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Fire Buildup in Shipboard Compartments - Characterization of Some Vulnerable Spaces and the Status of Prediction Analysis

B. T. Lee and W. J. Parker

Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*
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Abstract

A review of shipboard fire incidents in the Navy over the past six years was made to determine the spaces of greatest vulnerability to fire and the most common sources of ignition in these areas. Some of these compartment spaces are characterized with regard to their furnishing and interior finish materials. Their fire loads are specified. The various factors which determine the extent and rate of fire buildup in a compartment are discussed in terms of a simplified prediction model. Although substantial progress has been made in developing a prediction model for room fire development, a satisfactory treatment of flame spread on combustible interior finish materials along with a better understanding of the effect of the fire environment on fire buildup are needed. Meanwhile, criteria for choosing fire safe materials must continue to rely on existing laboratory fire tests. The application of laboratory fire tests on ignition, flame spread, and heat release rate to control the use of interior finish materials aboard ship is explored. Test data on ignition, flame spread, and heat release rate of typical shipboard materials are provided.

Key words: Fire growth; fire statistics; flame spread; fuel load survey; heat release; interior finish; laboratory fire tests; material ignitability; prediction model; shipboard spaces.

1. INTRODUCTION

Practical fire safety is a necessity in Naval ship design and operation. Inadequate fire protection may be costly, in terms of human life, operation time and replacement costs. Passive fire protection through judicious selection of materials for shipboard interior finish and choice of furnishings can substantially reduce this threat from fire. In this report, interior finish is taken to mean the materials serving as the exposed surfaces of bulkheads, overheads, decks, and which may be in the form of panels, sheets, tiles, insulation, carpet, coatings, etc. The present Navy fire performance requirements given in MIL STD 1623 B for interior finish and furnishings has contributed significantly in the selection of fire safe materials [1][1]. Research on shipboard compartment fires [2] has helped reinforce the flame spread requirements in this standard and has provided the rationale and guidelines for restricting the ignitability, flame spread, rate of heat release, potential heat and smoke generation of interior finish materials.

In general, material performance in a fire depends on many factors. The ignition source, the quantity and arrangement of combustible items, the space configuration, the degree of ventilation, and the thermal properties of the materials in the compartment all affect its fire behavior. The performances of some materials have been evaluated in test fires in a shipboard compartment arrangement where the ventilation and interior finish were varied [2]. More fire situations must be studied to help generalize the fire behavior characteristics of materials. Hence, there is a need to characterize and to conduct fire experiments in representative compartment spaces having a relatively frequent occurrence of fire.

Further effort is also required for an improved interpretation and application of the present test methods and for the development of additional tests, if needed, to complement existing ones. A preliminary prediction model for compartment fire buildup was developed for the Navy [2] to help provide insights into more meaningful correlations between laboratory fire analysis of materials and their behavior in a compartment fire. This model indicated how fires involving compartment furnishings and interior finish affect the heated air temperatures, and hence the fire intensity, in the space. The contribution of the interior finish to the fire buildup was analytically related to its area of fire involvement, the rate of heat release per unit area of the affected surface, the heat losses through the interior surfaces and the ventilation to the compartment.

The work described in this report addresses many of the above problem areas and has the following objectives:

(1) To review shipboard fire statistics identifying the spaces having a relatively frequent incidence of fires,

(2) To characterize these areas and related occupancies such that a limited number of representative spaces and arrangements can be used for a comprehensive study of shipboard fires,

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

(3) To extend the preliminary prediction model for estimating the extent and rate of fire buildup, and

(4) To improve the laboratory fire test methods on ignitability flame spread and rate of heat release and their application in controlling the use of interior finish materials aboard ship.

2. SURVEY OF SHIPBOARD SPACES AND FIRE INCIDENTS

2.1 Review of Fire Statistics

Information supplied by the Navy Safety Center at Norfolk, Virginia indicated that shipboard areas having major fires in the past six years can be listed in the following order of decreasing fire occurrences: (1) machinery spaces; (2) supply areas such as the mess hall and laundry room; (3) habitability spaces such as berthing quarters, wardrooms, and lounges; and (4) deck storage areas. Most fire-related injuries also occur in the machinery areas.

Machinery space fires generally arise from the overheating of equipment, faulty wiring, and other incidents not associated with direct human error or activities. When coupled with a nearby source of fuel resulting from leakage, spillage or poor housekeeping, serious fires have occurred. Occasionally, personnel performing welding jobs have also caused fires. Deck area fires sometimes occur during painting and cleaning operations, with matches, cigarettes, welding torches and faulty electrical wiring or connections being the typical ignition sources. Fires in berthing areas result principally from smoking and matches and sometimes from arson. Paint thinner and cleaning fluids have been used for this latter purpose. Research with simulated berthing quarters [2] has shown that serious fires could occur in these areas when the fire initiation source is small, e.g., a match flame ignition of 800 ml (0.2 gal) of alcohol absorbed in part of a mattress. The occurrence of fires in the laundry areas is due to an abundance of loose combustible material and the availability of ignition sources. Combat activities could also initiate serious fires but are not considered here.

2.2 Characterization of Compartment Areas

A tour was conducted of the quarters on board the following three ships at the Naval Operating Base, Norfolk, Virginia:

Ship	Type (Launch Date)
U.S.S. Detroit	Combat Support Ship (late '60s)
U.S.S. Mullinnix	Destroyer (1957)
U.S.S. Donald B. Beary	Destroyer Escort (1971)

Of all the shipboard areas, machinery spaces and deck storage areas were the most complex and difficult to characterize. Furthermore, fire initiation and available fuel for fire growth at these locations were highly dependent on accidental occurrences or housekeeping practices. On the other hand, crew's berthing compartments, wardrooms, lounges, mess facilities and laundry rooms were fairly easy to typify.

The principal combustible contents in berthing quarters consisted of mattresses, bed linens, blankets, pillows and clothes. All sleeping quarters for the crew had three-man berthing units. Each unit was 71 cm (28 in) wide and 198 cm (78 in) long and had three tiers of bunks with 48 cm (19 in) vertical spacings between tiers. These units were frequently located end to end and side by side with other units. On the USS Detroit, there were 50 cm (20 in) long aluminum partitions between the head space on berths located side by side. Aside from these, there were no other partitions between units. An aluminum plate or storage locker was used beneath each bunk to support the bedding. In addition, each crew member had a standing locker in the room. The bunks were somewhat different on the USS Mullinnix. About one-half of the berths had bedding supported only by canvas tied to the frame of the bunk. The others had an aluminum locker for the mattress support. Almost every berthing unit had both types of bedding supports. Ships built before 1960 used this canvas in the berths. This meant that two-thirds of the fleet still have berthing with this kind of mattress support. Aluminum partitions running the whole length of the bunk were also used between berths that were located side by side. On the USS Donald B. Beary, most berths were like those on the USS Detroit. It was noticed, however, that the chiefs' quarters and officers' staterooms had canvas and wire supporting the bedding.

In general, the berthing spaces were similar in the different types of ships. The overhead height varied from 2.4 to 2.7 m (8 to 9 ft) and had exposed piping and ductwork beneath it. The deck was typically tiled with vinyl-asbestos, and interior bulkheads were constructed of uninsulated painted steel. Exterior bulkheads were insulated with fibrous glass having a painted glass fabric cover. The bunks were similar except for the differences mentioned earlier. Bedding consisted of one chloroprene mattress with fire retarded treated cotton ticking and cover, a single sheet, one wool blanket and one covered pillow. Accommodations for as many as 30 to 50 men in a single berthing area were common. Spacing between rows of berths varied from 0.6 to 0.9 m (2 to 3 ft). The occupancy density in these quarters was about four men per 9.3 m^2 (100 ft^2) of deck area. In terms of combustible bedding materials, this amounted to a potential heat loading of about 5.8 kg/m^2 (1.2 lb/ft^2) or 136 MJ/m^2 (12 000 Btu/ft^2). (Potential heat is defined in appendix A7.) In addition, there was an estimated 18 to 27 kg (40 to 60 lbs) of Navy-issued and civilian clothing stowed in the lockers for each crew member. However, not much of this clothing would be expected to contribute to the effective fire load in the compartment. Lockers are normally closed, and only a small percentage would be open at the time of an undetected fire. Furthermore, only a relatively small fraction of the closed metal lockers could be expected to be penetrated and the contents affected by the fire. It has been estimated [3] that probably less than 20% of the combustible contents in closed steel lockers would contribute to the fire. Thus, the lockers could add an additional 2 kg/m^2 (0.4 lb/ft^2) of combustibles. The fuel loadings for the berthing areas are shown in table 1. The information is presented in terms of the potential heat per unit deck area. Aside from the items listed no personal furnishings such as rugs or wall hangings were evident from the inspection. Thus, the total potential heat loading for this type of compartment space is approximately 240 MJ/m^2 (21 000 Btu/ft^2) of deck surface.

These sleeping quarters usually occupied areas of between 37 to 121 m^2 (400 to 1300 ft^2) and had a width, length and height ratio (W:L:H) ranging from 4:4:1 to 4:2:1. Each of these spaces had at least two exits. Some of the portals had no doors while others had swing-in doors. Several of the latter were of the self-closing type. Occasionally, the only exits from a berthing space were hatchways to the deck above. Much of the fresh air ventilation to the compartment entered through several diffusers 20 cm (8 in) from the floor. This air was carried through exposed aluminum ductwork extending across the ceiling and down the wall. There was also provision for overhead ventilation at each individual berth. This was in contrast to officers' staterooms where the ventilation air came through ceiling vents. In the event of a fire on board ship, ventilation could be manually curtailed in the region of the fire origin.

