Door	Air Supply**	Bunk	Bunk Location
M1	1	Standard Set	Closed	Off	Closed	Side
M2	2	Standard Set	Closed	On	Closed	Side
M3	3A	Standard Set	Open	At Bunks	Closed	Side
M3B	3B	Standard Set	Open	On	Closed	Side
	4A	Standard Set	Open	On	Open	Side
M4B	4B	Standard Set	Open	On	Open	Side
M5	5	High Density Acoustical Panels on Overhead	Open	On	Closed	Side
M6	6	Melamine Coated Panels on Bulkhead	Open	On	Closed	Side
M7	7	Wool Carpet and Pad on Deck	Open	On	Closed	Side
M8	8	Wool Carpet and Pad on Deck	1/2 Open	Off	Closed	Back
M9	9***	Wool Carpet and Pad on Deck and Curtains Over Bunk Openings	1/2 Open	Off	Closed	Back
	10***	Acrylic Carpet and Pad on Deck and Curtains Over Bunk Openings	1/2 Open	Off	Closed	Back
	11	80% Wool-20% Phenol-Formaldehyde Carpet and Pad on Deck and Curtains Over Bunk Openings	1/2 Open	Off	Closed	Back

*Used one inch bunk mattresses.
**Mainly from ceiling vent unless otherwise specified.
***Ignition along length of bottom bunks. All other tests had localized ignitions on the bottom bunk.

STANDARD SET OF LININGS

Low Density Acoustical Panels on Overhead
Fibrous glass Insulation on Two Bulkheads
Vinyl Coated Panels on Two Bulkheads
High Temp Polyamide Carpet Bonded to Steel Deck

Table 2. Bedding and Locker Materials in Full Size Compartment Fire Tests

Item	Weight (lb)
A. Bunk Contents	
3 Chicken Feather Pillows	11.5
12 Cotton Sheets*	12.5
3 Wool Blankets	11.0
3 3-inch Thick Neoprene Mattress and Fire Retarded Cotton Ticking	55.5
3 Cotton Mattress Covers	5.5
3 Cotton Pillow Cases	0.7
Total Bedding	96.7
B. Locker Contents	
Cotton Rags and Cotton Waste**	68.0
1 Wool Blanket	3.7
Total Locker Materials	71.7

*Two sheets per bunk plus two extra sheets per bunk to simulate pajamas or other clothing.

**Distributed throughout locker.

2.2. Quarter-Scale Compartment Fires

The model test enclosure was a one-quarter-scale replica of the full size compartment except for the doorway width, which had to be reduced by only one-half in order to secure the proper air inflow. This model enclosure consisted of a steel shell with interior lining materials identical with those of the full-scale test. Several preliminary experiments with a gas burner on the center of the floor and with a noncombustible interior lining of 2.5 cm (one inch) thick asbestos insulation board were conducted to assist in the selection, development and placement of adequate instrumentation to characterize the fire behavior in the model and in the full-scale compartment. Instrumentation in the model was similar to that used in the full size compartment except that smoke and gas analysis inside the enclosure and the wall and floor temperatures were not monitored.

2.3. Small Laboratory Fire Tests

2.3.1. Radiant Panel Test Apparatus

The ASTM E-162 radiant panel test [6] requires a 15.2 by 45.7 cm (6 by 18 inch) specimen, facing and inclined 30 degrees to a vertically-mounted, gas-fired radiant panel. The energy output of the panel is controlled to be the same as that from a blackbody of the same dimensions operating at a temperature of 670 °C (1,238 °F). Ignition is caused by a pilot flame just above the upper edge of the test specimen and observations are made of the progress of the flame front down the specimen surface, as well as the temperature-rise of the thermocouples in a stack supported above the test specimen. The test is terminated when the flame reaches the end of the specimen or in 15 minutes, or whichever time is less. The flame-spread index, I_s, is computed as the product of the flame-spread factor, F_s, and the heat evolution, Q_s, or $I_s = F_sQ_s$, where

$$F_s = 1 + \frac{1}{t_3} + \frac{1}{t_6-t_3} + \frac{1}{t_9-t_6} + \frac{1}{t_{12}-t_9} + \frac{1}{t_{15}-t_{12}} + \text{ and } Q_s = \alpha\Delta T/\beta$$

the symbols t_3 to t_{15} correspond to times in minutes from specimen exposure until arrival of the flame front at a position 7.6 to 38.1 cm (3 to 15 inches), respectively, along the length of the specimen. The value of α in the relation for the heat evolution is a constant arbitrarily chosen to yield a flame-spread index of approximately 100 for red oak. The quantity ΔT is the observed maximum stack thermocouple temperature-rise over that observed with an asbestos-cement board specimen, and β is the maximum stack thermocouple temperature-rise for unit heat imput rate to the calibration burner.

This test procedure has been adopted as an ASTM standard method for measuring the flammability of building materials. Flame-spread index values vary from zero for asbestos-cement board to approximately 100 for uncoated wood and can be considerably greater for highly flammable materials.

2.3.2. Flooring Radiant Panel Test

This test is under development and is intended to replace the ASTM E-162 method for flammability testing of deck and floor coverings. The flooring radiant panel test [7] measures the critical radiant flux for flame spread of horizontally-mounted floor covering systems exposed to a flaming ignition source in a graded radiant heat energy environment. Critical radiant flux is the level of incident radiant heat energy on the specimen surface at the most distant flame-out point. The specimen can be mounted over underlayment, bonded to a simulated structural floor or otherwise installed in a typical and representative way.

The radiant energy source is a premixed air gas fueled panel inclined at 30 degrees to and directed at a horizontally-mounted 22.2 cm (8.75 in) by 104.1 cm (41 in) specimen. The radiant panel generates an energy flux distribution ranging from a maximum of 1.0 W/cm^2 (0.88 $Btu/s/ft^2$) to a minimum of 0.1 W/cm^2 (0.09 $Btu/s/ft^2$) under the low panel temperature setting of between 490 to 510 °C (914 to 950 °F) and from 0.2 to 2.4 W/cm^2 (0.18 to 2.1 $Btu/s/ft^2$) in the high panel temperature range of 660 to 680 °C (1,220 to 1,256 °F). Test results are reported as the critical radiant flux, W/cm^2, for flame-out.

2.3.3. Potential Heat Test

The potential heat test [8] provides a quantitative measure of the total heat released under typical fire exposure conditions without regard to the rate at which the heat is released.

The heat of combustion, Q_r, of a sample of the material measured by an oxygen bomb calorimeter, after it has been exposed to a "standarized fire" (2 hours in a muffle furnace at 750 °C (1,382 °F)) is compared with the heat of combustion Q_m of an unexposed sample. The potential heat Q_t, is given by

$$Q_t = Q_m - R\,Q_r$$

where R is the fractional weight remaining after the exposure.

Determinations may be made on simple materials, or on composite assemblies of materials from which a representative sample can be taken and pulverized into a homogeneous mixture.

2.3.4. Smoke Density Chamber

The smoke density chamber [9] is a 0.51 m^3 (18 ft^3) closed cabinet in which a specimen 58.1 cm^2 (three inches square) is supported vertically in a holder and is exposed to an irradiance of 2.5 W/cm^2 (2.2 $Btu/s/ft^2$) under one of two exposure conditions, designated as "flaming" or "non-flaming" (smoldering). For each specimen, the combustion generated smoke accumulates within the chamber and the reduction of light transmission during the test is reported in terms of the optical density of the smoke.

The method assumes the applicability of Bouguer's law to the attenuation of light by smoke, and the quantity of smoke is therefore reported in terms of optical density rather than light absorption. Optical density is the single measurement most characteristic of a "quantity of smoke" with regard to visual obscuration. To take into account the optical path length, L, the volume of the chamber, V, and the specimen surface area producing smoke, A, a specific optical density is defined as $D_s = V/LA\ (\log_{10} 100/T)$, where T is the percent light transmittance and the term in parenthesis is the optical density.

During the smoke chamber tests, indications of the concentrations of CO, HCl, HCN, NO + NO_2 and SO_2 are obtained by drawing a sample of the gas mixture through commercial colorimetric detector tubes. Essentially, a colorimetric tube is a small-bore glass tube containing a chemical packing which changes color when exposed to a specific component of a gas mixture, and the length of color stain is related to the concentration of that component, for a given quantity and rate of gas flow.

2.3.5. Heat Release Rate Calorimeter

The heat release rate calorimeter [5] measures the rate of heat generation for building materials exposed to radiant fluxes up to 10 W/cm^2 (8.8 $Btu/s/ft^2$) with a response time of a few seconds. A 11.4 x 15 cm (4-1/2 x 6 in) specimen, up to 2.5 cm (1 in) in thickness, is oriented vertically in front of gas fired radiant panels lining three sides of a combustion chamber. The radiation comes from the surface of these panels whose temperatures may be varied between 627 and 1,027 °C (1,160 and 1,880 °F) to produce the desired irradiance level on the sample. The edges of the specimen are shielded by an insulated holder. The rear surface of the specimen is exposed to a 2.5 cm (1 in) thick water-cooled brass block. Four adjustable standoff screws prevent the sample from contacting the water-cooled block and position the front surface of the specimen flush with the front of the holder. This configuration represents a section of a burning wall where the back surface of the wall is exposed to a relatively cool surface. The heat released from the rear surface is absorbed by the block and is calculated from the flow rate and temperature-rise of the cooling water. Air for combustion of the sample passes up through the porous floor of the chamber.

The fast time response of the calorimeter to the heat leaving the front surface of the specimen is achieved by maintaining the instrument at a constant temperature so that there is little heat loss between the combustion products and the apparatus itself. The constant temperature operation is accomplished with an auxiliary burner whose fuel supply is regulated by an automatic temperature controller. An increase in heat due to the burning of the specimen is then compensated by a decrease in the fuel flow rate. The calorimeter measures this decrease in the rate of flow of the fuel, which is also proportional to the rate of heat release of the specimen.

2.3.6. Ease-of-Ignition Test

The ease-of-ignition test [4] measures the exposure time required to produce flaming ignition of building materials in contact with flames from incidental or low energy fires. Two specimens 14.0 cm (5-1/2 in) wide and 15.2 cm (6 in) high face each other 2.2 cm (7/8 of an inch) apart. Natural gas is then introduced into the gap and is ignited with a coiled Nichrome heater wire. The exposing flame passes between the specimen surfaces and extends about 25.4 cm (10 in) above them. The heat flux from the flame source averages 3.3 W/cm^2 (2.9 $Btu/s/ft^2$) with a variation of 40% over the height of the specimen.

The object of the test is to determine the flame exposure time required to produce ignition in at least one of the two specimens. Ignition is defined here as the persistence of flames for one second or longer any place on the specimen following the curtailment of the gas flow.

3. ANALYSIS

The study of compartment fires involves the investigation of many parameters affecting the process of fire development, because of the complexity of the fire growth phenomena, which involves combustion chemistry, heat transfer, and fluid dynamics. An analytical technique for predicting the fire hazard potential of a compartment can outline the more pertinent parameters to be measured or observed during the compartment fire tests. It can provide a framework in which to analyze the actual fire performance of a material and relate it to the laboratory ratings for that material. Furthermore such a prediction method can offer insights into scaling possibilities for experimental work on a reduced size.

Small-scale modeling is necessary in order to permit a large number of experiments to be conducted under controlled laboratory conditions and at reduced cost. Under this phase of the program, modeling techniques were also devised, and a quarter-scale model of the full-scale compartment was constructed. Some corner tests, which were run in the burnout room on another project [2], were duplicated in the model. Results from these model tests showed good simulation of the full size behavior [10].

A simplified prediction scheme for fire buildup in an enclosure along with modeling principles and preliminary studies on reduced scale experiments are discussed in this section.

3.1. Prediction Model for Potential Fire Hazard

A simplified analytical technique for predicting the fire hazard potential of a compartment has been developed on this project and has been reported by Parker and Lee [10]. A description of the prediction model is the subject of this section.

A complete analytical description of the compartment fire is too complex for exact solution. It is necessary to make many simplifying assumptions and approximations. In order to predict the magnitude of fire severity there must be some quantitative measure of the level of fire buildup in a compartment. A suitable measure appears to be the upper air temperature which is the temperature of the hot air layer below the ceiling. The hot air layer, as the term is used here, includes flaming and non-flaming gaseous pryolysis and combustion products. When this upper air temperature reaches 500 °C (932 °F) there is a rapid pyrolysis and ignition of all combustibles in the upper part of the compartment. When it exceeds 700 °C (1,292 °F) there is sufficient radiation emitted from the heated upper surfaces or hot smoke layer to cause ignition of all combustible materials in the lower part of the compartment. This condition is sometimes referred to as flashover. The above critical temperatures are based on observations during the course of these experiments.

The fire buildup potential of a compartment can, therefore, be considered as the highest value that the average upper air temperature might achieve during the course of a fire.

The upper air temperature in a compartment of given size and enclosing surfaces of prescribed physical and thermal properties can be estimated by means of an overall energy balance for the enclosed space. This treatment is only concerned with the growth of the fire up to the time of flashover. The compartment is assumed to be divided into two temperature regions with the higher air temperature, T_g, in the upper part of the compartment and the ambient air temperature, T_o, in the lower part of the compartment. Furthermore there is a continuous inflow of cool air through a single open doorway into the lower portion of the compartment and gaseous combustion products exhausting from the upper part of the doorway. There is no other opening (door or window). Under quasi-steady-state conditions the heat balance equation for the compartment can be written as

Rate of heat generated	=	Rate of heat convected through the opening	+	Rate of heat absorbed by and conducted through the interior surfaces	+	Rate of heat radiated through the opening	(3-1)

If the mass flow rate of the exhaust gas is assumed to be that of the incoming air and that its heat capacity is the same as that of air at the same temperature, the heat convected through the doorway may be expressed as $DC\dot{V}\ (T_g - T_o)$, where D is the density of the ambient air; C is the average heat capacity of air between the temperatures T_o and T_g; and $\dot{V}$ is the volumetric flow rate of the incoming air which may be supplied by the ventilation system or be induced by the fire. The error due to these assumptions decreases as the volumetric airflow rate increases for a given total rate of heat generation in the compartment. While the heat transferred to the hot upper surfaces depends on a temperature difference between the gas and the surface, it is assumed that this difference is small and that the upper surfaces are approximately at the temperature T_g. The heat conducted through the lining materials in the upper part of the compartment is proportional to the temperature difference across their thickness, which is approximately equal to $(T_g - T_o)$. It is assumed that the unexposed surface is at the ambient temperature, T_o. The net heat loss by radiation from the upper surfaces and the hot gas layer is proportional to

$$(T_g^4 - T_o^4) \text{ or } (T_g^2 + T_o^2)\ (T_g + T_o)\ (T_g - T_o)$$

where the air and surface temperatures in the lower part of the compartment are taken to be at the ambient temperature, T_o. The radiation transferred into the lower part of the compartment either passes out the doorway or is absorbed in lining materials. The temperature-rise of these lining materials in the lower region of the compartment is assumed to be small prior to flashover so that their temperature is taken to be T_o. The total heat losses within the compartment and by radiation through the doorway are given, approximately, by $L\ A_u\ (T_g - T_o)$ where A_u is the total area of the hot upper surfaces and L is the heat loss coefficient which depends on T_g and T_o.

The total rate of heat generation in the compartment is QB, the product of the effective heat of combustion of the burning material and the mass burning rate, respectively. Here it is assumed that all of the combustion takes place inside the compartment. With the above approximations, equation (3-1) can be written as

$$QB = DC\dot{V}\ (T_g - T_o) + L\ A_u\ (T_g - T_o) \qquad (3\text{-}2)$$

The loss factor, L, can be represented by a sum of terms,

$$L = L_T + L_c + L_R \qquad (3\text{-}3)$$

where L_T corresponds to the initially high rate of transient heat conduction into the surface, L_c accounts for the steady-state heat conduction, and L_R is due to radiation losses which usually dominate at the temperatures corresponding to flashover. Since this model is not concerned with the time of fire buildup but its maximum extent, L_T will be neglected. The steady-state conduction coefficient is given by

$$L_c = \frac{K}{X} \qquad (3\text{-}4)$$

where K is the thermal conductivity of the lining material and X is its thickness. The radiation coefficient is given by

$$L_R = f\varepsilon\sigma\ (T_g^4 - T_o^4)/(T_g - T_o) = f\varepsilon\sigma\ (T_g^2 + T_o^2)\ (T_g + T_o) \qquad (3\text{-}5)$$

where ε is the effective emittance of the radiation source which will in general include both gas and solid surfaces, σ is the Stefan Boltzmann constant, and f is the ratio of the effective radiating area to the area of the heated surface, A_u, in the upper part of the room. If the radiation is from the gas layer or if the upper surfaces were black the effective radiating surface would be equal to the area of the overhead which is the same as the floor area, A, so that $f = A/A_u$. If the radiation were all from the upper surfaces and none of it were absorbed in other regions of the upper surface, the effective radiating area would be A_u so that f = 1.

Equation (3-2) can be rearranged to give the temperature rise:

$$(T_g - T_o) = \frac{QB/(DC\dot{V})}{1+LA_u/(DC\dot{V})} \qquad (3\text{-}6)$$

Equation (3-6) can be expanded to yield

$$(T_g - T_o) = \frac{(B/B_s)(QB_s/DC_o\dot{V})(C_o/C)}{1+(C_o/C)(L/DC_o)(A_u/A)/(\dot{V}/A)} \qquad (3\text{-}7)$$

where B_s is the stochiometric burning rate (i.e. the burning rate of the fuel requires to consume all of the oxygen entering the compartment), C_o is the heat capacity of the air at ambient temperature, and A is the floor area. Equation (3-7) contains some important groupings as illustrated in equation (3-8):

$$(T_g - T_o) = \frac{Y\Theta^* (C_o/C)}{1+(C_o/C)(L/DC_o)(A_u/A)/(\dot{V}/A)} \qquad (3\text{-}8)$$

where B/B_s is identified as the fraction of the oxygen depleted from the incoming air and is denoted by Y, and the quantity $(QB_s/DC_o\dot{V})$ is a characteristic temperature rise, Θ^*. Y has a maximum value of unity and can be measured during the course of the room fire tests.

The ratio of the heated area to the floor area, A_u/A, will vary with the room configuration, and the location and severity of the fire. For a 3.1 x 3.1 x 2.4 m (10 x 10 x 8 ft) high compartment with the heated air layer extending down to one-half of the ceiling height, it would be 2.6. For larger compartments of the same height it will be less than this. (A_u/A) has been observed to vary during the course of a fire.

$\dot{V}/A$ is a ventilation parameter equal to the volumetric inflow divided by the floor area. For forced air ventilation this would be specified by the designer. For open doorways it would be proportional to the $wh^{3/2}$ factor, where w and h are the width and height of the doorway, respectively. For fully developed compartment fires the inflow would be about 45 $wh^{3/2}$ ft^3/min if w and h are in feet and approximately 25 $wh^{3/2}$ m^3/min if w and h are in meters [11]. In developing fires, the inflow would be less than this value.

The calculation of the characteristic temperature rise, Θ^*, is based on the combustion of cellulose. However, the value of Θ^* should be relatively independent of the material used for its determination. The following values were used for its calculation:

$$Q = 1.53 \times 10^4 \text{ J/g } (6.6 \times 10^3 \text{ Btu/lb}) \text{ [net heat of combustion]}$$

$$D = 1.32 \times 10^{-3} \text{ g/cm}^3 \ (0.08 \text{ lb/ft}^3),$$

$$C_o = 1.01 \frac{J}{g°C} \ (0.24 \text{ Btu/lb/°F})$$

and

$$B_s/\dot{V} = 2.31 \times 10^{-4} \text{ g/cm}^3 \ (1.44 \times 10^{-2} \text{ lb/ft}^3)$$

The burning rate per unit volume of air consumed, B_s/V, is based on the following data. The molecular weight of cellulose is 162. There are 6 moles of oxygen consumed per mole of cellulose burned. The oxygen fraction of normal air is assumed to be 0.208 and the volume of one mole of air at ambient temperatures is 0.86 ft^3. This results in a characteristic temperature-rise of 2,650 °C (4800 °F). C/C_o is 1.035 at the 700 °C (1,292 °F) temperature assumed for flashover. Substituting the calculated values of Θ^* and C/C_o for air into equation (3-8), the temperature-rise for the freely burning fire in a compartment will be given approximately by

$$(T_g - T_o) = \frac{2560 \ Y}{1 + 725 \ L \ (A_u/A)/(\dot{V}/A)} \qquad (3\text{-}9)$$

Equation (3-9) separates the expression for temperature into convenient factors which can be measured individually during the compartment fire tests.

Y is measured as the oxygen depletion fraction and can be expressed as

$$Y = \frac{B}{B_s} = \frac{BQ}{DC_o\dot{V}} \ \frac{1}{\Theta^*} = \frac{1}{DC_o\Theta^*(\dot{V}/A)} \sum_i \dot{q}_i \ (A_i/A) \qquad (3\text{-}10)$$

The summation which includes all of the combustibles involved in the fire, focuses down on the fire test requirements. The per unit area heat release rate, q_i, must be obtained with a heat release rate calorimeter, and the area involved in the fire, A_i, requires information from some kind of flame spread test. Both q_i and A_i depend on the radiation field and this should be reflected in the test methods. Whether there is an i-th term depends on the ignitability of the material which is related to the ease-of-ignition test.

Note that in a ventilation limited fire Y approaches unity and the fire buildup potential, T_g-T_o, is determined by the denominator of equation (3-9). As will be seen later this condition was present in the compartment fire test with the door closed.

This expression also displays some scaling requirements. The ratio of the involved area to the floor area, A_i/A, should be preserved. This requires geometrical scaling since the i-th combustible may be a wall or a ceiling.

However, $(\dot{V}/A)$ must also be preserved so one must make adjustments of the dimensions of the openings to secure the proper airflow.

A correlation can also be derived for relating the oxygen depletion and temperature of the air in the upper part of the compartment. The derivation assumes that all losses are by radiation into the lower part of the compartment. It further assumes that the product fA_u/A is equal to unity. Then from equations (3-5) and (3-8) the theoretical relationship between Y and $(T_g - T_o)$, can be written for any ventilation parameter $\dot{V}/A$ as

$$Y = \frac{(T_g - T_o)}{\Theta^*}\left(\frac{C}{C_o}\right)\left[1 + \frac{\varepsilon\sigma}{DC(T_g - T_o)}(T_g^4 - T_o^4)/(\frac{\dot{V}}{A})\right] \quad (3\text{-}11)$$

For purposes of calculation, the following numerical values are recommended:

$$\Theta^* = 2{,}640\ °C,$$

$$c_o = 1.01\ \frac{J}{g°C}\ (0.24\ Btu/lb/°F);$$

$$C = 1.01 + 10^{-4}\left((T_g - T_o)/2\right)\frac{J}{g°C}$$

$$\text{or}\ \ 0.24\left(1 + 0.56 \times 10^{-4}\ (T_g - T_o)/2\right) Btu/lb/°F,$$

$$\varepsilon = 0.8,$$

$$T_o = 298\ K\ (537\ °R),$$

$$D = 1.32 \times 10^{-3}\ g/cm^3\ (0.08\ lb/ft^3).$$

3.2. Modeling Principles and Preliminary Studies

Reduced scale modeling methods are available for simulating the fire buildup in compartments [12,13]. One of these used at the Illinois Institute of Technology Research Institute (IITRI) [12], requires a constant ratio of heat release rate to the volumetric rate of air inflow in order to maintain the same temperature in the room. Their method can be stated briefly as follows:

$$L \sim W\ \text{scale}$$

$$LH^{3/2} \sim (\text{scale})^2$$

$$\text{Air Inflow} \sim wh^{3/2} \sim (\text{scale})^2$$

$$\text{Fuel Input} \sim (\text{scale})^2$$

where L is the room length, W is the room width, H is the room height, w is the window width and h is the window height. These rules lead to the requirement that the fuel input from a combustible wall is proportional to $LH^{3/2}$, rather than to LH as it needs to be.

Factory Mutual Research Corporation (FMRC) approached the scaling problem from dimensional analysis considerations [13]. Their findings indicate that the temperatures and gas compositions in a room scale reasonably well for geometrically similar enclosures where the heat release rates are proportional to the 5/2 power of the scale factor. This method places the ceiling of the model and prototype at homologous points of the convection column generated by the flame. However, since LH is proportional to the square of the scale factor for geometrical scaling, this leads to a fuel input requirement from a combustible wall that is proportional to $(LH)^{5/4}$.

