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**LIGHTWEIGHT FIRE BARRIER DEVELOPMENT FOR AIRCRAFT**

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16. Abstract  A study was conducted on various lightweight thermal barrier materials to ascertain whether a thermal protection system could be devised which could be used in airsuperiority aircraft to prevent fire propagation through the aircraft and thus affecting critical components. The paper describes various materials, material properties, and thermal performance in simulated environments of lightweight foam materials. The paper also describes the thermal performance criteria the materials must attain to be acceptable and formulations for several compositions which were considered satisfactory in meeting the pre-established criteria.			
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## LIGHTWEIGHT FIRE BARRIER DEVELOPMENT FOR AIRCRAFT

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### INTRODUCTION

Inflight aircraft fires, whether the result of direct hostile action or the result of operational failures, are a major cause of military aircraft losses. Efforts to date to reduce this hazard have concentrated on fuel system containment. Where fuel containment and ignition prevention fail, fire propagation through an aircraft will usually fail a flight-critical component, such as directional controls, in an unacceptably short time period. The effort, herein described, has been directed towards developing barriers which will compartmentalize aircraft interiors, thus protecting critical components until, hopefully, the fire burns out or is actively extinguished. Emphasis has been placed on developing a barrier system for application to airsuperiority aircraft.

### OBJECTIVES

1. To develop a preliminary aircraft fire barrier specification containing realistic and attainable acceptance criteria while ensuring that any barrier system meeting these criteria would provide adequate aircraft thermal protection.
2. To develop and supply an example barrier system which would comply with the above criteria at minimum aircraft weight penalty.

3. To conduct aircraft fire simulator tests to evaluate the effectiveness of a number of candidate systems and to identify the particular problem areas of aircraft structure and equipment penetration through barriers, clearance requirements, and flight induced loads while in a fire environment.

#### ACCEPTANCE CRITERIA

The detailed acceptance criteria are included in Appendix I, "Fire Barrier, Lightweight; Protection of Aircraft, Structures and Parts; General Specification for a draft military specification." In general, the acceptance criteria demand that the barrier system neither burn through nor let the temperature of the air space measured 15 cm (6 inches) normal to the barrier unexposed face exceed 200°C (400°F) for 10 minutes when tested in a fire barrier test simulator. The criteria also detail the environmental test and physical characteristics required of the barrier.

#### DEVELOPMENT OF AN ADVANCED BARRIER SYSTEM

##### Formulations

Ten formulations were investigated in thermally optimizing polyurethane foam. Three potentially significant variables were addressed within these formulations, basic foam density, alternate high temperature resistant reinforcing fibers, and the effects of a special char stabilizer additive, potassium fluoroborate ( $\text{KBF}_4$ ). Density variation of the basic polyurethane foam (5A43), flight qualified and used to reduce ballistic damage, was easily controlled with the amount of Freon blowing agent used. Silica fibers were chosen to compare with conventional glass fibers because the silica has the advantages of good strength and stability at high temperatures while not being exorbitantly expensive. Effect of adding  $\text{KBF}_4$

was investigated because it had previously been found to be endothermic at hydrocarbon fuel flame temperatures and the boron reacted with the carbonaceous char to form a more thermally stable network. The exact foam formulations used are contained in Table 1. The ingredients were mixed one-at-a-time in the order given except that the MEG 440 polyol and the Freon liquid were thoroughly mixed together prior to addition to the ingredients preceding them. The final chemical, 33 LV, the catalyst agent, was mixed, diluted by an equal amount of Freon. Immediately after addition of the catalyst and rapid mixing, the final product was poured into the bottom of a waxed (releasing agent) mold and allowed to free rise to the top. Mold dimensions were: height - 41 cm (16 inches), width - 41 cm, thickness - 5 cm (2 inches). The foam was then allowed to cure for 24 hours prior to removal from the mold.

#### Thermal Screening Test Procedures

The test specimen foam blocks were cut to 30.5 cm (12 inches) square by 5 cm (2 inches) thick, mounted in asbestos frames and the unexposed face instrumented with chromel-alumel thermocouples as shown in figure 1. A 43 cm (17 inches) to a side cubic stainless steel box structure was used in the last four tests with the specimen mounted exposed in one wall of the box fixture. Inside, mounted 15 cm (6 inches) normal from the unexposed specimen face, was a still air thermocouple. The five sides of the box specimen that were not exposed to the furnace were insulated with 2.54 cm thick blanket-type silica insulation material. The test setup is shown in figure 1.