Corridors had exposed electrical cables running along either the overhead or bulkheads. These passageways had decks covered with vinyl asbestos tile, painted metal bulkheads and painted overheads with exposed piping underneath them.

Officers' wardrooms and crew's lounges had both wood and steel frame sofas and cushioned chairs. Further inspection revealed that almost all of these used flexible polyurethane foam as the padding material. Many of the bulkheads in these spaces were covered with aluminum paneling coated with 0.79 mm (1/32 in) thick vinyl or melamine laminate. Tables and cabinets were also aluminum with a veneer of 0.79 mm (1/32 in) melamine or vinyl plastic. Decks were finished with polyamide carpeting or vinyl asbestos tile. Draperies were also available in some of these areas. All of these compartments had drop ceilings of fibrous glass or mineral base tiles, and the overhead light fixtures were covered with plastic light diffusing panels. The potential heat loadings per unit deck area for the wardroom and lounge facilities are given in table 2. Analysis of the data indicates that these areas could have a potential heat loading of 108 MJ/m^2 (9500 Btu/ft^2) of deck area, excluding papers, magazines, books and other public and personal objects.

Large mess halls appeared to have an even smaller fire load per unit area. Small mess areas with lounge facilities have roughly the same fire load as officers' wardrooms and crew's lounges.

The laundry room on board the USS Detroit covered an area 9 x 12 m (30 by 40 ft) and was estimated to have as much as 1.5 kg/m^2 or 28.0 MJ/m^2 (0.30 lb/ft^2 or 2500 Btu/ft^2) fire load during a rush period. Similar facilities on the USS Mullinnix only occupied a 3.0 x 3.7 m (10 x 12 ft) area. It is conceivable that the fire load per unit floor area there can be an order of magnitude larger than that on the USS Detroit.

3. PREDICTION MODEL FOR FIRE BUILDUP IN A COMPARTMENT

The prediction scheme for compartment fire growth presented here is an extension and refinement of earlier treatments on the subject [2,4]. Components of the earlier models are discussed in greater detail.

3.1 Fire Buildup Potential

The severity of a compartment fire can best be described in terms of the temperature of the hot air layer below the overhead. The hot air layer, as the term is used here, includes flaming and non-flaming gaseous pyrolysis and combustion products. When this air temperature exceeds 500° C there is rapid pyrolysis of all combustibles in the upper part of the compartment. When this temperature reaches 700° C there is sufficient radiation into the lower part of the compartment to ignite virtually everything combustible there. The latter condition is referred to here as "flashover." The maximum temperature which can be reached with a given set of lining materials, furnishings, and ventilation can be identified as the "fire buildup potential" of the compartment. The estimation of the fire buildup potential of a compartment then is based on a prediction of the maximum temperature rise. This prediction depends on setting up an energy balance between the heat produced, the heat lost through the lining materials, and the heat carried out the doorway.

For simplicity in prediction modeling, the compartment is assumed to be divided into two uniform temperature regions with the higher air temperature, T, in the upper part of the compartment and the ambient air temperature, T_o, in the lower part of the space. It is further assumed that there is a continuous inflow of cool air through a single open doorway into the lower portion of the compartment and hot air carrying gaseous combustion products exhausting from the upper part of the doorway. The mass flow out is assumed to be equal to the mass flow in, even during periods of increasing temperature and expansion of the hot air zone at the top of the room. Since the flow exhausting from the room consisted mainly of hot air and the heat capacity of air does not change appreciably over the range of temperatures encountered, the averaged heat capacities of the flow into and out of the room were assumed to be the same for simplicity. The chemistry of combustion and the mass of the pyrolysis products produced in the compartment is neglected. Under quasi-steady-state conditions the energy rate balance can then be expressed as

$$\dot{Q} + \sum_i A_i \dot{q}_i = L(T - T_o) + \dot{m}cT - \dot{m}cT_o \qquad (1)$$

where $\dot{Q}$ is the total rate of heat production by the furnishings kW;

A_i is the area of the fire involvement of the i-th lining material m^2;

$\dot{q}_i$ is its average heat release rate per unit surface area kW/m^2;

L is the ratio of the average heat loss rate by conduction and radiation to the air temperature rise, $T-T_o$ kW/°C;

$\dot{m}$ is the mass flow rate of combustion product laden air out of the doorway kg/S;

c is the heat capacity of air averaged over the temperature range from T_o to T kJ/kg/°C.

T is the air temperature in the upper region of the compartment °K

T_o is the air temperature in the lower region of the compartment °K

Equation (1) can be solved for the temperature rise as follows:

$$T - T_o = \frac{\dot{Q} + \sum_i A_i \dot{q}_i}{\dot{m} c + L} \qquad (2)$$

Equation (2) displays the relationship between the temperature rise and the heat contribution of the furnishings plus lining materials, the airflow rate, and the heat losses.

Equation (2) is complicated by the fact that each of the factors in it depends on time and, to some extent, upon the temperature. The burning rate of the furnishings, the area of flame spread and the heat release rate of the lining materials depend on the incident heat flux, convective and radiative, to which these materials are exposed. This flux is a function of the hot gas and smoke layer and the upper surface temperatures. The volumetric flow rate is a weak function of temperature. Where radiation is the dominant heat loss mechanism, the loss factor, L, is a strong function of temperature. These factors also depend on the time. Therefore, it is necessary to solve equation (2) in a succession of small time steps, starting at the beginning of the fire and taking the temperature dependence into account at each step. This will require the development of a suitable computer program. The four separate terms that are included in equation (2) will now be discussed.

3.2 Burning Rate of Furnishings

The burning items of furniture may serve as an ignition source for the lining materials as well as produce additional heating. In some cases the rate of heat generation of the furnishings may be of sufficient magnitude to cause flashover without any additional contribution from the lining materials. The heat generation rate for an item of furniture is equal to the product of the burning area times its heat release rate per unit area. However, this rate depends on the orientation and on the incident heat flux. At the present time we are not able to predict this rate without conducting experiments. However, we can list some typical values. In the compartment fires study [2], where each mattress was supported by an aluminum plate, the highest measured burning rate for the three-man berth was 42 g/s (5.5 lb/min). It is likely, however, that higher rates were actually achieved in some of the more severe bunk fires for which the burning rates were unfortunately not recorded due to instrumentation malfunctions. The upholstered chairs used in the experiments by Fang [5] had burning rates as high as 25 g/s (3.3 lb/min). The burning rates for the couches used by Waterman [6] ranged from 19 to 90 g/s (2.5 to 11.9 lb/min).

It was determined during the berthing compartment fire tests [2] that 670 kW (38 000 Btu/min) was sufficient to cause flashover of a 3 x 3 x 2.1 m (10 x 10 x 7 ft) compartment having an open doorway. This corresponds to a burning rate of approximately 40 to 45 g/s (5.3 to 5.9 lb/min). Thus, fire involvement of the three-man Navy berth could, by itself, lead to flashover of the compartment.

Before undertaking further studies on the effect of compartment lining materials on the fire growth in Navy berthing compartments, the burning rates of Navy bunks should be examined in more detail. The effects of bunk construction, bedding materials, and ventilation should be systematically investigated in a compartment lined with fibrous glass to provide the maximum realistic radiation feedback to the bunks. The compartment fire study recently completed for the Navy [2] suggests that bunks closed along three sides to prevent cross flow of air will reduce significantly the burning rate. On the other hand, privacy curtains, which in effect make a small compartment of the bunk itself, can lead to very high burning rates if a fire is started within. It was also noted in the above study that high airflows delivered directly at the bunk can provide the ventilation necessary for a large fire. These adverse conditions might be avoided by design or regulations. A recent study on the effect of insulating the chloroprene mattress core to cut down on the burning rate [7] indicated that an even more severe condition could be established due to a trapping of the heat generated by the chloroprene. Less combustible bedding materials may be necessary. Experiments on the spread of fire between and across tiers of bunks would also be germane to the problem of high burning rates in large compartments. In addition to providing information needed for safer bunks, a set of standard conditions could be specified for future fire tests of compartment lining materials.

3.3 Interior Finish Materials

The heat contribution of the finish materials is contained in the second term in the numerator while their insulation characteristics affect the loss factor term in the denominator of equation (2). The latter term is discussed in section 3.5. The heat contribution term establishes the need for certain fire properties which must be obtained from standard fire tests. The existence of the i-th term and the time at which each successive heat contribution becomes effective depend on the ignitability of that material and the exposure that it receives from its igniting source, which may be a burning item of furnishing or an already burning section of lining material. The ease of ignition test [8], described in section A.1 of appendix A, exposes the specimen to a prescribed methane gas flame and measures the time at which the material starts to contribute heat to the fire.

The heat release rate of the i-th material, q_i, which is averaged over the area, A_i, depends on the incident heat flux which can be as high as 8 W/cm^2 at the time of flashover. The heat release rate of a material can vary considerably with time during the period over which the material releases heat. The heat release rate versus time at any incident radiant flux up to 8 W/cm^2 can be measured by the calorimeter [9] described in section A.2.

The area of involvement, A_i, of the i-th material needs to be determined from a flame spread test. There are two generally recognized ASTM flame spread tests for interior finish materials. These are the E 84 tunnel test [10] and the E 162 radiant panel test [11] described in sections A.3 and A.4 , respectively. There is also a new test for floor covering materials, namely, the flooring radiant panel test [12,13]. The latter, which is described in section A.5, was designed for the evaluation of carpeting or other flooring materials in corridors. Generally, the flooring materials do not become involved in a room fire until flashover is imminent. However, the flooring radiant panel can be used to classify floor covering materials in terms of their tendency to spread fire according to the level of the exposed flux.