Neither scaling approaches can handle the contribution of combustible walls, ceilings or floors. When such interior coverings are fully involved with flames, their rates of heat release are proportional to the scale factor squared. In order to evaluate the seriousness of this problem, quarter-scale model runs of several full size fire tests of combustible paneling materials using the IITRI method were performed. Their scaling requirement exaggerated the doorway and ceiling heights and resulted in 59% more paneling surface than necessary to produce the proper fuel contribution necessary to maintain the same fuel to air ratio. The prototypes for this modeling were the corner fire tests run inside of the burnout room for HUD [2]. In those full size experiments 1.2 x 2.4 m (4 x 8 ft) panels of the specimen material formed one corner in the rear of the room. The ceiling above the corner was lined with another 1.2 x 2.4 m (4 x 8 ft) panel of gypsum board. The fire exposure source was a 6.4 kg (14 lb) wood crib placed in the corner. The model fire exposure source was a gas burner consisting of a steel box with a mineral wool cover to even out the flow. The gas flow was adjusted to produce one-sixteenth of the heat release rate of the wood crib based on a value of 15.1×10^3 J/g (6,500 Btu/lb) for wood. The area of the top surface of the burner was one-sixteenth of that of the wood crib so that the fuel flow rates per unit area were the same. Comparison of the model and full-scale results showed fair agreement prior to active fire involvement of the wall. Once the wall was burning well, air temperatures in the upper part of the room were about 70% higher in the model burn [14].

Next a model having geometrically scaled room dimensions was evaluated [10]. The same ratio of heat release rate to the volumetric rate of air inflow as in the full size corner test was retained to secure the same temperatures in the model. The wall above the doorway height traps the hot combustion products from the fire and is critical to the phenomena taking place in the room so that this height was also scaled geometrically. The air inflow which scales as $wh^{3/2}$ was controlled by changing the width of the doorway in the small enclosure. These scaling rules are summarized as follows:

1. All dimensions are proportional to the scale factor except for:

   a. the width of the doorway which is proportional to the square root of the scale factor and

   b. the thickness of the materials which remains the same.

2. Fuel content and fuel surface area are proportional to the floor area.

3. Air supply rate is proportional to the floor area.

The thickness should remain the same in order to maintain the same surface temperature for a given incident heat flux. However, this heat flux will be somewhat lower in the model because the reduced velocity will result in a smaller heat transfer coefficient. Although the times at which a particular surface temperature is reached will be increased to some extent by this reduction in heat transfer, the times in the model will still be similar to those in the full-scale test. Adjustments in the thickness to account for differences in the heat transfer coefficient are not practical particularly for composite materials. Therefore the same thickness is used even though some error in time will result. At earlier times when flame spread is significant, the same rate of flame spread as in the prototype would mean a relatively faster and more intense fire involvement in the small enclosure. For rapid fire spread upward, this time difference for maximum fire involvement may not be large, e.g., figure 3. However, for situations where much of the fire spread is along the horizontal plane, the peak fire development could occur much sooner in the model than in the prototype compartment. Figure 3 shows a comparison of the time histories of the air temperatures at 2.5 cm (1 inch) from the ceiling and at the mid-height of the compartment for full-scale and model corner experiments with Lauan walls and gypsum board ceiling. Figure 4 shows the inflow velocity profile at the doorway for enclosures having both gypsum board walls and ceiling. The maximum inflow air velocity, which occurs near the bottom of the doorway, should be proportional to the square root of the height of the doorway. So the full-scale velocities have to be divided by two for the comparison with the model. These similarities between the model and prototype tests suggested the potential usefulness of this scaling technique, which was adopted for the remainder of the modeling work.

4. RESULTS AND DISCUSSION

Preliminary experiments were performed with the quarter-scale enclosure to arrive at a suitable set of full-scale test arrangements which were then tested along with their reduced scale counterparts. Results from these compartment fire experiments are discussed in this section.

4.1. Preliminary Experiments with the Model

Exploratory tests were conducted in the model enclosure with a scaled down three-man bunk in simulated sleeping quarters to check on the effect of ignition methods, arrangement of the bedding, bunk location and openness, overhead coverings, ventilation, and rate of heat release on the fire development as well as to check on the performance of the instrumentation.

The findings indicated that variations in any one or combination of these parameters could lead to one of three typical situations. Fire involvement in the enclosure could be slight, moderate or extensive, and these conditions correspond to a slight temperature-rise of the air in the upper part of the compartment (less than 200 °C (392 °F)), temperatures in the vicinity of 250 °C (482 °F), or temperatures above 500 °C (932 °F), respectively.

4.1.1. Ignition Method

Two modes of fire initiation in the berths were considered. In one case a match flame was used to ignite a cotton sheet that was part of the bedding. The other method was the ignition of 50 ml of ethyl alcohol, poured in the middle of the bottom bunk. The latter method was found to assure a sustained ignition and a more repeatable localized involvement of the bedding and was used for the full-scale test arrangements and their model counterparts. In the full-scale test 800 ml of the alcohol was employed.

4.1.2. Arrangement of Bedding

When the bedding on the berths was well made the pillow and wool blanket were the principal fuels exposed. These items were difficult to ignite and sustain a fire. Bedding in considerable disarray with much of the cotton sheets exposed resulted in a low level fire involvement. Kindling fuel, such as a crumpled-up sheet placed on the bedding to simulate pajamas or other clothes did not significantly increase fire activity in well made bedding, but did lead to heavy involvement in the bedding in considerable disorder. Two crumpled-up sheets led to somewhat higher compartment air temperatures. Additional kindling had no further effect. From this study it was decided to use two extra bed sheets as kindling in each of the full size bunks.

4.1.3. Mattress Thickness

Although the modeling rules require that the thickness of materials remain the same, the maintenance of adequate ventilation in the spacing between the tiers of the bunk necessitated some reduction in the thickness of the mattress used in the model. The 7.6 cm (3 in) thick neoprene mattress could barely be squeezed along with the other bedding into the space between the tiers of the model bunk. Little fire involvement of the bedding occurred because of the insufficient airflow to the fire. Even berthing fires with 5.1 cm (2 in) mattresses appeared under-ventilated compared to fires using a 2.5 cm (1 in) mattress. To evaluate the adequacy of using the latter a burn test with a three-tier bunk outfitted with 1-inch thick mattresses was conducted in the open alongside a full size three-man bunk in the NBS fire facility. The degree of fire involvement appeared similar up to 10 or 12 minutes, at which time a reduced level of fire activity was observed for the small model bunks due to a heavy depletion of the fuel. All of the model Navy compartment fires discussed in this report had bunks with the 2.5 cm (1 in) mattresses unless stated otherwise.

4.1.4. Bunk Placement and Openness

The location of the bunk relative to the doorway can sometimes affect the severity of the fire in the compartment. No difference was observed for the bunk on the left side or rear of the compartment with a half open doorway (see fig. 1). Both positions allowed sufficient ventilation, leading to moderate fire involvement in the bunk. However, only a low level fire was found for the bunk on the right side. The air inflow to the compartment had a less direct path to the fire because the right half of the doorway was closed. Consequently, the fire development was less severe in that situation. For a fully opened doorway the fire buildup was independent of the wall location of the bunk.

Openness of the bunk was also important to the fire development. Normally the bunks were closed by aluminum panels at the back and at both ends. When the back panel was removed from the bunk, the fire intensity increased. Further enhancement of the fire occurred when both end panels were also taken off. On the other hand when the front of the bunk was partially closed up with privacy curtains and the back and end panels were in place the intensity of the fire was markedly increased. The former effect was due to increased ventilation while the latter was due to increased heat trapping.

4.1.5. Room Ventilation

The effect of room ventilation on the enclosure temperatures depended not only on its degree but also on its distribution. The fires were more severe when the forced air was delivered at each bunk than when the same amount of air was delivered at the ceiling. Tests showed that a reduced doorway opening and the absence of forced ceiling ventilation could result in an increased fire intensity. Once the air supply is sufficient for complete combustion, the effect of additional air is to reduce the air temperature in the compartment by dilution.

4.1.6. Thermal Inertia of Overhead Linings

The effect of the thermal inertia of overhead linings on the fire behavior in the compartment was also investigated. The rate of temperature-rise of a surface exposed to thermal radiation depends on its "thermal inertia," the product of thermal conductivity, density and heat capacity or $k\rho c$. If the quantity $k\rho c$ is low the surface temperature rises rapidly and radiation feedback increases the heat release rate of the burning contents. This enhancement may be enough to induce flashover when it might not otherwise occur. Three materials, fibrous glass, high density acoustical paneling and asbestos insulation board, having $k\rho c$ values of 58, 445 and 1276 $W^2\ min/m^4/°C^2$ (0.03, 0.23 and 0.66 $Btu^2/hr/ft^4/°F^2$), respectively, were used for the overhead of the enclosure. Results of the model tests with these materials are shown on table 3.

The percent difference between the overhead temperature and the upper air temperature 2.5 cm (1 in) from the overhead should decrease with decreasing $K\rho c$. However the results presented in table 3 indicated that surface emissivity or other presently unexplainable factors may sometimes override the effect of thermal inertia.

4.1.7. Rate of Fuel Supply

In order to determine the air temperature rise of the compartment as a function of the heat supplied, experiments were conducted with a fully open doorway and a gas diffusion burner on the center of the deck. Gypsum board was used to line the bulkheads and overhead of the enclosure. The deck consisted of a piece of asbestos insulation board. Methane was metered to the burner and the model compartment was allowed to reach equilibrium conditions. The rate of methane flow was gradually increased for each run until newsprint samples at various positions on the deck ignited. These ignitions were taken to indicate the onset of flashover. Ignition times for these newspaper specimens varied from 5 to 7-1/2 minutes for a gas rate of 42 kW (40 Btu/s) or a scaled-up rate of 670 kW (630 Btu/s) for the full-scale compartment.

4.2. Model and Full-Scale Compartment Fires

Table 1 shows the range of conditions covered by the 13 full size and ten model tests. Runs 1 to 4B were similar except for differences in ventilation in the compartment and to the bunks. The following three tests, runs 5 to 7, involved variations in the interior coverings of the compartment. Subsequent tests considered reduced but adequate ventilation to the bunks along with three kinds of carpeting with pads. Visual observations taken during all of the full size compartment fires are included in the appendix. Summaries of the experimental results are indicated on tables 4 and 5. The data on air temperature inside the compartment, the air temperature at the top of the doorway, the overhead temperature, the incident radiant flux on the deck, the weight loss rate, the airflow, and the oxygen, carbon monoxide, and carbon dioxide are tabulated on tables 4a and 5a at the times of the peak upper air temperatures and at the occurrence of flashover. Each test may have successive maxima in temperatures over the duration of the test, and these are included. Shown in tables 4b and 5b are maximum values and corresponding times of the overhead and doorway temperatures, the oxygen depletion and the concentrations of CO and CO_2.

Table 3. Results of Model Tests With Three Different Overhead Linings

Overhead Lining	Thermal Inertia $K\rho c$ $Btu^2/ft^4/hr/F^2$	Two Minute Average Upper Air Temperature* (°C)	Corresponding Two Minute Average Overhead Temperature (°C)	Difference Between Upper Air and Overhead Temperatures (%)	Time Interval in Test (min)	Notes
Asbestos, Insulation Board	0.66	227	124	45	3-5	--
		450	260	42	5-7	Highest Average Upper Air Temperature
High Density Acoustical Panels	0.23	590	497	16	3-5	Highest Average Upper Air Temperature
Low Density Acoustical Panels	0.03	510	335	34	3-5	--
		720	506	30	5-7	Highest Average Upper Air Temperature

*The air temperature 1 inch below the ceiling averaged over the two-minute time interval indicated in column 6.

Table 4a. Summary of Results of Full Size Compartment Fires At Times of Peak Upper Air Temperatures

Test No.	Time of Max Upper Air Temperature (min)	Maximum Upper Air Temperature (°C)	Doorway Temperature (°C)	Ceiling Temperature (°C)	Incident Radiative Flux on Deck (Btu/s/ft²)	Weight Loss Rate in Bedding (lb/min)	Inflow Air Velocity (ft/min)	Volumetric Air Inflow (ft³/min)	Forced Air Ventilation (ft³/min)	Doorway Smoke† % Obscuration	Oxygen in Doorway % Depletion	Carbon Monoxide In Doorway (%)	Carbon Dioxide In Doorway (%)	Smoke In†† Compartment % Obscuration	Oxygen In Compartment % Depletion	Carbon Monoxide In Compartment (%)	Carbon Dioxide In Compartment (%)
1	1.6	161	166	148					0	4	2.2			18	2.5		
	4.3	191	166	186		0.81	120.	56.*	0	39	3.7			71	7.1		
	21.0	185	190	166		0.52			0	69	6.8			100	4.6		
2	2.1	153	164	141		0.45	0	0	160.	9	4.3			34	4.7		
	12.6	172	160	162		0.53	0	0	160.	79	8.3			100	7.2		
3A	1.6	255	246	265		1.0			160.	37	17	~0	~0	72	~0	~0	~0
	12.9	506	545	506		3.5	140.	926.	160.	91	41	1.8	6.7	100	1.6	0.2	0.24
3B	2.4	230	188	261		0.85	140.	926.	185.	22	14.9	0.29	3.5	38	30.5	~0	6.5
	6.4	219	200	231		1.85	140.	926.	185.	67	8.3	0.35	1.7	88	19.9	0.16	4.5
4A	3.8	326	238	316		2.7	190.	1,250.	160.	22		0.15	3.1	43		~0	0.38
	6.5	490	420	475		3.8	190.	1,250	160.	73		0.63	6.2	88		~0	0.80
4B	2.25	570	485	505		5.5	190.	1,158.	185.	34	37.	0.45	7.8	90	1.6	~0	0.42
5	2.8	215	160	135			110.	726	185.	9	8.6	~0	2.0	34	7.8	~0	1.0
	10.25	232	225	190			110.	726.	185.	64	13.1	~0	2.7	92	1.3	~0	~0
6	3.7	200	150	195			110.	726.	185.	60	8.4	~0	2.1	84	<1	~0	~0
	11.6	190	166	171			110.	726.	185.	98	16.2	0.28	3.0	100	<1	~0	~0
7	5.9	242	202	245		2.0	100.	661.	185.	28	15.9	~0	3.0	52	1.2	~0	~0
	9.2	244	253	255		1.8	100.	661.	185.	55	13.4	0.40	2.9	100	1.2	~0	~0
8	2.2	354	202	208			110.	363.**	0	22	10.	~0	2.4	63		~0	~0
	6.2	270	255	234			110.	363.**	0	74	13.	~0	3.0	100		~0	~0
	15.5	199	196	170			110.	363.**	0	94	15.5	0.31	2.2	100		~0	~0
9	1.3	312	225	281	0.17		100.	330.**	0	55	25.8	0.28	4.4	93	2.3	~0	~0
	5.3	296	248	286	0.41		110.	363.**	0	100	20.9	0.70	3.0	100	4.7	~0	~0
	11.9	402	326	384	0.60		110.	363.**	0	100	24.0	1.12	3.1	100	2.3	~0	~0
	21.2	800	685	728	1.76				0	100	87.0	4.6	12.0	100	60.5	3.3	12.4
10	5.0	306	270	280			160	528.**	0	100		0.21	1.8	100		1.8	4.7
	9.7	820	700	724					0	100		~0	1.2	100		3.3	7.4
11	10.3	772	640	781	1.76		115	379.**	0	100	86.0	6.0	12.0	100	61.0	2.0	9.2

*Through small exhaust port

**Through half opened doorway

†Effective smoke path length of 27 inches

††Effective smoke path length of 42 inches

Table 4b. Summary of Results of Full Size Compartment Fires

Peak Values of Other Measurements and Their Corresponding Times

Test No.	Max. Doorway Temp. (Time)		Max. Ceiling Temp. (Time)		Max. Doorway Oxygen Depletion		Max. Doorway Carbon Monoxide (Time)		Max. Oxygen Depletion In Compartment (Time)		Max. Carbon Monoxide In Compartment (Time)	
	(°C)	(min)	(°C)	(min)	(%)	(min)	(%)	(min)	(%)	(min)	(%)	(min)
1	170	(1.9)	149	(2.3)	No Max.				No Max.			
	166	(4.3)	186	(4.3)	No Max.				7.1	(4.3)		
	190	(21.0)	166	(21.0)	No Max.				No Max.			
2	164	(2.0)	141	(2.1)	6.5	(3.4)			8.1	(3.4)		
	160	(12.6)	162	(12.6)	No Max.				No Max.			
3A	246	(1.6)	265	(1.6)	52.	(7.7)	2.2	(7.8)	No Max.		No Max.	
	545	(12.9)	506	(12.9)	No Max.		2.4	(11.8)	No Max.		No Max.	
3B	188	(2.4)	261	(2.4)	16.1	(2.2)	No Max.		33.8	(1.0)	No Max.	
	205	(7.3)	231	(6.4)	No Max.		No Max.		No. Max.		No Max.	
4A	238	(3.8)	316	(3.8)	11.	(3.4)	0.15	(3.8)	No. Max.		No Max.	
	460	(6.2)	475	(6.5)	36.	(6.3)	0.63	(6.5)	No. Max.		No Max.	
4B	485	(2.25)	505	(2.25)	39.	(2.3)	0.49	(3.0)	No. Max		No Max.	
5	160	(2.8)	149	(3.6)	12.	(3.0)	No Max.		7.8	(2.8)	No Max.	
	225	(10.25)	190	(10.25)	14.	(9.7)	No Max.		No Max.		No Max.	
6	168	(3.2)	195	(3.7)	14.	(3.2)	No Max.		No Max.		No Max.	
	236	(9.8)	171	(11.6)	18.4	(10.6)	No Max.		No Max.		No Max.	
7	211	(6.1)	245	(5.9)	15.9	(5.9)	No Max		No Max.		No Max.	
	274	(8.7)	255	(9.2)	14.7	(8.9)	1.0	(13.2)	No Max.		No Max.	
8	244	(2.4)	243	(2.9)	19.8	(1.6)	No Max.		No Max.		No Max.	
	265	(6.4)	234	(6.2)	15.1	(6.4)	0.25	(8.2)	No Max.		No Max.	
	205	(15.1)	170	(15.5)	10.7	(15.5)	0.34	(16.0)	No Max.		No Max.	
9	230	(1.5)	281	(1.3)	25.8	(1.3)	0.64	(3.5)	No Max.		No Max.	
	253	(5.5)*	286	(5.3)	No Max.		0.70	(5.3)	No Max.		No Max.	
	332	(12.1)	384	(11.9)	27.2	(10.0)	1.16	(12.3)	No Max.		No Max.	
	No Max.		728	(21.2)	87.	(21.2)	No Max.		No Max.		No Max.	
10	271	(5.2)	280	(5.0)	9.7	(7.1)	0.21	(5.0)	No Max.		2.8	(5.5)
	No Max.		742	(9.7)	No Max.		No Max.		No Max.		No Max.	
11	No Max.		781	(10.1)	No Max.		No Max.		No Max.		No Max.	

*Through Small Exhaust Port

Table 5a. Summary of Results of Quarter-Scale Compartment Fires

At Times of Peak Upper Air Temperatures

Test No.	Time of Max. Upper Air Temp. (min)	Max. Upper Air Temp. (°C)	Doorway Temp. (°C)	Ceiling Temp. (°C)	Incident Radiative Flux on Deck Btu/s/ft²	Weight Loss Rate in Bedding lb/min	Inflow Air Velocity ft/min	Volumetric Air Inflow ft³/min	Forced Air Ventilation ft³/min	Doorway† Smoke % Obscuration	Oxygen In Doorway % Depletion	Carbon Monoxide In Doorway (%)
M1	0.5	107	97	56	.084				0		1.3	0.15
	9.3	65	71	55	.053				0		30.	0.76
M2	1.2	168	158	107	.079				10	19	6.5	0.05
	5.2	94	103	74	.056				10	56	24.	0.66
	13.8	101	107	86	.088				10	74	20.	0.73
M3A	1.4	221	168	168	.152				10	13	9.	0.28
	6.0	463	460	429	.664				10	60	22.	0.84
M3B	0.8	202	126	150		0.10	<30.	<25.	10		5.5	0.15
	5.0	120	108	110		0.13	37.	31.	10.		9.5	0.18
M4B	1.8	282	346	269	.28				10.		21.	0.37
	3.8	660	810	569	1.06		60.	50.	10.		54.	1.12
	4.3	875	783	620	2.18				10.		66.	1.50
M5	0.8	265	187	169	.164	0.10	40.	33.4	10.		4.	~0
	6.6	203	253	182	.115	0.165	80.	66.8	10.		10.	0.22
M6	1.0	209	162	98	.185	0.152	<35.	<29.	10.		7.	
	3.8	151	142	120	.109	0.152			10.		7.	
M7	0.8	250	115	143	.136	0.11	37.	31.	10.		5.	0.15
	3.7	198	119	156	.083	0.11	37.	31.	10.		11.	0.17
M8	1.5	463	272	291		0.091	40.	16.7*	0		11.	0
	6.7	241	223	217		0.35	60.	25.*	0		22.	0.40
	9.5	706	480	493		0.515	60.	25.*	0		51.	1.53
M9	0.5	228	150	112			30.	12.5*	0		7.	0.43
	13.1	398	355	369		0.20	70.	29.2*	0		28.	1.24
	17.0	531	375	474		1.37	70.	29.2*	0		36.	1.46
P41**	0.8	437	477	342	.466							
	2.0	592	683	466	.985							

†Effective Smoke Path Length of 13.5 in

*Doorway Half Open

**A Preliminary Experiment

Table 5b. Summary of Results of Quarter-Scale Compartment Fires

Peak Values of Other Measurements and Their Corresponding Times

Test No.	Max. Doorway Temp. (Time)		Max. Ceiling Temp. (Time)		Max. Doorway Oxygen Depletion (Time)		Max. Doorway Carbon Monoxide (Time)	
	(°C)	(min)	(°C)	(min)	(%)	(min)	(%)	(min)
M1	97	(0.5)	63	(1.6)	40	(4.5)	1.37	(4.5)
	71	(9.3)	55	(9.3)	34	(11.0)	No Max.	
M2	158	(1.2)	116	(1.3)	No Max.		No Max.	
	103	(5.2)	74	(5.2)	24	(5.2)	No Max.	
	107	(13.8)	90	(16.0)	No Max.		No Max.	
M3A	173	(1.2)	168	(1.4)	No Max.		No Max.	
	471	(6.8)	429	(6.0)	30	(8.2)	1.09	(8.2)
M3B	126	(0.8)	150	(0.8)	12.5	(2.0)	0.32	(1.3)
	140	(6.3)	110	(5.0)	No Max.		No Max.	
M4B	346	(1.8)	269	(1.8)	No Max.		No Max.	
	810	(3.8)	569	(3.8)	No Max.		No Max.	
	815	(4.2)	620	(4.3)	88	(6.5)	2.2	(7.3)
M5	187	(0.8)	169	(0.8)	No Max.		No Max.	
	254	(6.4)	182	(6.6)	13	(8.75)	0.31	(10.)
M6	162	(1.0)	100	(1.2)	No Max.			
	165	(3.7)	129	(4.6)	7	(3.8)		
M7	115	(0.8)	151	(1.0)	No Max.		No Max.	
	142	(3.8)	156	(3.7)	11	(3.7)	No Max.	
M8	272	(1.5)	291	(1.5)	24	(3.9)	0.49	(3.6)
	256	(6.3)	217	(6.7)	No Max.		No Max.	
	508	(10.1)	518	(11.5)	No Max.		No Max.	
M9	150	(0.5)	127	(0.75)	19	(1.75)	0.65	(1.9)
	362	(12.7)	369	(13.1)	37	(14.8)	1.6	(15.3)
	375	(17.)	474	(17.)	No Max.		1.6	(15.3)

4.2.1. Discussion of Individual Tests

A temperature history of the upper air, as determined by a thermocouple one inch down from the center of the overhead, the overhead temperature directly above the air temperature measurement thermocouple, the average temperature of the upper surfaces (see fig. 1), and the temperature of the exhaust flow out of the compartment are presented for each test on figures 5 to 17. These temperature histories, which indicate the degree of involvement, provide a framework for discussing the individual tests.