The NASA T-3 fire test facility was used to provide  $11.35 \text{ watts/cm}^2 \times 10^4$  (10 Btu/ft<sup>2</sup>-sec) of total heat flux with a JP-4 flame temperature of

approximately 900°C. When the oven was stabilized at the above heat flux rate, the instrumented specimen was exposed to the thermal source and the thermocouple recorder (Esterline-Angus D-2020) started. Each individual test was terminated when the backface temperature exceeded 205°C (400°F).

#### Fire Test Results

First investigated was the effect of density on the thermal response of the basic 5A43 polyurethane foam. As can be seen from figure 2, a near linear relationship exists when considering time to a given backface temperature as a function of density. The polyurethane foam acts as an efficient thermal ablator while decomposing to the basic char structure (fused glass fibers and carbon). This is then followed by a rapid rise to elevated temperatures at an approximately uniform and repeatable rate due to the char matrix thermal conductivity being about an order of magnitude greater than the virgin foam.

Next, the potential benefits of silica fibers as the reinforcing agent were determined. After the ablation process had been completed, the remaining silica char exhibited clearly superior thermal properties as compared to the glass char. Figure 3 presents the results as time versus temperature data. The silica formed a white blanket-like surface to the fire, lowering the foam infrared absorptivity, thus reducing the effective heat transfer coefficient of the basic char structure.

The time versus temperature data for the polyurethane foam, with and without  $\text{KBF}_4$  additive, is presented in figure 4. Differences in initial ambient temperature alone can explain the apparent reduction in performance of the foam with the additive. The  $\text{KBF}_4$  additive does not significantly enter into the reaction until it is at elevated temperatures (600°C) except

that it appears to increase the apparent foam thermal conductivity until sufficient quantities of it are decomposing (in this test case when the backface temperature has reached about 150°C). At this point the foam apparent conductivity becomes less than the basic silica char.

Tests conducted with the unexposed face of the foam specimen enclosed in a box structure with the still air temperature recorded are not representative of any actual aircraft structure thermal response to the barrier (mass of the structure, coatings, distance from the barrier, view factors, air density, and air velocity must all be considered) but it is an indicator that air is an excellent insulator and limiting the foam backface temperature at 200°C is extremely conservative. These data are contained in Table 2.

Figures 5 through 14 present post-test photographs of the fire exposed face of each test specimen. Figures 9 through 11 show the effects of varying the length of the silica fibers with about 25% 0.32 cm (1/8") to 75% 0.64 cm (1/4") achieving the best combination of strength and uniform blanket effect. Table 3 presents a summary of the results from each individual test. Figure 15 illustrates the reduction in char shrinkage attributable to the use of silica fibers by careful reaction of small block samples in a high temperature furnace (800°C for 1/2 hour). Figures 16 and 17 illustrate the foam test specimen with holder, the enclosing test chamber to measure still air temperatures, and the NASA T-3 fire test facility.

#### Physical Test Results

All mechanical properties testing was conducted in accordance with the procedures and requirements of the American Society for Testing and

Materials (ASTM). Table 4 presents the results of these tests for the standard 5A54 polyurethane foam, for the 5F14 foam with  $\text{KBF}_4$  added and silica fibers substituted for glass fibers (designated 5F14RS).

Normally 5A43 foam is mixed and applied through a spray gun in multiple passes thereby orienting the reinforcing fibers in the x-y plane. The 5F14 foam prepared for these tests was spray gun applied into a confining mold resulting in orientation parallel to the rise direction. The 5F14RS foam was hand mixed and poured into a confining mold with much the same resulting fiber orientation as the 5F14; however, the silica fibers were only one-quarter as long as the glass fibers. Molding of polyurethane foam creates a thin tough "skin" on all outer surfaces in direct contact with the mold. For the mechanical properties tests these skins were removed. Depending on geometry the presence of these skins can more than double the mechanical strength of a foam block, and friability goes effectively to zero.