3.4 Ventilation

The air used for the burning of combustibles may be delivered mechanically through a duct in the compartment, or by convection through the doorway, or some combination of both. Flow through a supply duct is known while the induced flow through the doorway can be estimated following the treatment of Prahl and Emmons [14].

Based on the assumption of a uniform temperature above the hot and cold flow interface, they derived the following equation for the induced mass flow out of the doorway:

$$\dot{m} = \frac{\sqrt{8}}{3} C_f \rho_o \quad [gr(1 - r)]^{1/2} \, b \, h^{3/2} \qquad (3)$$

where C_f is an orifice coefficient which is determined empirically to be approximately 0.7;

ρ_o is the density of the ambient air kg/m^3;

g is the acceleration due to gravity m/S^2;

r is the ratio of the density of the hot air to the ambient air density, ρ/ρ_o;

b is the doorway width m; and

h is the height of the hot outflow region below the top of the doorway m.

Taking the mass outflow equal to the mass inflow, neglecting the mass of the fuel released in the compartment, and converting to the volumetric flow rate, $\dot{V}_o$, to facilitate comparison of the calculated rates with the measured volume flow rates, we have

$$\dot{V}_o = \frac{\sqrt{8}}{3} C_f \left[g \left(\frac{T_o}{T}\right) \left(1 - \frac{T_o}{T}\right)\right]^{1/2} b\, h^{3/2}. \qquad (4)$$

If we assume that h is approximately equal to one half of the doorway height, H, as is usually observed near flashover [2],

$$\dot{V}_o = \frac{C_f}{3} \left[g \left(\frac{T_o}{T}\right) \left(1 - \frac{T_o}{T}\right)\right]^{1/2} b\, H^{3/2} \qquad (5)$$

The quantity $\left[\left(\frac{T_o}{T}\right) \left(1 - \frac{T_o}{T}\right)\right]^{1/2}$ is not very sensitive to temperature. At flashover, where T is approximately 3 T_o, it is 0.47; when $T \sim 2\,T_o$, it is 0.50.

Taking $g = 9.8\ m/S^2\ (1.15 \times 10^5\ ft/min^2)$,

$C_f = 0.7$, and

$[(T_o/T)\ (1-(T_o/T))]^{1/2} = 0.47$,

$\dot{V}_o = 0.34\ b\ H^{3/2}\ m^3/S$ with b and H in meters

$(37\ b\ H^{3/2}\ ft^3/min$ with b and H in ft) (6)

For the berthing compartment fires [2] there was a 0.69 x 1.9 m (2.25 x 6.25 ft) doorway. Thus the volume flow rate would be expected to reach a maximum of 0.62 m^3/S 1300 ft^3/min). For the half open doorway the volume flow rates might be expected to reach 0.32 m^3/S (650 ft^3/min). The maximum flow rates measured during the compartment fire tests were 0.58 m^3/S (1250 ft^3/min) for the fully opened doorway and 0.25 m^3/S (530 ft^3/min) for the half–opened doorway.

Using equation (6) the approximate mass outflow rate, $\dot{m}$, is given by

$$\dot{m} = \rho_o \dot{V}_o = 0.020 \, b \, H^{3/2} \text{ kg/S } (2.75 \, b \, H^{3/2} \text{lbs/min}) \qquad (7)$$

The mass flow rate is sensitive to the height of the neutral pressure plane, i.e., the plane separating the inflow and outflow of air. Proven techniques for predicting this height do not exist at the present time. The best that one can do is to substitute equation (7) into equation (2).

3.5 Heat Losses

The losses by conduction through the walls and ceiling and by radiation to the outside of the compartment and to the lower part of the room are important in determining the maximum temperature that can be reached and the time at which it is attained. The loss factor L is merely a ratio of these thermal losses and the air temperature rise in the compartment. It will depend in general upon both temperature and time.

Initially, the largest component of the losses is the transient heat conduction into the lining materials. Some insight into the importance of this term can be obtained by considering the temperature rise of a semi-infinite solid with a constant flux, q, at its surface [15], where,

$$T_s - T_o = \frac{2}{\pi^{1/2}} \; \frac{q \, t^{1/2}}{(K\rho c)^{1/2}} \qquad (8)$$

and where T_s is the temperature of the surface °K,

π is 3.14,

K is the thermal conductivity kW/m/°C,

ρ is the density kg/m^3,

c is the heat capacity kJ/kg/°C, and

t is the time

For rough calculational purposes, the surface temperature is assumed to be equal to the air temperature in the upper part of the compartment. Then, to the extent that the linings can be considered infinitely thick and that there is a constant heat flow through the surface, the early loss term is given by

$$L = \frac{qA}{T-T_o} = 1/2 \quad {\frac{\pi}{t}}^{1/2} \quad (K\rho c)^{1/2} \quad A \qquad (9)$$

where A is the exposed area. Initially L is very large and the time required for it to become small depends on Kρc. Low density materials like foam plastics and fibrous glass permit flashover to occur much more rapidly than similar high density lining materials in a compartment because of the smaller thermal losses with materials of smaller Kρc values. Of course, in the case of fibrous glass there must be a large enough contribution from the furnishing materials in order to have a flashover at all.

At some intermediate stage of the fire development, the thermal conductivity K will become a more important heat loss factor than the quantity Kρc in determining the ultimate course of the fire. If the temperature in the upper part of the compartment continues to increase, at some later stage of the fire, radiation to the lower part of the compartment becomes the dominant heat loss mechanism. It was found in the berthing compartment fires study [2] that the maximum temperature rise could be estimated from the rate of heat production, as indicated by the oxygen depletion of the exhaust gases from the compartment, if it were assumed that the heat losses to the lower part of the compartment and to the outside were due to radiation. Therefore, as an approximation, let L in equation (2) be given by the expression,

$$L = A_f \sigma (T^4 - T_o^4)/(T - T_o) \qquad (10)$$

where σ is the Stefan Boltzmann constant, A_f is the deck area, and T is the effective temperature of the radiating hot surfaces and gas and smoke layer in the upper part of the compartment assuming an emissivity of unity.

3.6 Prediction Model Summary

The fire buildup potential of a compartment, as indicated by the air temperature developed in the upper part of the compartment, can be predicted from equation (2), provided the terms in the latter are known. The term for the mass flow rate of air out of the doorway, $\dot{m}$, can be estimated from equation (7). Heat loss by conduction and radiation, L, can be approximated by neglecting the conduction term and using equation (10). The burning rate, Q, is difficult to predict and must be measured. The average heat release rate per unit surface area of each interior finish material must also be measured. The term for the area of fire involvement in equation (2) for each material is difficult to measure and is presently estimated from flame spread tests of the material. Experimental and analytical studies are continuing to determine a suitable measure of surface fire spread. It is anticipated that the prediction model will become operational once the problem of fire spread is resolved.

4. APPLICATION AND MODIFICATION OF LABORATORY FIRE TESTS

This section discusses the refinement and/or practical employment of the ease of ignition, ASTM E 84, ASTM E 162, flooring radiant panel, rate of heat release and potential heat tests for interior finish materials. Whenever possible the interior linings used in the Navy compartment fires program [2] were reevaluated with the modified fire performance tests. The overhead and bulkhead sheathings and the wool deck covering used in that program were no longer available in the same color, surface texture or backing construction. Except for these variances, the substitute materials were judged to be similar to the original materials.

Table 3 outlines the materials that have been evaluated for their fire performance. Tables 3 and 4 and figures 1 to 5 summarize the experimental results from the fire tests. From three to six separate ease of ignition tests of each material were run to obtain the ignition data shown in table 3. All of the tabulated flame spread values were averaged from three tests of each material. The rate of heat release data were averaged from two tests of each material.

4.1 Ignition

In the ease of ignition test for measuring the ignitability of materials [16], operational improvements in the test method and more meaningful interpretation of the data have been investigated by Lawson and Parker [8]. C.P.

grade methane (99% purity) has been substituted for natural gas to ensure more repeatability in the exposure flame particularly when the test is to be used at different locations. A phototube was incorporated to detect the onset of fuel contribution by the specimen. The time at which a flame will attach to the material surface is noted during the test. The time at which the material will sustain surface flaming in the absence of the exposing flame can still be determined as it was in the earlier version of the test. However, it has become apparent that the time at which a material first begins to contribute fuel to the fire is a better indicator of the contribution of the material to an early compartment flashover. Furthermore, some materials which cannot sustain a flame can contribute significantly to the growth and intensity of a fire when they are exposed to an external flame.

Certain materials which swell or intumesce during the ignition test have caused serious obstruction of the igniting flame in the gap separating the parallel specimens. To alleviate this problem, Lawson and Parker widened this gap from 22 mm (7/8 in) to 50 mm (2 in). Ease of ignition data using the modified test are indicated on table 3.

From our experience with material behavior in compartment fires [2,17] a flame exposure time of less than 60 seconds for the onset of fuel contribution from a material indicates that the material is likely to have a significant effect on fire growth. Of the materials listed in table 3 only the low density acoustical panel substitute, the acrylic carpet and the wool carpet substitute exhibited times to fuel contribution which were less than 60 seconds in the ease of ignition test.

4.2 Flame Spread

4.2.1 General Discussion

Flame spread along a surface is presently evaluated using comparative numerical index values in the ASTM 84 tunnel and the ASTM E 162 radiant panel. Flame propagation in the former test is in the direction of the ventilation through the tunnel. The heat and fuel generated from the burning material also flows in the same direction and contributes to the extension of the flame front. Flame travel on the E 162 radiant panel is downward, counter to the air updraft. Heat produced by the burning specimen moves vertically away from the specimen and does not contribute to the flame spread. Both modes of fire spread are found in compartment type fires. In the initial stages of a fire the flame spread along the interior finish is upwards from the ignition flame in the direction of airflow similar to flame propagation and flow in the E 84 tunnel. Lateral flame travel across the bulkhead, away from this initial flame zone, is more a function of the ignitability of the material. Similarly, flame propagation downward is closely related to the ignitability of the material. Thus, the flame spread away from the initial flame zone may be some function of the performance of the material on the ease of ignition test and on the E 162 radiant panel test.