4.2.1.1. Tests M1 to M4B and 1 to 4B

The first two model compartment fire tests, M1 and M2, had no openings except for a 7.6 x 7.6 cm (3 x 3 in) exhaust vent at the top of the closed door. There was no forced ventilation in the first test. In the second test there was 4.5 m^3/min (160 ft^3/min) of air delivered at the overhead vent near the rear of the compartment. Neither test led to air temperatures above 200 °C (392 °F), as seen in figures 5 and 6. In tests M3A and M3B with the door open, figures 7 and 8, the upper air temperatures were more a function of the forced air distribution in the room than of the increased convection from the doorway. When this forced air was mainly introduced through the ceiling vent, the highest air temperature attained was 202 °C (396 °F). Diverting this ventilation to the outlets on the bunks, as was the case in run M3A, resulted in peak air temperature approaching 500 °C (932 °C). This temperature would probably have been maintained for awhile or even increased if the full mattress thickness could have been used. Except for a localized bunk fire this was still not very spectacular. In all but test M4B, the bunk had closed ends and back. In that test the back and ends were removed allowing easy flow of air across the bunk. As had been observed from the preliminary experiments, bunk openness was quite important to the degree of fire development. Figure 10 indicates that the air temperatures in test M4B reached a peak of 660 °C (1,220 °F), and a short time later the locker material ignited leading to room flashover.

Figures 5 to 10 also show the corresponding tests in the full-scale compartment. In test 1 there may have been sufficient air leakage into the closed compartment to raise the temperature above that found in the counterpart model test M1. More important is that the first two tests again exhibited low intensity fires with temperatures less than 200 °C (392 °F). As in the corresponding model test, run 3B also had a peak air temperature in the vicinity of 200 °C (392 °F). Test 3A barely went over 500 °C (932 °F) but it maintained the high temperature long enough to ignite the locker material in the upper part of the compartment, causing a very severe localized fire. On the other hand, runs 4A and 4B reached temperatures of 490 °C (914 °F) and 570 °C (1,058 °F), respectively, but not flashover conditions as in their model counterpart. Test 4A was conducted on a warm moist day. Run 4B was a repeat of 4A except it was performed under a lower humidity condition. Qualitatively, one might say that the model did not scale well for tests 3A, 4A and 4B. There were large fires in M4B and 3A but not in the corresponding tests 4A or 4B and M3A. However, the temperatures in all of these tests approached or exceeded 500 °C (932 °F) which is a danger point. In one case, the model enclosure became more involved; in another case it was the full size compartment that had the most severe fire. It could have been deduced from tests M3A and M4B that the potential for flashover was there. This is all that the model is required to do.

4.2.1.2. Tests M5 to M7 and 5 to 7

Runs 5, 6 and 7, figures 11 to 13, were similar to test 3B except for variations of the interior coverings. The high density acoustical panel which had a high thermal inertia was used in run 5. Theoretically, this should result in a steeper temperature gradient in the hot air adjacent to the ceiling. Data from tables 4 and 5 for tests 3B and 5 and their corresponding model tests show that this temperature gradient in runs M5 and 5 is at least twice that found in runs M3B and 3B. However, the ceiling temperature may not be any lower, due to variations in the fire behavior between tests, e.g., the ceiling temperature in M5 is higher than that in run M3B.

Melamine coated aluminum wall paneling was used in runs M6 and 6. The surface coating was somewhat different from the vinyl coverings used in runs M3B and 3B. However, the fire buildup in these situations did not adequately involve the wall linings to show differences in flammability of the two materials. As a result the peak air temperatures were expected to be and were similar to these observed for tests M3B and 3B.

In runs M7 and 7 a pad was used under the carpet. This had the effect of reducing heat losses to the floor. This can be critical for fire involvement of the floor covering near flashover conditions. However, at much lower temperatures this reduction of floor losses is minimal. Air temperatures were somewhat higher than those in runs M3b and 3b, but these differences could well have been within the experimental variation expected between tests of the same arrangement.

In tests 5, 6 and 7 and their model counterparts the changes in the interior linings were not major ones, and the fire growth and resulting peak air temperatures were similar to those observed for run 3b. This indicates fairly good reproducibility of the fire buildup in the compartment fire tests. Secondly, the peak temperatures in the model tests were close to the values of 200 to 244 °C (392 to 471 °F) observed in the full size fires.

4.2.1.3. Test M8, M9 and 8 to 11

The remaining four full size tests were used to check out a room arrangement which preliminary experiments indicated could lead to a more severe fire development. Forced ventilation to the room was curtailed and the doorway opening was closed halfway for these tests. Jute-hair underlayment was also used in conjunction with carpeting to minimize heat losses to the metal deck.

The chronology of each fire, as indicated by the upper air and surface temperatures, is shown on figures 14 to 17. Run 8 experienced peak temperatures in the neighborhood of 350 °C (662 °F), between the low level fire range of 200 to 250 °C (392 to 482 °F) and the 500 °C (932 °F) area where pyrolysis of combustibles such as clothes in the locker can occur and further buildup to flashover becomes more of a possibility. Model test M8, on the other hand, reached 706 °C (1,303 °F). The carpet blackened and the newspaper on the floor discolored. One contributing factor to this difference in fire behavior between the model and prototype fires could be due to the non-scaling of flame spread. As mentioned in section 3.2, the same rate of flame spread as in the full size compartment would result in a relatively earlier and more intense fire involvement of the fuel in the model. Figure 14 shows the temperature history of both tests 8 and M8. In the early stage of the fire development, the light combustible materials such as the sheets and blankets were the principal fuel involved. At about 5 and 12 minutes in the model and prototype, respectively, the temperatures began to increase again. This later stage of fire involvement included the mattress and the pillows. A faster involvement of the bedding at this point could have meant the difference between an accelerated growth leading to a potential flashover and a low intensity fire.

The following test, run 9, was similar to run 8 and was designed to yield information on the fire performance of three bunk privacy curtain materials, the effect of a partial confinement of the incipient fire and the effect of a more rapid involvement of the bedding on the lowest bunk. The curtains were positioned in front of each tier of the 3-man bunk and consisted of two high temperature polyamide cloths of different weights placed side by side alongside another piece of 50% polyamide — 50% phenol formaldehyde material. The alcohol used previously to initiate the fire was spread along the length of the bottom bunk rather than localized on the bedding as in the preceding tests. This method of ignition was also necessary to assure uniform exposures for all three materials making up the curtains. Roughly one-quarter of the bunk opening was left to allow for ventilation of the fire.

Early in run 9, it was apparent that the curtains were confining the fire to the bunk of fire origin. Fire quickly enveloped the overhanging sheets from the upper berths as in all of the previous tests, but would not involve the sheets on the top of each bunk. Once the overhanging portions of the sheets burned away, the fire extinguished itself on the top and middle tiers and was then confined to the lowest berth. All this occurred within the first two minutes. In all of the preceding tests, except the first two having the closed doorway, the fires involved the sheets which simulated clothes on the upper bunks. The polyamide curtains also burned off within the first two minutes, while the polyamide-phenol formaldehyde material remained almost to the end of the test. Confinement of the fire resulted in very dense smoke out of the doorway. This smoke, in the opinions of the observers, was more dense than in any of the previous tests. After 7-1/2 minutes the fire penetrated the aluminum panel supporting the mattress on the second bunk and quickly involved the bedding. The fire continued to preheat the uppermost bunk, until at about 17 minutes, when the fire burned through the aluminum panel to involve the fuel on the top bunk. Five minutes later the entire combustible contents of the compartment was aflame.

The fire scenario was somewhat similar in the model test M9. Unfortunately the thin mattress used to achieve the proper ventilation to the bedding led to a depletion of fuel after 17 minutes. Nevertheless the upper air temperature reached a peak of 531 °C (988 °F) by that time and indicated a potential flashover condition.

Run 10 was similar to run 9 except only 50% polyamide-50% phenol formaldehyde material was used for the privacy curtains, and acrylic carpeting was used on the deck. This test demonstrated how easily deck coverings with high flame spread ratings can contribute to the complete fire involvement of a compartment. The fire scenario was very similar to that of run 9 with the fires extinguishing in the upper bunks after the first couple of minutes. At about the same time, a piece of burning material from the bedding ignited the carpeting. Within 10 minutes the compartment was a hot inferno. Much of the curtains lasted over this time duration.

In run 9, most of the curtains were burned off by two minutes. Much of the curtains endured the entire fire exposure in test 10, but the effect of a longer duration partial confinement of the bunk fire was masked by the fire involvement of the deck covering. Run 11 was performed to evaluate this parameter. Localized ignition was reverted to for comparison of results between tests having the same ignition pattern. A carpet with thermal properties similar to wool, but having a lower flammability rating was chosen to assure that no ignition of the deck material would occur until at or near flashover. The initial fire buildup was similar to those in runs 9 and 10. After 7-1/2 minutes the compartment was filled with very heavy smoke and flames could only be observed along the bottom bunk. Then at about ten minutes, flames shot out of the doorway and the carpet ignited. The compartment cleared somewhat, and it became obvious that the upper berths had been involved in fire for some time. The longer confinement of the bunk fire had evidently resulted in a more rapid fire buildup in the compartment.

Intuitively one would have expected a longer time to flashover for run 11 than that for run 10 because of the additional heat release from the deck covering in the latter test. However smoke from the burning carpet stratified in a low dense layer, blocking off radiation from the hot upper surfaces of the compartment to the unignited portions of the deck. Other experimental evidence [14] shows that fires having short flames, such as those observed on the carpeting, result in a thicker thermal layer in the compartment and not in a concentrated layer near the overhead. Thus, much of the heat generated from the burning carpet in run 10 flowed out of the compartment at an elevation far from the overhead. Consequently, the compartment temperature in run 10 was only somewhat higher than that in run 11, but because of the smoke stratification in the former case, radiation to the deck was probably similar in both runs. This would account for the similar times to flashover for the two tests.

4.2.2. Supporting Measurements

In addition to the temperatures in the upper part of the compartment which indicated the degree of fire buildup, a number of diagnostic measurements was made to help understand the phenomena taking place. These included the vertical temperature profile at the center of the compartment, the concentration of oxygen, carbon monoxide, and carbon dioxide at the top of the doorway, smoke obscuration in the compartment, rate of air inflow, and the thermal radiation at the deck level.

4.2.2.1. Thermal Radiation

Values of the radiation flux to the deck have been plotted as a function of upper air temperature, figure 18. The limited data available from the full size fires compared reasonably well with the small scale values. This correlation is similar to one for overhead temperatures. However the advantages of relating flux to upper air temperatures are that the latter is a reliable measure of fire buildup in a compartment, is independent of the physical properties of the overhead material and can more easily be treated analytically. Calculations show that if the overhead or adjacent hot air layer is the principal radiating source, the view factor between it and the deck below lies between 0.24 and 0.36 over most of the deck area. This is in agreement with the averaged value of 0.31 found for the data plotted on figure 18, assuming an emissivity of unity for the radiating source. A solid line representing the case where both the view factor and emissivity of the radiating source are unity is superimposed on the figure.

In actuality radiation to the deck results from both the hot gases and the upper surfaces. From figure 18 a view factor higher than $0.31/\varepsilon$ fits the lower values of the radiative flux, while a value less than $0.31/\varepsilon$ correlates the higher fluxes.

The higher view factor at the lower fluxes can possibly be explained in the following way. It is known that low intensity fires and short flames lead to a thicker and lower thermal layer in the compartment [14]. This results in a lowering of the radiating surfaces and hence to effectively higher view factors. A severe localized fire would produce flames much taller than the compartment but here such flames are deflected horizontally beneath the ceiling and lengthen further because of the lower rate of entrainment between the heavy air and the light hot flame gas stream. This results in high temperatures and intense radiation from the air in the upper part of the compartment. This also results in a vertical constriction of the zone of hot gases flowing across the overhead toward the exit. A consequence of this is lower view factors.

It is evident from figure 18, that rather limited data was available for the correlation. In most of the full size and several quarter-scale tests, the radiometer was either not working properly, or was not calibrated correctly. For tests 9 and 11, it was necessary to assume that the radiant flux to the deck was 2 W/cm^2 (1.8 $Btu/s/ft^2$) at the time of flashover in order to retrieve the data at earlier times. This is a reasonable assumption [2,14].

4.2.2.2. Temperature Distribution in Compartment

Comparison of localized overhead and upper air temperatures for the two scale fires have already been made. To obtain a more complete understanding of modeling enclosure fires on a reduced scale as well as a better general understanding of compartment fires, temperature distributions in the compartment were examined. Figures 19 and 20 show vertical distributions of temperatures from the overhead down to the deck for two representative fire situations.

Due to non-scaling of fire spread, a topic discussed earlier, times can not be easily scaled for a phenomena as complex as a fire in a furnished compartment. Temperature profiles from the model runs should be compared with the prototype fires at comparable stages of the fire development. It can be argued that the successive peaks in upper air temperatures define these stages of the fire buildup. However, it is sometimes difficult to compare results, e.g., where the model test has three peaks and the prototype only two maxima. Therefore temperature profiles at times corresponding to all peak upper air temperatures have been presented for these two tests. It is important to keep in mind that the principal objective is to determine whether a potential exists for flashover. In an earlier discussion, a temperature in the vicinity of 500 °C (932 °F) was selected as a lower limit for this flashover potential. Thus only the highest peak temperature during a test is of major concern. What these vertical distributions of temperatures should show is whether there is a similarity of these profiles between the model and prototype fires. From the figures given one can conclude that such similarities exist.

Analysis of the data also discloses a thicker thermal layer in compartments having reduced openings, test 1, 2, 9, 10 and 11. Results also indicate that the vertical temperature profile in the model follows the prototype temperature distribution as long as the upper air temperatures did not greatly exceed 500 °C (932 °F).

Horizontal temperature variations along the overhead surface were monitored only in the full size fires. Overhead temperatures were highest over the fire source and along the path of the hot gas flow exhausting towards the doorway. Surface temperatures decreased rapidly away from these localized areas of intense heating. The averaged upper surface temperature histories for all thirteen tests are shown on figures 5 to 17. Data taken at six overhead and three bulkhead positions four inches down from the ceiling were used in these averages. Superimposed on each of these figures are the air temperature measurements taken at 2.5 cm (1 inch) from the ceiling, the temperature of the ceiling directly above it, and the thermocouple reading at the doorway. Analysis of the data indicated that the single best measurement used to approximate the averaged upper surface temperature would be the air temperature near the top of the doorway.

4.2.2.3. Compartment Ventilation

As mentioned in section 3.1., the upper limit for the volumetric air inflow through the doorway would be 45 $wh^{3/2}$ ft^3/min if the width w and the height h are in feet and 25 $wh^{3/2}$ m^3/min if the dimensions are in meters. This value is achieved only under fully developed and ventilation controlled fires. No airflow measurements were taken under flashover conditions in the compartment fire tests. Consequently, all of the recorded volumetric inflows were expected to be less than this value. In many of the full size and quarter-scale enclosure fires, there was forced ventilation in addition to the fire induced inflow of air through the doorway. For the full size tests, this total ventilation varied from 13 to 22 $wh^{3/2}$ m^3/min (24 to 40 $wh^{3/2}$ ft^3/min). The total volumetric air to the reduced-scale model fires ranged from 9 to 19 $wh^{3/2}$ m^3/min (16 to 35 $wh^{3/2}$ ft^3/min).

4.2.2.4. Oxygen Depletion and Carbon Monoxide

Air temperatures and oxygen depletion were the highest in runs 9 and 11 and so were the air temperatures in run 10. The oxygen sampling line was clogged in the latter test and the data could not be taken. Figures 21 and 22 show the temperature rise versus oxygen depletion for tests 9 and 11, respectively. The concentration of oxygen in these tests is shown at 2 minute intervals and at flashover. A similar plot is also presented on figure 23 for all of the quarter-scale and full size fire tests. However only the data corresponding to peak upper air temperatures are indicated. Where there were two or more successive peaks for any single run, the oxygen depletion values for all of the temperature maxima were indicated. The open data points denote model data and the solid data points denote full-scale data.

Equation 3-11 was used to relate the oxygen depletion and temperature of the air at the top of the doorway and was superimposed on all three figures. The equation demonstrates the effect of the thermal losses. The solid line on figures 21, 22 and 23 is the theoretical curve assuming no heat losses while the dashed lines are the theoretical curves taking radiative heat losses into account with certain assumptions. It assumes that all losses are by radiation into the lower part of the compartment. This latter assumption is not unreasonable at temperatures above 400 °C (752 °F). At these higher temperatures radiation is the dominant mode of thermal losses from the upper surfaces. At lower temperatures conduction losses to these surfaces cannot be ignored. Two typical ventilation parameters of 1.8 and 5.1 cm/s (3.5 and 10 ft/min) were considered for the partially and fully opened door situations. As is evident from the figures, the correlations between the temperature rise of the doorway air and the oxygen depletion were reasonably good.

Carbon monoxide and oxygen depletion values corresponding to temperature maxima from all of the quarter-scale and full-scale tests were plotted together on figure 24. CO concentrations varied linearly with oxygen depletion down to an O_2 concentration of about 7% at the doorway. At lower O_2 concentrations, the levels of CO increased sharply.

4.2.2.5. Smoke Optical Density

Production and spread of smoke are especially hazardous in confined spaces such as the quarters on board ship. Smoke impairment of vision can seriously impede the safe escape of occupants and reduces the effectiveness of the crew fighting the fire.

The smoke obscuration reading on the vertical smoke meter inside the compartment could be used to approximate visibility for the space. If the smoke is assumed to be evenly distributed over the upper half or 1.07 m (3.5 ft) of the compartment then the visibility is independent of the path orientation through the smoke. Gross, et al. [9] defined a critical smoke optical density of 0.26 per meter (0.08 per foot) or 16% light transmission as the upper limit of visibility of objects due to smoke obscuration over a 3.05 m (10 ft) viewing distance. This is roughly equivalent to a 47% smoke obscuration reading across the vertical smoke meter. Percentage obscuration in the compartment is plotted against time on figure 25 for all thirteen full size fire tests. Selected representative data from each run are shown. The numbers on the figure correspond to their respective compartment fire tests.

On the average, smoke production from fires with peak upper air temperatures at or over 500 °C (932 °F) exceeded this visibility limit after 1-1/4 minutes. In the compartment fires where the maximum air temperatures were kept below 500 °C (932 °F), the average time to achieve this obscuration level was roughly 2-3/4 minutes.

Light transmission data recorded near the top of the doorway also substantiates this anticipated trend of higher obscuration in the compartment due to an increased combustion of the bedding. Smoke obscuration values at both interior and doorway locations are also given on table 4a at times of peak upper air temperatures.

4.2.3. Heat Balance for Compartment

While there is a considerable net radiation exchange between the upper and lower regions of the compartment, ultimately the heat production from a fire is dissipated to its surroundings by convection and radiation losses through the doorway and conduction through the compartment surfaces. The relative magnitudes of these losses depend on the ventilation to the space. A well ventilated area will lose more heat to the hot flow exhausting from the compartment than one having a slow rate of air change in the room. This fact is well illustrated by the approximate thermal losses calculated during the relatively steady burning periods in runs 3B and 9, which had a fully opened and half opened doorway, respectively. The time intervals taken for these calculations were between 3 and 9 minutes in run 3B and between 6 and 18 minutes for run 9. Table 6 summarizes these findings.

Table 6. Heat Losses from Compartment

Mode of Energy Transfer	Test 3B Opened Doorway (percent loss)	Test 9 1/2 Opened Doorway (percent loss)
Convection out doorway	71	40
Radiation out doorway	3	4
Conduction through vinyl coated bulkhead	15	37
Conduction through fibrous glass insulated bulkhead	2	3
Conduction through fibrous glass suspended ceiling	2	2
Conduction through deck covering	7	14

Analysis of these results showed that the energy convected out the doorway accounted for a larger percentage of the total energy dissipated from the compartment in run 3B than in test 9. The restricted inflow of air in the latter case also resulted in higher room temperatures and hence increased conductive losses through the interior linings and more energy radiated to the deck covering and out the compartment opening. The convective losses of 71 and 40% for runs 3B and 9, respectively, agree with the results from gas burner fires in a somewhat similar room configuration lined with one inch thick asbestos insulation board [14]. Those experiments indicated that approximately 56% of the energy generated by the fire escapes the enclosure in the form of a hot outflow through the doorway.

Complete accounting of heat generation within the enclosure and thermal losses from the compartment interior were complicated by incomplete combustion of the burning materials and by the limited instrumentation of the test compartment. In run 3B the bedding was the only material burning. Calculations showed that only about 68% of the weight loss monitored over the period of steady burning experienced complete combustion. The remainder of the fuel left the compartment as unburned combustible gases and dense grey black smoke. Weight loss data from test 9 was not available.

5. LABORATORY FIRE TEST DATA

All materials considered or used in the compartment fires series were evaluated with the five laboratory fire tests. Table 7 summarizes the results from the ASTM E-162 (radiant panel), potential heat, smoke density chamber, heat release rate calorimeter and ease-of-ignition tests.

The radiant panel data are presented in terms of the flame-spread factor, F_S, as well as the flame-spread index, I_S, which is the product of F_S and the heat evolution term. These quantities have been described in section 2.3. The factor F_S has been included as it is a direct measure of the rate of flame propagation and is not biased by the rate of heat generation of the material. The latter property is measured with the heat release rate calorimeter. Currently materials are being screened by the flame-spread index I_S. Usually materials evolving little heat also exhibit low rates of flame spread. Analysis of the data in table 7 and data on some materials used in home building [2], table 8, indicates that a F_S of under 5 corresponds to an I_S value of 25 or less.

Materials submitted as part of the Navy's habitability program and which had I_S values of 25 or lower performed well in the compartment fires. None of these interior linings became significantly involved until near flashover conditions were attained.

Materials were tested separately and in the composite actual use configuration. The substrate material of a specimen can noticeably affect both the the flame-spread factor and index for the specimen. Inspection of the data for the polyamide carpet indicated that I_S decreases by an order of magnitude when 0.64 cm (1/4 inch) steel is substituted for the 1.27 cm (1/2 inch) asbestos-cement board used on the standard tests. A two to three fold difference was also noted in the F_s values.