TABLE 1. POLYURETHANE FOAM FIRE BARRIER FORMULATIONS EVALUATED

FORMULATION PARTS BY DRY WEIGHT

COMPONENTS	1	2	3	4	5	6	7	8	9	10
Mondur MR	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Saran 113	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
KBF <sub>4</sub>	—	—	—	16.5	16.5	16.5	16.5	16.5	—	—
Fyrol 2	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
MEG 440	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
Freon 11	35.0	30.0	40.0	80.0	80.0	80.0	100.0	75.0	75.0	75.0
"E" Glass	25.0	25.0	25.0	25.0	—	—	—	—	—	—
Refrasil ,32cm	—	—	—	—	—	6.5	25.0	6.5	6.5	6.5
Refrasil ,64cm	—	—	—	—	25.0	18.5	—	18.5	18.5	18.5
DC 195	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
33 LV	8.0	8.0	8.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5

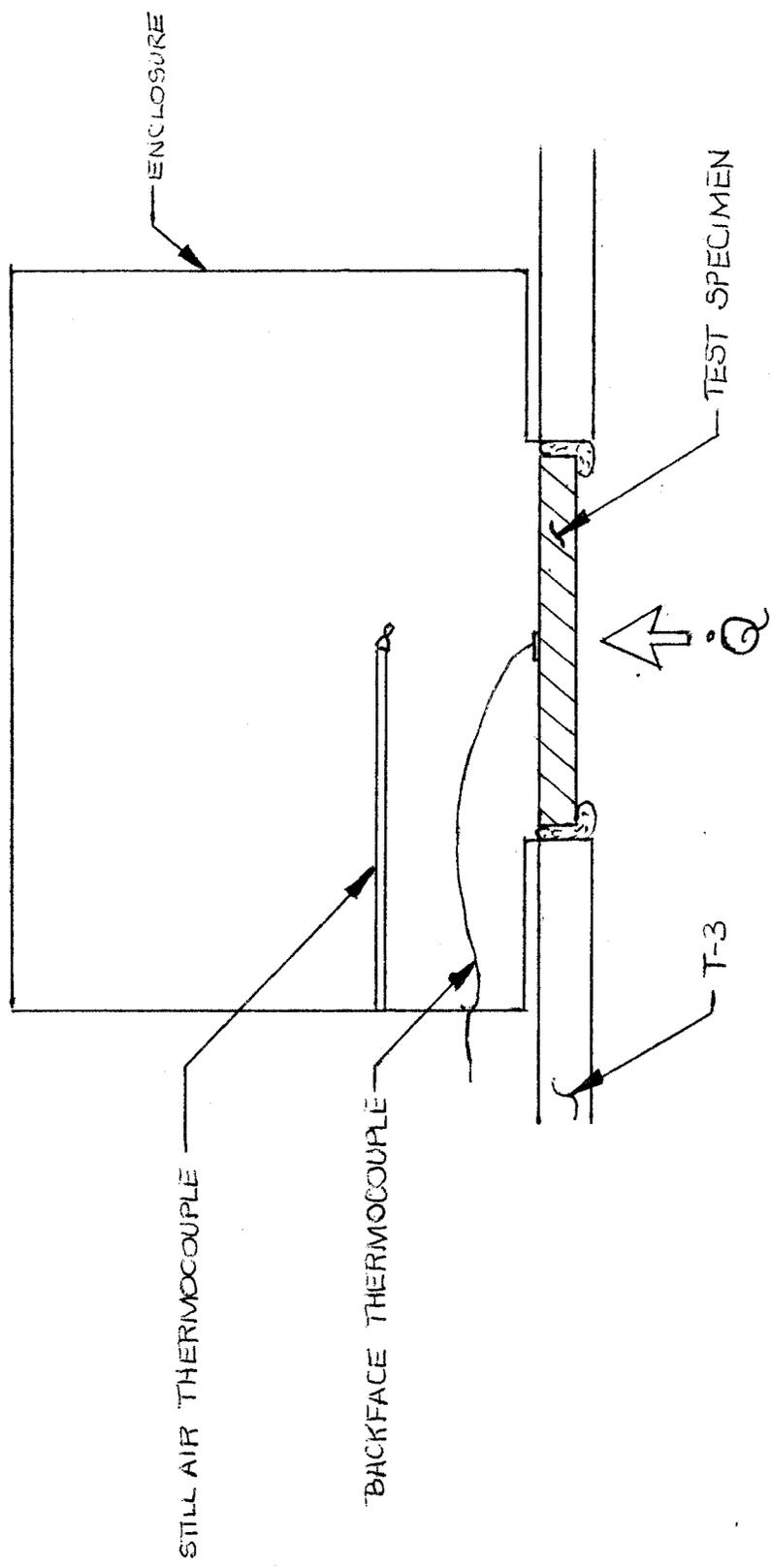


Figure 1. Thermal screening test setup.