Until the new method of calculation was adopted in 1976, the standard tunnel test distinguished between two classes of materials: those in which the flame extends over the end of the tunnel and those that do not. A tunnel flame spread classification (FSC) of 77.5 formed the dividing line between these classes. There is evidence [18] that for FSC values less than 77.5, a linear correlation may exist between the FSC and the rate of heat release values for materials. This is consistent with the earlier observation that the surface flame propagation along a material in the tunnel is dependent on the heat and fuel generated from the burning material. Flame spread along a material with a FSC of 77.5 or more might be considered to be self-propagating, and A_i in equation (2) of section 3.1 should be set equal to the area of the exposed material surface for this case, because flame would be expected to extend to the boundaries of the material. If the flame stops within the confines of the tunnel then the flame is not self-propagating, and the area of flame coverage in a room fire will depend on the size of the exposing flame and on the incident radiant flux originating from other regions of the room.

The radiant panel produces an index number, I_s, which is a product of a flame spread factor, F_s, and a rate of heat contribution. Intuitively, it may provide less information as to the extent of the upward flame spread than the E 84 test. However, if the overhead becomes immersed in flame, the next stage of the fire development is downward flame propagation over the bulkhead surfaces. The quantity F_s represents some weighted average rate of flame spread for a material exposed over the flux range from 0.5 to almost 4 W/cm^2. Thus F_s and, to a lesser degree, I_s, can give some indication of the potential surface flame spread for a material.

However, in making use of the flame spread rate in the E 162 test it is important to realize that the rate depends strongly on the slope of the heat flux distribution along the length of the test specimen as well as on the flux level along the flame front. This distribution, which depends on the angle between the specimen and the panel, affects the preheating of the specimen ahead of the flame front. The rate of flame spread is inversely proportional to the time required to heat the specimen surface from the preheat temperature to the pyrolysis temperature. Thus one cannot directly apply the flame spread rates obtained in the test to the calculation of flame spread in a room where the incident heat flux distribution is different.

Correlations between the flame spread ratings or the flame distance in the tunnel with the flame coverage of the compartment finish, or with the air temperatures in compartment fires have been attempted [18,19], but exceptions to such correlations occur. In our analysis of some fire tests conducted at Underwriters Laboratories [20], little correlation was found between the flame spread ratings for the interior finish and the degree of fire buildup in a room. Their test compartment was lined with plastic board materials and a 9.1 kg (20-lb) wood crib, positioned in one corner, served as the ignition source. These tests demonstrated that fires with some plastic interior finish having a 25 or lower rating on either or both of the E 84 and E 162 tests still led to flashover of the compartment.

Samples of some of the low FSC plastic foam materials used in the above tests [20] were also tested on the ease of ignition test and were found to contribute fuel in only 1 second of flame exposure. Thus, even though materials might have low flammability ratings, the ignition criterion in section 4.1 must also be applied to assure a higher reliability in screening out such materials. The ignition test by itself should not be used for eliminating these interior finish materials. It is not certain that a long time to fuel contribution on the ease of ignition test will always ensure that the flame spread in a fire will not be sustained, or whether it will be slow under irradiance levels higher than that found in the ignition test.

4.2.2 Critical Flux and Propagation Rate

Application of the E 84 and E 162 tests is complicated by the fact that the numerical classifications from both tests do not necessarily indicate the relative rates of flame spread among materials nor do they show under what conditions of external thermal reinforcement flame spread might or might not occur along materials. Data from the E 162 radiant panel test may, however, be used to estimate the lowest or critical heat flux for sustained flame propagation. Values of critical flux for some interior finish materials are given on table 3. The relative flame spread of these materials on the E 162 test are indicated on figures 1 and 2. Of the materials shown on these figures only the acrylic deck covering has a critical flux considerably lower than the other materials. It also has a relatively fast flame spread. However, a high critical flux value does not necessarily mean a slow flame spread once this flux value has been exceeded, e.g., the low density acoustical panel material on figure 1.

Critical flux for flame spread and the rate of flame propagation along a material are functions of its orientation, the direction of flame travel, and the irradiance field along the length of the specimen. Upward flame spread is faster and easier to sustain than flame travel in the other directions. However, flame spread differences among materials are easier to ascertain for the slower lateral and downward flame travel. Table 3 along with figures 1 and 3 compare downward flame spread on the E 162 test with lateral flame spread, as measured with the developmental flame spread test discussed in section A.6, for several materials. The data showed that critical fluxes measured from two different tests can differ significantly and that relative flame spread rates among materials could also change with the type of test. In figure 1 the vinyl laminate had a slower fire spread rate than that for the high density acoustic panel. But figure 3 shows the opposite behavior when the developmental flame spread test was used.

Results from the E 162 and flooring radiant panel tests for deck coverings, table 3 and figures 2 and 4, also demonstrated that significant differences can occur due to specimen orientation. However, the data from either test can be applied to find the good performers, e.g., both tests indicated that the polyamide carpet and vinyl asbestos tile have much lower flame spread rates than those for the wool carpet with the latex-jute back and the acrylic carpet. Critical fluxes from the two tests were similar for the materials considered, with the exception of the wool deck covering. The latter material had a critical flux value of 2.2 on the E 162 test as compared with about 0.85 in its actual use orientation on the flooring radiant panel test. The fact that such large differences may occur seriously warrant testing deck materials only with the flooring radiant panel. Critical heat flux values for the deck coverings tested with the developmental flammability test, table 3 and figure 5, were in reasonable agreement with those measured with the flooring radiant panel, table 3 and figure 4.

4.3 Rate of Heat Release

The previous sections discussed the roles of material ignitability and flammability on the fire involvement of the compartment finish. A material may readily ignite and spread the fire over a large area, but if it is also accompanied by a low rate of heat release per unit surface area, the compartment space would not lead to flashover. It has been demonstrated in the Navy berthing fires [2] that the total heat generation rate in the compartment must be less than an approximate rate of 72 kW/m^2 (6.3 $Btu/s/ft^2$) of deck area to avoid flashover conditions.

The rate of heat generation from a burning material under adequate ventilation conditions depends on the degree of external heating and on its configuration and construction. Orientation of a material is particularly important if it melts and drips under heating. Material thickness and substrate can affect its rate and duration of heat production.

Heat release rates of some shipboard interior finish had been measured in the vertical orientation under an irradiance of 6 W/cm^2 [2]. These same or similar materials have now been investigated over a range of irradiances from 2 to 6 W/cm^2, and the deck coverings have also been studied in a horizontal test position. Experimental results are shown in table 4.

In general, the rate of heat generation increases with an increased irradiance. In order to apply the data in table 4, the approximate irradiance field throughout the compartment must be known. Several fire experiments had been conducted in a one-quarter scale compartment having an opened doorway to obtain some indication of this irradiance environment [17]. These tests simulated the situation where a burning 14-pound wood crib was positioned in one corner of a 3 x 3 x 2.4 m (10 x 10 x 8 ft) high compartment with the bulkhead and overhead lined with 2.5 cm (1.0 in) PVC nitrile rubber. These tests showed that the flux to the overhead quickly exceeded 5 W/cm^2 at flashover. Averaged irradiance levels along the upper half of the bulkhead were roughly the same and the irradiance on the deck was approximately one-quarter to one-half of the overhead values measured during the fire development up to flashover. These values suggest that exposure fluxes of 6, 6, and 2 W/cm^2 may be appropriate for evaluating the rates of heat release for overhead, bulkhead and deck materials, respectively. As is evident from the data in table 4, orientation of the specimen is also important and the deck coverings should always be tested in the horizontal position facing up.

Various ways can be used to characterize the heat release rate from a burning material. As an example, the data can be displayed in terms of the peak rate, the highest 1-minute average rate and the maximum 3-minute average value, as has been done in table 4. Although it is not apparent from the tabulated results, each of these rates could conceivably rank a set of materials in quite different order, and the one which is best depends on the duration of the fire. In the absence of better information, it is recommended that the highest 1-minute average values be used.

4.4 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. The latter requirement is intended to limit the effect of the fire on the structural integrity of the compartment components as well as to reduce the probability of fire penetration into adjoining occupancies. This fire duration or severity is related to the potential heat production of the compartment finish and contents. The potential heat test [21], described in section A.7 of the appendix, adequately provides a quantitative measure of the available heat from materials. A commonly used relation between fire severity and fire load [3] 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 240 MJ/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 [2] have indicated the seriousness of such exposures on 0.25 cm (0.10 in) thick aluminum bunk partitions. There is further experimental evidence [22] that exposure times as short as 6 minutes could also be detrimental to 0.64 cm (1/4 in) thick aluminum plating. Based on the survey of compartment spaces in section 2.2., lounges and wardrooms may have a fire duration as long as 7 minutes, while laundry areas may have a fire duration of up to 18 minutes.

5. SUMMARY

A review of statistics of fire incidents on board ship has identified machinery spaces, supply areas, habitability spaces such as the berthing quarters, wardrooms and lounges, and deck storage areas as the spaces having a relatively high incidence of fires. The machinery and deck storage areas were too complex to characterize in a simple manner and were not evaluated in this report. However the crew's living areas were relatively easy to characterize. Berthing quarters were observed to occupy deck areas ranging from about 37 m^2 (400 ft^2) up to 121 m^2 (1300 ft^2) with a potential heat loading of about 240 MJ/m^2 (21 000 Btu/ft^2). Officers' wardrooms, crew's lounges and mess halls were found to have less than one half of the potential heat loading of the berthing spaces. However, the potential heat loading in the laundry rooms could sometimes approach that in the berthing areas.

