NBSIR 76-1012

Fire Performance Testing of Bulkhead Insulation Systems for High Strength to Weight Ship Structures

B. T. Lee

Center for Fire Research
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

Final Report

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Ship Damage Prevention and Control
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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*

Edward O. Vetter, *Under Secretary*

Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

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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

Volume

1 ft^3 = 0.0283 m^3

Mass

1 lb = 0.4536 kilogram

Density

1 pcf (lb/ft^3) = 0.0160 g/cm^3

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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B. T. Lee

Abstract

Sixteen insulated aluminum bulkhead specimens were subjected to a material screening process as well as evaluated for their comparative fire performance with a 2-foot horizontal slab furnace. Two insulated and two unprotected glass-reinforced plastic specimens were also tested to obtain fire performance data on these structural materials. In addition, painted aluminum and steel panel specimens were included to determine the fire protective merits of two types of intumescent paints. Potential heat release, smoke, and combustion gas generation were also determined for the insulation and coating materials. Specimens insulated with organic base foams released high levels of combustion gases and could contribute considerable heat to an on-going fire. Specimens insulated with either refractory fibrous material or with mineral wool gave the best overall performance. The same thickness of insulation needed to protect an aluminum panel for over an hour can provide up to 20 minutes of protection for a glass-reinforced plastic panel of the same thickness. The intumescent paints did little to protect the specimens during the fire exposure. Parameters of insulation thickness, heat capacity, density, and thermal conductivity as well as fire duration on specimen temperature were analytically investigated.

Key words: Aluminum bulkhead; combustion gases; fire endurance; insulation; intumescent paint; potential heat; reinforced plastic; small furnace test; smoke.

1. INTRODUCTION

Fire at sea presents a serious threat to a ship and to the life safety of its crew. It is essential that fires are contained and that the structural integrity of naval vessel bulkheads are maintained for a sufficient time period to permit operation of automatic suppression systems or effective manual firefighting. This is accomplished through the use of fire-resistive materials and design and is referred to as passive fire protection. This need is especially critical when aluminum ship bulkheads are to be protected due to their greater fire-susceptibility compared to steel. Depending on the exposure conditions aluminum and its alloys lose one-third to over one-half of their yield strength at temperatures above 232 °C (450 °F) [1][1] as opposed to about 538 °C (1000 °F) for steel and do not regain their full strength upon cooling. A temperature in the range of 232 °C (450 °F) therefore, would represent the limiting temperature to ensure a yield strength at least equal to the design allowable stress during a fire test exposure of an aluminum bulkhead.

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

The superstructure of many Naval ships is mostly all constructed of aluminum, and aluminum is being considered for the construction of entire hulls of some high speed high performance craft to save weight, and materials for fire protection of such vessels must of necessity also be lightweight. At the same time, protected aluminum structures must still be cost competitive with a steel design. Since many lightweight insulating materials have combustible components, care must be taken to ensure that the crew will not be subjected to high levels of smoke and toxic combustion products from the burning insulation, in the event of fire.

An alternate bulkhead material with desirable properties for shipboard use is glass-reinforced plastic (GRP) and similar considerations apply.

Thus, the combined considerations of cost, weight, and fire performance including the generation of smoke and combustion gases are all crucial for optimizing the value of passive fire protection for high strength to weight ship structures. Unfortunately, the choice of materials known to be suitable for the adequate protection of aluminum is very limited. A state-of-the-art study [2] documented all known research and testing programs relative to passive fire protection of aluminum structures. It found that little work was done in this area outside of the SNAME (Society of Naval Architects and Marine Engineers) program [3], which indicated that 3 inches of mineral wool or 3/4 inch of 36 pcf asbestos board will protect the aluminum for a one-hour fire exposure. The state-of-the-art study [2] did, however, focus on some lightweight materials being considered or used by the aerospace industry. From the survey, polyisocyanurate and polyimide foams and a refractory fibrous material appeared to be likely candidates for protecting aluminum in ships.

In order to evaluate the fire performance of these materials the Navy initated a screening program described in this report. Mineral wool and fibrous glass hull board were also included in the study for comparative purposes. Sixteen insulated aluminum panels were subjected to a 60-minute fire exposure following the ASTM E-119 time-temperature curve. This standard curve was based on temperatures found in the various stages of growth of actual fires in buildings [4] and represents a widely accepted fire exposure for evaluating the fire performance of materials and construction in terms of the time period during which the construction serves as an effective fire barrier. In addition, the fire performance of two insulated and two unprotected GRP specimens and the effect of two types of intumescent paints on four steel and aluminum panels were investigated. Also included as part of this evaluation were laboratory determinations of the potential heat and smoke and combustion gas generation of the insulation and coating materials.

Along with the experimental results presented in this report, a brief analysis, given in appendix A, has been prepared on the specimen substrate temperatures as affected by the parameters of thickness, heat capacity, density, and thermal conductivity of the insulation, and fire exposure time.

2. EXPERIMENTAL AND TEST PROCEDURES

Twenty-four bulkhead specimens were fabricated by the Wayne Manufacturing Corporation in Waynesboro, Virginia, under the supervision of Gibbs and Cox, Inc. for testing at NBS. The composite specimens consisted of selected combinations of base insulating materials, covering laminates, cloth facings and coatings on 1/4-in bulkhead panels. The base insulating materials included conventional fiber glass and mineral wool, refractory fiber felt and blanket, and polyimide and polyisocyanurate foams of different densities and thicknesses. The laminate coverings were mineral wool and refractory fiber felt. The facing materials were glass cloth and a fiber blend of phenol-formaldehyde resin and polyamide. Coatings were two kinds of intumescent paints. Twenty of the bulkhead panels were of 1/4-in aluminum alloy 5086-H32. The remaining four panels were of 1/4-in GRP. Two of the latter specimens were made in conformance with military specification MIL-P-17549C, grade 3 with DION FR6692 fire retardant resin. The other two were similar except for the addition of alumina trihydrate and antimony trioxide fillers. All twenty-four of the plate panels were 30 x 30 inch in size. The insulation systems mounted on these panels were cut 28-1/2 x 28-1/2 in. This permitted an overlap of 3-1/4 in along the entire periphery of the 22 x 22-in furnace opening. In addition, a 3/4-in asbestos board frame was fabricated and installed around the outside edge of the insulation to prevent the escape of furnace heat around the sides of the insulation. Specimen mounting on the furnace is shown on figure 1. Specimen construction details are shown on figure 2. Detailed descriptions of these test samples are presented in table 1. In the evaluation of the fire performance of these bulkhead panels, consideration was given to the fire endurance capability, and to the heat release, smoke, and combustion gas generation potentials of the materials when involved in compartment type fires.

2.1. Fire Endurance

Preferably, fire endurance tests with an E-119 type fire exposure should be conducted on full size bulkhead specimens. However, these tests are expensive and time consuming. Reduced-scale tests, e.g., with a small slab furnace, are relatively inexpensive, easy to run and are ideal for screening purposes. The NBS slab furnace, figure 1, takes 30 x 30-in specimens with a fire-exposed area of approximately 22 inches square. Where assemblies do not experience excessive lateral heat transfer and are uncomplicated by air spacing, the slab furnace test can generally simulate full size test behavior. For example, slab furnace fire endurance data for unprotected wood floor constructions compared reasonably well with their corresponding full size deck test results [5]. However, for bulkhead constructions consisting of a very good thermal conductor such as steel plating [6] and for sandwich type construction with an air spacing [7], slab furnace testing gave considerably lower unexposed panel temperatures than their counterpart large-scale tests.

In spite of these deficiencies with slab furnace testing, it can be used effectively to screen out less promising candidate materials among specimens having similar construction. All of the aluminum bulkhead configurations submitted for evaluation have similar construction, i.e., 1/4-in aluminum alloy 5086-H32 insulated on the fire side. In the slab furnace tests of these assemblies, the specimen was positioned horizontally over the furnace opening as is shown on figure 2. As the specimen extends 4 inches beyond the furnace opening along the entire periphery, considerable lateral heat dissipation could occur beyond the exposed area.

The effect of the lateral heat transmission in the samples can be experimentally ascertained, and test results can easily be modified to give approximate full-scale bulkhead fire test behavior. Preliminary slab furnace experiments were conducted to assess the effect of lateral heat transfer in the 30-in samples and to determine whether heat transmission through the 3/16-in fastener pins, attaching the insulation to the plate, had an effect upon the temperature of the unexposed surface. Two 30 x 30-in specimens consisting of two-in thick mineral wool applied to a 1/4-in aluminum plate of the same area were tested with the insulation fire exposed. Two additional specimens, similar to the above two, except using a 24 x 24-in aluminum plate, were also tested under the same conditions to measure temperatures that are relatively unaffected by lateral heat dissipation beyond the exposed area. All four of the above test specimens used fine nichrome wires for attachment of the insulation. A fifth sample, similar to the first two, but having a 3/16-in diameter fastener pin in addition to the nichrome wires, was also tested.