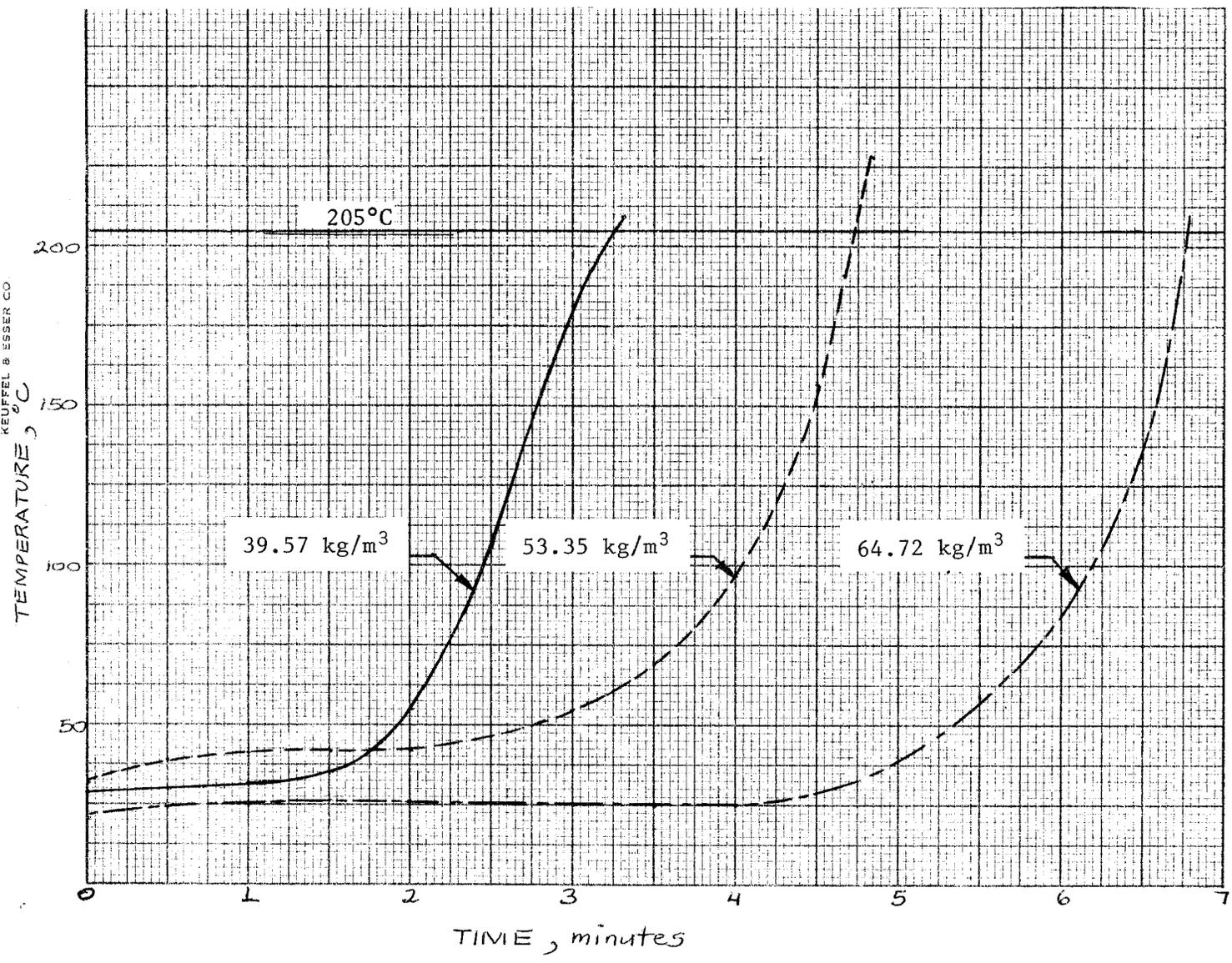


Figure 2. NASA 5A43 polyurethane thermal response as a function of foam density.