The prediction model for compartment fire growth, developed previously for the Navy, was extended to include a derivation for determining the fire induced airflow into the fire room. In addition, the components of this fire buildup model along with the associated problem areas were discussed in detail. The concepts of critical heat flux for sustained flaming and the effect of radiation reinforcement on heat release and flame propagation rates have been discussed. However, more effort is needed to relate the irradiance field in a compartment to the degree of fire buildup in the space before such concepts can be applied effectively. Until this becomes feasible and until compartment fire buildup can be adequately predicted from such information, criteria for choosing fire safe materials must rely on the state of the art knowledge of fires. This means relying upon existing laboratory fire tests.

Refinement of the test methods has resulted in an expanded application of the ASTM E 162 test apparatus to include the measurement of the critical flux for sustained flame spread along materials. In the ease of ignition test the time at which a material first begins to contribute fuel to the fire appears to be a better indicator of the contribution of the material to an early compartment fire growth than the time for self-sustained flaming, which was used previously. Significant progress has also been made in the interpretation of the flame spread potential of materials, as measured by the laboratory fire tests. Flame spread phenomena along interior finish materials in a compartment fire may often be related to the laboratory fire tests of the materials. In a typical fire scenario, the flame spread is initially upwards from the ignition flame. The ultimate height of this flame zone or, if the flame zone exceeds the height of the overhead, its extension across the overhead depends on the same factors as the flame travel distance along the ASTM E 84 tunnel. However, the flame spread distance along a material in the tunnel appears to be a function of the rate of heat generation of the burning material. Since measurement of the latter fire property is needed to fully describe the potential contribution of the material to the fire development in the compartment, the E 84 flame spread classification for the material becomes a redundant measurement.

Lateral flame travel across the bulkhead, away from the initial flame zone, is related to the flame spread factor F_s, and to a lesser extent, to the flame spread index I_s in the ASTM E 162 test and is some function of the ignitability of the material. Similarly, flame propagation downward along the interior finish can be characterized with this flame spread factor and should be relatable to the ignition properties of the material. Thus, the flame spread away from the initial flame affected zone appears to be some function of the material's performance on the ease of ignition and on the ASTM E 162 tests. However, no single test by itself can adequately assess the flame spread potential of bulkhead and overhead finish.

As for deck coverings, surface flame spread cannot occur until the irradiance level on the deck has reached the critical value for sustained flaming on the material. This critical flux can be adequately measured with the flooring radiant panel test.

The degree of compartment fire involvement is indicated by the average temperature in the upper part of the space. Any increase in this temperature, and hence in fire involvement, beyond that created by the burning furnishings in an adequately ventilated space, depends not only on the compartment surface area covered by the fire but also on the rate of heat production per unit area of the affected surface. This latter quantity can be measured with the rate of heat release calorimeter. It is recommended that exposure fluxes of 6, 6 and 2 W/cm^2 be employed in the latter for evaluating the rates of heat release for overhead, bulkhead, and deck materials, respectively. Deck coverings should be tested in the horizontal position.

In addition to limiting the intensity of the fire, there is also a need for restricting its duration. This can be met by requiring a reasonable limit on the total potential heat content of the compartment finishes and furnishings.

Fire performance evaluations of materials with the ASTM E 162 or the flooring radiant panel tests along with the ease of ignition, the heat release rate calorimeter and the potential heat tests are, therefore, all important in assuring a higher reliability in screening out potentially fire hazardous materials which can contribute significantly to compartment fire growth. Although the generation of smoke and combustion gases from materials burning in the room are also important for fire safety considerations, they are less important in determining room fire buildup.

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APPENDIX A. TESTS OF FIRE PROPERTIES

A.1 Ease of Ignition Test

The ease of ignition test [8] measures the exposure times required to produce flame attachment and fuel contribution of building materials in contact with flame. Two specimens 14.0 cm (5-1/2 in) wide and 15.2 cm (6 in) high face each other 50 mm (2 in) apart. Natural gas is introduced into the gap and is ignited with a spark. The exposing flame passes between the specimen surfaces and extends about 25.4 cm (10 in) above them. The incident heat flux on the specimen surface averages 3.2 W/cm^2 (2.8 $Btu/s/ft^2$).

The time of flame attachment is observed visually. The time of fuel contribution is indicated by a phototube which is sampling the radiation from the flame.

A.2 Heat Release Rate Calorimeter

The heat release rate calorimeter [9] measures the rate of heat generation for building materials exposed to radiant fluxes up to 10 W/cm^2 (8.8 Btu/ft^2) with a response time of a few seconds. A 11.4 by 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. 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.

A.3 ASTM E 84 Tunnel Test

The ASTM E 84 tunnel test [10] measures the flame spread performance of the specimen material relative to that of asbestos-cement board and red oak flooring under similar test conditions for a duration of 10 minutes. A 50.8 cm (20 in) wide and 7.3 m (24 ft) long specimen is horizontally-mounted in an overhead orientation in a 7.6 m (25-ft) long test chamber. The fire end of the tunnel is provided with two gas burners delivering flames upward against the surface of the test sample. An air intake port 7.6 cm (3 in) high, measured from the floor level of the test chamber, is provided at the fire end. The vent end is fitted to a 40.6 cm (16 in) diameter flue pipe. Changes in smoke density in the latter is monitored photometrically. A thermocouple is also mounted 2.5 cm (1 in) from the sample surface, within 30.5 cm (1 ft) of the vent end.

Results are given for flame spread, fuel contributed and smoke developed. These values, obtained from burning the test material, represent a comparison with those of asbestos-cement board expressed as zero and red oak flooring expressed as 100. Until the new method of calculation was adopted in 1976, the flame spread classification, FSC, was determined as follows:

(1) For materials on which flame spreads 5.94 m (19-1/2 ft) in a time, t, of 5-1/2 min or less, FSC = 550/t.

(2) If the flame front spreads to 5.94 m (19-1/2 ft) in more than 5-1/2 min, then FSC = 50 + 275/t.

(3) For materials on which the flame spreads less than 5.94 m (19-1/2 ft) but more than 4.11 m (13-1/2 ft), FSC = 50 + 4.62 d where d is in meters, and FSC = 50 + 1.41 d where d is in feet.

(4) When the extreme flame spread distance is 4.11 m (13-1/2 ft) or less, the classification is FSC = 16.84 d for d in meters and 5.128 d for d in feet.

According to the new method of calculation the FSC is proportional to the area under the flame distance versus time curve during the 10-minute exposure period. In the event that the flame recedes during the test, the distance used in plotting the curve is the maximum distance traveled up to time at which the distance is being plotted.

The value for fuel contributed is derived by calculating the net area under the time-temperature curve from the thermocouple near the vent end for the test material and comparing this area with the net area under the curve for untreated red oak strip flooring.

The smoke developed during the test is determined from the time dependent increase in obscuration of a light source due to the smoke in the vent pipe. The smoke rating is derived by calculating the net area under the time-obscuration curve for the test material and comparing this area with the net area under the curve for untreated red oak strip flooring.

A.4 ASTM E 162 Radiant Panel Test

The ASTM E 162 radiant panel test [11] requires a 15.2 x 45.7 cm (6 x 18 in) 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

$$F_s = 1 + \frac{1}{t_3} + \frac{1}{t_6-t_3} + \frac{1}{t_9-t_6} + \frac{1}{t_{12}-t_9} + \frac{1}{t_{15}-t_{12}} \quad \text{and} \quad Q_s = 0.1\ \Delta T/\beta$$

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 in), respectively, along the length of the specimen. The value of 0.1 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 input 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.

A.5 Flooring Radiant Panel Test

The flooring radiant panel test [12,13] 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 flameout 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 2.4 to 0.2 W/cm^2 (2.1 to 0.18 $Btu/s/ft^2$) in the high panel temperature range of 660 to 680° C (1220 to 1256° F). Test results are reported as the critical radiant flux, W/cm^2, for flameout .

A.6 Developmental Flame Spread Test

This test measures either horizontal flame spread in deck coverings or the lateral flame travel along bulkhead and overhead interior finish materials when exposed to a flaming ignition source under a prescribed range of irradiances. In the testing of deck coverings a 15.5 cm (6.1 in) by 80 cm (31.5 in) specimen is mounted with its length perpendicular to a vertically oriented premixed air-gas fueled radiant panel. The panel produces an energy flux distribution ranging from 2.8 W/cm^2 (2.5 $Btu/s/ft^2$) on the edge closest to the panel to 0.14 W/cm^2 (0.12 $Btu/s/ft^2$) at the far end of the specimen. For bulkhead testing, a specimen, having the same dimensions, is positioned at a 90 or 45 degree angle with respect to the vertical radiant source, corresponding to the low and high irradiance exposures, respectively. The flux distributions along the sample surface range from 3.3 to 0.18 W/cm^2 (2.9 to 0.16 $Btu/s/ft^2$) and from 7.0 to 0.14 W/cm^2 (6.2 and 0.12 $Btu/s/ft^2$)for these two exposure settings, respectively.

Deck coverings would be mounted in their actual use installation and orientation. Bulkhead and overhead sheathing would be tested in the vertical position. Results are presented in terms of the critical radiant flux in W/cm^2 for flameout .

A.7 Potential Heat Test

The potential heat test [21] 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 "standardized fire" (2 hours in a muffle furnace at 750° C (1382° 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.