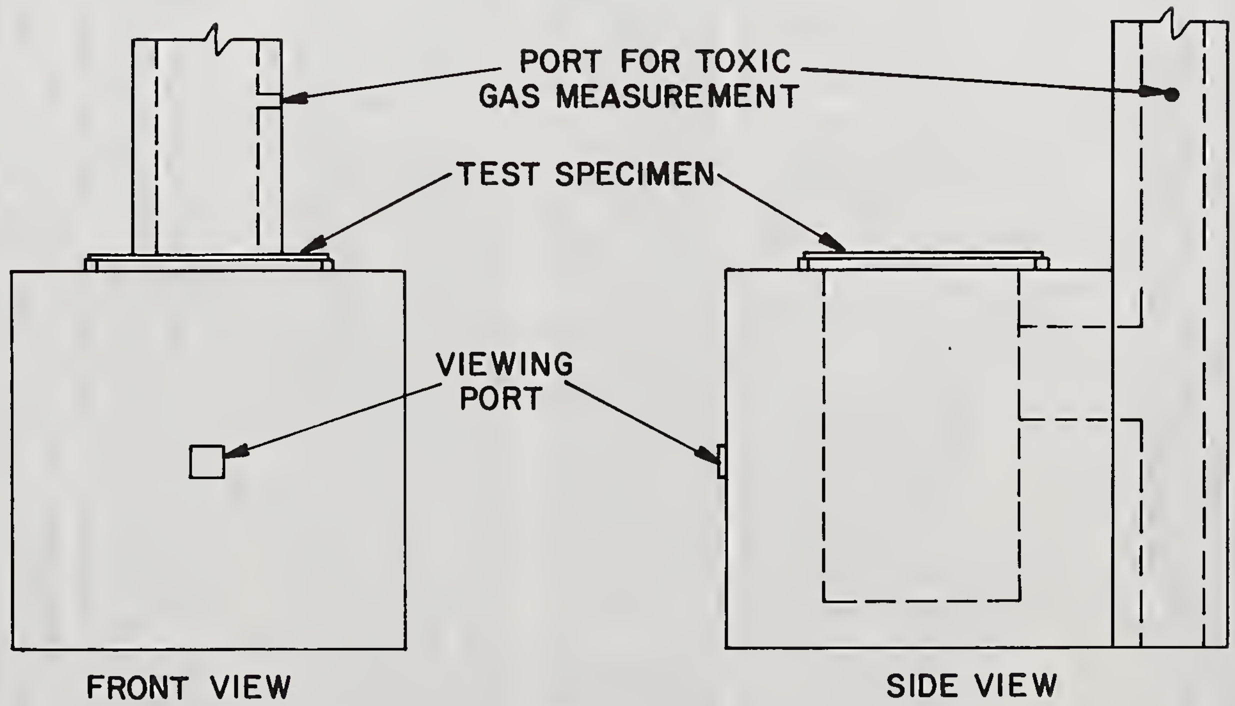


Figure 1. Test Furnace

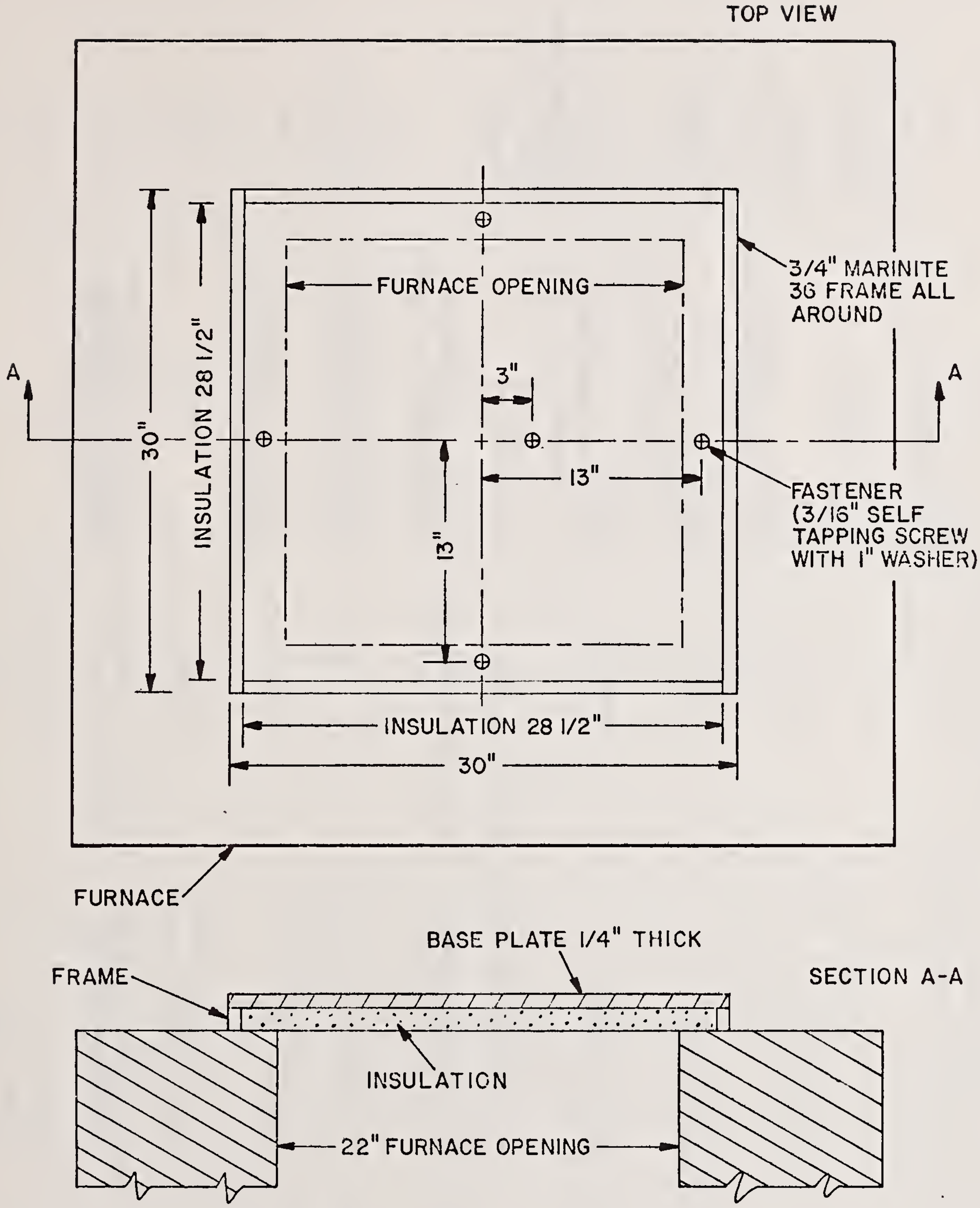


Figure 2. Panel Detail and Relationship to Furnace

Table 1. Description of Specimens

Test & Panel No.	Base Plate	Base Insulating Material	Laminate Over Base Insulation	Facing	Coating	Estimated lb/ft^2†
1	1/4" Aluminum Alloy 5086-H32	3"-6 lb/ft^3 Mineral Wool*	None	0.015" Fibrous Glass Cloth***	None	1.15
2	1/4" Aluminum Alloy 5086-H32	3"-6 lb/ft^3 Mineral Wool*	None	0.015" Fibrous Glass Cloth***	None	1.15
3	1/4" Aluminum Alloy 5086-H32	1-3/4"-6 lb/ft^3 Refractory Fiber Felt	None	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend ††	None	1.06
4	1/4" Aluminum Alloy 5086-H32	1-3/4"-4 lb/ft^3 Refractory Fiber Felt	None	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	0.82
5	1/4" Aluminum Alloy 5086-H32	1-3/4"-4 lb/ft^3 Refractory Fiber Felt	None	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	Intumescent Paint A, 0.020" Thick	0.90
6	1/4" Aluminum Alloy 5086-H32	1"-3 lb/ft^3 Fibrous Glass Navy Hull Board MIL-I-742C	1-3/4"-4 lb/ft^3 Refractory Fiber Felt	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	1.04
7	1/4" Aluminum Alloy 5086-H32	2"-6 lb/ft^3 Refractory Fiber Blanket	None	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	1.10
8	1/4" Aluminum Alloy 5086-H32	2"-4 lb/ft^3 Refractory Fiber Blanket	None	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	0.95
9	1/4" Aluminum Alloy 5086-H32	2"-2.5 lb/ft^3 Preformed Polyisocyanurate Foam	None	None	None	0.49
10	1/4" Aluminum Alloy 5086-H32	2"-2.5 lb/ft^3 Preformed Polyisocyanurate Foam	1/2"-4 lb/ft^3 Refractory Fiber Felt	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	0.76
11	1/4" Aluminum Alloy 5086-H32	1-3/4"-4 lb/ft^3 Preformed Polyimide Foam	None	None	None	0.58
12	1/4" Aluminum Alloy 5086-H32	1-3/4"-4 lb/ft^3 Preformed Polyimide Foam	1/2"-4 lb/ft^3 Refractory Fiber Felt	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	0.85

13	1/4" Glass Reinforced Plastic (without filter)**	1-3/4"-4 lb/ft^3 Refractory Fiber Felt	None	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	0.82
14	1/4" Glass Reinforced Plastic (without filter)**	None	None	None	None	0.
15	1/4" Glass Reinforced Plastic (with filler)**	1-3/4"-4 lb/ft^3 Refractory Fiber Felt	None	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	None	0.82
16	1/4" Glass Reinforced Plastic (with filler)**	None	None	None	None	0.
17	1/4" Aluminum Alloy 5086-H32	2"-3.7 lb/ft^3 Preformed Polyisocyanurate Foam	None	None	None	0.62
18	1/4" Aluminum Alloy 5086-H32	2"-3.7 lb/ft^3 Preformed Polyisocyanurate Foam	1"-6 lb/ft^3 Mineral Wool*	0.015" 70% Phenol Formaldehyde 30% Polyamide Fiber Blend	Intumescent Coating A,0.020" Thick	1.12
19	1/4" Aluminum Alloy 5086-H32	3"-3 lb/ft^3 Fibrous Glass Navy Hull Board MIL-I-742C	None	0.015" Fibrous Glass Cloth***	None	0.70
20	1/4" Aluminum Alloy 5086-H32	3"-3 lb/ft^3 Fibrous Glass Navy Hull Board MIL-I-742C	None	0.015" Fibrous Glass Cloth***	Intumescent Coating A,0.020" Thick	0.78
21	1/4" Aluminum Alloy 5086-H32	None	None	None	Intumescent Coating A,0.020" Thick	0.08
22	1/4" Aluminum Alloy 5086-H32	None	None	None	Intumescent Coating V,0.020" Thick	0.08
23	1/4" Steel	None	None	None	Intumescent Coating A,0.020" Thick	0.08
24	1/4" Steel	None	None	None	Intumescent Coating V,0.020" Thick	0.08

*Two equal size pieces with facing, each covering one-half of plate. Mineral wool complying with USCG 164.007

**Panels 13 and 14 conform with MIL-P-17549C, Grade 3, DION FR 6692 fire retardant resin.
Panels 15 and 16 are the same except for addition of Alumina Trihydrate and Antimony Trioxide fillers.

***Glass cloth conforming with MIL-I-742C

†Estimated weights per unit surface area based on actual weights shown on table 3. Weights do not include the aluminum, plastic or steel base plates.

††Percentages by material weight.

In each of these preliminary tests and for each of the twenty-four bulkhead panels, the temperature of the unexposed surface was determined by five thermocouples constructed in the same manner as those used in the full-scale fire endurance tests of bulkhead panels [8]. As indicated on figure 3 these were located at the center of the specimen and at the center of each quadrant. In addition, thermocouples were embedded midway through the insulation and between the different material layers of a composite specimen.

The average furnace temperature, as determined from four rapid response mineral insulated thermocouples, was made to follow the ASTM E-119 time-temperature curve. The points on the curve that determine its character are:

538 °C (1000 °F) at 5 minutes

704 °C (1300 °F) at 10 minutes

843 °C (1550 °F) at 30 minutes

927 °C (1700 °F) at 1 hour

1010 °C (1850 °F) at 2 hours

During each test, the combustion products in the furnace exhaust were examined for the presence and approximate concentrations of hydrogen cyanide, HCN, hydrogen fluoride, HF, hydrogen chloride, HCl, and the oxides of nitrogen, NO and NO_2, using commercial colorimetric detector tubes. Carbon monoxide, CO, and carbon dioxide, CO_2, were continuously monitored with infrared analyzers. The furnace test had no provision for measuring the smoke emission from the burning specimens.

2.2. Smoke Density Chamber

The relative amount of smoke produced during the burning of test specimens was measured photometrically in the smoke density chamber [9]. The test utilizes a closed chamber of 18 ft^3 volume containing an electrically heated furnace which provides an irradiance of 2.2 $Btu/s/ft^2$ on the surface of a 3-in square specimen. Smoke quantity is reported in terms of optical density, 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, 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. Thus, for a selected exposure in the test chamber, and within certain limitations, a single test permits rough extrapolation to other surface areas and chamber volumes.

Specimens are subjected to two modes of exposure conditions, namely flaming and non-flaming. Both conditions can be considered typical in a real fire situation. Under the non-flaming exposure mode, the specimen receives an average irradiance of 2.2 $Btu/s/ft^2$ on its exposed surface to cause pyrolysis and emission of smoke. Under the flaming mode, in addition to the same surface irradiance, the specimen is subjected to pilot flames consisting of six small (0.37 in length) premixed air-propane flamelets impinging on the base of the specimen.

Wherever CO, HCN, HF, HCl, and the oxides of nitrogen were found in the exhaust from the slab furnace tests, colorimetric indications of the concentrations of these gases were sought in the smoke density chamber. In addition, the presence of SO_2 was investigated for samples having intumescent paint coatings.