Sometimes test behavior of composite specimens can obscure the performance of the substrate material. A sample of neoprene mattress material with ticking, cover, and a single sheet over its surface had a flame-spread index of 226. The same neoprene specimen by itself had an index of only 4. Whereas the surface layers burn away quickly and frequently contribute mainly to the initial phase of the fire growth, heat release from the neoprene substrate is slow and sustained over a relatively long time and can ultimately lead to

Table 7. Results from the Five Laboratory Fire Tests

Material	Thickness (inch)	Thermal Conductivity κ (Btu/ft/hr/F)	Density ρ (lb/ft³)	Heat Capacity c (Btu/lb/F)	ASTM† E-162 Radiant Panel F_s	ASTM† E-162 Radiant Panel I_s	Potential Heat Btu/ft²	Potential Heat Btu/lb	D_m F-Flaming N-Nonflaming	Smoke Density Chamber Gas Concentration at Flaming Exposure, ppm (min) NO + NO_2	SO_2	HCN	CO	HCL	Heat Release Rate Calorimeter q_m Btu/s/ft²	Q_T Btu/ft²	Ease of Ignition Exposure Time for Lower Limit of Ignition** (s)
Overhead																	
1. Low Density Acoustical Panel	0.7	0.02	7.2	0.2	4.1	7.3	279.	665.	F3.5N4.	12.5 (14)	5. (10)	15. (11)	250. (12)	0. (13)	1.76	212.	>200
2. High Density Acoustical Panel	0.55	0.037	25.	0.25	3.1	5.0	18.	13.	F1.5N4.	2.5 (4)	0. (8)	1. (5)	50. (6)	1. (7)	0	0	>480
Bulkhead																	
3. Vinyl Laminate on 0.0 63" Aluminum	0.071	79	173.	0.22	2.7	25.0			F124.N94.	25. (10)	50. (11)	25. (12)	900. (13)	20. (14)	2.12	124.	180
4. Vinyl Laminate	0.008						610.	10,221.									
5. Melamine Laminate on 0.0 63" Aluminum	0.098	79.	173.	0.22	1.0	3.0			F108.N50.5	27.5 (14)	30. (18)	75. (15)	500. (16)	20. (17)	5.02	609.	105
6. Melamine Laminate	0.035						2109.	8436.									
7. Fibrous Glass	1.0	0.02	3.9	0.2	4.2	8.0	99.	303.	F17.5N15.	7.5 (15)	20. (11)	8.3 (12)	200. (13)	4. (14)	1.94	397.	>600
Deck																	
8. High Temp. Polyamide Carpet on $\frac{1}{4}$" Steel	0.45				2.9	8.3			F179.N127.	10. (14)	10. (11)	12.5 (12)	500. (13)	45. (14)	2.03	705.	420
9. High Temp. Polyamide Carpet and Glue	0.20				7.3	87.0	3378.	8750.									
10. Wool Carpet on Hair Pad, $\frac{1}{4}$" Steel	0.88				3.1	24.3			F476.N328.	20. (7)	75. (8)	50. (9)	1200. (10)	0. (11)			300
11. Wool Carpet on $\frac{1}{4}$" Steel	0.53				2.9	20.			F258.N133.	30. (17)	100. (18)	50. (19)	1000. (20)	50. (21)	8.2	2700.	>1020
12. Wool Carpet on Hair Pad	0.63																
13. Wool Carpet	0.28				10.2	129.	2898.	6469.							17.6	4970.	
14. 80% Wool-20% Phenol-formaldehyde Carpet	0.20				1.0	6.5									12.3	2770.	
15. Acrylic Carpet	0.50				17.2	413.											
16. Hair Carpet Pad	0.35						2079.	8522.									
17. Vinyl Asbestos Tile on $\frac{1}{4}$" Steel	0.34				3.1	14.7			F263.N182	10. (13)	40. (14)	10. (15)	250. (16)	0. (17)	4.41	>660.	>420
18. Vinyl Asbestos Tile***	0.094						1982.	2207.							9.7	1156.	
Bedding																	
19. $\frac{3}{4}$" mattress, FR Cotton Ticking, Cover, 1 Sheet	0.80				19.7	226.			F441.N512	12.5 (10)	150. (11)	25. (12)	1800. (13)	100. (14)			22
20. $\frac{3}{4}$" Mattress, FR cotton Ticking	0.75					4.0*			F602.*N516*	7.*		25.*	1200.*	1000.*	12.33*		
21. $\frac{3}{4}$" Mattress, Nylon Ticking	0.75					22.0*			F379.*N325.*	12.*		25.*	700.*	600.*	4.76*		
22. $\frac{3}{4}$" Mattress	0.75					4.0*	3352.	9948.	F485.*N440.*	13.*		10.*	1000.*	700.*	5.74*		
23. FR Cotton Ticking							452.	7063.									
24. Mattress Cover							322.	6993.									
25. Cotton Sheet							195.	6969.	F24.N80	2. (12)	0. (14)	0. (11)	5. (15)	0. (10)			
26. Wool Blanket							864.	9096.	F82.N96	15. (12)	20. (13)	20. (11)	5. (15)	1. (10)			
27. 1" Pillow and Case	1.00				19.8	193.	1653.	8265.	F537.N305.	25. (10)	60. (11)	50. (12)	500. (13)	20. (14)			22

* Reference 20

** Ignition taken as self-sustained surface flaming for one second or longer

*** Used extensively on board ship

† Unless 0.64 cm (1/4 in) steel is specified, all other E-162 tests have 1.27 cm (1/2 in) asbestos-cement board as the substrate material

Table 8. Results of Corner Fire Tests with Gypsum Board Ceilings [2]

Wall Lining Material	Thickness (in)	Bulk Density (lb/ft^3)	Ease-of-Ignition Exposure Time* (s)	ASTM E-162 Radiant Panel F_s	ASTM E-162 Radiant Panel I_s	Heat Release Rate Calorimeter q_m ($Btu/s/ft^2$)	Heat Release Rate Calorimeter Q (Btu/ft^2)	Max. Upper Air Temp in Compartment** (°C)	Observations on Fire Involvement of Surface Area After 10 min
Gypsum wallboard finished with 2 coats of white latex paint	1/2	44	>200	2.9	8.	6.5	476	129	Fire affected area covered 19 to 25% of total surface.
Vinyl covered gypsum wallboard, cloth textured surface	1/2	47	150	3.5	23.	5.2	511	147	Fire affected area covered 22% of total surface.
Particle board, unfinished	5/8	44	150	5.9	118.	17.7	11800	549	About 90% of surface affected.
Douglas fir plywood, prefinished 3-ply	1/4	42	105	9.4	135.	13.9	4040	571	More than 90% of surface was affected.
Luan plywood, sanded, unfinished 3-ply	11/64	31	95	9.0	141.	14.5	2400	439	More than 90% of surface was affected.
Melamine Finished, tempered hardboard	1/8	73	152	5.1	117.	46.1	5380	662	More than 90% of surface was affected.
Acoustic tile (fiber board base), painted, holes	1/2	20	70	6.2	60.	10.8	5150	390	About 90% of surface area was affected.
Coated acoustic tile (mineral-base coating on fiber board base)	1/2	20	>240	1.0	6.	5.4	2660	299	Fire affected area covered 51% of total surface.

* Ignition taken as self-sustained surface flaming for one second or longer. Times indicated are not necessarily the values sustained ignition reported in reference [2].

** Temperature buildup from burning crib alone without any contribution from the interior finish is in the vicinity of 100 °C [2].

flashover conditions. To assure proper interpretation of test data, it is recommended that materials be tested individually and in actual use configurations.

The potential heat of the compartment materials having an organic base varied within the range of 16,300 to 23,200 J/g (7,000 to 10,000 Btu/lb). Mineral base and fibrous glass materials such as high and low density acoustical overhead paneling and low density bulkhead sheathing are naturally expected to have low values. Coatings and thin laminates contribute relatively little potential heat to the compartment even though the potential energy per gram of material is high.

Measurements in the smoke density chamber include the peak specific optical density for both flaming and smoldering exposures and determinations of the potentially hazardous gases NO + NO_2, SO_2, HCN, CO and HCl.

The rate of energy released from a material depends on its fire exposure. For this program, material specimens were subjected to a constant moderate irradiance level of 6 W/cm^2 (5.3 $Btu/s/ft^2$). Both the maximum one minute average rate of heat release per unit surface area and the total heat generation per unit area for each material are also included in table 7.

Results of the ease-of-ignition test are presented in terms of the time for the exposure flame to ignite the specimen surface. Ignition is taken to be the persistence of flames for one second or longer on the specimen following the curtailment of the exposure flame.

6. DESIGN GUIDELINES

6.1. General

In this study of compartment fires the overhead and bulkhead linings and two of the deck coverings were limited by the Navy to several candidate materials for shipboard application. The interior finish was restricted to two overhead materials, three bulkhead sheathings and four deck coverings. With the exception of the latter, these materials also had a fairly narrow range of flame spread and smoke generation potential. For the deck coverings the variability in these fire properties was less limited. However, the deck material usually does not become involved in the fire until flashover conditions are imminent or has occurred. Consequently, relationships between laboratory fire test performance of materials and their behavior in actual compartment fires were difficult to establish. Nevertheless, there is sufficient state-of-the-art information available together with the observed fire behavior of materials on which to draw some conclusions and to improve present rules for fire safe material usage.

The design criteria suggested in this section for the lining materials for the crews berthing compartment are based on the following laboratory fire tests: the radiant panel (E-162), the potential heat method, the heat release rate calorimeter, the ease-of-ignition test and the smoke density chamber. In choosing the highest acceptable level for the outputs of each of these tests, the following points were taken into account:

(1) The tests performed to date provide no justification for relaxing the requirements on flame spread, potential heat, and smoke density from those recommended earlier in phase 1 of this project [3].

(2) The lining materials, used in the compartment fire tests, met the phase 1 requirements and did not provide a large increase in the fire hazard beyond that provided by the bedding itself. Therefore, any new criteria presented here should not rule out the use of these materials which have been successfully employed in the full-scale compartment tests.

(3) While the phase 1 criteria were adequate in choosing the safe materials used in the present tests, demonstrations [15] of rapid fire buildup in rooms lined with low density foam plastics have indicated that flame spread ratings alone may not be capable of ruling out all potentially hazardous lining materials. Therefore it is suggested that any lining material to be used must also satisfy certain heat release rate and ignitability requirements. These requirements can be set on a more rational basis taking heat balances and fire buildup times into account.

The criteria presented here represent the state-of-the-art, and the ongoing analysis of compartment fire buildup is aimed at their improvement.

6.2. Flame Spread and Rate of Heat Release

No reason was found to alter the flame spread requirement of equal to or less than 25 for the overhead and bulkhead materials. The measurement, however, must be made on the material in the same thickness and backed in the same manner as it would be installed. The effect of backing material is dramatically illustrated for carpets in table 7. Although the same flame spread requirement can be given for the deck coverings, more suitable alternative acceptance criteria may be based on the material's ability to sustain flame propagation under the thermal radiation levels anticipated on the deck surface. The flooring radiant panel test [7] described in section 2.3.2. measures this critical radiant flux for sustained horizontal flame spread along the surface of a material. This test is expected to replace the ASTM E-162 method for measuring the flammability hazard of deck coverings. As indicated on table 4, the upper air temperature due to fires in full size compartments, having closed bunks without privacy curtains and with typical ventilation at each berth, does not exceed 400 °C. Even if temperatures were as high as 450 °C the irradiance on the deck would only be about 0.5 W/cm^2. Thus, deck coverings having a critical flux equal to or higher than this value would not be expected to contribute significantly to the fire.

The preliminary experiments with the quarter-scale model indicated that a total heat release rate of approximately 670 kW (630 Btu/s) would be required to produce an upper air temperature of 700 °C (1,292 °F) which is necessary for full involvement of a 3 x 3 x 2.1 m (10 x 10 x 7 ft) compartment having an opened doorway. In most situations this temperature must be maintained for a duration on the order of a minute in order for the irradiance from the heated upper surfaces to ignite the combustible contents in the lower part of the compartment.

This heat generation rate is equivalent to 72 kW/m^2 (6.3 Btu/s/ft^2) of deck area. Evidence from the full size corner fire experiments [2] supports this finding. It was found in those tests that just 3 m^2 (32 ft^2) of wall paneling having a maximum one minute average heat release rate of 200 kW/m^2 (17.7 Btu/s/ft^2), as measured in the heat release rate calorimeter with an exposure level of 6 W/cm^2 (5.3 Btu/s/ft^2), together with a fire source (6.4 kg or 14 pound wood crib) can flashover a room having 9.3 m^2 (100 ft^2) of deck space. The ceiling material was gypsum board whose paper surface burned away in the early part of the test, and thus contributed little to the overall heat release at the time of flashover.

A simple calculation based on the above number indicates that the maximum rate of heat generated by the paneling would be 600 kW (570 Btu/s) in addition to the 180 kW (170 Btu/s) from the burning crib. In actuality the entire burning surface was not releasing heat at the maximum one minute averaged value, and a somewhat lower rate occurred. This calculation is essentially in agreement with the above finding from the model experiments.

In order to effectively apply this critical rate of heat generation to the Navy berthing quarters, an estimate must first be made of the potential thermal contribution from the furnishings. Then the balance of the energy production needed to attain the critical air temperature in the compartment could establish the limits for the rate of heat generation from the interior finish.

The burning rate of the bedding in test 4B with the opened bunks reached a maximum of 41.6 g/s (0.092 lb/s). The median value of the potential heat of the bedding materials is seen from table 7 to be about 19.7 kJ/g (8,500 Btu/lb). Then a maximum heat release rate of 820 kW (780 Btu/s) could occur if there were complete combustion of the materials. This was enough to exceed the critical temperature for flashover without any contribution from the locker or the material lining of the compartment.

However, for the closed bunks with no privacy curtains or abnormally high airflow rate at the bunks, the maximum burning rate recorded was only 15.1 g/s (0.033 lb/s) or 300 kW (280 Btu/s). This would allow a total heat release rate of 370 kW (350 Btu/s) from the lining materials before full involvement could be reached. The criteria for the heat release rate of the lining materials could be based on the concept of keeping their total heat production rate below 370 kW (350 Btu/s).

Since the carpet did not contribute any heat until full involvement occurred in the compartment fire tests, only the bulkhead and the overhead will be considered in the heat contribution calculation.

Hence the requirement for no flashover could be stated:

$$A_B \, q_B + A_o \, q_o \leq 370 \text{ kW (350 Btu/s)}$$

or

$$\frac{A_B}{A_o} q_B + q_o \leq 4 \text{ W/cm}^2 \text{ (3.5 Btu/s/ft}^2\text{)} \qquad (7\text{-}1)$$

where q_B and q_o are the heat release rates per unit area of the bulkhead and overhead surfaces, respectively. A_B and A_o are the areas of the bulkhead and overhead, respectively, that could potentially be contributing heat prior to flashover. In a compartment fire this could include the entire overhead and the upper half of the bulkhead surface. Extensive fire spread along the bulkhead in the lower part of the compartment is much less likely to occur than that along the bulkhead surface exposed to the hot air layer in the upper part of the compartment. Experimentally, little fire involvement of the upper bulkhead surface was observed in the compartment fires until flashover conditions were approached. In those tests in which there were closed bunks and no privacy curtains or unusual ventilation conditions there was no flashover of the compartment or flame spread down the bulkheads. While flame spread across the ceiling is relatively easy, even for low flame spread materials, downward flame spread is not likely to occur for these materials until the high radiation levels characteristic of flashover are approached. Hence, the requirement of $I_s \leq 25$ should be sufficient to eliminate the first term of equation (7-1). Hence the area of potential involvement could be considered to be the overhead which must have a heat release rate of less than 4.0 W/cm^2 (3.5 Btu/s/ft^2). The overhead materials used in these tests will pass this criteria.

The bulkhead lining materials can be given a greater margin of safety by requiring them to have heat release rates $\leq$ 6 W/cm^2 (5.3 Btu/s/ft^2). This additional requirement would pass the bulkhead lining materials which performed satisfactorily in the compartment fire tests while ruling out materials having high heat release rates. It would also help eliminate marginal materials such as the coated fiber acoustical tile shown on table 8. This material did not have a high maximum one minute average rate of heat release per unit surface area. However a significant rate is maintained over a sufficiently long period, as evidenced by its relatively high effective heat of combustion, Q, to result in an additional increase in air temperature of about 200 °C over that from the burning crib in the compartment.

The above recommended limits on the heat release rate from materials is based on the maximum one minute average rate of heat release per unit surface area as measured in the heat release rate calorimeter [5] under an irradiance level of 6 W/cm^2 (5.3 Btu/s/ft^2).

6.3. Potential Heat

In addition to the necessity for limiting the rate of heat production and thus the intensity of the fire, there is also a need for restricting the duration of the fire in the unlikely event that flashover did occur. The latter requirement assures the structural integrity of the compartment components as well as reduces the probability of fire penetration into adjoining occupancies. A commonly used relation between fire severity and fire load [16] shows that for every 12.1 kg/m^2 (2-1/2 lb/ft^2) in fire load, the fire severity, in terms of ASTM E-119 type of fire exposure, increases by 1/4 hour. This represents about 2.38 x 10^8 J/m^2 (21,000 Btu/ft^2) of deck area. The typical contents in shipboard berthing compartments would then lead to about 15 minutes of fire exposure. The compartment fire tests have indicated the seriousness of such exposures on 0.25 cm (0.10 inch) thick aluminum bunk partitions. There is further experimental evidence [17] that exposure times as short as 6 minutes could also be detrimental to 0.64 cm (1/4 inch) thick aluminum plating. However it is recognized that realistic limits must be set to allow for a minimal of necessary furnishings and interior finish on board ship. For this reason it is suggested that a practical limit of 1.1 x 10^7 (1,000), 3.4 x 10^7 (3,000) and 5.6 x 10^7 J/m^2 (5,000 Btu/ft^2) be set for the overhead, bulkhead and deck coverings, respectively. For a 3.1 x 3.1 m (10 x 10 ft) space having a 2.1 m (7 ft) overhead, the compartment interior finish could then contribute another 10 minutes of fire severity. These limits would also allow the use of the materials which performed satisfactorily in the compartment fire tests.

6.4. Time to Ignition

Compartment fire tests with some low density foam materials [15] have demonstrated that low flame spread ratings do not always assure low fire risk performance in compartment type fires. These materials also exhibited ignition times of less than 60 seconds. Ignition is defined here as the persistence of flames for one second or longer any place on the specimen following curtailment of the ignition source. Ignition time is the duration of flame impingemen required to produce ignition. All of the overhead and bulkhead finish materials used for the compartment fires shown on table 1, had ignition times greater than 60 seconds and performed well in the compartment fires. In order to eliminate those low thermal inertia materials which ignite quickly it is suggested that ignition times greater than 60 seconds, as determined from the ease-of-ignition test [4], be set as the criterion for the ease-of-ignition.

6.5. Smoke Production

Criteria for limiting the generation of smoke in the compartment is difficult to establish for interior finish and furnishings in the room. The burning of a relatively small quantity of certain materials could produce sufficient smoke to completely obscure visibility in the compartment, in critical spaces such as passageways, and in neighboring spaces.

For instance, a burning rate of about 7.6 g/s (1 lb/min) in the bedding produced sufficient smoke to exceed the limit of visibility of objects within 1-1/2 minutes in compartment test 3A, which had a fully opened doorway.

The smoke meter in the test compartment monitored the rate of smoke production as it mixed with the volumetric air inflow to the space. The smoke density chamber, on the other hand, measured the total smoke produced in a fixed enclosure volume. Ideally the optical density per meter of viewing distance through the smoke, OD/m, should be the same for both situations when the ratio of the burning rate to the inflow to the compartment, R_c, is the same as the ratio of the specimen weight loss to the enclosure volume, R_s, in the smoke density chamber. The quantity R_s was 1.4×10^{-5} g/cm^3 (0.00085 lb/ft^3) for the mattress material tested in the smoke density chamber and corresponded to an OD/m of 4.3.

For compartment fires having a fully opened doorway, the burning rate and volumetric air inflow were available for tests 3A, 3B, 4A, 4B and 7. Two of these runs, tests 3A and 4B, attained this OD/m value of 4.3 over the 2.1 m (7 ft) viewing distance in the smoke meter inside the compartment within 3 minutes as shown on figure 25. The averaged rates of weight loss and air inflow were 19.7 g/s (2.6 lb/min) and 32.8 m^3/min (1,160 ft^3/min), respectively, over this time period for these two tests. This corresponded to a R_c ratio of 3.6×10^{-5} g/cm^3 (0.00224 lb/ft^3) or 2.6 times greater than the R_s ratio used in the smoke chamber to produce the same optical density per meter of viewing distance. Runs 3B and 7 took much longer to achieve this value of OD/m, and this smoke level was never reached in run 4A.

The differences between the smoke chamber readings and smoke levels in the compartment tests were not surprising. In the smoke chamber, the material was completely burned and the smoke is representative of the entire composite specimen. In an actual fire the smoke concentration at any moment would be dependent on the materials burning at the time. There could be as much as a 30% variation in the specific optical density, D_s, and consequently the same variation in the values of OD/m, resulting from the differences in the smoke potential among the bedding component materials.

More important and larger variations between laboratory and actual smoke concentrations could result from differences in the fire exposure, material configuration, spatial distribution and coagulation of smoke particles in the two cases.

As mentioned earlier a burning rate of 7.6 g/s (1 lb/min) could fully obscure visibility in the compartment. It is then conceivable that under some fire conditions a typical rate of 15 to 23 g/s (2 to 3 lb/min) over a 10-minute burn duration could easily produce enough smoke to fully obscure vision, e.g., over a 3-m (10-ft) viewing distance, in a space which is twenty or more times larger than the compartment of fire origin, assuming uniform mixing of the smoke, no deposition on surfaces, and an absence of coagulation of the smoke particles.

Although such visibility limits are logical in terms of ease of egress and more effective fire fighting capabilities, they are impractical and are difficult to apply in the real world. In spite of this there is still a need to limit the smoke generation ability of materials as the duration and quantity of smoke production determine its residence time and frequently its ultimate spread through the ship.

The laboratory ratings of the materials considered under the Navy's habitability program and used in this study indicated that the phase I criteria need little revision. As improved materials having lower smoke outputs become available, it may be advisable to consider tightening the requirements for all materials used in the berthing areas.

It is suggested that the smoke control requirements for interior finish be as follows:

Location	Maximum Optical Density, D_m for Flaming and Non-flaming Exposures
Overhead	$\leq$ 150
Bulkheads	$\leq$ 150
Deck	$\leq$ 450

6.6. Toxicity of Combustion Products

In order to relate the measurements of combustion gases in the smoke density chamber to their potential concentrations in the compartment and neighboring spaces, the volume of the space accessible to the combustion products must be known and certain assumptions must be adopted. The fire related gases are assumed to be uniformly distributed throughout the compartment and connecting areas. Then if the gas concentrations were to vary directly with the ratio of the surface area of the burning material to the accessible shipboard space, some estimate may be made of the immediate environment on board ship.

The most potentially hazardous environment will occur where there is full involvement of the entire compartment. When this happens, even bulkhead materials having a flame spread of 25 or less and deck linings contribute to the spread of potentially hazardous combustion products throughout neighboring shipboard spaces. The concentrations of fire associated gases will be estimated for this situation. The gas concentrations from the smoke density chamber were based on a sample area to chamber volume ratio of 0.0083 m^{-1} (0.0025 ft^{-1}). If, e.g., we have a 283 m^3 (10,000 ft^3) space, the equivalent burning surface area would be 2.3 m^2 (25 ft^2) to maintain this area to volume ratio found in the smoke density chamber. Table 9 outlines the estimated potential gas concentrations for this example along with the toxicological information [18,19] for the various combustion products analyzed.

All of the above by-products of combustion exceeded their life safety range for 2 to 5 minute exposures. The neoprene mattress alone accounted for most of the oxides of nitrogen, almost all of the HCl and a good proportion of the CO. Another major producer of the latter was the vinyl laminate. Even without the contribution from the mattress, the combustion products from the remaining materials would have exceeded the lethal range for all of the gases.

The gas concentrations presented in table 9 are only for one fire condition where a dilution factor of fifteen occurs and uniform mixing with the surrounding air is assumed. It doesn't necessarily represent a typical situation on board ship. Without further fire tests on board ship or in simulated shipboard spaces, the movement, stratification and hence dilution of combustion products in adjacent corridor and compartment spaces are difficult to ascertain. Without this further information criteria for limiting the potentially toxic products of combustion cannot be presented at this time.

Table 9. Estimated Potential Concentrations of Selected Gases from Berthing Compartment Fires* and Their Toxicological Limits

Material	Surface Area A ft^2	Area Multiplication Factor A/25.3	Thickness Multiplication Factor **	Estimated Concentrations*				
				$NO + NO_2$ ppm	SO_2 ppm	HCN ppm	CO ppm	HCL ppm
Low density acoustical panel	100	3.95	1	49.4	19.8	59.3	987.5	0
Fibrous glass	140	5.53	1	41.5	110.6	45.9	1106.0	22.1
Vinyl on 0.63" Aluminum	140	5.53	1	138.3	276.5	138.3	4977.0	110.6
3 mattresses with FR cotton ticking	3(13.7)	1.62	4	45.4	972.0	162.	7776.0	6480.0
3 pillows and covers	3(4.1)	0.49	4	49.0	117.6	98.0	980.0	39.2
3 mattress covers***	3(20.0)	2.37	1	4.7	0	0	11.9	0
3 wool blankets	3(38.5)	4.57	1	68.6	91.4	91.4	22.9	4.6
12 cotton sheets	12(37.1)	17.60	1	35.2	0	0	88.0	0
Polyamide carpet on $\frac{1}{4}$" steel deck	100	3.95	1	39.5	39.5	49.4	1975.0	177.8
Total				471.6	1627.4	644.3	17924.3	6834.3
Irritation on brief exposure [ref. 18]				25.	20.-50.			35.
Immediate danger to life (2 to 5 min) [ref. 18,19]				200.	500.	200.-300.	4000-10000.	1000.-2000.

*Based on total surface involvement, uniform distribution in 10,000 ft^3 of shipboard space, and on data from the smoke density chamber.
**Ratio of actual thickness used in compartment to thickness of test specimen in the smoke density chamber.
***Assumed to have same properties as cotton sheets.

6.7. Summary of Criteria

The criteria recommended for the lining materials in the crews berthing compartment are given in table 10. They are based on the five laboratory-scale fire tests discussed in this report, namely the E-162 radiant panel, the potential heat test, the NBS smoke density chamber, the NBS heat release rate calorimeter, and the ease-of-ignition test. These criteria represent the state-of-the-art and have been formulated from a restricted range of lining materials. Additional research is required to examine their range of applicability.

7. CONCLUSIONS

The air temperature in the upper part of the compartment is a good measure of its fire buildup. At 500 °C (932 °F), there is rapid pyrolysis and ignition of most combustible materials in the upper portion of the room. When the air temperature near the ceiling reaches 700 °C (1,290 °F) ignition of light combustibles can occur in the lower part of the compartment due to thermal radiation. In general the rate of heat production needed to attain such temperatures is dependent on the size of the enclosed space, the degree and distribution of the ventilation, the location of heat sources, and the thermal properties of the interior finishings. For a 3 x 3 x 2.1 m (10 x 10 x 7 ft) compartment having a fully open doorway, a heat generation rate of roughly 72 kW/m^2 (6.3 $Btu/s/ft^2$) of deck area is necessary to achieve the highest of these temperatures.