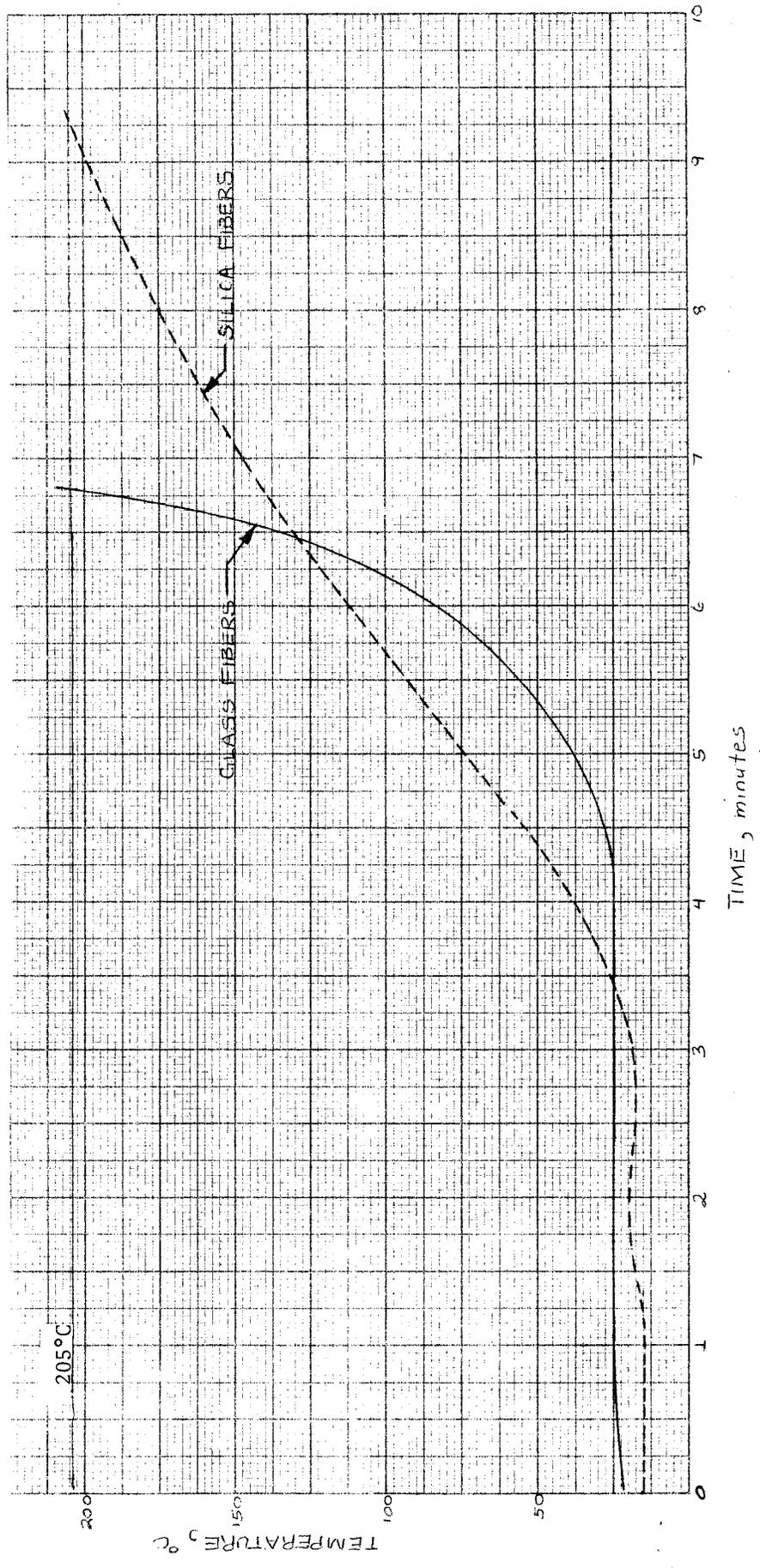


Figure 3. NASA polyurethane foam thermal response as a function of reinforcing fiber type.