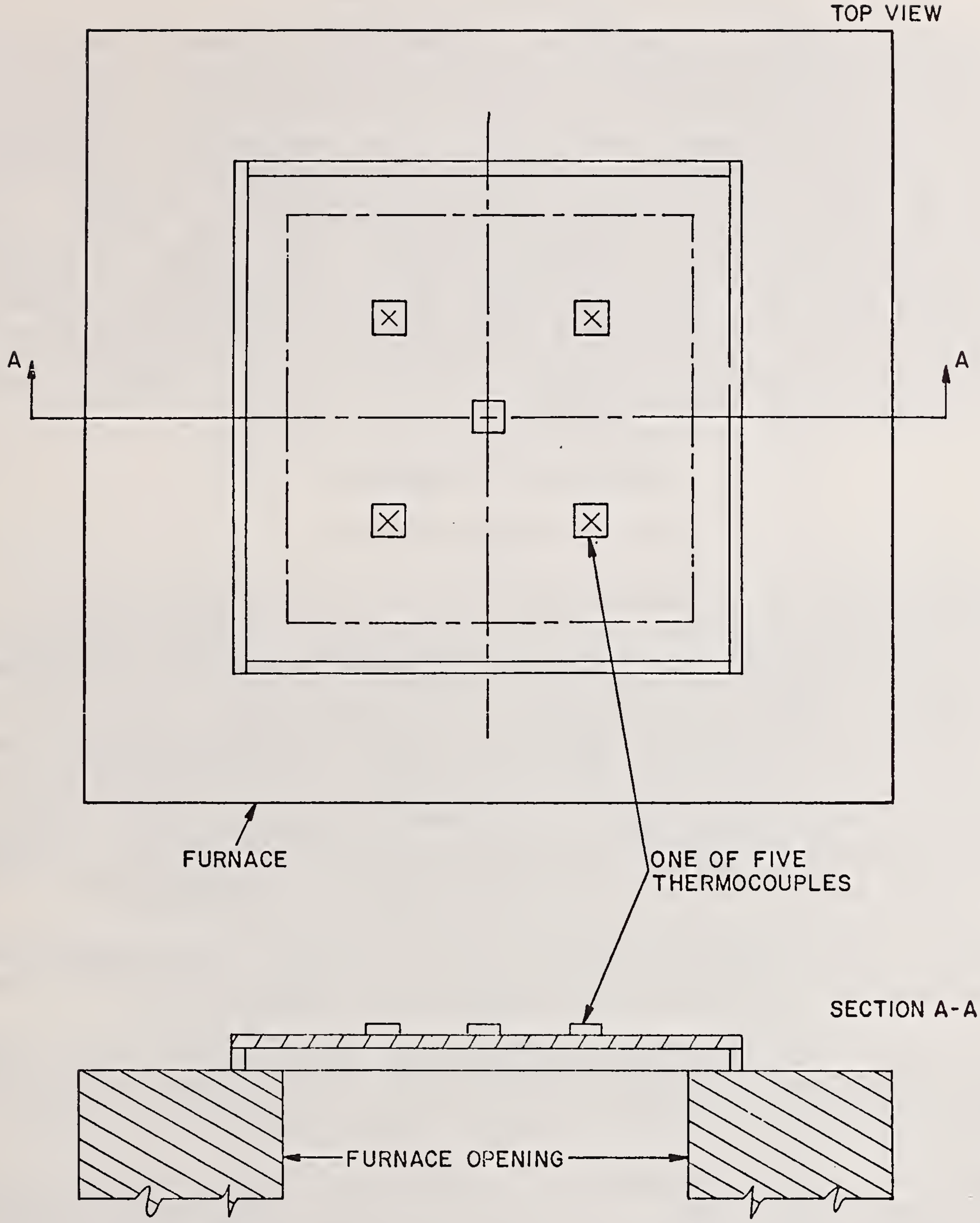


Figure 3. Thermocouple Locations on Unexposed Surface

2.3. Potential Heat Release

All of the insulation, facing and coating materials used in the program were measured for their potential heat release [10]. Potential heat of a material is the difference between the heat of combustion of a representative sample of the material and the heat of combustion of any residue remaining after exposure to a simulated standard fire, using combustion calorimetric techniques. One of two samples removed from the material to be tested is pulverized, pelleted, and burned in a high-pressure oxygen atmosphere. This determines the gross heat of combustion of the material. The second specimen is heated in air for 2 hours at a temperature of 750 °C (1382 °F), conditions adopted as representing a standard fire exposure. A portion of the resulting residue of this specimen, if any, corresponding to a predetermined weight of original material, is ground or pulverized, mixed with a combustion promoter, and pelleted for burning as was the first specimen. After correcting for the heat produced by the combustion promoter, the difference in heating values of the two specimens is the potential heat.

3. RESULTS AND DISCUSSION

3.1. Fire Endurance Testing

Preliminary tests to evaluate the effect of lateral heat conduction indicated that full size bulkhead fire tests could give temperatures roughly 19% higher than those shown on table 2. This is based on the temperature differences noted when testing over 24-inch versus 30-inch square aluminum plates. An average temperature of 161 °C (322 °F) was found for the two 30 x 30-inch specimens after a fire exposure time of 60 minutes. The two 24 x 24-inch panels, tested under the same furnace conditions and exposure time, reached an average temperature of 192 °C (376 °F). The latter panels were considered to be relatively unaffected by lateral heat conduction to the aluminum beyond the exposed area, and thus represented more nearly the one-dimensional heat flow conditions in a full-size bulkhead fire test. Another preliminary test showed that heat conduction through 3/16-inch steel fastener pins had negligible effects on the aluminum substrate temperatures.

Temperature data and combustion gas concentrations for the twenty-four specimens described in table 1 are presented on tables B-1 to B-24 in appendix B. Observations on each specimen test are found in appendix C.

Table 2 gives a brief summary of the average temperatures on the unexposed side of the aluminum, GRP and steel panels. In addition, table 2 includes the maximum recorded percentages by volume in air of CO and CO_2 and parts-per-million concentrations of HCN, NO and NO_2, HCl and HF.

Temperatures on the unexposed side of specimens 1 and 2, which were insulated with 3-inch thick mineral wool, were well within the limiting temperature of 232 °C (450 °F). These two tests also substantiated the preliminary finding that the fastener pin did not provide a significant heat transfer path to the base panel. Specimen 1 had a metal fastener, yet its plate temperature was lower than that for the second specimen without the fastener. Photographs of specimen 1, before and following testing, are shown in figure 4. With samples having 1-3/4-inch and 2-inch thick refractory fibrous material as the base insulation, i.e., tests 3, 4, 5, 7 and 8 on table 2, or as a laminate over the base insulation, test 6, the thermal protection was as good as or better than with the mineral wool. Figure 5 shows the condition of the refractory insulation in specimen 3 before and after furnace exposure. The pictures are typical of specimens having the refractory material as the surface insulation. Heat retention capability, i.e., the product of the material weight per unit surface area and its heat capacity, for the 6 pcf mineral wool is greater than that for the 6 pcf refractory felt. The thermal conductance of the

Table 2. Summary of Furnace Test Results†

Sample	Insulation Material*	Avg. Plate Temp. At 15 min (°C)	Avg. Plate Temp. At 60 min (°C)	Time when Plate Temp. Reaches 232 °C min	Max. CO (%)	Max. CO_2 (%)	Max.†† HCN ppm	Max.†† NO & NO_2 ppm	Max. HCL ppm	Max. HF ppm
1	3" 6 pcf mineral wool, glass cloth facing	43	162	>60	0.37	12.	0	20.	0	0
2	3" 6 pcf mineral wool, glass cloth facing	47	178	>60	0.61	---	0	20.	0	0
3	1 3/4" 6 pcf refractory fiber felt, fiber blend cloth facing	56	160	>60	0.17	11.	5.	19.	0	0
4	1 3/4" 4 pcf refractory fiber felt, fiber blend cloth facing	67	183	>60	0.15	11.	4	>9.	0	0
5	1 3/4" 4 pcf refractory fiber felt, fiher blend cloth facing, paint A	54	165	>60	0.23	10.	>30.	>9.	0	0
6	1" 3 pcf fibrous glass, 1 3/4" 4 pcf refractory fiber felt, fiber blend cloth facing	44	141	>60	0.56	11.	14.	20.	0	-
7	2" 6 pcf refractory fiber blanket, fiber blend cloth facing	55	146	>60	0.46	---	13	>9.	0	0
8	2" 4 pcf refractory fiher hlanket, fiber blend cloth facing	48	123	>60	0.64	15.	4	7.	0	0
9	2" 2 1/2 pcf polyisocyanurate	66	---	---	0.40	8.	>35.	10.	0	2.
10	2" 2 1/2 pcf polyisocyanurate, 1/2" 4 pcf refractory fiber felt, fiber blend cloth facing	37	145	>60	0.56	10.	75.	20.	0	8.
11	1 3/4" 4 pcf polyimide	52	---	39	0.41	11.	3	30.	0	0
12	1 3/4" 4 pcf polyimide, 1/2" 4 pcf refractory fiber felt, fiber blend cloth facing	42	159	>60	0.44	12.	38	28.	0	0
13**	1 3/4" 4 pcf refractory fiber felt, fiber blend cloth facing	62	185	---	0.69	11.	10.	15.	0	0
14**	none	226.	---	---	1.85	7.	1.	13.	0	-
15**	1 3/4" 4 pcf refractory fiber felt, fiher blend cloth facing	57	182	---	0.93	8.	17.	>10.	0	0
16**	none	217.	---	---	---	---	1.	6.	0	-
17	2" 3.7 pcf polyisocyanurate	71	---	26	0.75	7.	100.	30.	0	38.
18	2" 3.7 pcf polyisocyanurate, 1" 6 pcf mineral wool, fiber blend cloth facing, paint A	44	159	>60	0.71	9.	25.	25.	0	4.
19	3" 3 pcf fibrous glass, glass cloth facing	60	---	37	---	---	8.	25.	0	0
20	3" 3 pcf fibrous glass, glass cloth facing, paint A	59	---	35	0.35	2.	40.	25.	0	3.
21	Paint A	277	---	9	0.75	9.	25.	13.	0	-
22	Paint V	296	---	6	0.67	9.	50.	25.	0	-
23***	Paint A	248	---	12	---	---	---	---	---	-
24***	Paint V	286	---	8	---	---	---	---	---	-

*Refer to table 1 for complete description of samples
**Panel is 1/4 in thick fiberglass reinforced plastic
***Panel is 1/4 in thick steel

†Gas concentrations were estimated with colorimetric indicator tubes. This detection technique gives only an approximation and is affected by elevated temperatures and moisture in the sampling line. HCl analysis has the added disadvantage in that indication of the gas can be upset by the presence of the oxides of nitrogen. When the concentration of NO and NO_2 is higher than that for HCl, there may be no indication of HCl using this method.

††Whenever gas concentration levels exceeded the upper limit of the colorimetric detector tube used, the data is indicated as being greater than the limiting value.