Fires in the bedding on the currently used berthing units having opened sides have been found to exceed this critical rate of heat production. However, the burning of the bedding in the redesigned units resulted in less intense fires. These berthing units had partitions along three sides and were proposed under the Navy's habitability program for making shipboard spaces more liveable for the crew. Fires in these newer bunks could still contribute 45% of the critical rate of heat release, but allowed some leeway for additional interior finish and other contents.

The full-scale and quarter-scale fire experiments have helped establish the ability of the laboratory fire tests to provide interim acceptance limits for fire-safe selection of materials aboard ship. Comparison of the fire experiments have also indicated that fire testing in a quarter-scale enclosure is a useful tool for investigating fire performance in full size compartments. Observations and analysis of these fires along with an analytical treatment of fire buildup in an enclosed space have resulted in an improved interpretation of fire test ratings. As a result, more rational criteria for minimum fire risk material usage have been formulated for interior finish and furnishings in Navy berthing quarters. These design rules have been summarized in section 6.7 of this report (see table 10).

Table 10. Selection Criteria for Interior Finish in Berthing Quarters

Location	Flame Spread	Potential Heat (Btu/ft^2)	Smoke* (D_m)	Heat Release Rate ($Btu/s/ft^2$)	(W/cm^2)	Time to Ignition (s)	Critical Heat Flux for Flame Spread ($Btu/s/ft^2$)	(W/cm^2)
Overhead	≤ 25	1000	≤150	≤3.5	(4)	≥60	--	--
Bulkhead	≤ 25	3000	≤150	≤5.3	(6)	≥60	--	--
Deck Covering	--	5000	≤450	--	--	--	≥0.44	(0.5)

*For flaming and non-flaming exposures

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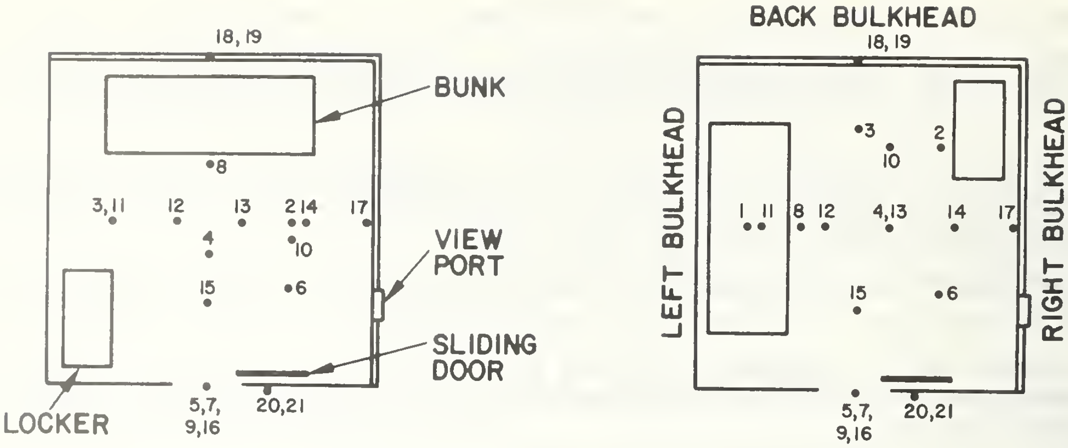

Bulkheads on Front and Left Sides - 1 inch fibrous glass attached to 0.75 inch thick asbestos insulation board walls

Bulkheads on Back and Right Sides - 1/16 inch aluminum paneling separated from 0.75 inch thick asbestos insulation board walls with 2 x 4 inch steel studs

Station		Instrument
1	-	Load Cell
2	-	Radiometer on deck
3,4	-	Flashover indicator (newsprint) on deck
5	-	Velocity measurement near botton of doorway
6	-	Vertical smoke meter
7	-	Horizontal smoke meter at top of doorway
8	-	Gas sampling at elevation of lowest berth
9	-	Gas sampling near top of doorway
10	-	Vertical strand of 11 thermocouples extending from ceiling to underneath carpet
11 to 15	-	Ceiling thermocouples
16	-	Thermocouple near top of doorway
17	-	Thermocouple on right side of specimen wall surface 4 inches from ceiling
18	-	Thermocouple on back side of specimen wall surface 4 inches from ceiling
19	-	Thermocouple on asbestos insulation board surface across from thermocouple 18
20	-	Thermocouple on front surface of fibrous glass 4 inches from ceiling (above door)
21	-	Thermocouple on back surface of fibrous glass behind thermocouple 20

Figure 1. Plan View of Two Compartment Arrangements Showing Locations of Furnishings and Instrumentation.

Figure 2a. A Typically Furnished Navy Compartment Fire Test and Locker Prior to Ignition.

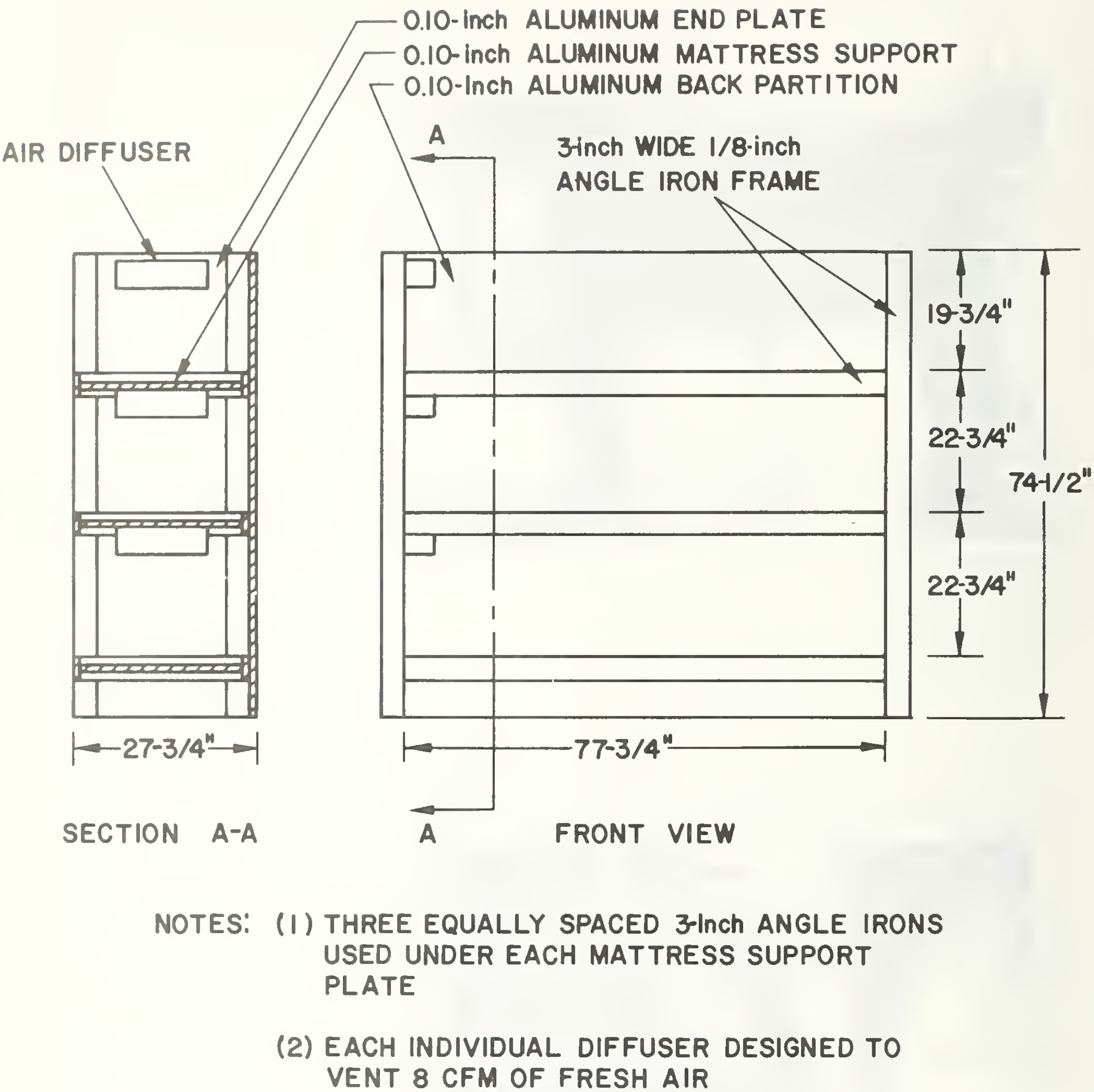

Figure 2b. Description and Dimensions of 3-Man Berthing Unit.

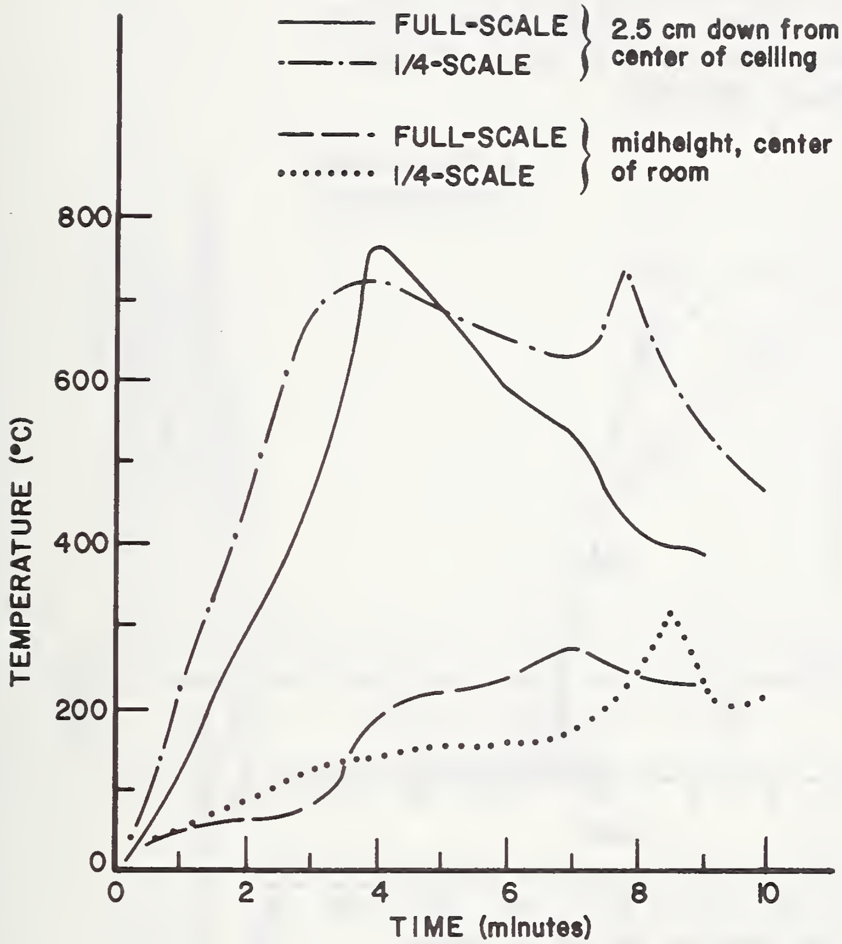

Figure 3. Air Temperatures Inside Compartment - Lauan Walls, Gypsum Board Ceiling.

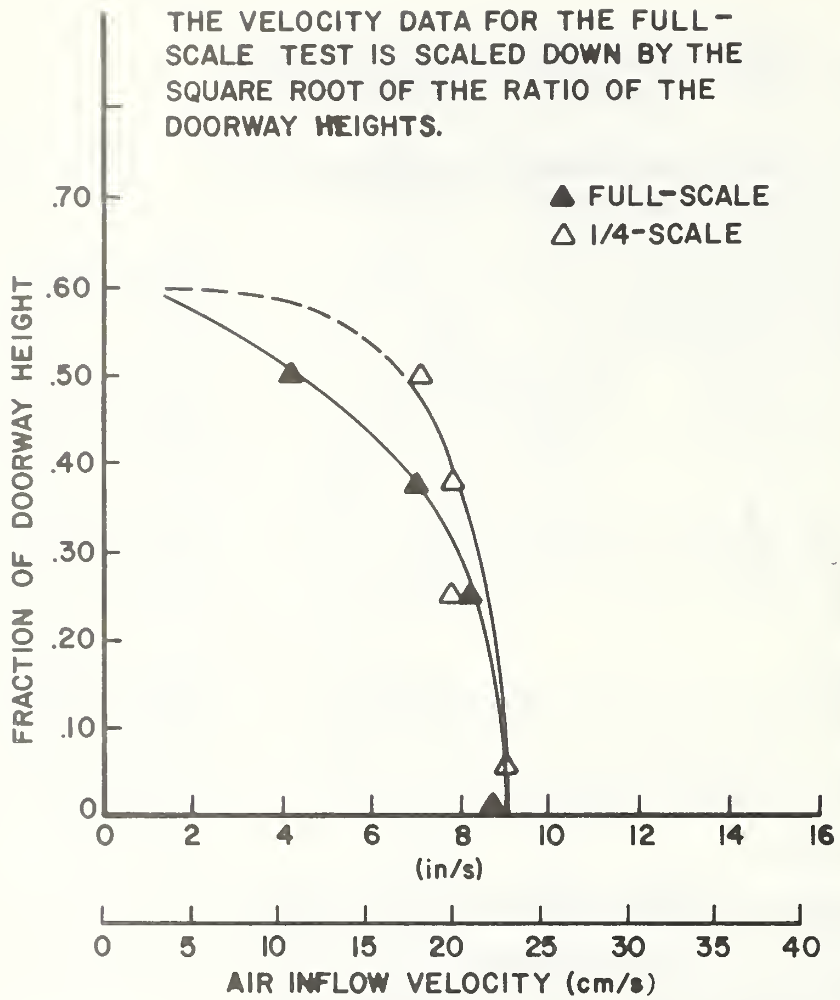

Figure 4. Velocity Profiles in Doorway at 10 Minutes for Full- and Quarter-Scale Enclosures with Gypsum Board Linings.

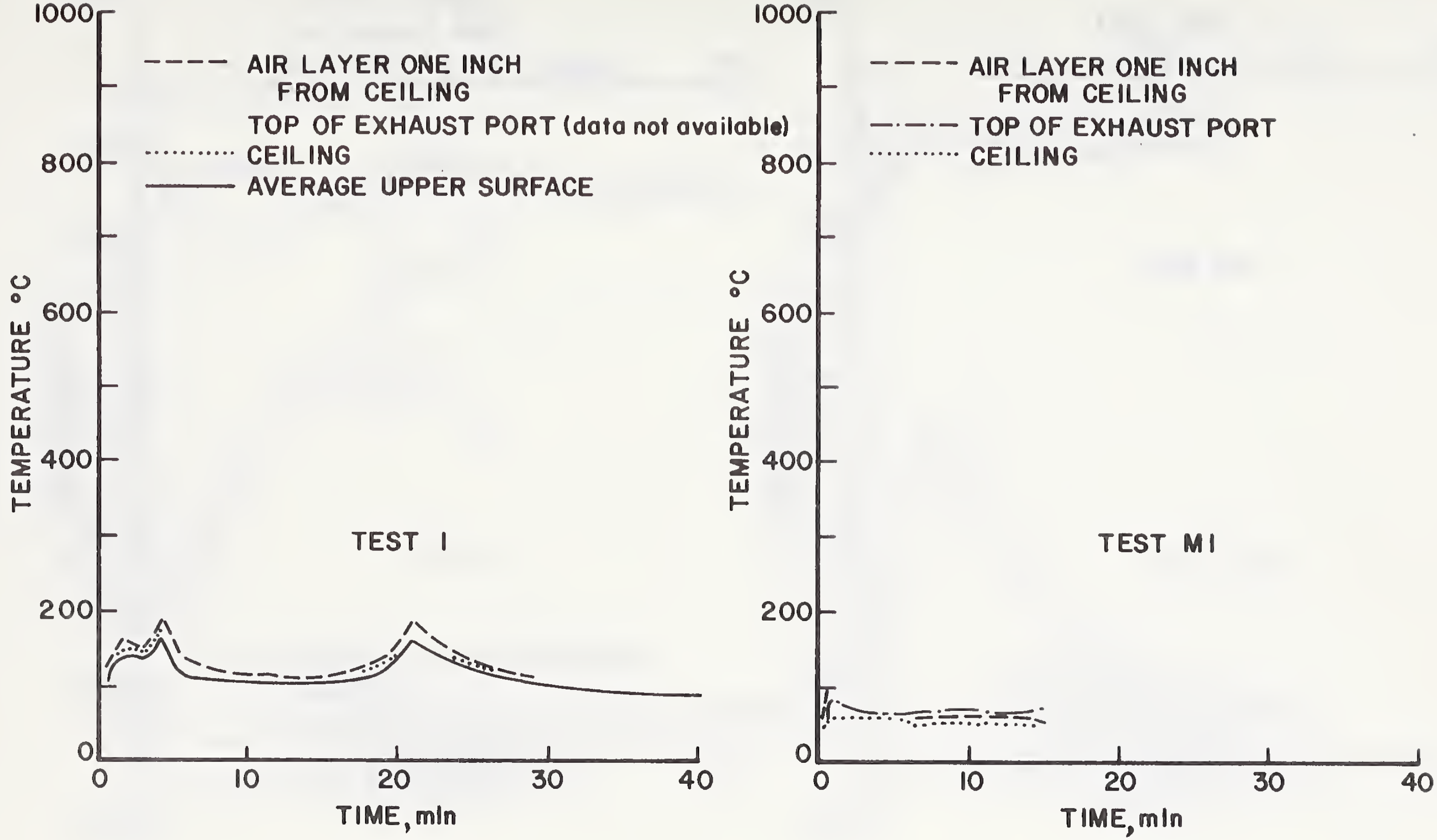

Figure 5. Temperatures in Upper Part of Compartment for Fire Tests 1 and M1.

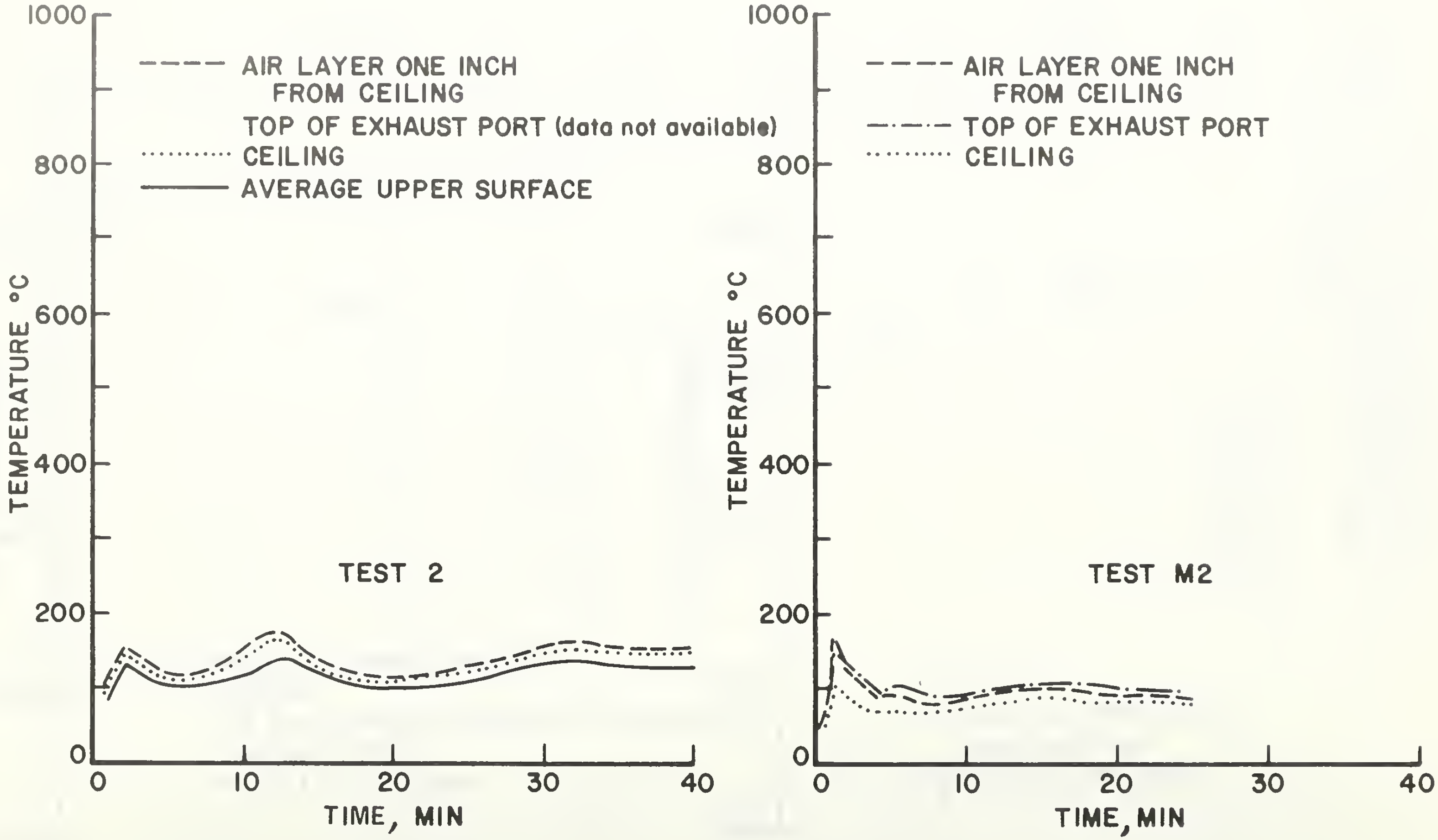

Figure 6. Temperatures in Upper Part of Compartment for Fire Tests 2 and M2.

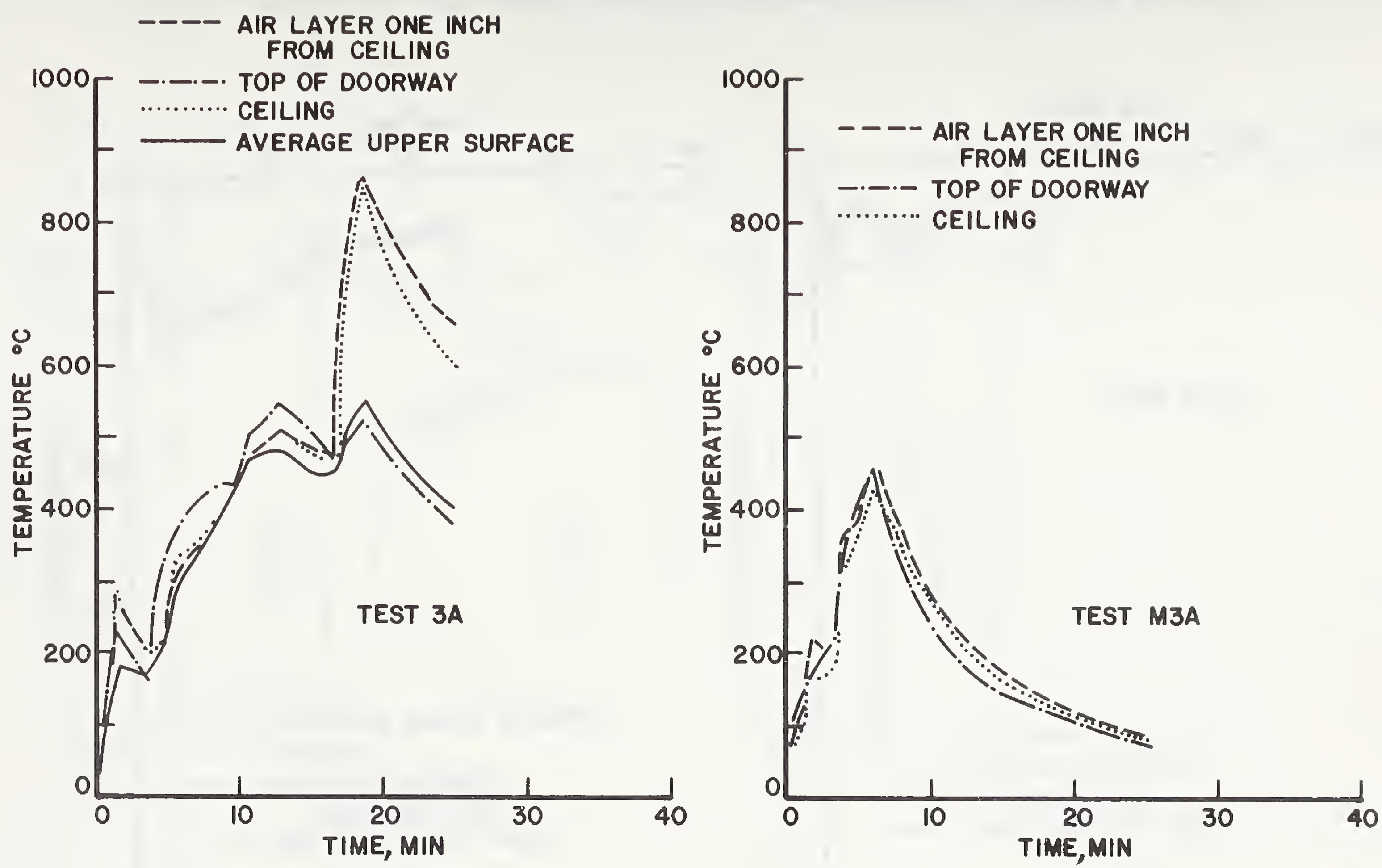

Figure 7. Temperatures in Upper Part of Compartment for Fire Tests 3A and M3A.