Table 1. Potential heat loading for berthing quarters

Item	Specification	Potential heat per unit mass		Potential heat per unit deck area	
		J/g	Btu/lb	MJ/m^2	Btu/ft^2
Furnishings					
Bedding	-	23 300	10 000	136.1	12 000
Locker contents	-	19 800	8 500	38.6	3 400
Overhead					
Chlorinated alkyd paint	MIL-D-17970C	7 400	3 200	9.6	840
Plastic light diffuser panels	MIL-P-24191	26 800	11 500	22.7	2 000
Bulkhead					
Chlorinated alkyd paint*	MIL-D-17970C	7 400	3 200	10.2	900
Fibrous glass*	MIL-I-742C	700	300	0.3	26
Deck					
Vinyl asbestos tile	MIL-T-18830	5 100	2 200	22.7	2 000

*Based on a 9.1 x 9.1 x 2.4 m (30 x 30 x 8 ft) high space with one insulated bulkhead and all four bulkheads painted with a 0.61 mm (24 mil) coating of chlorinated alkyd enamel.

Table 2. Potential heat loading for wardroom and lounge areas

Item	Specification	Potential heat per unit mass		Potential heat per unit deck area	
		J/g	Btu/lb	MJ/m^2	Btu/ft^2
Furnishings					
Sofas, chairs, tables	-	24 000	10 700	7.9 to 13.6	700 to 1 200
Overhead					
High density acoustical panel	SS-S118	20	10	0.23	20
or Low density acoustical panel	SS-S118	1 560	670	3.4	300
Light diffuser panel	MIL-P-24191	26 800	11 500	22.7	2 000
Bulkhead					
Vinyl and melamine laminated surfaces	MIL-L-24518 MIL-T-17171	19 600 to 23 700	8 400 to 10 200	20.4	1 800
Paint*	MIL-D-17970C	7 400	3 200	5.1	450
Drapery**	-	19 800	8 500	1.5 to 3.6	130 to 320
Deck					
Vinyl asbestos tile	MIL-T-18830	5 100	2 200	22.7	2 000
or polyamide carpet	-	20 500	8 800	38.6	3 400

*Based on a 0.61 mm (24 mil) coating on two bulkheads in a 9.1 x 9.1 x 2.4 m (30 x 30 x 8 ft) space.

**One set of drapes every 9.3 m^2 (100 ft^2).

Table 3. Summary of ignition and flame spread test results on some interior finish materials

Material*	Thickness		Weight per** Surface Area		Ease of Ignition Time to Fuel Contribution (sec)	Downward Flame Spread E-162			Developmental Flame Spread Test Lateral Flame Spread
	(mm)	(in)	(g/cm^2)	(lb/ft^2)		Flame Spread Factor F_s	Flame Spread Index I_s	Critical Heat Flux (W/cm^2)	Critical Heat Flux (W/cm^2)
Overhead									
1. Low Density Acoustical Panel No. 1	17.8	0.70	0.21	0.42	>120	4.1	7.3	2.8	
2. Low Density Acoustical Panel No. 2	17.8	0.70	0.21	0.42	25	11.9	13.1	2.4	5.2
3. High Density Acoustical Panel No. 1	14.0	0.55	0.56	1.15	>120	3.1	5.0	3.1	
4. High Density Acoustical Panel No. 2	14.0	0.55	0.56	1.15	>120	3.1	3.4	2.7	4.3
Bulkhead									
5. Vinyl Laminate No. 1 on 1.6 mm (0.063") Aluminum	0.20	0.008	0.029	0.059	82	2.7	25.0	2.2	
6. Vinyl Laminate No. 2 on 1.6 mm (0.063") Aluminum	0.20	0.008	0.029	0.059	96	5.1	19.7	1.7	2.8

*Materials used in the Navy compartment fires [2] are denoted by No. 1, while the No. 2 materials are the substitute materials.

**Excluding metal substrate.

Table 3. (Cont'd)

Material*	Thickness		Weight per** Surface Area		Ease of Ignition Time to Fuel Contribution (sec)	Downward Flame Spread E-162			Developmental Flame Spread Test Lateral Flame Spread
	(mm)	(in)	(g/cm^2)	(lb/ft^2)		Flame Spread Factor F_s	Flame Spread Index I_s	Critical Heat Flux Rate (W/cm^2)	Critical Heat Flux (W/cm^2)
Bulkhead, cont'd									
7. Melamine Laminate No. 1 on 1.6 mm (0.063") Aluminum	0.89	0.035	0.12	0.25	61	1.0	3.0	≥ 3.6	
8. Melamine Laminate No. 2 on 1.6 mm (0.063") Aluminum	0.89	0.035	0.12	0.25	>120	1.0	5.5	3.4	4.1
9. Fibrous Glass (unpainted) No. 1	25.4	1.0	0.16	0.33	>120	4.2	8.0	3.2	
10. Fibrous Glass (unpainted) No. 2	25.4	1.0	0.16	0.33	>120	1.0	2.0	≥ 3.6	>6.0

*Materials used in the Navy compartment fires [2] are denoted by No. 1, while the No. 2 materials are the substitute materials.

**Excluding metal substrate.

Table 3. (Cont'd)

Material*	Thickness		Weight per** Surface Area		Ease of Ignition Time to Fuel Contribution (sec)	E-162 Flame Spread			Developmental Flame Spread Test Deck Orientation	Flooring Radiant Panel
	(mm)	(in)	(g/cm^2)	(lb/ft^2)		Flame Spread Factor F_s	Flame Spread Index I_s	Critical Heat Flux (W/cm^2)	Critical Heat Flux (W/cm^2)	Critical Heat Flux (W/cm^2)
Deck										
11. High Temp. Polyamide Carpet on 0.64 cm (0.25") Steel	5.1	0.20	0.19	0.39	>120	2.9	8.3	1.9	2.3	1.8
12. Wool Carpet No. 1 on 0.64 cm (0.25") Steel	7.1	0.28	0.22	0.45	---	2.9	20.0	2.9		
13. Wool Carpet No. 2 on 0.64 cm (0.25") Steel	7.6	0.30	0.23	0.48	41	8.7	99.5	2.2	1.1	0.85
14. Vinyl Asbestos Tile on 0.64 cm (0.25") Steel	2.4	0.094	0.44	0.90	>120	3.1	14.7	2.1	2.4	2.4
15. Acrylic Carpet on 0.64 cm (0.25") Steel	11.4	0.45	0.23	0.47	18	16.4	235.	<0.5	0.25	0.27

*Materials used in the Navy compartment fires [2] are denoted by No. 1, or are unnumbered, while the No. 2 materials are the substitute materials.

**Excluding metal substrate.

Table 4. Heat release rates of some interior finish materials

Material	Vertical Orientation									Deck Orientation		
	2 W/cm^2 Exposure			4 W/cm^2 Exposure			6 W/cm^2 Exposure			4 W/cm^2 Exposure		
	Peak (W/cm^2)	Maximum One Minute Average (W/cm^2)	Maximum Three Minute Average (W/cm^2)	Peak (W/cm^2)	Maximum One Minute Average (W/cm^2)	Maximum Three Minute Average (W/cm^2)	Peak (W/cm^2)	Maximum One Minute Average (W/cm^2)	Maximum Three Minute Average (W/cm^2)	Peak (W/cm^2)	Maximum One Minute Average (W/cm^2)	Maximum Three Minute Average (W/cm^2)
<u>Overhead</u>												
2. Low Density Acoustical Panel No. 2	1.0	0.2	0.2	4.3	1.4	1.2	3.3	1.3	1.1			
4. High Density Acoustical Panel No. 2	0.9	0.1	0.1	2.9	0.5	0.4	2.6	0.2	~0			
<u>Bulkhead</u>												
6. Vinyl Laminate No. 2 on 1.6 mm (0.063") Aluminum	3.2	1.9	0.9	9.5	3.3	2.0	10.3	4.1	2.5			
8. Melamine Laminate No. 2 on 1.6 mm (0.063") Aluminum	5.5	3.7	2.3	18.5	5.5	2.9	44.5	14.4	7.1			
10. Fibrous Glass No. 2 on 1.6 mm (0.063") Aluminum	1.2	0.5	0.3	1.7	~0	~0	2.0	0.7	0.7			
<u>Deck</u>												
11. High Temp. Polyamide Carpet on 0.64 cm (0.25") Steel	1.1	0.3	0.1	3.8	2.4	2.3	3.9	2.4	2.2	2.7	1.4	1.3
13. Wool Carpet No. 2 on 0.64 cm (0.25") Steel	1.1	0.8	0.6	13.3	9.4	6.4	18.3	10.3	6.8	14.2	8.2	3.8
14. Vinyl Asbestos Tile on 0.64 cm (0.25") Steel	2.4	1.4	1.0	7.4	4.1	2.7	5.3	4.1	3.3	3.6	2.4	2.0
15. Acrylic Carpet on 0.64 cm (0.25") Steel	9.3	6.0	3.0	25.8	11.6	7.1	18.7	10.2	6.5	28.5	10.3	5.5