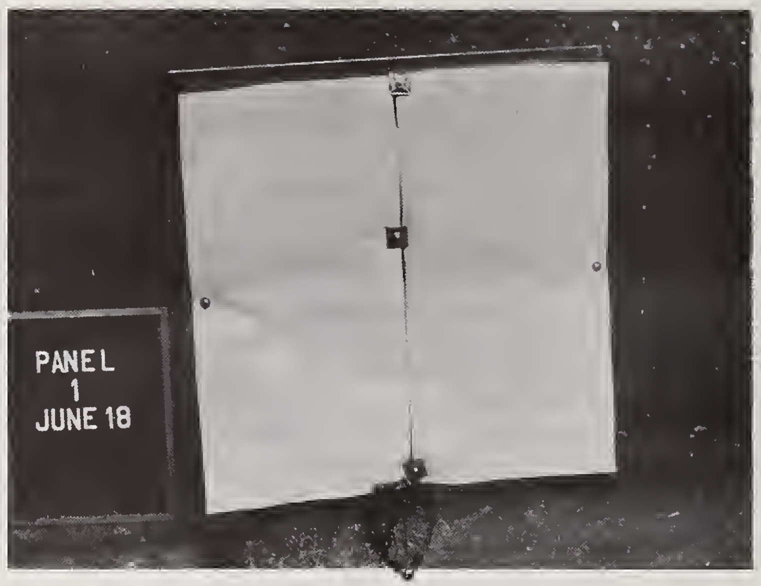


Figure 4. Specimen 1 — Before and After Fire Exposure

Figure 5. Specimen 3 — Before and After Fire Exposure

former is lower than that for the refractory material. Thus, the mineral wool would be expected to yield lower substrate temperatures. However, the data in table 2 showed that the 3-inch mineral wool gave fire resistance only comparable to the 1-3/4-inch refractory insulation. A possible explanation for this unexpected performance of the mineral wool sample is that the seam in the mineral wool specimen, shown on figure 4, may have opened during the test, partially exposing the substrate to the fire.

As expected, tests 3, 4, 6 and 7 indicated that the substrate temperature decreased as the density and thickness of the insulation increased. However, since there can be considerable variation in the experimental results for several furnace tests of the same material, e.g., ± 20 °C (36 °F) at a temperature of 200 °C (392 °F), it should not be surprising to observe a contrary effect of increasing density for tests 7 and 8.

In test 5, it is likely that the apparent increase in fire protection from the intumescent paint is partly due to experimental variation. The intumescence on the sample surface helped retard the heat conduction for only about 10 minutes, at which time the covering split and was hanging down, exposing the insulation. This latter behavior was typical for the phenol formaldehyde-polyamide cloth facing used for many of the specimens.

Test 11 with the 4 pcf polyimide insulation and test 17 with the 3.7 pcf polyisocyanurate material reached the limiting temperature of 232 °C (450 °F) at 39 and 26 minutes, respectively. These foam insulations tended to shrink and crack upon exposure to the furnace fire. Post-fire analysis showed that the shrinkage in these materials left one- to two- inch wide cracks, exposing the substrate. Test 9 with the 2-1/2 pcf polyisocyanurate was stopped after 16 minutes because of the high smoke and combustion gas concentrations in the test area. It was decided that in subsequent tests, personnel would leave the room rather than prematurely terminating the test whenever smoke and combustion product gas levels were considered unsafe. From the results in table 2, the polyimide foam in test 11 gave 50% longer protection than the polyisocyanurate in test 17. Little difference in plate temperature was observed for the two different density polyisocyanurate foams. When 1/2-inch thick refractory fiber felt or 1-inch mineral wool was laminated over the polyimide and polyisocyanurate foams, tests 10, 12 and 18, considerable shrinkage and cracking still occurred in the foam materials. However, the overlay acted as a barrier to the furnace flames and helped achieve acceptable plate temperatures. The condition of the fire exposed and base insulations for specimens 10 and 12 are shown on figures 6 and 7. The shrinkage and cracking indicated on the latter figures are typical of the post-fire foam insulations in tests 9, 10, 11, 12, 17 and 18.

Three-inch fibrous glass insulation, tests 19 and 20, gave thermal protection comparable to that of 1-3/4-inch refractory insulation for the first 20 minutes. However, fusing of the fibers and sagging of the insulation had started by that time. Melting and opening of the insulation occurred after 30 minutes. Complete exposure and attainment of the limiting temperature of 232 °C (450 °F) occurred within 37 and 35 minutes for tests 19 and 20, respectively. Figure 8 shows the condition of the fibrous glass before and following the fire exposure.

When the substrate material is fibrous glass reinforced plastic (GRP) instead of aluminum, tests 13 and 15, the structural failure temperature of the panel is dependent on the type of resin and fire retardant fillers used. In general the temperature range in which GRP begins to lose its strength is between 65 and 93 °C (150 and 200 °F) [11]. The results of tests 13 and 15 indicated that 1-3/4 inches of refractory fiber material protected the plastic panels from attaining these temperatures for as long as 20 minutes. The unprotected plastic panels, specimens 14 and 16, quickly reached the above temperature range within 2 minutes.

Figure 6. Specimen 10 — Top and Base Insulations Following Fire Exposure

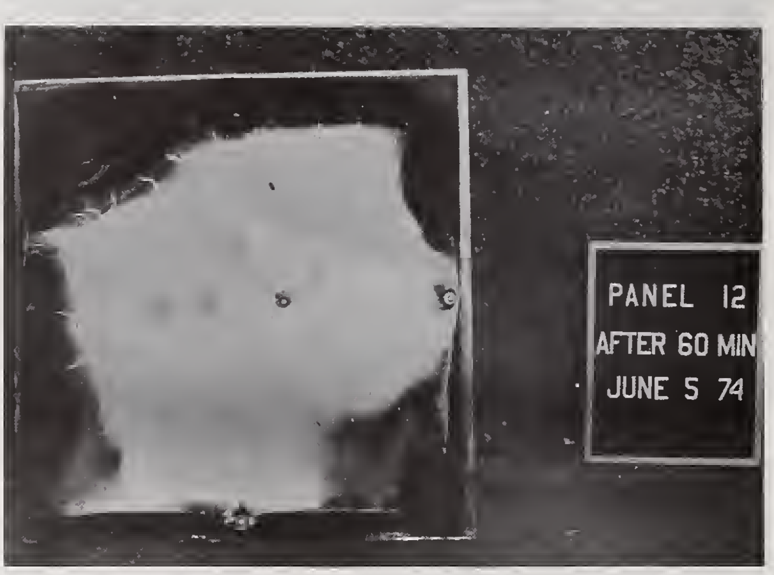
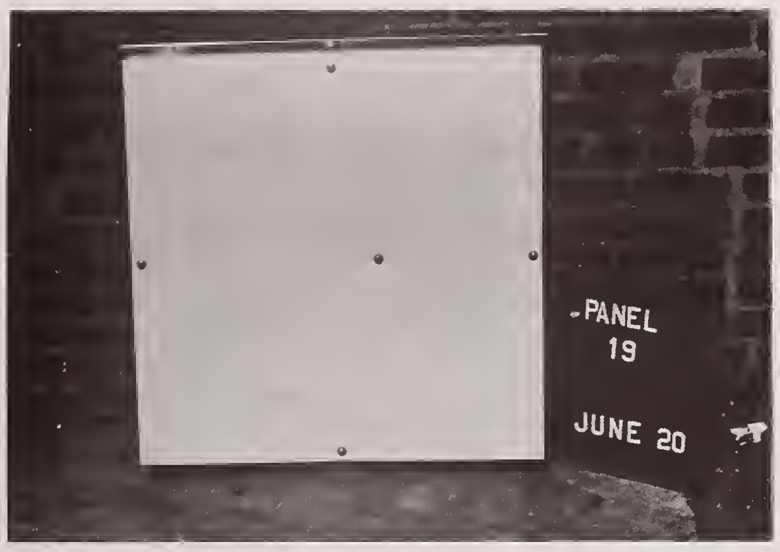


Figure 7. Specimen 12 — Top and Base Insulations Following Fire Exposure



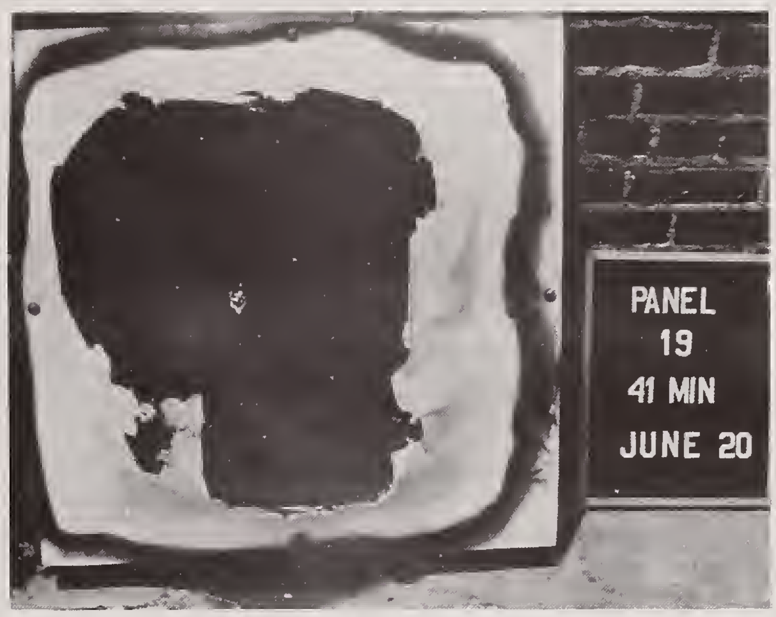


Figure 8. Specimen 19 — Before and After Fire Exposure

In the aluminum panels protected with the intumescent coatings, samples 21 and 22, it took only 9 and 6 minutes, respectively, for the panels to reach 232 °C (450 °F). These times should not imply equivalent thermal protection times for the paints. Heat must be slowly stored in the metal substrates before attainment of that temperature level, and the storage periods alone would approach the above times. Steel panels, specimens 23 and 24, protected with the same paints approached their limiting value of 538 °C (1000 °F) only after an hour's exposure in the furnace. The temperature of the steel panel is somewhat lower than that for the aluminum plate at comparable times because the heat storage, i.e., the product of heat capacity and density, is greater for steel of the same thickness.

Specimens 1 to 20 also had thermocouples embedded within the insulation, as requested by the sponsor, to ascertain the temperature gradient through the material and to detect either excessive heat generation or mass transfer cooling from the out-gassing of volatiles. However, the temperature data from these thermocouples were not always consistent. The erratic temperature behavior measured within many of the specimen insulations made it difficult to determine reliable thermal gradients for any of the specimens tested. One possible explanation was that the semi-rigid thermocouples were sometimes inadvertently moved when the samples were positioned over the furnace.

Neither heat generation nor mass transfer cooling was obvious from the specimen tests with the exception of panel 18, which had mineral wool laminated over a high density polyisocyanurate foam. In this latter test the thermocouples at mid-depth through the foam and between the two insulation layers both registered temperatures higher than the average temperature in the furnace after 60 minutes of fire exposure.

Inspection of the combustion gas concentrations shown in table 2 for the twenty-four tests showed that the mineral wool, refractory fibrous material and fibrous glass insulations generated relatively low levels of HCN and oxides of nitrogen when exposed to the furnace flames. The intumescent paints generated higher concentrations of HCN, and the polyisocyanurate foams produced the highest levels of HCN and HF in the tests. Concentrations of these two gases were especially high for the 3.7 pcf polyisocyanurate foam, run 17. The only other sample for which HF was detected was the fibrous glass with paint V. Combustion of the polyimide insulation also produced measurable indications of HCN. Small concentrations of nitrogen oxides are normally produced during furnace combustion and their levels can vary from one run to another. None of the specimens produced particularly high levels of NO and NO_2. Furthermore, none of the specimens generated measurable quantities of HCl using the colorimetric indicator tube technique. The presence of the oxides of nitrogen could completely suppress any indication of HCl with this method when HCl occurs in concentrations equal to or less than those for NO and NO_2. In table 2 a value of zero was assigned to any non-measurable concentration of the combustion products analyzed. As for the production of carbon monoxide, the furnace test of the fiberglass reinforced plastic panel, specimen 14, resulted in the highest concentrations of this combustion gas. Like the nitrogen oxides, CO and CO_2 are naturally occurring products of furnace combustion and unless measured levels are considerably greater than in most of the tests, they are not very meaningful.