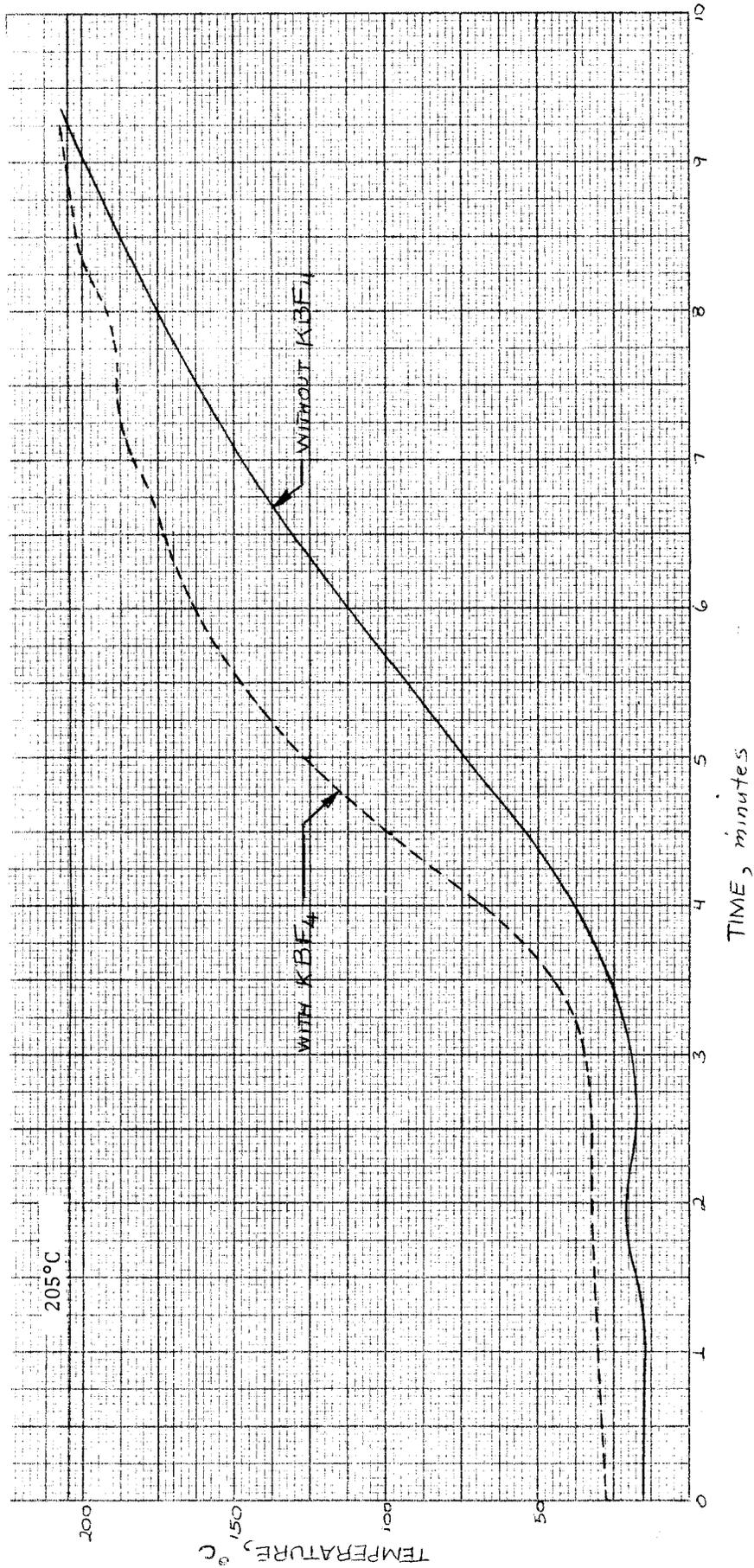


Figure 4. Thermal response effect of KBF<sub>4</sub> additive to NASA 5A43 polyurethane foam.

TABLE 2. TIME TO TEMPERATURE DATA FOR POLYURETHANE FOAM FORMULATIONS

FORMULATION NUMBER	TIME TO 205°C (400°F)* (minutes)	STILL AIR TEMPERATURE † (°C)	FOAM DENSITY (kg/m <sup>3</sup> )
1	4.75	—	53.35
2	6.50	—	64.72
3	3.17	—	39.57
4	6.00	—	65.20
5	3.50 ††	—	69.20
6	8.67	—	64.56
7	5.33	103	45.66
8	7.00	78	59.43
9	8.75	78	56.55
10	9.33	96	64.72

\* Specimen backface

† Thermocouple located 6 inches normal from backface of Specimen.  
 † Temperature at 10 minutes burn duration.