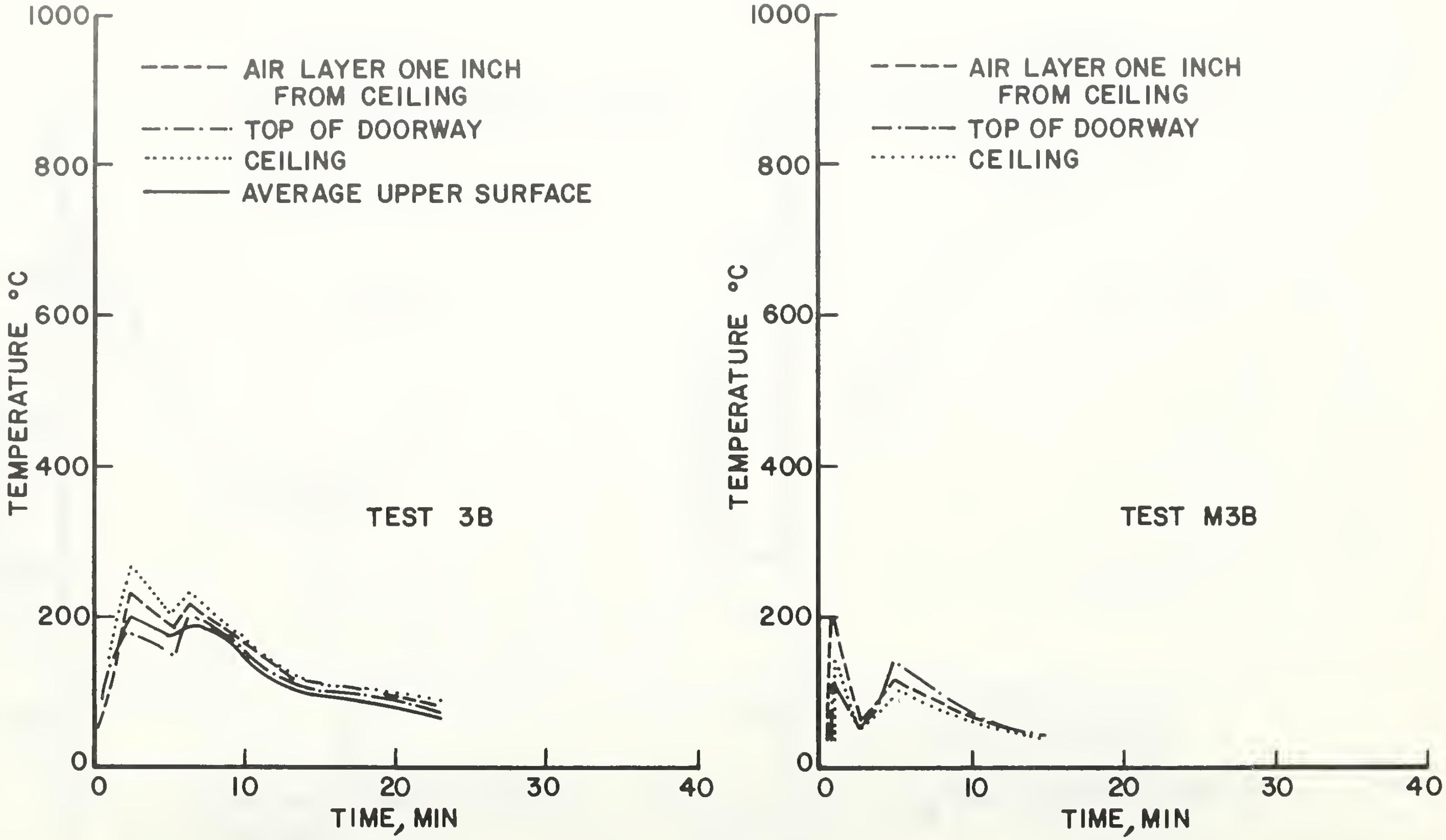

Figure 8. Temperatures in Upper Part of Compartment for Fire Tests 3B and M3B.

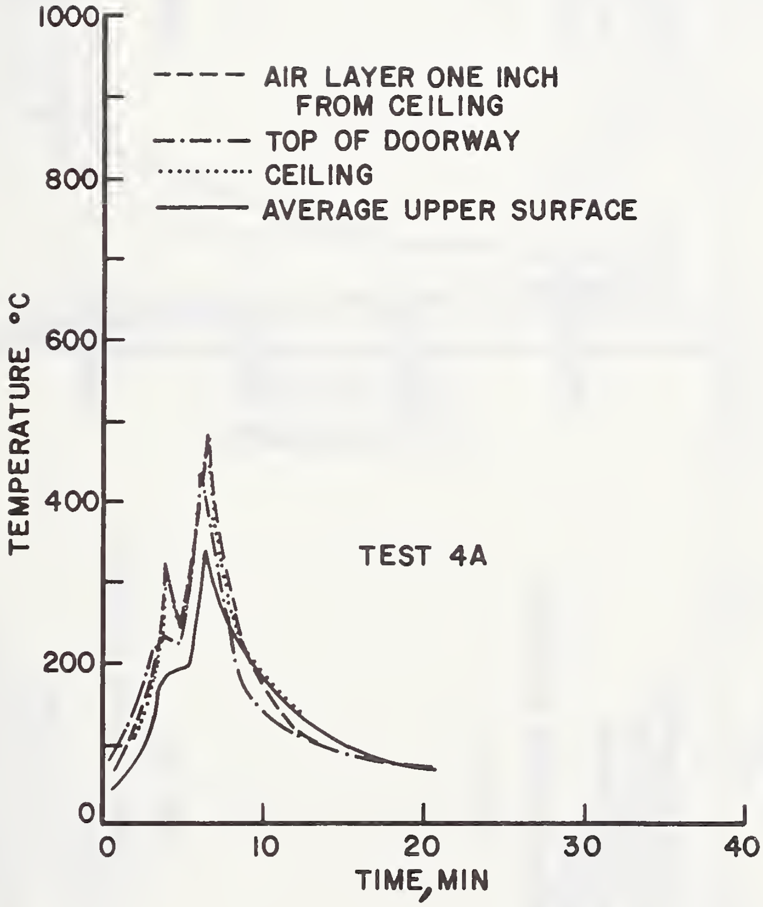

Figure 9. Temperatures in Upper Part of Compartment for Fire Test 4A.

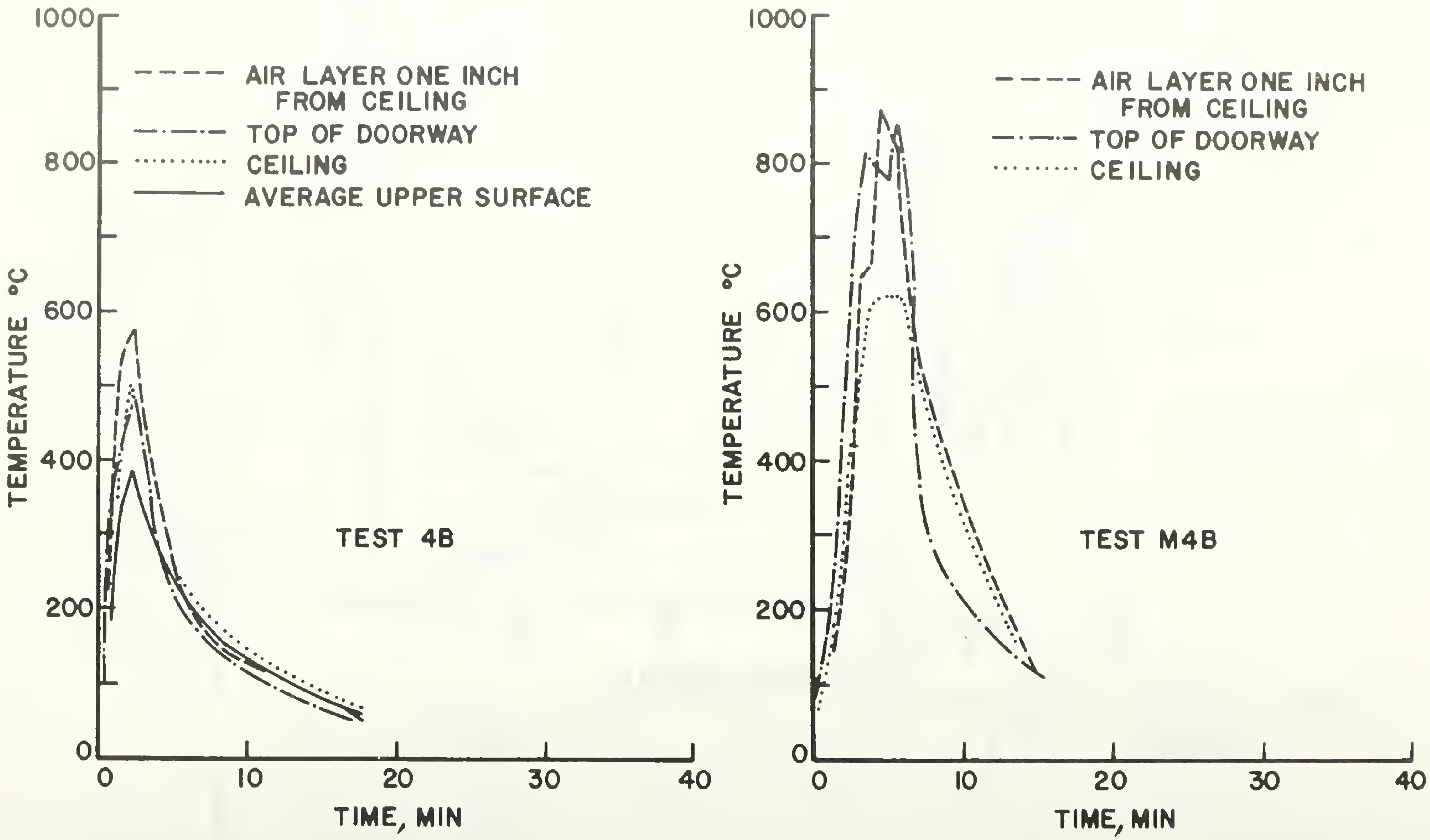

Figure 10. Temperatures in Upper Part of Compartment for Fire Tests 4B and M4B.

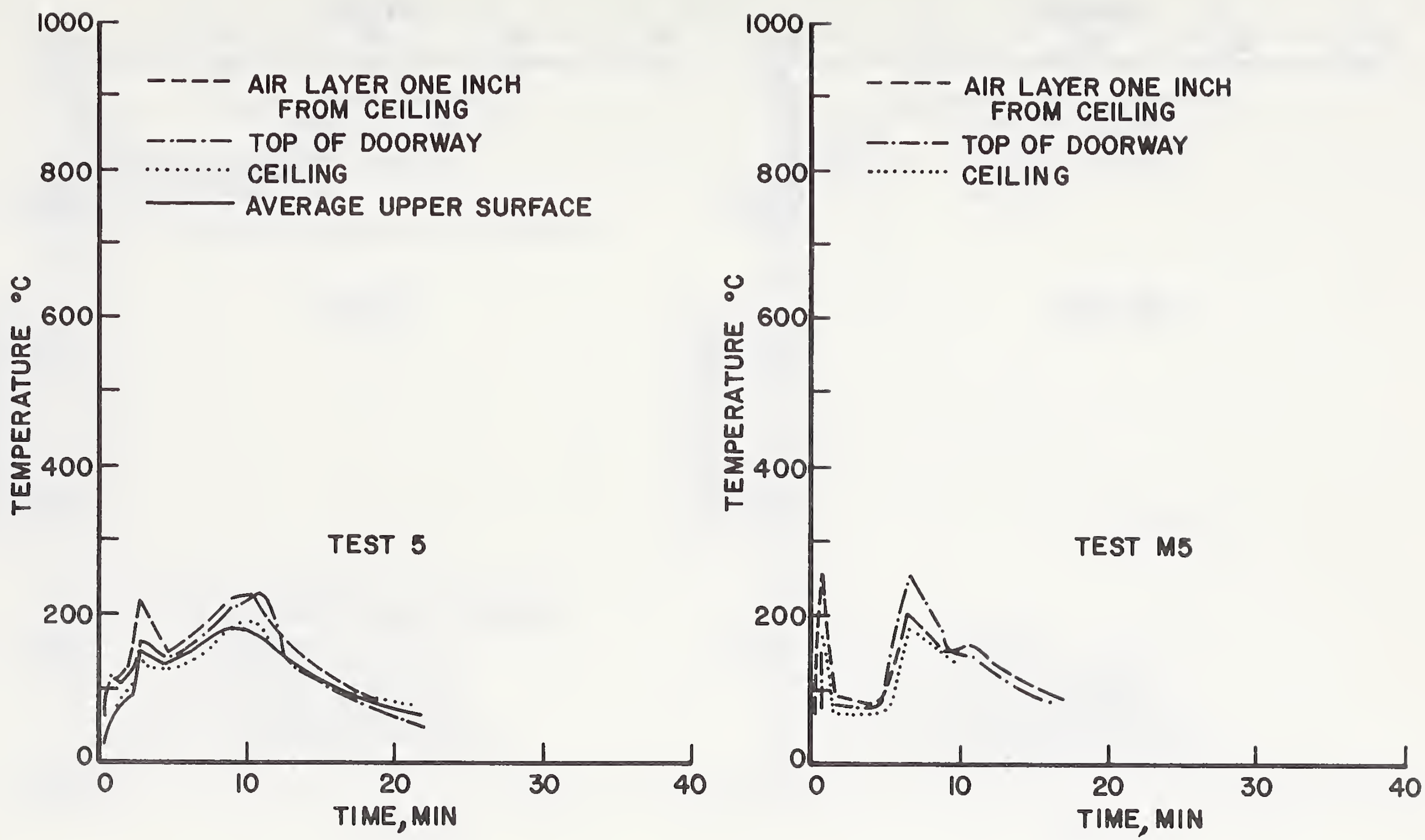

Figure 11. Temperatures in Upper Part of Compartment for Fire Tests 5 and M5.

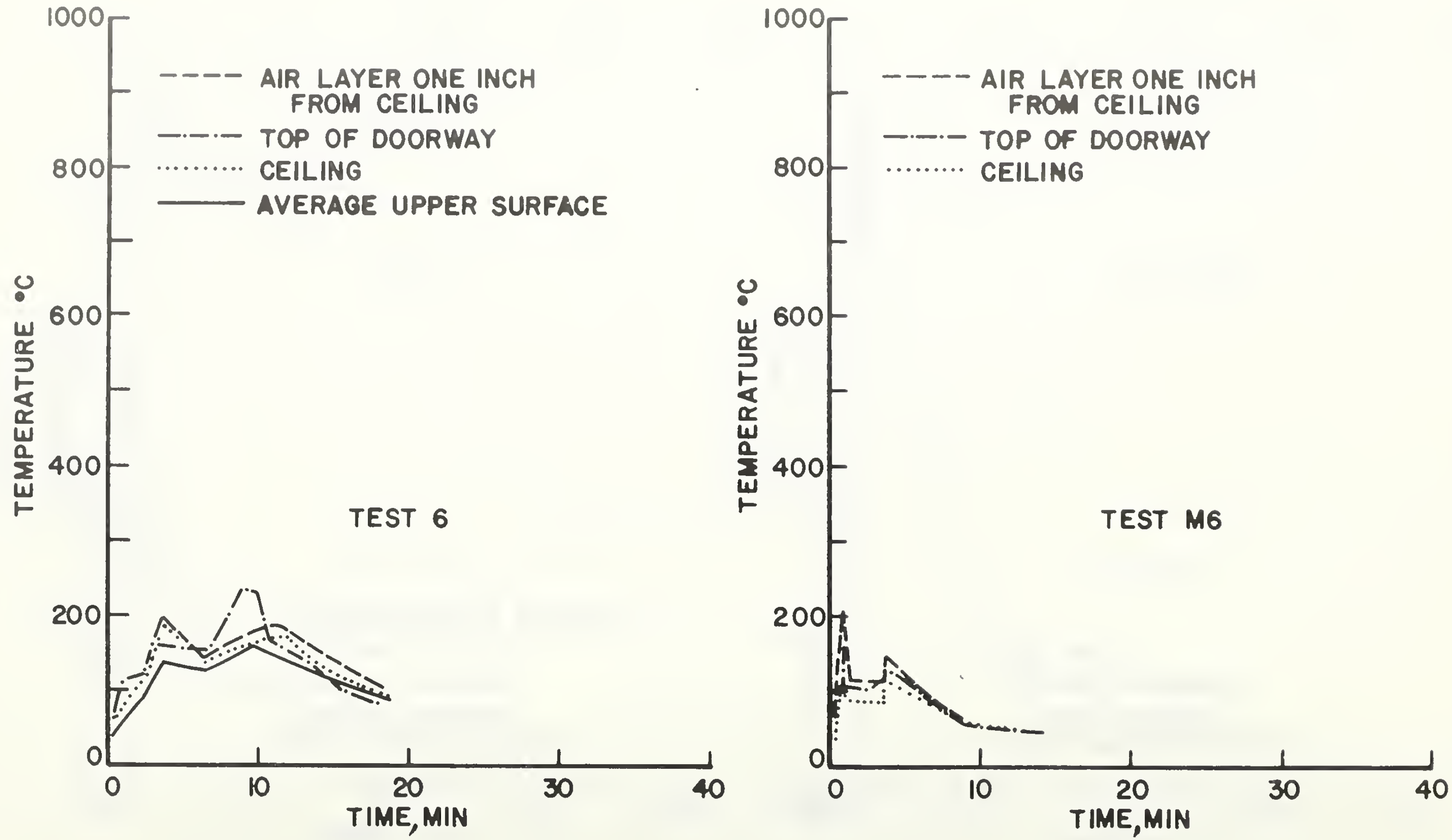

Figure 12. Temperatures in Upper Part of Compartment for Fire Tests 6 and M6.

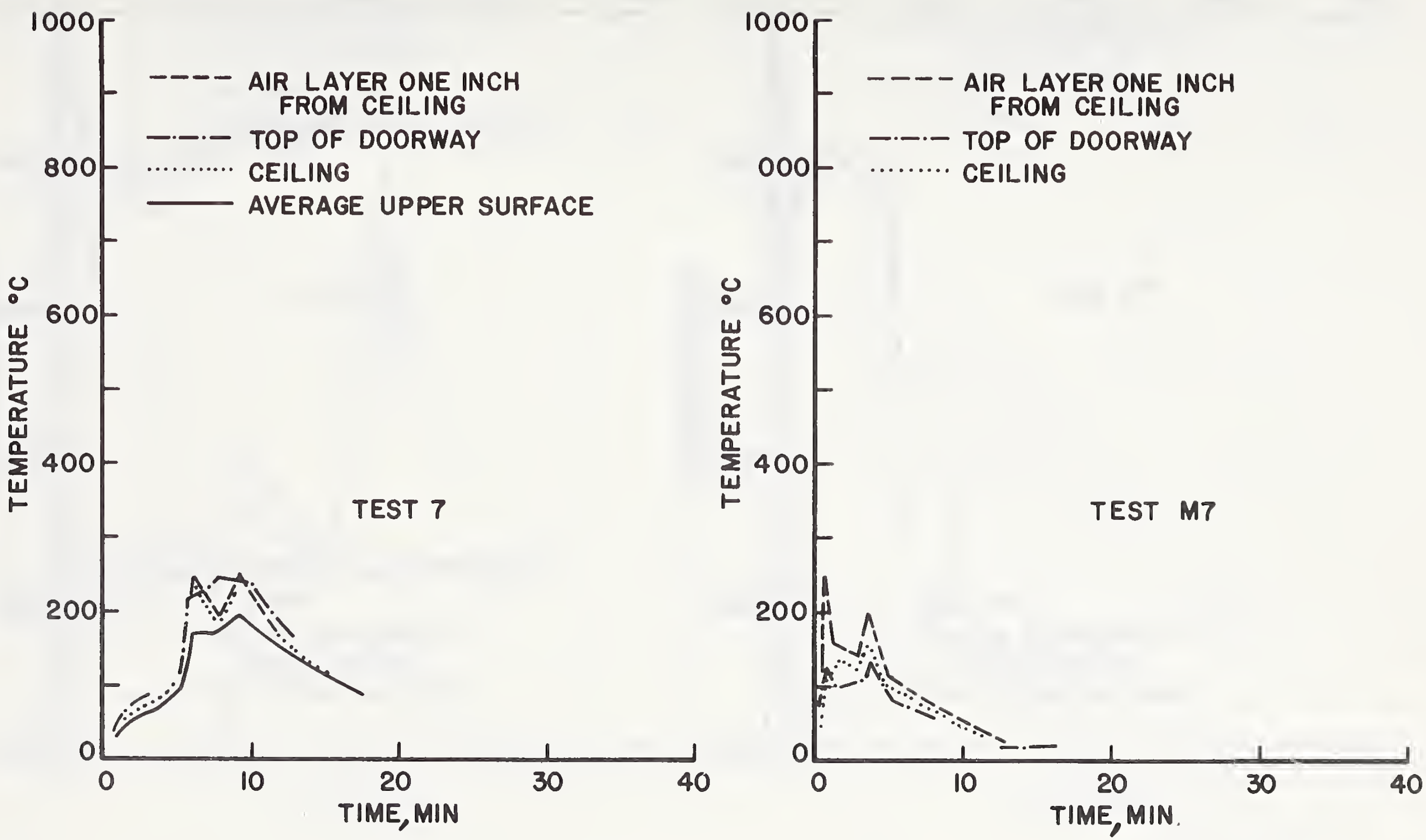

Figure 13. Temperatures in Upper Part of Compartment for Fire Tests 7 and M7.