3.2. Other Laboratory Fire Tests

All of the base insulations, laminates, coverings and coatings shown on table 1 were evaluated with the smoke density chamber (SDC) and potential heat tests. Colorimetric indications for fume emissions were also included as part of some of the SDC tests with the flaming mode of radiant exposure. Whenever relatively high levels of the gases CO, HCN, NO and NO_2, HCl and HF were found in the exhaust from the slab furnace test of a specimen, the concentrations of those gases were also measured in the SDC tests on the component materials of the specimen. For comparative purposes the refractory fibrous material which produced little combustion fumes from the furnace test was also included. In addition, the presence of SO_2 was also sought in the SDC test of the intumescent paint A. Table 3 summarizes the results from the SDC tests.

Each of the specimen component materials was also subjected to a potential heat analysis. The potential heat of a material is the maximum heat that can be released to the environment during the materials exposure to a typical fire. This data is also presented in table 3.

3.2.1. Measurement of Combustion Products

The relative quantity of smoke produced, as indicated by the maximum specific optical density, for the bulkhead insulations and coverings is shown on table 3. These values varied from almost zero for the refractory fibers and fibrous glass insulations to a high of 180 for the 3.7 pcf polyisocyanurate evaluated under the flaming mode of radiant exposure. A distant second to the polyisocyanurate foam was the intumescent coating A. Close behind was the phenol formaldehyde-polyamide fabric. Non-flaming exposure in the SDC test also resulted in a similar ranking of the polyisocyanurate and the intumescent paint materials. However negligible smoke from the fabric material was generated under this type of exposure. The remaining materials listed on table 3 produced little or no smoke in the SDC tests.

The gas measurements from the smoke density chamber tests were, in general, in agreement with some of the findings from the furnace tests. As in the latter tests, the refractory fibrous insulation produced little combustion products, and the highest concentrations of HCN were found for the polyimide and polyisocyanurate foams, followed by the phenol formaldehyde-polyamide fabric and the intumescent paint A. The polyisocyanurate material also generated a relatively high level of HF. A measureable quantity of the latter was also found for the paint.

As mentioned in section 3.1., small quantities of nitrogen oxides were generated by the furnace fire and these levels varied from test to test. Consequently, it was difficult to ascertain the relative concentrations of these gases from the burning materials. This may have accounted for the comparatively high NO and NO_2 production in the furnace test of a material, e.g., the 3.7 pcf polyisocyanurate, and a low NO and NO_2 level in the SDC test of the same material. The only case where somewhat high levels of NO and NO_2 was found in both laboratory tests involved the polyimide foam.

The range of CO levels in the slab furnace tests of the thermally protected aluminum panels was rather narrow, and it was felt that additional measurement of this gas in the SDC was not necessary.

A comparison of the SDC concentrations of SO_2 for the refractory fibrous material and the intumescent paint A showed that the level of SO_2 was only slightly higher for the paint.

3.2.2. Potential Heat Analysis

Table 3 shows that the potential heat values ranged from 55 to 6600 Btu/ft^2 for the insulations and coverings used for the bulkhead test specimens. A review of the data indicates that only the polyimide and polyisocyanurate foams had high values of potential heat per unit surface area. These values ranged from 5200 to 6600 Btu/ft^2 for the three foam insulations. Such high levels of potential heat release could add considerably to the fire risk of the overall furnished space.

Table 3. Results from Potential Heat and Smoke Density Chamber Tests

Material	Thickness		Density		Weight per Unit Area (lb/ft^2)	Potential Heat		Max Specific Optical Density (D_m)		Gas Concentrations Under Flaming Exposure** (ppm)			
	Nominal (in)	Actual (in)	Nominal (lb/ft^3)	Actual (lb/ft^3)		Btu/lb	Btu/ft^2	Flaming	Nonflaming	HCN	NO and NO_2	HF	SO_2
1. Mineral Wool with Glass Cloth	3	3	6	4.6	1.15	337	338	10	8	---	---	--	---
2. Refractory Fiber													
Felt	1-3/4	1-3/4	4	5.3	0.77	226	174	0	0	3	4	0	100
Felt	1-3/4	1-3/4	6	6.9	1.01	156*	158*	1	1	---	---	--	---
Blanket	2	2	4	5.4	0.90	167*	150*	1	1	---	---	--	---
Blanket	2	2	6	6.3	1.05	52	55	0	0	---	---	--	---
3. Fibrous Glass	3	3	3	2.6	0.65	398	259	1	0	---	1	--	---
4. Foams													
Polyimide	1-3/4	1-3/4	4	4	0.58	10496	6088	3	1	25	15	--	---
Polyisocyanurate	2	2-9/16	2.5	2.3	0.49	10549	5169	177	54	40	2	15	---
Polyisocyanurate	2	2	3.7	3.7	0.62	10636	6594	180	70	25	3	20	---
5. Phenol Formaldehyde-Polyamide Cloth	---	.02	---	---	0.05	12265	613	24	0	12	9	--	---
6. Intumescent Paint A	---	.02	---	---	0.08	7477	598	30	15	12	---	2	130

*Low levels of potential heat are difficult to measure accurately and deviations of ± 100 Btu/lb are not unusual.

**Flaming exposure was chosen because higher concentrations of combustion gases are generally found for non-cellulosic materials under this mode of exposure.

4. CONCLUSIONS

Most of the specimens experienced aluminum base temperatures within the limiting value of 232 °C (450 °F) during 60 minutes of fire exposure in the slab furnace. Candidate assemblies failing this criterion were panels having a single component insulation consisting of either polyisocyanurate foam or polyimide foam. The panels protected with fibrous glass or intumescent paint were included for comparative purposes; and these also did not meet the above temperature requirement. Addition of an overlay of refractory fiber felt or mineral wool to the foams and to the fibrous glass kept the aluminum panel temperature within the prescribed limit.

The polyisocyanurate and polyimide organic foams were found to shrink, crack and char, even when used as the base of a multicomponent insulation, so that their thermal protective properties are reduced. In addition, the foam materials have high values of potential heat, and thus, could contribute much heat to the fire environment. Furthermore, polyisocyanurate generated relatively high levels of HCN and HF as it pyrolyzed. Intumescent paints did little to protect the specimen, and contributed HCN as a combustion product.

The same thickness of insulation needed to protect an aluminum panel for over an hour can provide up to 20 minutes of protection for a GRP panel.

When insulation weight and the cost of installation are considered along with the fire performance of the material, three materials stand out among the possibilities evaluated. It can be concluded that either the 4 or 6 pcf refractory fibrous material or the 6 pcf mineral wool will afford the optimum passive fire protection for an aluminum bulkhead structure.

5. ACKNOWLEDGMENTS

Appreciation is expressed to Mr. F. Butler of Gibbs and Cox who assisted in taking test observations and to Mr. M. Womble and others who performed the actual testing.

This project was sponsored in part by the Naval Sea Systems Command, Department of the Navy, under the direction of Mr. A. Winer, technical agent for the Material and Application Office of Naval Ship Engineering Center.

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APPENDIX A. ANALYTICAL ANALYSIS OF HEAT CONDUCTION IN TEST SPECIMEN

The problem of heat flow through an insulated bulkhead panel exposed to an ASTM E-119 time-temperature environment can be very difficult to solve. It becomes a three dimensional composite flow problem requiring numerical, finite-difference solution techniques when there is significant lateral heat conduction in the panel. For materials which generate heat, intumesce, ablate, melt, shrink, disintegrate, etc., upon exposure to the fire, the variation of these physical alterations or chemical reactions with time and temperature must also be known. Even one dimensional computer solutions of difficult situations could readily exceed experimental determinations in cost and time without necessarily approaching the accuracy of the latter.

To arrive at a very quick and simple, but still useful, analytical solution for predicting the temperature of the aluminum substrate for some of the specimens, the following assumptions were made:

1. no chemical reaction in or physical alteration of the specimen

2. one dimensional heat conduction only, i.e., no lateral heat dissipation and no mass flow

3. no heat losses on the unexposed side of the specimen

4. no thermal resistance across the interface between the insulation and substrate

5. constant furnace temperature

6. exposed surface temperature is the same as the furnace temperature

7. no thermal gradient across the aluminum

8. constant averaged thermal properties

9. initial temperature of the aluminum substrate is at 20 °C (68 °F).

With the above simplifications the problem becomes one of heat transmission through an insulation in contact with a perfect conductor, and the solution to the heat conduction equation can be expressed in the form of an infinite sine series [12]. Computed substrate temperatures for the 4 and 6 pcf refractory fibrous material are indicated on table A-1 along with the actual values for the materials. Thermal conductivity values for the refractory fibrous material vary between 0.35 and 0.42 Btu in/hr/ft^2/°F and calculations for the 4 pcf material show the effect of this variation on the substrate temperatures.

It is apparent from the table that a conductivity value of 0.42 gives better agreement with the actual data. From assumptions 2 and 3, calculated temperatures should be considerably higher than the measured values. However, assumptions 4 and 6 can counterbalance these effects. Even slight separation of the insulation from the substrate can result in considerable resistance to thermal transmission. Temperatures on the exposed surface should also be lower than the furnace value. Lower surface temperatures mean less heat available for conduction through the material. Assumption 5 would affect the calculations only at early times.

Table A-1. Calculated Plate Temperatures

Exposure			Insulation				Aluminum Plate		
Time (hour)	Temp. (°F)	Temp. (°C)	Thickness (inch)	Thermal Conductivity k $\frac{Btu}{hr\ ft^2\ F/in}$	Heat Capacity c $\frac{Btu}{lbF}$	Density ρ lb/ft^3	Calculated Temp. (°C)	Test No.	Actual Temp. (°C)
1/2	1300	703	2	0.42	0.27	4	75	8	76
1/2	1300	703	1-3/4	0.42	0.27	4	93	4	109
1	1400	760	2	0.42	0.27	6	148	7	146
1	1400	760	2	0.42	0.27	4	160	8	123
1	1400	760	1-3/4	0.42	0.27	6	176	3	160
1	1400	760	1-3/4	0.42	0.27	4	186	4	183
1	1400	760	1-1/2	0.42	0.27	4	218	-	---
1-1/2	1500	815	2	0.42	0.27	4	244	-	---
1	1400	760	1	0.42	0.27	4	308	-	---
1/2	1300	703	2	0.35	0.27	4	62	8	76
1/2	1300	703	1-3/4	0.35	0.27	4	78	4	109
1	1400	760	2	0.35	0.27	4	135	8	123
1	1400	760	1-3/4	0.35	0.27	4	158	4	183
1	1400	760	1-1/2	0.35	0.27	4	187	-	---
1-1/2	1500	815	2	0.35	0.27	4	208	-	---
1	1400	760	1	0.35	0.27	4	267	-	---

Results are tabulated in the order of increasing substrate temperatures calculated from the aforementioned method. As expected, increasing the quantity, ρ c, means greater thermal storage in the material and less heat transferred to the aluminum substrate. Also, a higher conductivity results in more thermal transmission, and therefore higher temperatures on the unexposed surface. Similarly, less insulation means less resistance to heat flow and higher temperatures. The principal value of such calculations tabulated in the manner shown is to allow the engineer to predict at a glance the magnitude of the temperature change achieved by varying the parameters of insulation thickness, conductivity and the volumetric heat capacity, for various durations of fire exposure.