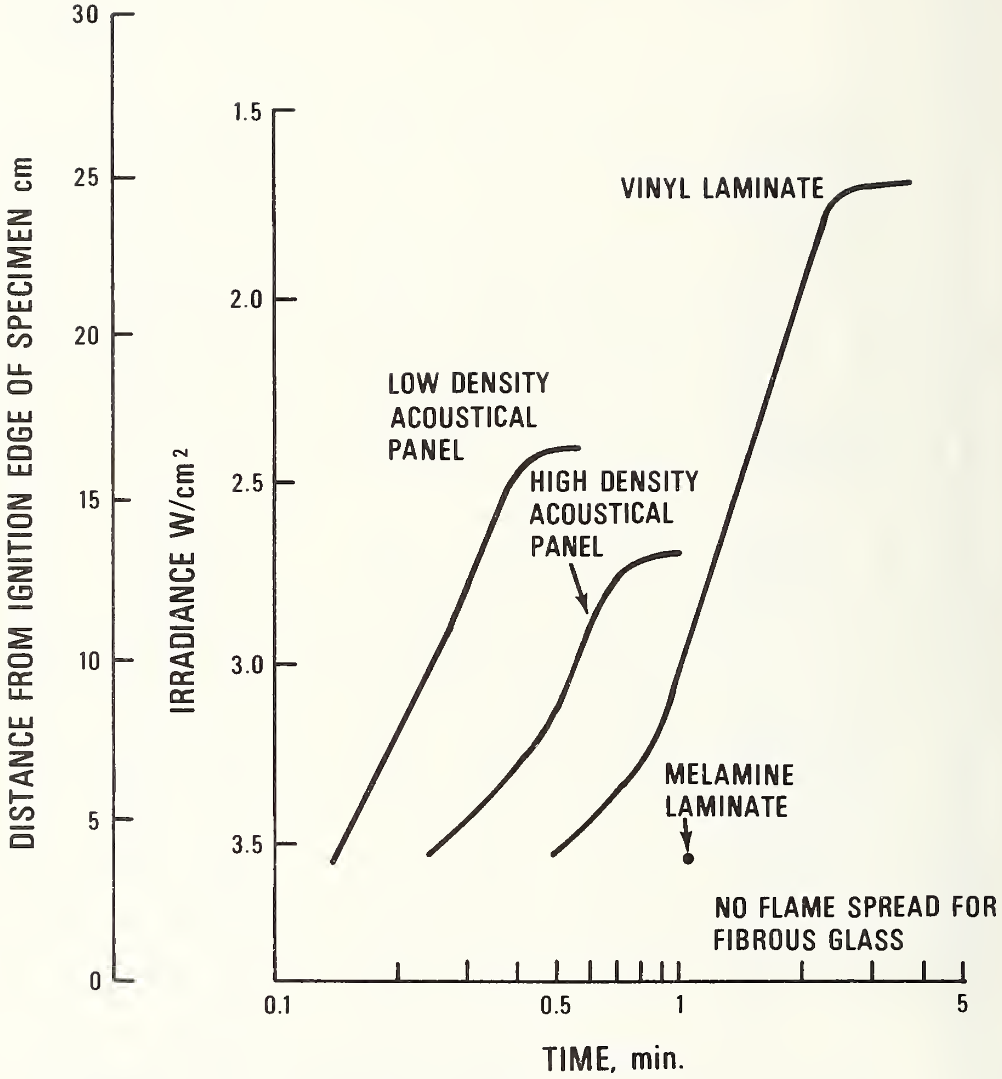

Figure 1. Flame spread by E 162 test

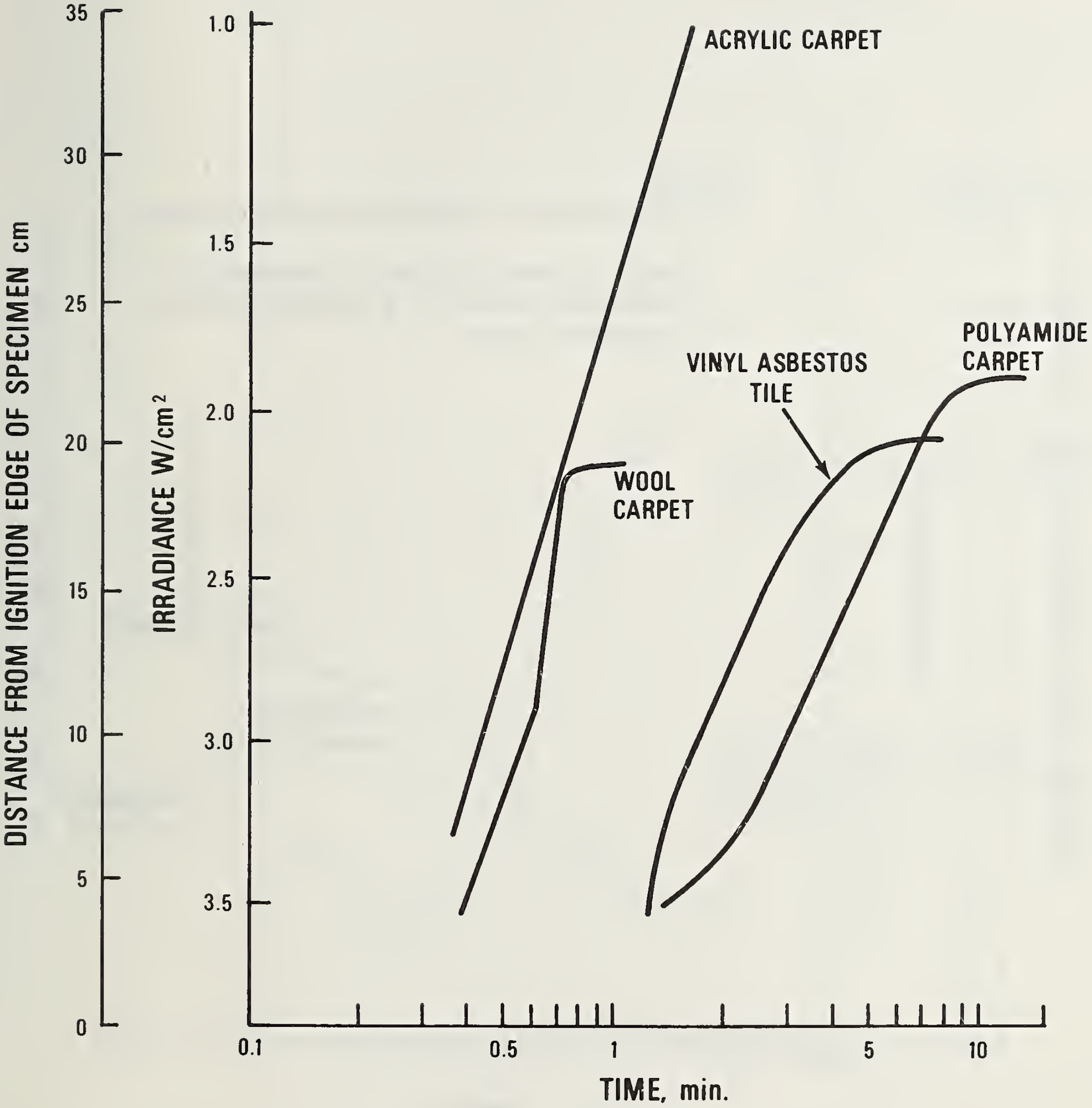

Figure 2. Flame spread by E 162 test

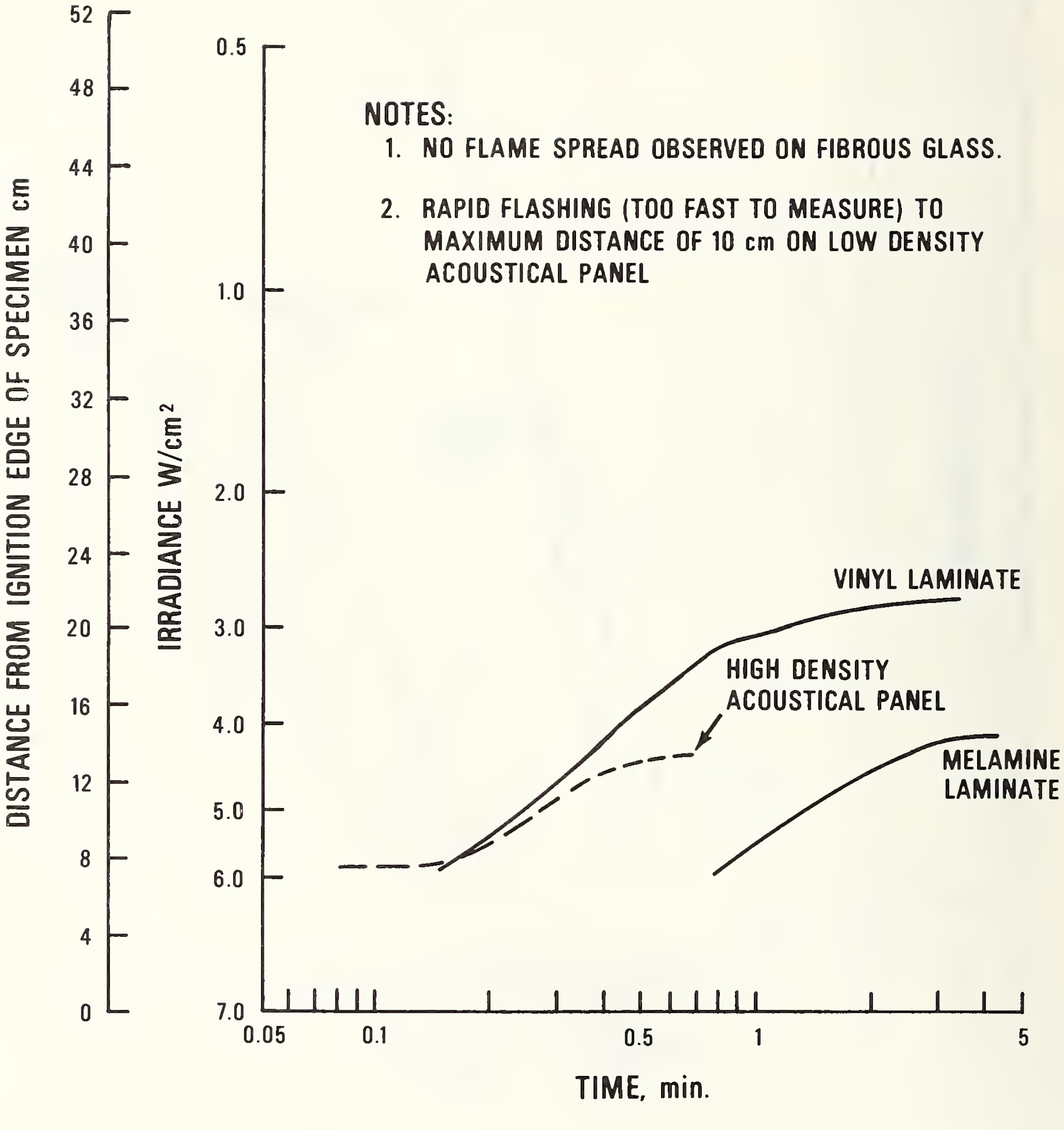

Figure 3. Lateral flame spread with developmental flame spread test

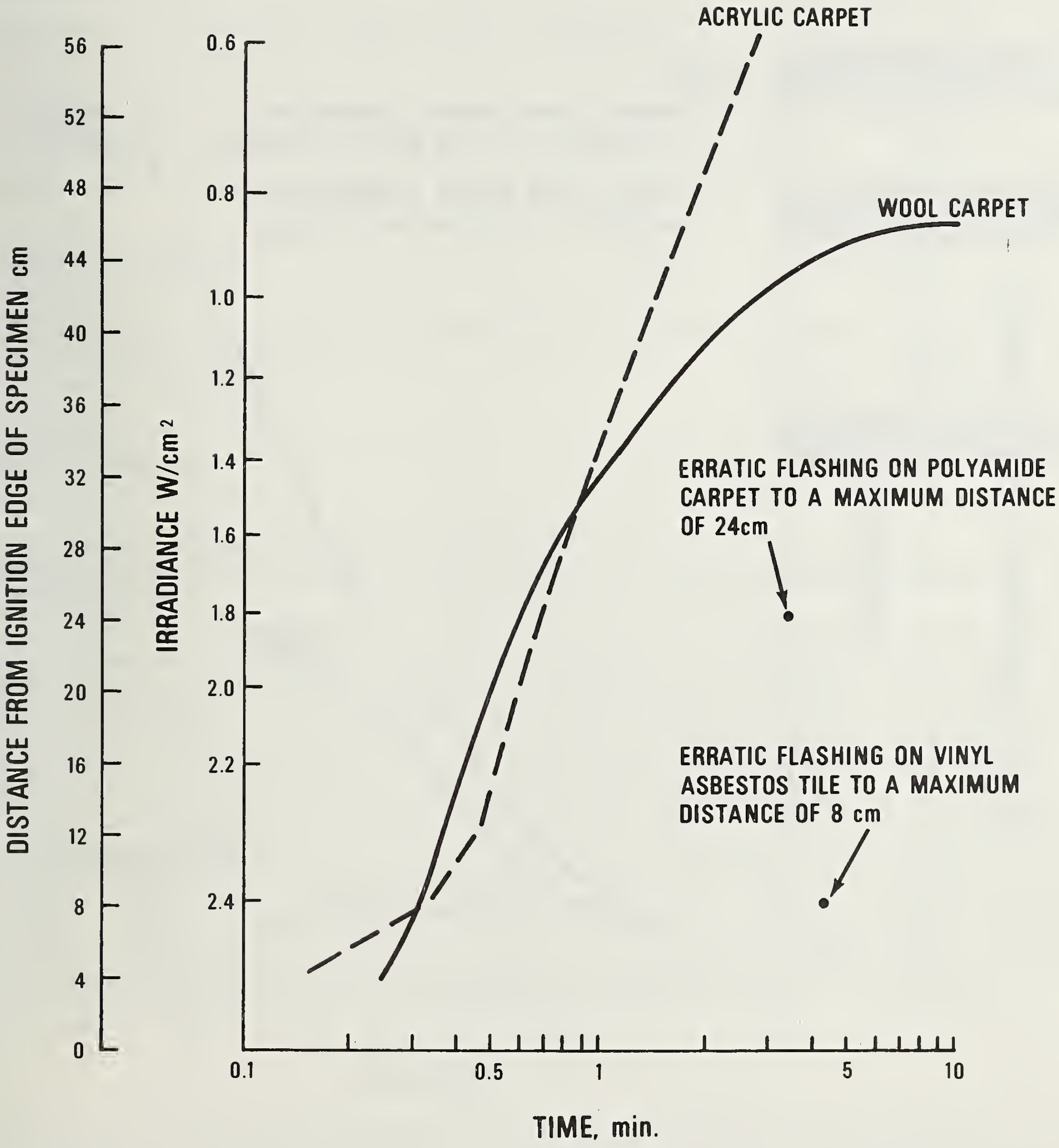

Figure 4. Flame spread with flooring radiant panel

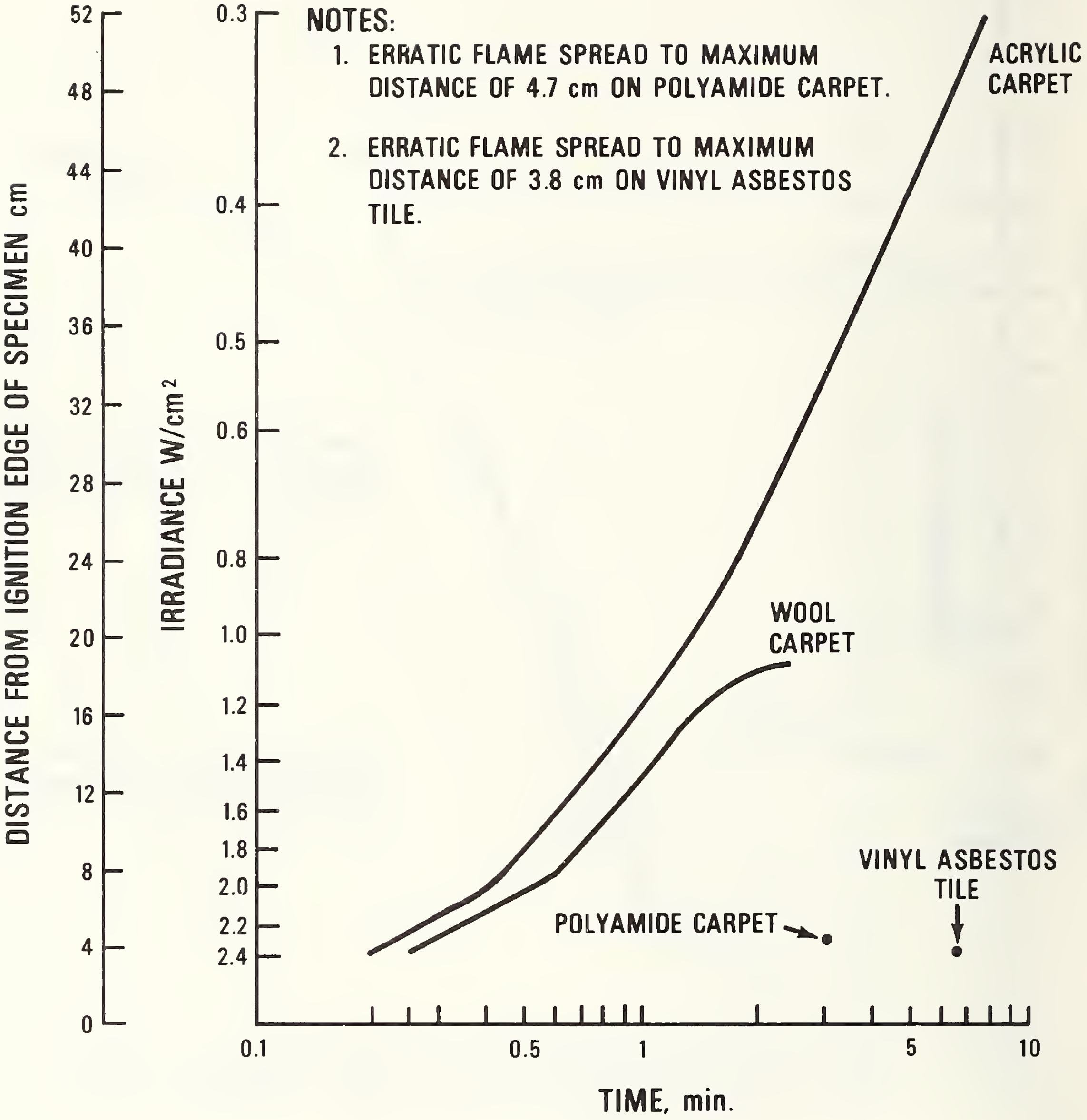

Figure 5. Flame spread along deck coverings with developmental flame spread test

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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.)*

A review of shipboard fire incidents in the Navy over the past six years was made to determine the spaces of greatest vulnerability to fire and the most common sources of ignition in these areas. Some of these compartment spaces are characterized with regard to their furnishing and interior finish materials. Their fire loads are specified. The various factors which determine the extent and rate of fire buildup in a compartment are discussed in terms of a simplified prediction model. Although substantial progress has been made in developing a prediction model for room fire development, a satisfactory treatment of flame spread on combustible interior finish materials along with a better understanding of the effect of the fire environment on fire buildup are needed. Meanwhile, criteria for choosing fire safe materials must continue to rely on existing laboratory fire tests. The application of laboratory fire tests on ignition, flame spread, and heat release rate to control the use of interior finish materials aboard ship is explored. Test data on ignition, flame spread, and heat release rate of typical shipboard materials are provided.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Fire growth; fire statistics; flame spread; fuel load survey; heat release; interior finish; laboratory fire tests; material ignitability; prediction model; shipboard spaces.

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