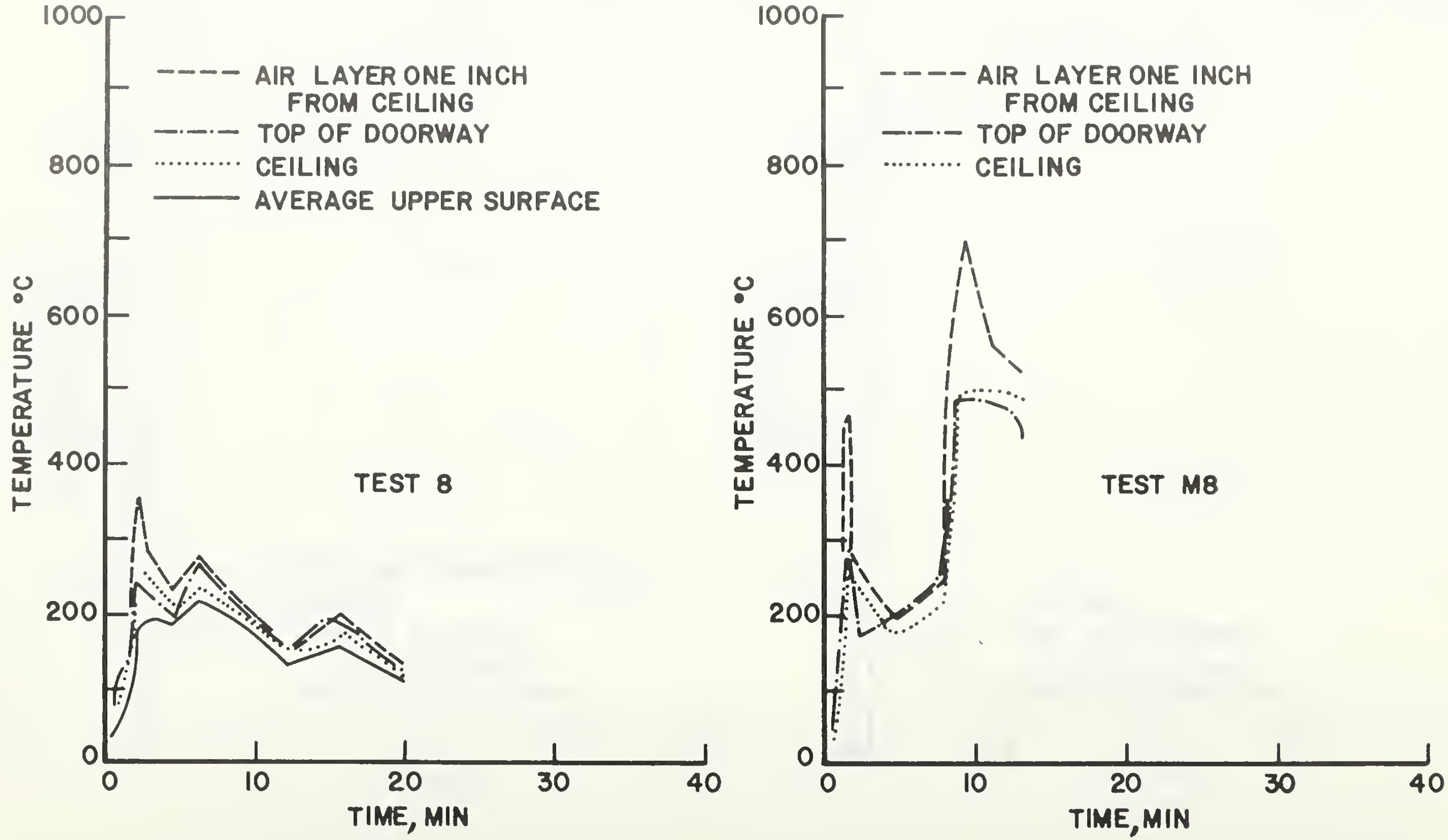

Figure 14. Temperatures in Upper Part of Compartment for Fire Tests 8 and M8.

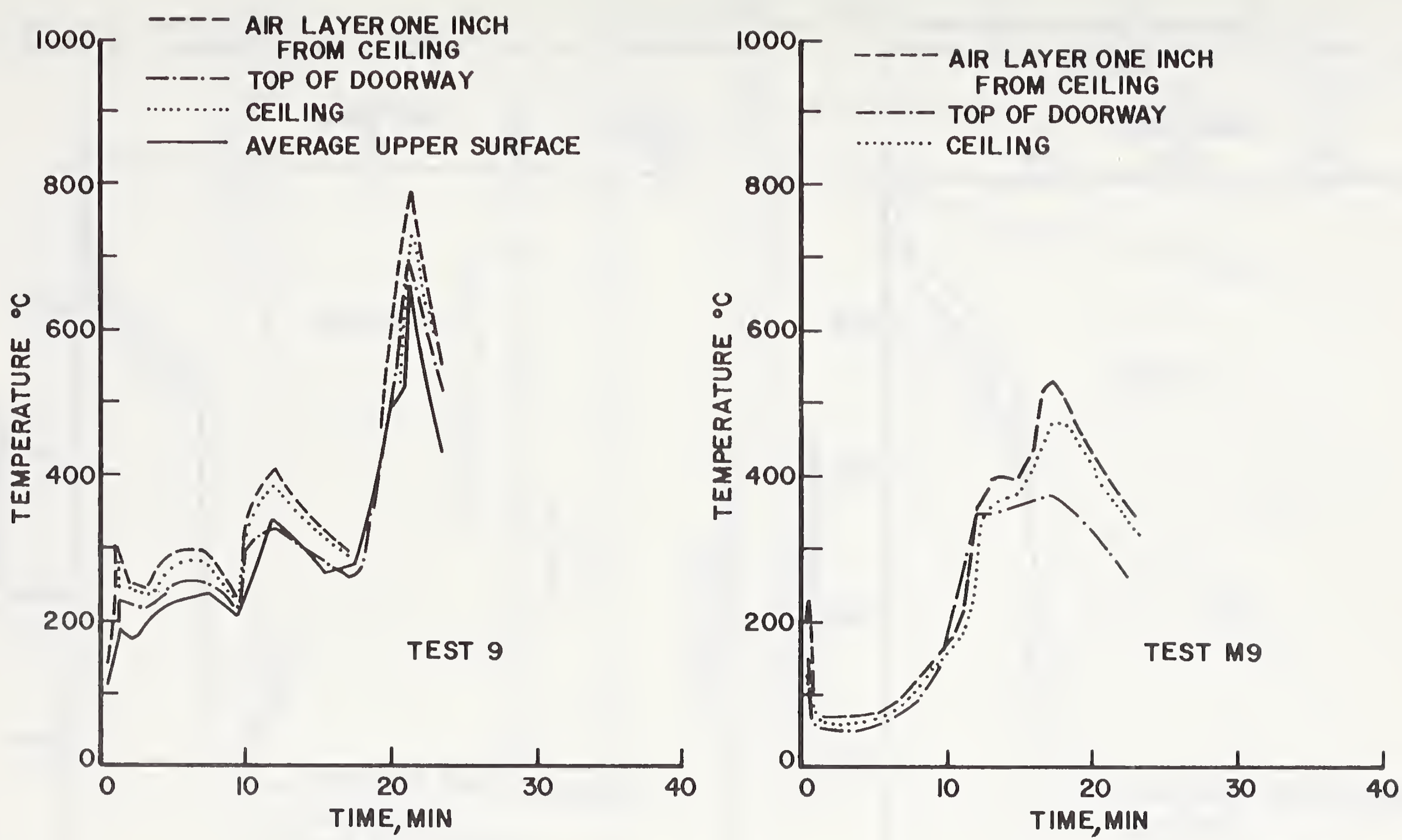

Figure 15. Temperatures in Upper Part of Compartment for Fire Tests 9 and M9.

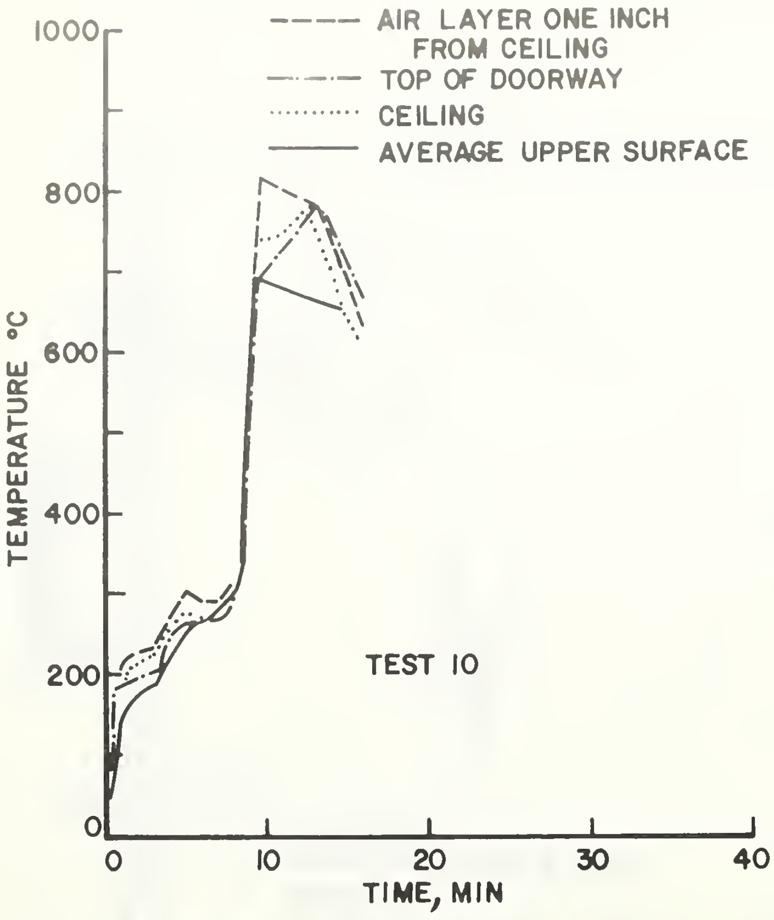

Figure 16. Temperatures in Upper Part of Compartment for Fire Test 10.

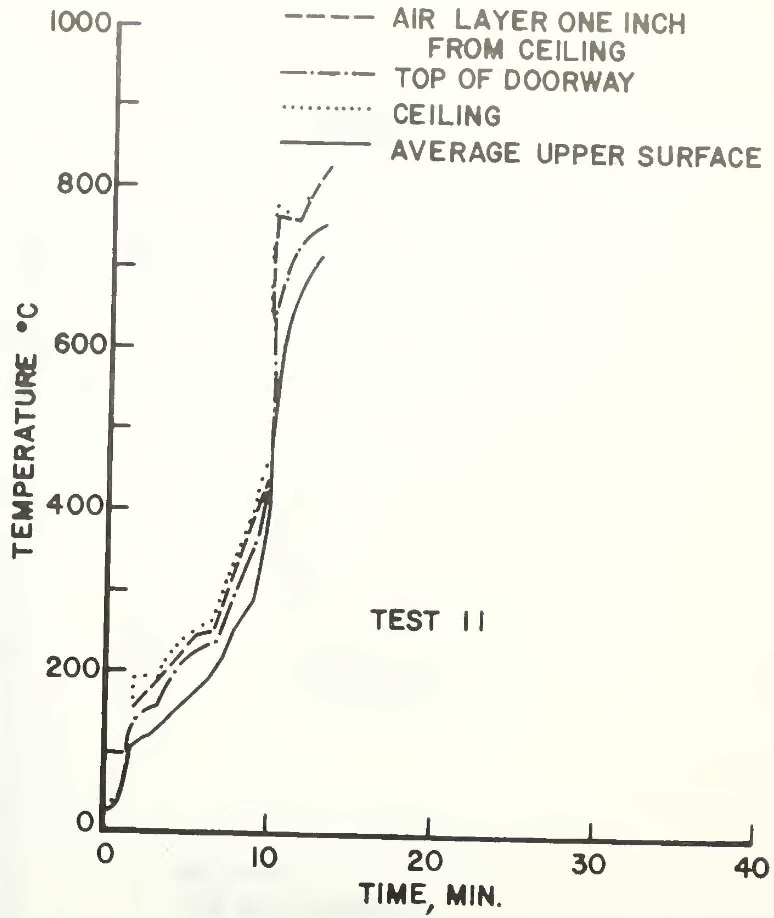

Figure 17. Temperatures in Upper Part of Compartment for Fire Test 11.

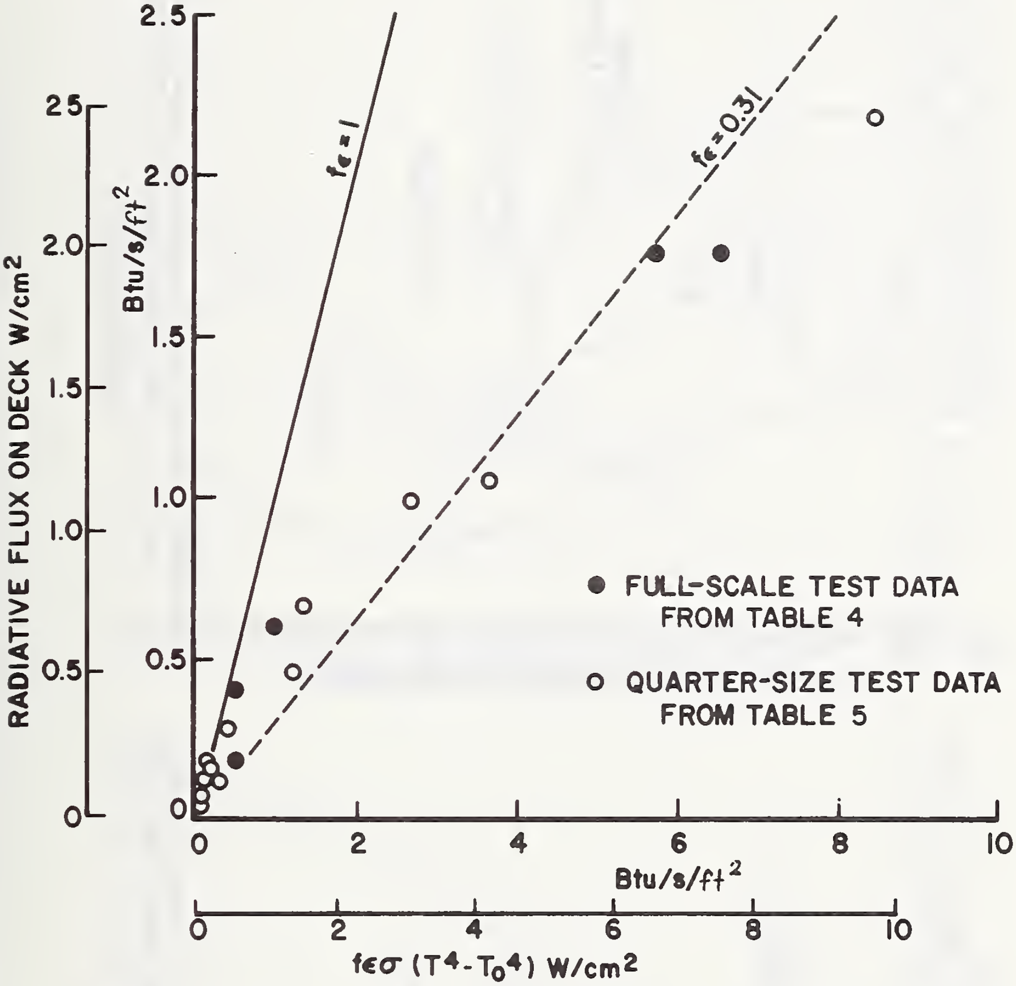

Figure 18. Thermal Radiation Incident on Deck as Function of Upper Air Temperature.

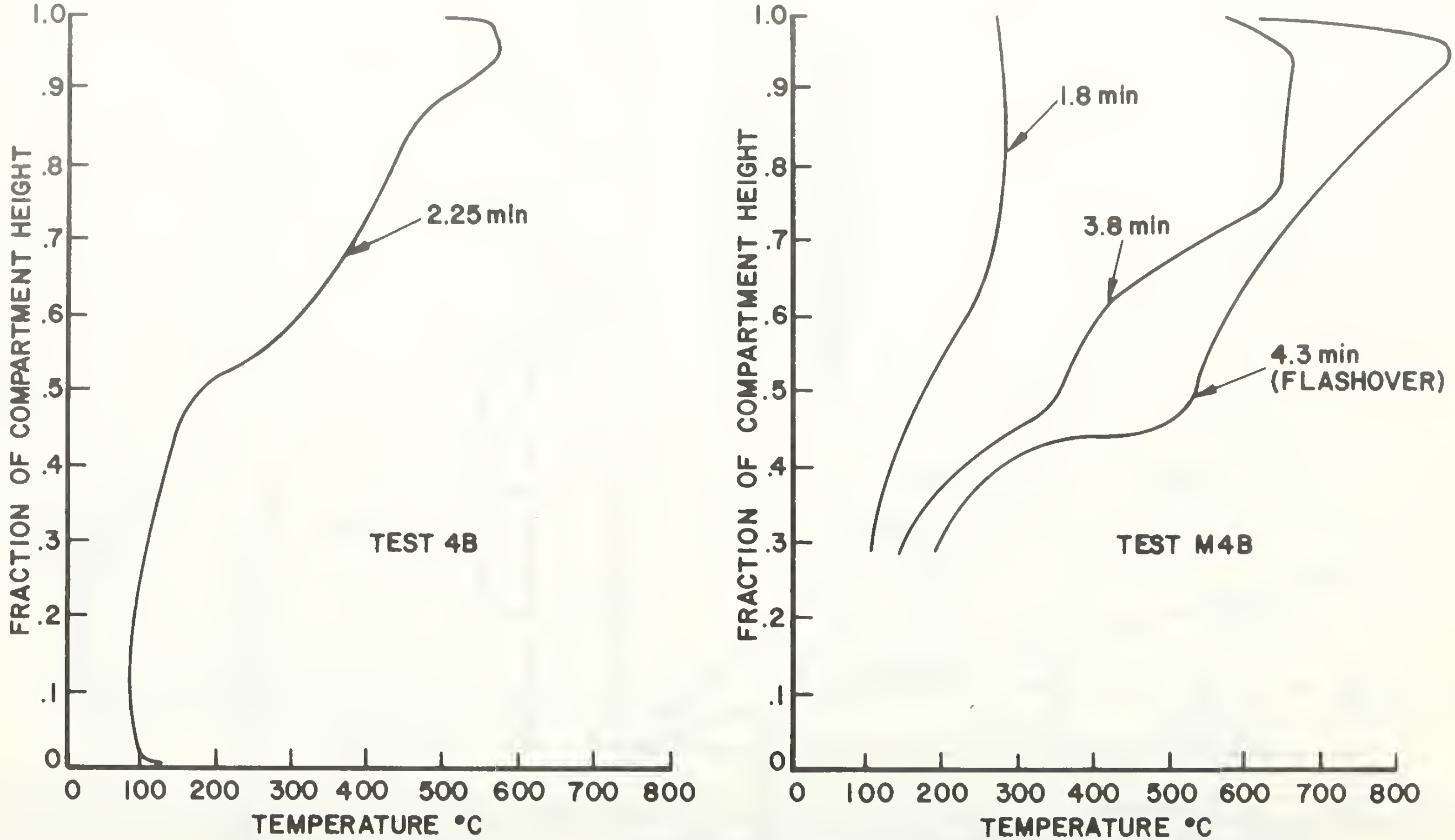

Figure 19. Vertical Temperature Profile in Compartment Fire Tests 4B and M4B.

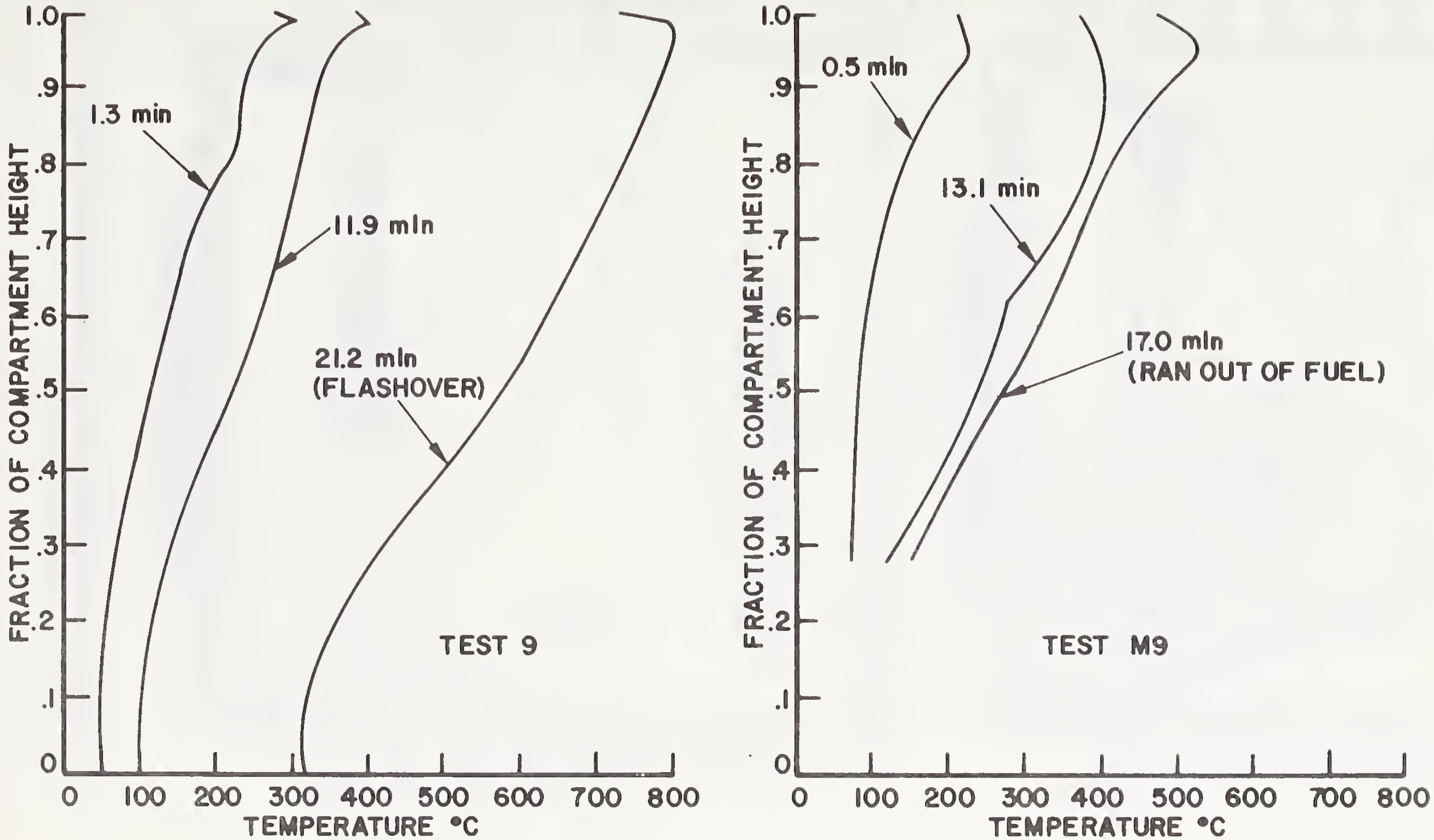

Figure 20. Vertical Temperature Profile in Compartment Fire Tests 9 and M9.

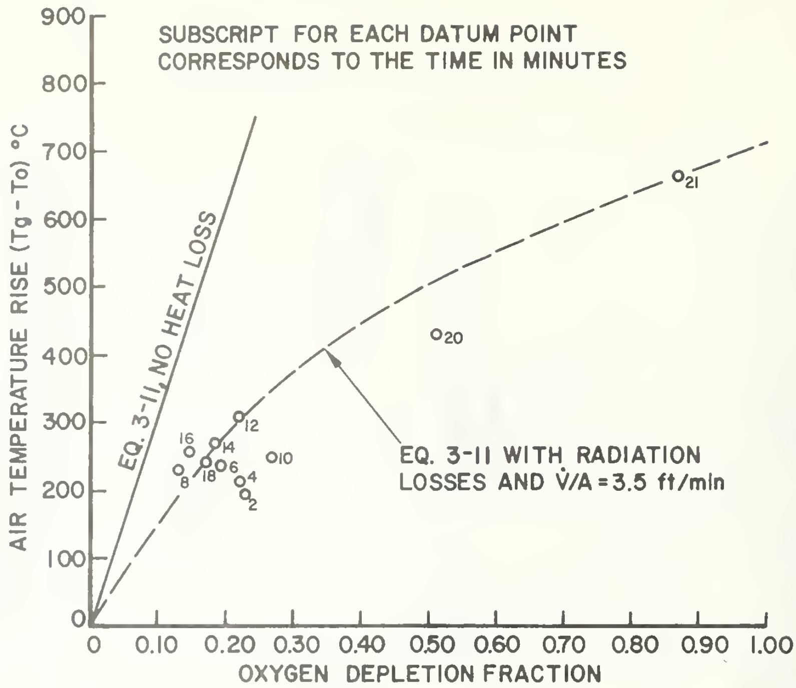

Figure 21. Temperature Rise in Doorway Exhaust Versus Oxygen Depletion for Test 9.