APPENDIX B.

FIRE ENDURANCE TEST DATA

Table B-1

Specimen 1	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products: CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
3" 6 pcf mineral wool, glass cloth facing on 1/4" aluminum panel	1	37	214	36	36						
	5	39	569	36	42	0	5.1		5		
	6							0			
	7										0
	8									0	
	10	38	720	37	42	0.20	10.8				
	15	43	774	44	47	0.31	12.0		10		
	16							0			
	18										0
	20	54	810	56	59					0	
	30	82	859	85	107	0.37	12.2				
	40							0	20		
	41									0	0
	45	122	915	130	167						
	50					0.20	12.3				
	55							0	10		
	56										0
	57									0	
	60	162	948	169	215						

Table B-2

Specimen 2	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products: CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
3" 6 pcf mineral wool, glass cloth facing on 1/4" aluminum panel, no center fastener used	1	32	215	30	193						
	5	36	540	34	520	0.08	---	0	10		
	7										0
	9									0	
	10	40	713	36	682	0.31	---				
	15	47	770	47	746	0.31	---		20		
	17							0			
	18										0
	19									0	
	20	63	811	64	790						
	30	93	859	97	841	0.43	---				
	35								10		
	45	140	903	147	886						
	50								10		
	60	178	940	182	915	0.61	---				

Table B-3

Specimen 3	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products					
						CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
1-3/4" 6 pcf refractory fiber felt, fiber blend cloth facing on 1/4" aluminum panel	1	38	348	37	41						
	5	38	592	38	56	0.05	2.5				
	8									0	
	10	48	712	45	151	0.16	9.1	5			
	12								10		
	15	56	775	56	284	0.17	10.2				0
	18								12-1/2		
	19-1/2							2			
	20	69	806	71	353						
	30	91	855	96	429	0.08	11.2				
	35							1	19		
	45	130	905	134	515						
	47								19		
	51									0	
	53										0
	60	160	931	162	540	0	11.1				

Table B-4

Specimen 4	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products: CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
1-3/4" 4 pcf refractory fiber felt, fiber blend cloth facing on 1/4" aluminum panel	1	33	270	33	33						
	3								5		
	3-1/2							3-1/2			
	4-1/2										0
	5	37	565	36	35	0	2.5				
	7									0	
	10	45	718	47	44	0.14	9.0				
	12										0
	12-1/2								>9		
	14							1			
	15	67	783	71	69	0.15	10.2				
	15-1/2									0	
	20	82	814	85	88						
	22										0
	24								>9		
	27							0			
	28									0	
	30	109	868	114	121	0.06	11.2				
	31							0			
	32										0
	35								>9		
	36									0	
	40									0	
	43										0
	45	147	912	152	166			0	>9		
	51									0	
	57								5		
	59										0
	60	183	952	184	202	0	11.2	0			

Table B-5

Specimen 5	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products					
						CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
1-3/4" 4 pcf refractory fiber felt, fiber blend cloth facing, paint A on 1/4" alu-minum panel	1	44	331	40	77						
	5	44	579	43	120	0.23	2.9		>9		
	7							>30			
	8										0
	10	46	731	44	285	0.17	9.0			0	
	15	54	789	54	443	0.19	9.4		5		
	17							7-1/2			
	20	66	814	67	523						0
	22									0	
	25								>9		
	27							1			
	30	89	864	91	620	0.12	9.7				0
	32									0	
	40								>9		
	43							0			
	45	131	921	137	716						
	46										0
	47									0	
	55								>9		
	57							0			
	60	165	950	170	751	0	6.9			0	

Table B-6

Specimen 6	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Other* Temps (°C)	Indicated Concentration of Gaseous Combustion Products: CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
1" 3 pcf fibrous glass, 1-3/4" 4 pcf refractory fiber felt, fiber blend cloth facing on 1/4" aluminum panel	1	34	208	32	37	46						
	5	34	---	32	34	146	0.17	4.9		12.5		**
	6								14.0			
	8										0	
	10	39	720	36	132	389	0.41	9.6				
	12									15.		
	14								3.3			
	15	44	773	43	275	509	0.41	10.3				
	16										0	
	20	53	811	54	359	580						
	23									20.		
	26								1.7			
	27										0	
	30	75	868	75	429	662	0.41	10.9				
	35									20.		
	36								0			
	38										0	
	45	103	910	104	497	753						
	48									20.		
	50						0.56	11.4	0			
	52										0	
	60	141	943	142	562	826						

*Between fibrous glass and refractory felt
**Data unavailable

Table B-7

Specimen 7	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products: CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
2" 6 pcf re-fractory fiber	1	40	215	39	48						
blanket, fiber blend cloth	3								3		
facing on 1/4" aluminum panel	4	42	517	41	51			12-1/2			
	5	45	584	42	62	0	---				
	7										0
	9									0	
	10	49	739	47	200	0	---				
	13								7		
	14							0			
	15	55	782	53	321	0.20	---				
	16										0
	18									0	
	20	63	806	63	399						
	23								>9		
	25							0			
	27										0
	29									0	
	30	85	858	85	491	0.41	---				
	37								>9		
	39							0			
	41										0
	44									0	
	45	115	906	119	570						
	53								>9		
	55							0			
	57										0
	59									0	
	60	146	948	149	610	0.46	---				

Table B-8

Specimen 8	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
2" 4 pcf refractory fiber blanket, fiber blend cloth facing on 1/4" aluminum panel	1	38	314	36	306						
	5	40	565	37	529	0.12	5.6		7		
	7							3-1/2			
	10	44	724	41	717	0.35	11.3				
	11										0
	12									0	
	15	48	786	47	785	0.64	13.5		7		
	18							1			
	20	56	819	57	823						0
	23									0	
	28								7		
	30	76	873	78	871	0.41	14.5				
	31							0			
	33										0
	36									0	
	40								7		
	42							0			
	45	96	916	101	911						0
	47									0	
	50					0.64	14.5		7		
	57							0			
	59										0
	60	123	948	129	936					0	

Table B-9

Specimen 9	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products					
						CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
2" 2.5 pcf polyisocyanurate foam on 1/4" aluminum panel	1							>35.	1.8	0	1.0
	3	30	338	29	42						
	5	32	599	30	72	0.07	2.3	>35.	10.	0	1.5
	10	42	699	41	393	0.20	5.7	>35.	9.	0	1.5
	15	66	765	71	516						
	16*					0.40	8.3				

*Test terminated due to excessive smoke in the test building.

Table B-10

Specimen 10	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Other* Temps (°C)	Indicated Concentration of Gaseous Combustion Products					
							CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
2" 2.5 pcf polyisocyanurate foam, 1/2" 4 pcf refractory fiber felt, fiber blend cloth facing on 1/4" aluminum panel	1	30	214	31	37	29			1			
	3									6.3		
	5	31	----	29	101	44	0.15	1.3				0
	6										0	
	7								50	11.3		
	9-1/2								65			
	10	32	736	31	395	176	0.27	1.5				
	12								75	20	0	8
	15	37	779	37	479	373	0.27	2				
	17								25	20		
	20											5
	21	51	815	54	534	438					0	
	24						0.56	4.2				
	25								7-1/2			
	26									19		
	30	82	873	85	599	487	0.52	2.7				
	35									20		
	38								6			
	45	114	915	117	644	519						
	54								2.8			
	56											4
	60	145	947	149	693	549	0.53	10.2				

*Between foam and refractory felt

Table B-11

Specimen 11	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products					
						CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
1 3/4" 4 pcf polyimide foam on 1/4" aluminum panel	2	32	240	29	57						
	3							1/2			
	4										0
	5	33	568	31	146	0.06	4.1				
	6-1/2							2			
	8										0
	9									0	
	10	39	706	37	500	0.17	9.2		15		
	15	52	779	52	725	0.36	10.2	2-1/2			
	17									0	
	19										0
	20	66	808	73	765						
	24							3			
	26									0	
	28										0
	30	149	862	167		0.41	11.4				
	31								25		
	35							1-1/2			
	44								30		
	46	318	911	356							
	47					0.41	11.4				

Table B-12

Specimen 12	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Other* Temps (°C)	Indicated Concentration of Gaseous Combustion Products					
							CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
1-3/4" 4 pcf polyimide foam 1/2" 4 pcf refractory fiber felt, fiber blend cloth facing on 1/4" aluminum panel	1	29	165	27	32	171						
	4								37-1/2			
	5	33	---	31	56	550				27-1/2		
	9											0
	10	38	720	35	121	711						
	10-1/2										0	
	12-1/2								5			
	14-1/2									22-1/2		
	15	42	781	41	307	761	0.44	11.3				
	20	48	812	47	516	785					0	0
	25	57		57	629	817						
	28-1/2								2			
	30	66	860	70	642	839	0.35	11.6				
	31									22-1/2		
	35	77		84	653	857						
	45	106	904	122	647	871						
	46								1			
	60	159	944	181	649	905	0.35	11.6				

*Between foam and refractory felt

Table B-13

Specimen 13	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products					
						CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
Panel -1/4" fiberglass	1	35	182	34	169						
reinforced plastic	3-1/2							5			
(without filler)	4	38		35	460						
	5	39	---	36	573	0.06	2.6		10-1/2		
Insulation - 1-3/4" 4 pcf refrac-	5-1/2									0	0
tory fiber felt, fiber	6	41		39	669						
blend cloth facing	10	44	705	41	829	0.23	8.3	10			
	11								9.2		
	13									0	0
	14-1/2							5			
	15	62	786	63	883	0.43	10.2				
	17-1/2								12		
	20	76	816	80	899	0.69	10.8				
	26							1-1/2			
	27-1/2								18		
	30	109	857	122	909	0.29	10.8				
	32									0	0
	45	159	914	176	933						
	46							1			
	48								15		
	50					0.35	10.8				
	59									0	0
	60	185	936	194	943						

Table B-14

Specimen 14	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Indicated Concentration of Gaseous Combustion Products					
					CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
Panel - 1/4" fiberglass	1	62	187	63						*
reinforced plastic	5	129	504	152	0.17	4.3				
(without filler)	6							12-1/2		
	10	190	704	194	0.93	5.7				
Insulation - none	11								0	
	15	226	760	254	1.12	6.0		5		
	18								0	
	20	258	814	295						
	27-1/2							7-1/2		
	28-1/2						1			
	29								0	
	30	334	856	422	1.85	7.1				

* Data unavailable

Table B-15

Specimen 15	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Other* Temps (°C)	Indicated Concentration of Gaseous Combustion Products: CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
Panel - 1/4" fiberglass reinforced plastic (with filler)	1	29	358	27	50	29						
	5	31	592	30	151	36			17	6.7	0	0
	10	37	719	36	435	59			6	5		
Insulation - 1-3/4" 4 pcf refractory fiber felt, fiber blend cloth facing	15	57	784	59	535	103	0.93	6.7				
	20	71	816	73	572	124			2	>10	0	0
	30	103	871	110	652	177	0.93	7.9				
	40								1	>10	0	0
	45	145	905	153	697	230						
	60	182	945	192	727	275	0.93	8.2	0.5	>10		

*Between felt and fiberglass panel

Table B-16

Specimen 16	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Indicated Concentration of Gaseous Combustion Products					
					CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
Panel - 1/4" fiberglass reinforced plastic (with filler)	1	54	180	53						*
	1-1/2						0	6		
	3						1	6		
Insulation - none	4								0	
	5	133	591	137	---	---				
	6-1/2							6		
	10	204	715	196	---	---				
	20	231	826	232	---	---				
	30	280	864	264	---	---				
	34	302	878	287						

*Data unavailable

Table B-17

Specimen 17	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products					
						CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
2" 3.7 pcf polyisocyanurate foam on 1/4" aluminum panel	5	41	565	39	54	0.17	0				
	7								30		
	8							100.			
	10	48	721	46	395	0.23	1.9				17.
	11									0	
	15	71	788	81	604	0.50	4.3				
	17								15.		
	19							12-1/2			
	20	122	812	162	694						37-1/2
	22									0	
	25	216	834	289	710						
	30	330	861	413	747	0.75	6.8				

Table B-18

Specimen 18	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Other* Temps (°C)	Indicated Concentration of Gaseous Combustion Products CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
2" 3.7 pcf polyisocyanurate foam, 1" 6 pcf mineral wool, fiber blend cloth facing, paint A on 1/4" aluminum panel	1	37	197	35	233	106						
	3								5	10		0
	4										0	
	5	41	544	35	454	347	0.09	1.4				
	10	42	720	39	646	600	0.35	7.9	25	17-1/2		2
	11										0	
	15	44	780	40	722	683	0.69	8.8				
	20	51	810	49	762	720			8	20		
	21										0	
	22											4
	30	74	859	74	831	790	0.71	8.9				
	41											3
	43									25		
	45	104	921	104	897	891			1			
	50						0.69	7.6				
	60	159	935	155	964	970						

*Between foam and wool

Table B-19

Specimen 19	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products: CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
3" 3 pcf fibrous glass, fibrous glass cloth facing on 1/4" aluminum panel	1	39	174	36	41						
	2							5			
	3								25		
	4										0
	5	42	626	40	79	---*	---*			0	
	8-1/2							8			
	10	46	717	44	346	---	---		20		
	12										0
	14					---	---			0	
	20	77	812	76	593	---	---				
	26							2			
	27								20		
	29									0	0
	30	128	862	130	779	---	---				
	35	197	860	199	853						
	39							3			
	40	370	921	371	875	---	---		17-1/2		

*Data unavailable due to experimental difficulties

Table B-20

Specimen 20	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Temp at Mid-Depth Base Insulation (°C)	Indicated Concentration of Gaseous Combustion Products					
						CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
3" 3 pcf fibrous glass, fibrous glass cloth facing, paint A on 1/4" aluminum panel	1	41	214	40	58	0	0				
	3							6	25	0	0
	6	46	624	43	159	0	0				
	7							40	20	0	0
	10	50	716	47	378	0.06	2.1	10	15	0	0
	15	59	777	57	525	0.17	1.0				
	20	73	816	76	627						
	23							1	17	0	2
	30	112	854	129	863	0.30	0.87				
	35	234	880	290	957						
	40	461	873	496	951	0.35	0.90	1	17	0	3

Table B-21

Specimen 21	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Indicated Concentration of Gaseous Combustion Products					
					CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
Paint A on 1/4" aluminum panel	1	60	157	68						
	5	200	545	216	0	1.9		12-1/2		*
	8						25.			
	9								0	
	10	242	721	251	0.20	7.8				
	13							7-1/2		
	15	277	780	291	0.54	9.4	9.			
	16								0	
	20	313	820	333	0.75	10.				

*Data unavailable

Table B-22

Specimen 22	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)	Indicated Concentration of Gaseous Combustion Products					
					CO (%)	CO_2 (%)	HCN (ppm)	NO & NO_2 (ppm)	HCL (ppm)	HF (ppm)
Paint V on 1/4" aluminum	2	106	300	121						
panel	5	214	553	231	0.09	3.5		20.		*
	7						50.			
	9								0	
	10	268	727	277	0.56	8.7				
	12							25.		
	14						14.			
	15	296	775	306	0.67	9.2				
	16								0	
	18	312	800	322	0.67	9.1				

*Data unavailable

Table B-23*

Specimen 23	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)
Paint A on 1/4" steel panel	1	47	131	45
	5	148	520	164
	10	224	705	229
	15	248	770	257
	19-1/2	266	797	279
	30	316	861	332
	45	391	908	417
	60	467	934	515

*Gas analysis not taken

Table B-24*

Specimen 24	Time (min)	Avg. Temp of Plate (°C)	Avg. Temp in Furnace (°C)	Temp at Center of Plate Surface (°C)
Paint V on 1/4" steel panel	1	58	163	60
	5	184	538	215
	10	258	720	267
	15	286	775	293
	20	315	820	322
	30	362	865	367
	45	433	909	431
	60	484	944	478

*Gas analysis not taken

APPENDIX C. FIRE ENDURANCE TEST OBSERVATIONS

Specimen 1

Nothing unusual occurred during the 60-minute duration of the test. The specimen had been constructed from two pieces of mineral wool pushed together. A large washer on a fastener pin between the pieces kept them against the plate center. During the test it was difficult to see how much of the seam had opened to expose the substrate.

The glass cloth facing was very brittle following exposure to the furnace fire. Even after the test it was difficult to tell how much the seam between the two pieces had opened as portions of the insulation fell apart upon removal from the furnace.

Specimen 2

Behavior of the sample was similar to the test of specimen 1. This specimen was also constructed from two separate pieces of mineral wool, but without a fastener pin in the central part of the sample. Nichrome wires tied to washers were then used at NBS to hold the wool against the plate.

Because portions of the insulation fell apart upon lifting from the furnace, it was also impossible to note whether the seam between the two pieces of mineral wool had opened up.

Specimen 3

After 5-1/2 minutes in the furnace the cloth facing split.

At six minutes the facing became loose and was just hanging, completely exposing the insulation.

At eight minutes the facing glowed red but was not flaming.

At 12 minutes, the facing still glowing red but not flaming.

At 15 minutes conditions unchanged.

At 19-1/2 minutes the insulation was bowing except at the attachment pin and it appears to have an irregular or alligator pattern throughout the insulation surface.

At 26 minutes all conditions are unchanged.

At 33 minutes the hanging facing is fraying and glowing pieces are falling off.

At 39 minutes no change in the specimen.

Forty-four minutes the facing has almost all dropped off.

At fifty minutes no change in appearance of the insulation.

At 60 minutes the test was terminated.

After the panel was removed from the furnace the alligatoring was found to be approximately 1/64 to 1/32 of an inch deep. From the exposure to the fire the furnace exposed face of the beige or grayish brown color insulation had turned white. This whiteness extended for 1-1/4 inch into the material. Natural refractory fibrous felt without binder is white, so it appears that the binder was distilled from the insulation to the above depth. Other than that, the insulation appeared to be in good condition with no other effects being apparent at the time.

Specimen 4

Behavior of sample similar to test of specimen 3 except the surface facing was not hanging down, exposing the insulation, until about 11 minutes.

Specimen 5

At 1-3/4 minutes, the surface paint flashed over.

At 6 minutes, the paint has intumesced.

At 10 minutes into the test, the cloth facing was hanging down, exposing the insulation.

Behavior of sample at subsequent times was similar to tests of specimens 3 and 4.

Specimen 6

At 3 minutes, some smoking around outside edge of specimen on unexposed side.

At 6 minutes cloth facing split.

At 10 minutes facing sagging down along one end of specimen.

After 15 minutes entire facing hanging down.

23 minutes into test, cloth facing breaking up and falling into furnace.

30 minutes into test, cloth facing almost totally gone.

At 32 minutes, irregular or alligatoring pattern over entire exposed surface.

At 57 minutes, exposed surface slightly warped.

After 60 minutes, test terminated.

Post fire observation of specimen showed surface irregularity, but no cracks of any depth.

Specimen 7

Behavior of sample similar to tests of specimens 3 and 4. The refractory fibrous blanket shredded on the surface and it alligatored similar to the felt. The shredding had the appearance of delamination, although in the original state, the material was not manufactured in layers.

Specimen 8

Behavior of sample similar to tests of specimens 3 and 4.

Specimen 9

At four minutes exposure to the fire, the polyisocyanurate foam burst into flames. Prior to this and even during the flaming the sample exuded heavy amounts of acrid smoke. At six minutes the isocyanurate is still flaming. Observation at ten minutes indicates some slight reduction in the flaming but the material is glowing red and has split open into wide cracks. Because of the heavy fume and smoke concentration this test was stopped after sixteen minutes.

After the panel was removed from the furnace it was noted that the polyisocyanurate was badly burned and had opened into very wide cracks which went all the way through exposing the aluminum base plate.

Specimen 10

At four minutes into the test smoke started to exude from the furnace. The smoke is apparently from the facing material.

At six minutes into the test a slight flaming occurred on the surface of the facing. Also at six minutes the cloth facing split open.

At 7 minutes into the test about half of the facing dropped loose. The facing material is flaming and glowing red.

At 8 minutes into the test the facing dropped off completely.

At 8-1/2 minutes the entire surface of the refractory fibrous felt is engulfed in flame.

At nine minutes into the test the sample is smoking quite heavily.

At ten minutes into the test large quantities of smoke now exuding from the furnace and the detectable odor of hydrogen cyanide (HCN) is present. Readings taken of this gas at this particular time indicate a high concentration of HCN.

The refractory fibrous material appears to be standing up well, although as opposed to other tests, it is flaming. This may be the consequence of the isocyanurate pyrolyzing under the refractory material.

At nineteen minutes into the test the alligatoring pattern, which has been present in all other panels using refractory fibrous material, has taken place on the fire exposed surface of the insulation.

At 23 minutes into the test it appears that the flaming on the surface of the refractory material has stopped, although the panel is glowing red.

At 25 minutes into the test the sample is still smoking rather profusely.

At 30 minutes into the test visual conditions of the sample and the smoke are unchanged.

At 45 minutes into the test the 1/2" refractory felt appears to be buckling. Aside from this all other conditions are the same. This buckling, however, is not too severe.

At 50 minutes into the test conditions seem to be unchanged except that the alligatoring had penetrated deeper and the refractory felt covering buckled more.

At 55 minutes into the test all conditions appear to be unchanged.

At 60 minutes the condition of the panel and smoke emission appear unchanged. The test was terminated at this time.

Five minutes after termination of the test, the panel was removed and placed outdoors, it was noted that the 1/2" refractory felt covering had buckled quite extensively and the alligatoring was rather deep. It was noted that the polyisocyanurate foam was still smoking heavily until about 45 minutes after the test before it subsided. During this period the foam was smoldering or burning internally. When the half inch refractory felt facing was removed it was noted that the polyisocyanurate foam had burned completely through and had broken up into smaller pieces.

Specimen 11

At three minutes into the test no visual change in the material, no smoking.

At six minutes there is no discernible change in the material, no smoking has occurred.

At six and one-half minutes a slight smoking is discernible at the top of the panel.

At seven minutes the butt joints in the specimen opened up as a result of material shrinkage and the material is cracking. The butt joints in the center of the panel opened up approximately 3/8".

At nine minutes the cracking of the polyimide material is increasing. The cracking in the four individual sections of the panel is approximately 1/4 to 3/8 of an inch wide. The cracking has taken on an alligator pattern appearance.

At ten minutes the slight smoking on top of the panel has stopped. It appears that all four individual pieces making up the panel have cracked extensively.

At twelve minutes the slight smoking re-occurred on top of the panel.

At thirteen minutes the polyimide material appears to be flaming to a slight degree.