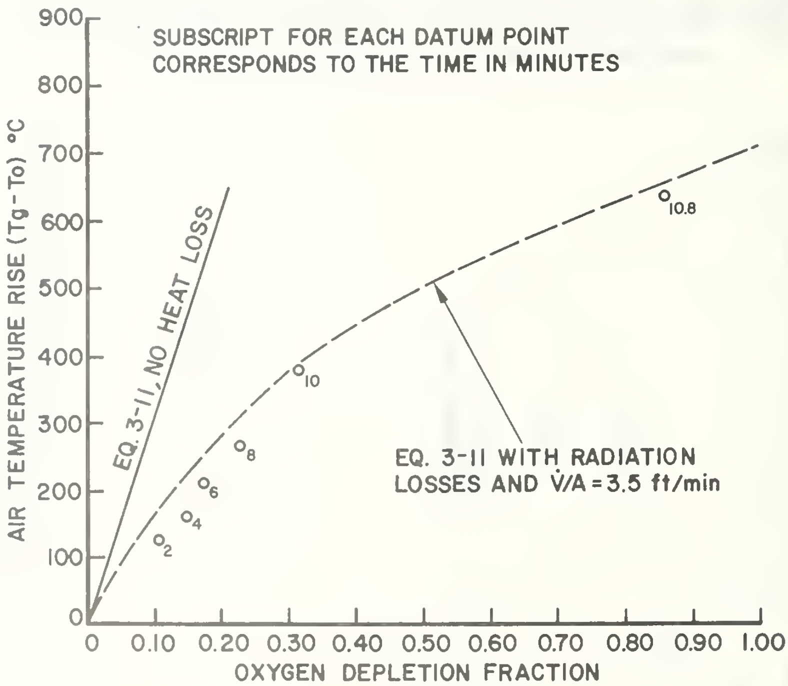

Figure 22. Temperature Rise in Doorway Exhaust Versus Oxygen Depletion for Test 11.

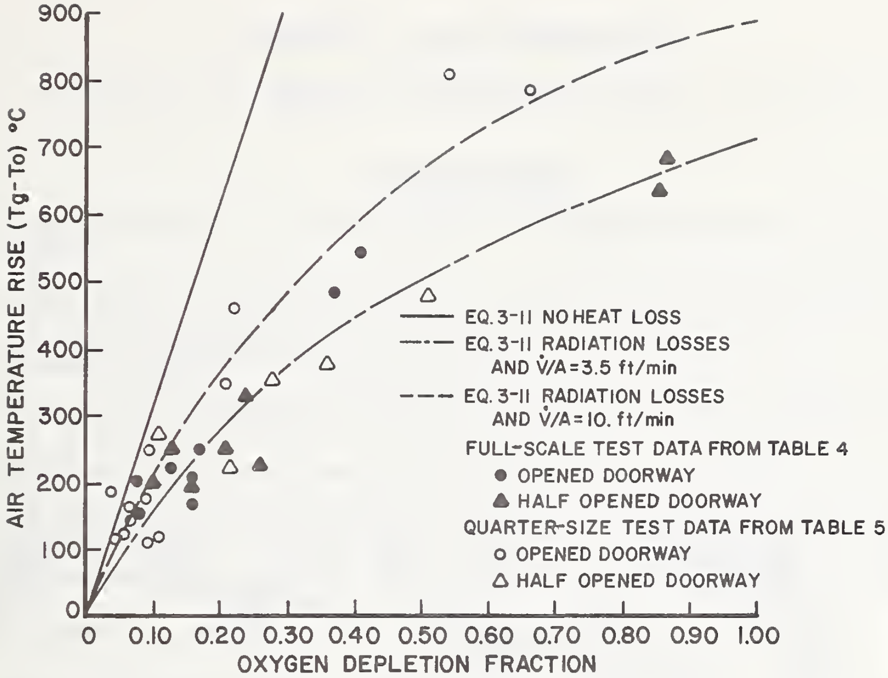

Figure 23. Temperature Rise in Doorway Exhaust Versus Oxygen Depletion for all Tests Having Opened and Partially Opened Doorways.

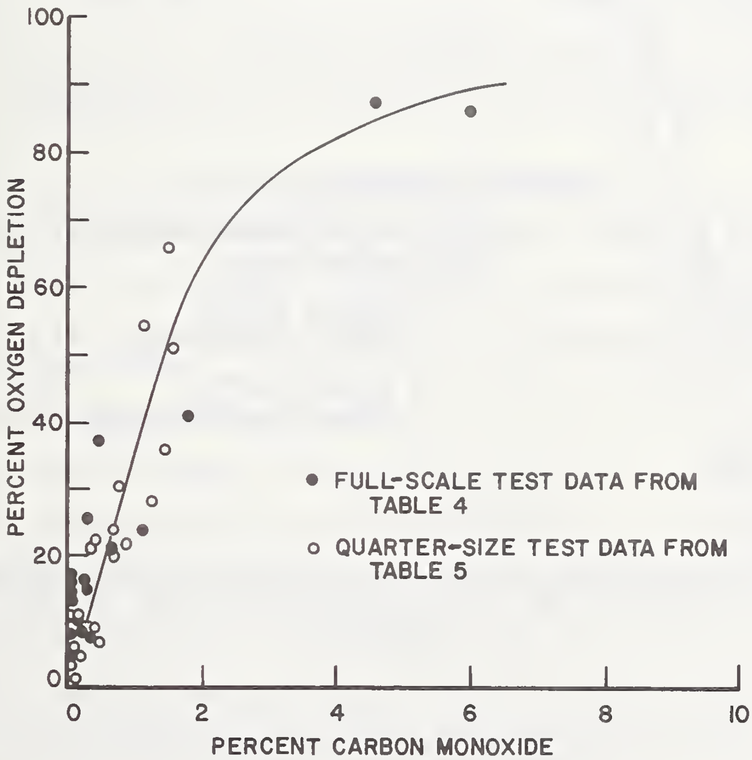

Figure 24. Oxygen Depletion Versus Carbon Monoxide Concentration in Doorway Exhaust for the Compartment Fire Tests.

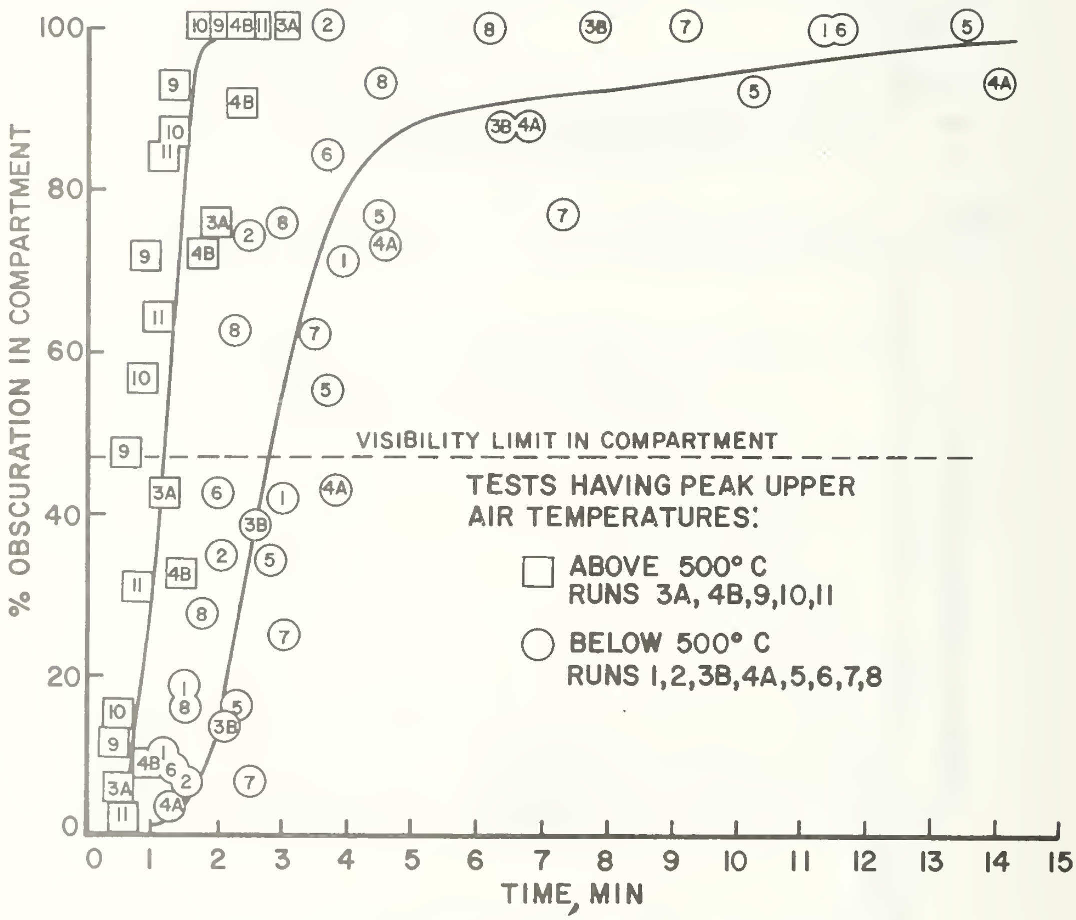

Figure 25. Smoke Obscuration in Full-Scale Compartment Fire Tests.

APPENDIX - TEST OBSERVATIONS

Test 1 - November 7, 1973

Time min:s	Observations
1:00	Fire confined to bottom berth. No smoke observed through exhaust port.
2:00	Fire still confined to lowest bunk. More smoke, but not heavy.
3:30	Flames appeared to have diminished.
5:50	Flames have spread along overhanging sheets to all three bunks.
7:00	Whitish more dense smoke coming out exhaust port.
8:15	Fire almost out inside compartment. Some flames near pillow areas.
20:00	Smoke has not abated. Flaming on uppermost bunk.
22:30	Flames out again.
39:00	Not much happening. Smoke has not diminished.
60:00	Test terminated.

Test 2 - November 14, 1973

Conditions prior to ignition 69 °F and 54% humidity

Time min:s	Observations
2:00	Two-thirds of bottom berth in flames. Middle bunk about to ignite.
2:15	Middle bunk ignited. Smoke fills the entire exhaust port.
4:00	Unable to see flames inside. Whitish-grey smoke coming out from exhaust port.
8:00	Conditions unchanged.
10:30	Bottom and middle berths aflame again.
14:00	No flames observed inside compartment.
15:30	Smoke is dense and yellowish in color. 2-1/2% CO at doorway.
18:00	HCl concentration greater than 100 ppm in the exhaust port.
20:30	HCN concentration went off scale on colorimetric detector tube. Concentration higher than 150 ppm.
40:00	Conditions unchanged inside compartment.
42:00	Test over.

Test 3A - November 21, 1973

Conditions prior to ignition - 64 °F and 60% humidity

Time min:s	Observations
0:30	One half of lowest berth is aflame.
1:00	Second bunk has ignited.
1:10	Third bunk has ignited. Large 3-ft diameter charred area on ceiling directly over top bunk.
2:30	Hot outflow from compartment extends 45 to 50% of the way down from top of doorway.
3:00	Top berth is flaming slightly. Middle bunk flaming somewhat more. Bottom bunk heavily involved in flames. White smoke, exiting from compartment, fills upper 40% of doorway.
5:[illegible]	All three bunks heavily involved with flames.
7:[illegible]	Short bursts of flames observed out doorway.
[illegible]:40	Flames no longer coming out of doorway.
8:00	Heavy grey smoke issuing from room, fills top third of doorway.
12:15	All three bunks flaming. Aluminum plate used in supporting the mattress on the top berth has melted. Crumpled newspaper used for indicating the occurrence of flashover in the compartment hasn't ignited.
13:00	Flames are half way down along the vinyl covered paneling.
14:00	Newspaper on the deck has ignited. Flaming material may have dropped onto it.
17:00	Materials in upper part of locker have ignited.
19:00	Cotton items in lower half of locker now flaming.
22:00	80 - 90% of vinyl covered paneling has burned away.
25:00	Test terminated.
Post-fire Analysis	Ceiling intact. Carpet unburned. Less than 50% of cotton waste and clothes in locker burned. Aluminum plates used for supporting the mattresses on the two highest bunks melted. Some melting also occurred in the two aluminum end plates of the 3-man berthing unit.

Test 3B - December 27, 1973

Conditions prior to ignition - 65 °F and 56% humidity

Time min:s	Observations
0:30	Lowest bunk is well aflamed.
1:10	Second berth has ignited.
1:30	Highest bunk has ignited.
1:50	Inflow air velocity at bottom of doorway is 110 fpm.
2:45	Doorway air velocity is now 140 fpm.
4:30	Air velocity at bottom of doorway has increased to 155 fpm.
5:00	Much of the lowest berth is burning. Mid-level berth has less fire involvement. Only about 20% of uppermost bunk aflame.
5:30	Inflow velocity along bottom of doorway now is about 140 fpm.
7:25	Doorway air velocity is 120 fpm.
9:00	Smoke departing from compartment fills upper 40% of doorway opening.
11:30	Mid-level bunk is covered with small isolated flames. Fire in top bunk is almost out. Intense glowing observed in part of the neoprene mattress on the bottom berth.
16:00	Only isolated flames left along mid-level bunk. Fires are out on the other two berths.
16:25	Fire is out on all three berths.
21:00	Conditions unchanged. Test over.

Test 4A - December 5, 1973

Conditions prior to ignition - 70 °F and 71% humidity

Time min:s	Observations
2:30	Inflow air velocity near bottom of doorway is 150 to 200 fpm.
2:45	Mid-level bunk has ignited.
3:00	Uppermost berth has ignited.
3:25	From motion of the smoke in the compartment the neutral plane (hot-cold flow interface) is at about half room height.
5:00	All three bunks burning evenly. Flames are reaching the ceiling.
5:30	Inflow velocity along bottom of doorway is 190 to 220 fpm.
5:45	Flames emerging from doorway.
6:10	Flames are no longer coming out of doorway.

7:25	All three berths still aflamed.
9:30	Lowest bunk still flaming. Upper two berths somewhat inactive.
10:30	Bottom and middle berths flaming slightly. Fire in uppermost bunk is out.
13:00	Conditions unchanged.
15:00	Isolated flames on middle bunk. Fires are out in the other berths.
17:00	Conditions unchanged.
20:00	Only smoldering remains in all three berths.

Test 4B - December 7, 1973

Conditions prior to ignition - 63 °F and 46% humidity

Time min:s	Observations
0:45	Middle berth has ignited.
1:00	Top bunk has ignited.
1:20	Air inflow velocity at bottom of doorway is 150 fpm.
1:35	Flames spreading across part of ceiling.
2:00	Ceiling has almost entirely blackened. Hot exhaust from compartment fills upper half of doorway.
2:25	Velocity at doorway is 190 to 200 fpm.
5:00	All three bunks still aflame.
5:30	Velocity along bottom of doorway is now 180 fpm.
9:30	Fire on uppermost berth is out. Only isolated small flames left on the middle and lowest bunks.
10:00	Doorway velocity is 150 fpm.
13:00	A few isolated flames on bottom berth. No flaming observed on upper two bunks.
17:00	Newsprint on deck still has not ignited. Test terminated.
Post Analysis	Uppermost 30% of the vinyl laminate on the back bulkhead is charred. Top 20% of the vinyl on the right side bulkhead is also charred. Contents on top shelf of locker has discolored.

Test 5 - December 5, 1973

Conditions prior to ignition - 55 °C and 44% humidity

Time min:s	Observations
2:36	Second bunk has ignited.
2:45	Third bunk has now ignited.
3:30	Smoke from compartment fills upper 40% of doorway.
7:30	All three bunks burning evenly.
8:00	Smoke exhausting from compartment now fills the top 25 to 33% of doorway.
9:00	Air inflow velocity along bottom of doorway is 110 fpm.
10:30	Top and middle berths are still aflame. Bottom bunk is smoldering.
15:25	All three berths are now smoldering. Smoke from compartment fills upper one-third of doorway.
21:00	Conditions unchanged. Test over.

Test 6 - January 29, 1974

Conditions prior to ignition - 67 °F and 38% humidity

Time min:s	Observations
2:35	Second berth has ignited.
2:55	Third berth has ignited. Air inflow velocity along bottom of doorway is 110 fpm.
4:00	Middle and bottom bunks burning well. Top berth flaming slightly. Velocity at doorway is still 110 fpm.
5:30	Air velocity at doorway remains unchanged. Smoke from compartment fills upper 40% of doorway.
6:30	All three bunks are still flaming.
8:00	Velocity along bottom of doorway is now 100 fpm.
8:30	Middle bunk burning vigorously. Pillows on top and middle berths are burning well. Bottom berth has only small isolated flames.
10:30	Doorway air velocity is 110 fpm.
12:00	Only small flames observed on all three bunks.
15:25	Air velocity at doorway is 85 fpm.
21:30	Doorway inflow velocity is now 100 fpm. All three berths are now smoldering.
25:30	Velocity at doorway is 90 fpm.

26:00	Test terminated.
Post fire Analysis	Newsprint on deck and carpet are unaffected. Contents of locker have not discolored. Large sections of melamine laminate separated from aluminum bulkhead.

Test 7 - February 7, 1974

Conditions prior to ignition - 56 °F and 42% humidity

Time min:s	Observations
3:00	Air inflow velocity at bottom of doorway is between 90 and 95 fpm.
4:00	Fire still confined to bottom berth.
5:10	Second berth ignited.
5:20	Third bunk has ignited.
7:00	Entire bottom berth aflame. About half of the uppermost and middle bunks is flaming.
7:30	Pillow on top berth is now burning.
9:00	Air velocity along bottom of doorway is 100 fpm.
10:00	Bottom berth has only small flames. Flames in middle berth are now spreading to the pillow area. Uppermost bunk is burning well only at the pillow area.
11:00	Pillow in middle bunk now burning vigorously.
12:00	Doorway air velocity is now 100 fpm. Only isolated small flames along top and bottom berths. Middle bunk is flaming on pillow area.
19:00	Only a flickering of flames left on pillow area on mid-level bunk.
24:00	Newsprint indicator on deck has not ignited. Test terminated.
Post fire Analysis	Vinyl covered bulkhead unaffected except for the uppermost five inches, which has an oily appearance. Some contents on top shelf of locker has discolored slightly. Top thirds of fibrous glass covered bulkhead also discolored somewhat.

Test 8 - February 28, 1974

Conditions prior to ignition - 66 °F and 24% humidity

Time min:s	Observations
1:00	Half of lowest berth is aflame.
1:30	Air velocity at bottom of doorway is 100 fpm.
1:40	Second berth has ignited.

2:04	Third bunk has ignited.
2:30	Inflow air velocity at doorway is now 120 fpm.
3:00	All three bunks are burning well. Smoke fills upper 40% of doorway.
3:30	Inflow velocity is still 120 fpm.
4:00	Inflow air is mixed with a little of the smoke exhaust and consequently can be observed. The air enters at about half doorway height and dips quickly towards the deck.
5:30	Inflow is now 110 fpm.
6:30	Inflow along bottom of doorway is about 100 fpm.
7:30	All three berths are still burning. Velocity is now 120 fpm.
9:30	Air inflow velocity is 110 fpm. Only the pillow area along middle bunk is flaming. The fires in the bottom and uppermost berths have gone out.
14:00	Velocity along the bottom of the doorway is still 110 fpm. No flames observed on all three bunks.
20:00	Test terminated.
Post fire Analysis	Upper one foot of the vinyl covered bulkhead surface appears oily following the fire exposure. Only contents along the top shelf of the locker has discolored.

Test 9 - March 7, 1974

Conditions prior to ignition - 74 °F and 58% humidity

Time min:s	Observations
0:20	Second berth has ignited.
0:34	Third berth has now ignited. Polyamide curtains aflame.
2:00	Flames extinguished in the two upper bunks. Flaming now confined only to bottom berth.
2:45	Smoke fills the upper 40% of doorway.
3:45	Have extremely dense smoke, more dense than any of the previous tests. Inflow of fresh air near the middle of the doorway is seen to dip quickly towards the deck.
6:00	Flames are still confined to the lowest berth.
7:45	Second bunk is suddenly aflame. Fire appears to have penetrated through the aluminum plate supporting the mattress.
12:00	Top berth still has no flaming. Middle and bottom berths only flaming slightly.
18:00	Top bunk now heavily involved in flames.

21:00	Only the top bunk is actively involved in flames. The other berths have little flaming and appear to be smoldering.
21:30	Flame front has spread one-quarter to one-third of the way down the fibrous glass on the left bulkhead.
21:45	Carpet is aflame. Flashover of room contents. Fire extinguished with water hose.
Post fire Analysis	Contents along whole length of locker was charred. Carpet was completely blackened. Vinyl on right bulkhead was completely burned away. Vinyl on back bulkhead burned off except along the lower eight inches. Rupture lines were found along the exposed aluminum bulkhead. Both of the bulkheads lined with fibrous glass were blackened over their entire lengths. Aluminum partition at pillow end burned completely away. The partition at the foot end of the bunks was badly warped. The aluminum mattress support plates on the upper two bunks had large gaping holes. Low density ceiling tiles above the bunks were warped considerably and probably allowed the fire to penetrate into the dead upper air space.

Test 10 - April 16, 1974

Conditions prior to test - 69 °F and 30% humidity

Time min:s	Observations
0:30	Inflow air velocity at bottom of doorway is 35 fpm.
1:00	Cotton bed sheets draping over the sides of the upper two berths have ignited.
1:30	Inflow air velocity is now 95 fpm.
1:45	Fires are out along the upper two bunks. Inflow air velocity is 105 fpm. Carpet has just ignited from a piece of burning bedding which had fallen on the deck.
3:00	Doorway air velocity is now 145 fpm. Smoke fills the upper 40% of the doorway.
3:45	Doorway velocity has increased to 160 fpm. Upper two bunks are not burning well.
7:00	Upper and middle berths still not burning well. Smoke from the burning carpet is stratified in a low dense layer.
9:30	Smoke from the compartment has turned whitish in color. There is active burning of all room contents.
14:00	All three bunks still burning.
18:00	Fire extinguished.

Test 11 - May 3, 1974

Conditions prior to test - 74 °F and 61% humidity

Time min:s	Observations
1:00	Cotton bed sheet hanging from middle berth has ignited.
1:10	Sheet hanging from top berth has ignited. Inflow air velocity at bottom of doorway is 55 fpm.
2:00	Fire in uppermost berth is out. Flaming only near the curtain opening on the middle bunk. Bottom bunk is still burning well. Inflow air velocity is now 80 fpm.
2:30	Fires have extinguished in upper two bunks. Flames are still evident along bottom berth. Inflow air velocity is 95 fpm.
3:30	Smoke fills the top half of the doorway. Inflow velocity is 90 fpm.
5:30	Smoke now fills the upper 55% of the doorway.
6:30	Air velocity at doorway has increased to 140 fpm.
7:00	Air velocity is now 125 fpm.
7:30	Fire still appears to be confined to lowest berth. Smoke exiting compartment is extremely dense. Smoke is obscuring the fire development inside the compartment. Inflow air velocity has decreased to 100 fpm.
8:30	Still very smokey inside compartment. Inflow velocity is about 100 fpm.
9:30	Doorway air velocity is now 115 fpm.
10:15	Flames shooting out of doorway. Fire spreading along carpet area closest to bunk.
10:30	Remainder of carpet flashed over. Smoke level in the compartment decreased markedly.
14:25	Fire dowsed with water from hose.
Post fire Analysis	Aluminum partition along the head end was completely gone. Gaping holes were left on the partition at the foot end of the bunk. The aluminum mattress support plates on the two upper berths either melted or were burned away. Two rather large holes were found on the bulkheads lined with the vinyl coated aluminum paneling.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Judicious application of shipboard materials and choice of compartment furnishings can significantly reduce the threat of serious fire on board ship. Unfortunately the fire performance of materials is currently difficult to ascertain from laboratory fire tests on the materials. Full size and quarter-scale compartment fires in conjunction with an analytical treatment were performed to obtain an improved understanding of the relationships between the laboratory fire test assessment and the observed behavior of materials in actual fires. The compartment fire experiments indicated that the temperature of the hot air layer below the ceiling is a suitable quantitative measure of the level of fire buildup in a compartment. When this temperature exceeds 700 °C there is sufficient radiation from the hot air layer and the heated upper surfaces to cause ignition of all combustible materials in the compartment. For a 3 x 3 x 2.1 m (10 x 10 x 7 ft) space lined with asbestos millboard having a 0.68 x 1.9 m (27 x 75 in) open doorway a heat production rate of about 72 kW/m^2 (6.3 $Btu/s/ft^2$) of deck area is enough to attain this condition. Fires in some bunk configurations alone could exceed this critical rate of heat generation. Ventilation and its points of application were found to be very important considerations. Observations of the fire scenarios in the compartment tests along with an empirical and analytical analysis of fire growth in compartment spaces have resulted in an improved application of the fire test ratings. Consequently more rational design rules for fire safe material usage have been developed taking into account the ignitability, flame spread, rate of heat release, potential heat and smoke generation potential of materials. The study also indicated the practicality of using quarter-scale fire tests for studying fire performance in full size compartments.

KEY WORDS: Fire tests; flame spread; heat release rate; ignition; reduced scale models; room fires.

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