At thirteen minutes into the test the butt joints between the sections of the polyimide have opened up to approximately 1 inch wide. The alligatoring pattern cracks have opened anywhere from 1/4" to 3/4".

At fifteen minutes the smoking has increased slightly on the top of the panel.

At 18 minutes the butt joints have opened up to some 1-1/4" wide. With the opening of the butt joints the overlap of the polyimide joints can now be readily seen.

At twenty-four minutes the cracks in the alligatoring pattern have opened up into very wide fissures and the butt joints between the individual panels have opened to about 1-1/2". The material is still flaming to some extent, and the smoke emission from the panel has increased somewhat.

At thirty-two minutes there are still flames along the face of the polyimide.

At thirty-three minutes the butt joints between the four panel sections have opened up beyond the overlap of the individual sections. While not visually apparent the aluminum plate may be exposed.

At thirty-four minutes the aluminum plate has deflected downward approximately 3/8" at the center of the panel.

At thirty-five minutes the panel is flaming quite extensively. At this particular point it is not known if the polyimide is flaming, or whether it is the adhesive between the polyimide and the aluminum plate. Visually it appears that the polyimide itself is flaming.

At thirty-six minutes the smoke emission from the panel is increasing.

At thirty-seven minutes the center of the aluminum panel has now sagged approximately 1-1/8", indicating excessive heating of the aluminum panel.

At thirty-nine minutes the polyimide is flaming very heavily over the entire face.

At 41 minutes the smoke from the panel is still increasing.

At forty-two minutes the entire face of the polyimide is still flaming heavily and the fissures or cracks in the individual sections of the panel have opened wide. One crack that is visible is almost 2" wide.

At forty-four minutes the depression at the center of the panel was still about 1-1/8".

At forty-five minutes the entire face of the polyimide is flaming heavily and smoke is being emitted quite extensively from the top of the panel.

The test was terminated after a period of 47 minutes when the temperature on the unexposed side of the aluminum panel had reached above 300 degrees centigrade.

Approximately 5 minutes after the termination of the test and before the panel was removed from the furnace, there was still some flaming over the surface of the polyimide foam and smoke was still being emitted from the top of the furnace. As the panel was being removed from the furnace two large pieces of the polyimide broke loose and fell off. Visual inspection of the sample after the test indicated that the polyimide had burned completely through. Apparently the adhesive between the polyimide and the panel prevented the foam from falling loose during the test.

Specimen 12

At 3-1/2 minutes into the test slight smoking occurred at the top of the panel. This may be from the cloth facing.

At 4-1/2 minutes the smoking has increased noticeably.

At 5 minutes the cloth facing has split and is hanging down.

At 7 minutes the facing is behaving as it did on previous tests, that is, the cloth is glowing and bits are fraying off and falling into the furnace.

At 8 minutes the smoking condition reported earlier has subsided noticeably. This would indicate that the initial smoking was coming from the cloth facing.

At 17 minutes into the test the alligatoring pattern on the exposed refractory felt which has been characteristic of this material in each of the previous tests, is definitely forming. The smoking has stopped.

At 22 minutes conditions unchanged.

At 25 minutes slight smoking has re-occurred on top of the panel.

At 31 minutes all visual conditions unchanged.

At 35 minutes into the test the 1/2-inch refractory felt has a slight bow in it. This is about the same as was experienced on panel No. 10.

At 40 minutes condition of the felt material is unchanged. Slight smoking continuing on top of the panel.

At 45 minutes into the test all visual conditions unchanged.

At 50 minutes into the test the aluminum panel has deflected downward between 1/4 and 3/8 of an inch. All other visual conditions of the panel are unchanged.

At 60 minutes the furnace test was terminated. There was no additional change in the specimen.

10 minutes after the panel had been removed from the furnace and placed outside, flaming still continued around the periphery of the polyimide.

When the refractory felt laminate was removed it was noted that the polyimide foam had split open with wide cracks. The cracks were in various widths up to 2". In all cases the cracks and openings were clear through, exposing the aluminum panel. The polyimide foam had charred through its entire thickness.

Specimen 13

After 6 minutes facing split and was hanging down exposing insulation.

At 16-1/2 minutes conditions unchanged.

At 23 minutes there's a slow venting of furnace gases around the area of the fastener pin. An area of about the size of a 50 cent piece around pin on unexposed side of the panel is turning dark green in color.

After 28-1/2 minutes the color on much of the unexposed side within the confines of the furnace opening has turned a dark green. Original color of panel was pale pink.

33 minutes into the test the dark green color has extended over the entire panel area within the confines of the furnace opening. A quarter-inch circle around the fastener pin has become brownish black and is melting.

At 35 minutes conditions unchanged.

At 40 minutes the circle of melting plastic around the fastener has increased to a 5/8-inch circle.

After 43 minutes the refractory felt insulation starting to bow slightly towards the flames.

At 57 minutes conditions unchanged.

At 60 minutes test terminated.

Specimen 14

At 5 minutes into the test the panel has started to smoke heavily.

At 9 minutes panel is sweating and there is some dripping into furnace.

At 11 minutes specimen is aflame. Furnace window covered with soot.

After 15 minutes the specimen is blistered and warped throughout. The fire has almost burned through the panel.

At 21 minutes into the test the plastic panel has shattered and smoke is rising from over most of its surface.

At 29 minutes the sample is smoking heavily.

At 30 minutes the test is terminated.

Specimen 15

The cloth facing reacts in exactly the same manner as in the test of Panel No. 3, i.e., it fell off early in the test, exposing the insulation.

At 25-28 minutes the plastic panel has deflected approximately 1/8" in the center.

At 38 minutes this depression has increased to 1/2", indicating that the panel is softening.

Between 40-45 minutes the backside of the plastic panel had discolored within the area of the furnace opening, which is 22 inches square.

At about 20 minutes into the test the area around the center fastener on the back side of the panel began to char, indicating a burn-through at the fastener. However, at 53 minutes the burn-through from the center fastener was still not sufficient to allow the insulation to fall free. The area of char, around the fastener is approximately 3/4" in diameter.

At 60 minutes test terminated.

Specimen 16

The panel sagged in the middle after 1/2 minute of test, the deflection was approximately 1/4".

After one minute of test the deflection in the middle of the panel was approximately 3/8".

After 1-1/2 minutes of test the deflection is still 3/8".

After 4 minutes of test the panel exuded large quantities of smoke.

After 5 minutes of test the deflection is still 3/8".

At six minutes into the test the panel is smoking profusely.

At seven minutes into the test the entire furnace is engulfed in smoke.

At 7-1/2 minutes the center of the panel has sagged 1/2".

At 8 minutes the panel is giving off heavy quantity of smoke and the entire top of the furnace cannot be seen and the deflection in the middle of the panel could not be measured.

Due to the heavy smoke, personnel cannot get near the panel to take measurements of various gases in the furnace exhaust.

At twelve minutes all rooms in the testing facility are completely engulfed in smoke. The smoke coming from the furnace stack is of a very dark gray color.

After 15 minutes into the test the deflection reported earlier in the center of the panel has now receded; as a matter of fact, the panel is level.

At 18 minutes the unexposed surface of the panel is turning brown and there appears to be trapped gases resulting in the formation of bubbles throughout the plastic. This may be due to air entrapment as the panel was manufactured. The large rings or bubbles, as they are referred to, run anywhere from two inches to six inches in diameter. The panel is still smoking profusely.

At twenty minutes, the panel is now again bowing, but this time it is bowing upward instead of downward as it was previously. The bowing is approximately 3/8".

At twenty-two minutes into the test the smoking has decreased slightly, although still smoking heavily.

After 33 minutes into the test it was noted that the entire face of the panel exposed to the fire was boiling in flame. While the smoke generation is still very heavy it is less than that previously reported.

At 36 minutes the panel face exposed to the furnace is still flaming over its entire surface.

The furnace flame was turned off after 39 minutes of the test.

As the panel was being removed from the furnace it cracked through the middle. At this crack there was delamination of the layers of resin and fibrous glass reinforcement. On the fire exposed surface the resin had burned off exposing the fibrous glass reinforcement.

Specimen 17

Behavior of sample similar to test of specimen 9.

Specimen 18

Behavior of sample similar to test of specimen 10 even though mineral wool instead of refractory felt was the laminate over the polyisocyanurate foam. As was in the test of specimen 10, the foam was charred and had cracks which went all the way through exposing the aluminum plate.

Specimen 19

At 7 minutes nothing unusual occurring.

At 13 minutes some bowing of the insulation towards the fire. Facing still intact.

17-1/2 minutes into the test and conditions are unchanged. Very little smoke on either side of specimen.

20 minutes into the test and the insulation is sagging more than before.

After 30 minutes the facing, and possibly the insulation too, is sagging badly except where it is attached with fastener pin. A two-inch hole has opened up and molten glass is dripping from the periphery of the hole into the furnace.

At 32 minutes the hole is roughly circular and about four inches across.

At 33 minutes the fibrous glass insulation has fused into a shell and is hanging. A large opening is observed, exposing the aluminum plate.

At 34 minutes the plate has sagged about 1/2-inch at the middle.

At 37 minutes there is moderate smoking on the unexposed side of the specimen. The deflection at the center of the plate is now about 3/4-inch. Small chunks of insulation are dropping into the furnace.

After 41-1/2 minutes the test was terminated.

Immediate inspection of the sample upon its removal from the furnace showed that the glass fibers of the insulation had fused together to form a 1/4- to 3/8-inch thick hard black solid layer, which ballooned away from the plate. Most of the central portion was gone, exposing almost all of the aluminum plate.

Specimen 20

Behavior of sample similar to test of specimen 19.

Specimens 21 to 24

These four samples had only an intumescent paint over the metal substrate. Behavior of the paint is similar for all four specimens.

At 4 to 5 minutes the paint starts to bubble up.

At 6 to 7 minutes the paint is burning.

At 7 to 9 minutes only a crisp charred layer is left on the panel surface.

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBSIR- 76-1012	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Fire Performance Testing of Bulkhead Insulation Systems for High Strength to Weight Ship Structures

5. Publication Date August 1976

6. Performing Organization Code

7. AUTHOR(S)

B. T. Lee

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No. 492 6677

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

Ship Damage Prevention and Control
Naval Sea Systems Command
Department of the Navy
Washington, D.C. 20362

13. Type of Report & Period Covered Final Report

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

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.)*

Sixteen insulated aluminum bulkhead specimens were subjected to a material screening process as well as evaluated for their comparative fire performance with a 2-foot horizontal slab furnace. Two insulated and two unprotected glass-reinforced plastic specimens were also tested to obtain fire performance data on these structural materials. In addition, painted aluminum and steel panel specimens were included to determine the fire protective merits of two types of intumescent paints. Potential heat release, smoke, and combustion gas generation were also determined for the insulation and coating materials. Specimens insulated with organic base foams released high levels of combustion gases and could contribute considerable heat to an on-going fire. Specimens insulated with either refractory fibrous material or with mineral wool gave the best overall performance. The same thickness of insulation needed to protect an aluminum panel for over an hour can provide up to 20 minutes of protection for a glass-reinforced plastic panel of the same thickness. The intumescent paints did little to protect the specimens during the fire exposure. Parameters of insulation thickness, heat capacity, density, and thermal conductivity as well as fire duration on specimen temperature were analytically investigated.

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)* Aluminum bulkhead; combustion gases; fire endurance; insulation; intumescent paint; potential heat; reinforced plastic; small furnace test; smoke.

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USCOMM-DC 29042-P74