†† Excessive voids in specimen.

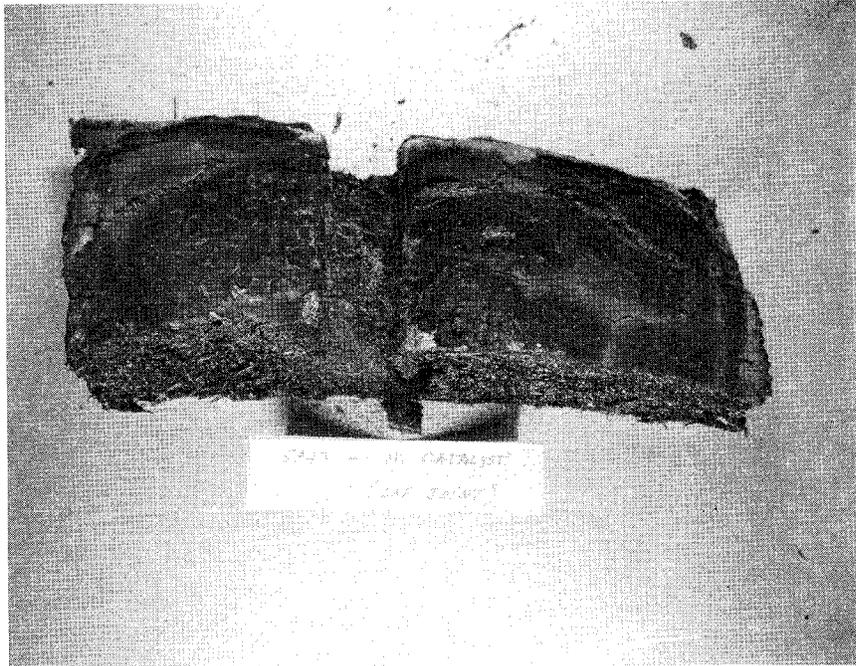


Figure 5. Fire exposed side of foam formulation 1.  
Note excessive shrinkage at lap joint.



Figure 6. Fire exposed side of foam formulation 2.



Figure 7. Fire exposed side of foam formulation 3.



Figure 8. Fire exposed side of foam formulation 4.



Figure 9. Fire exposed side of foam formulation 5.



Figure 10. Fire exposed side of foam formulation 6.

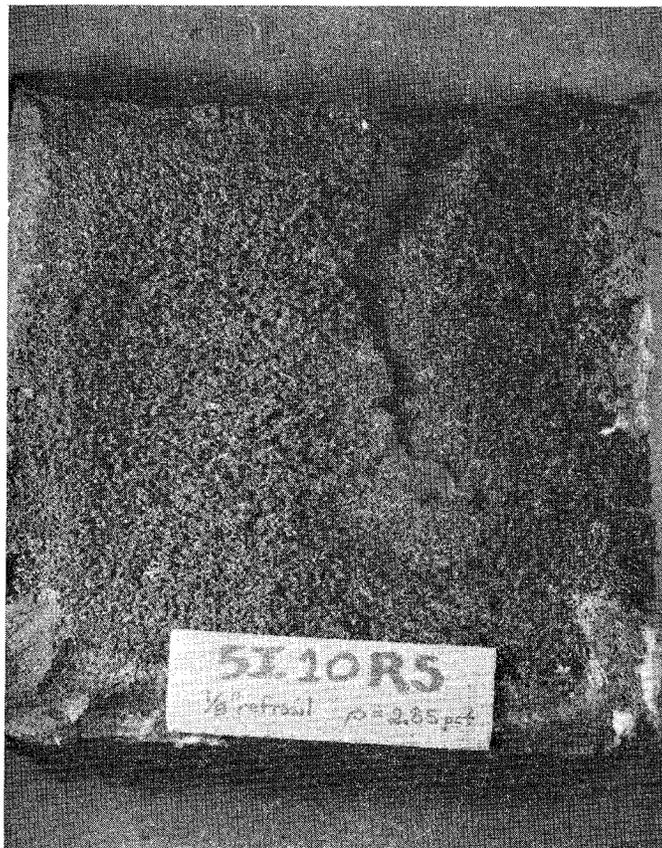


Figure 11. Fire exposed side of foam formulation 7.

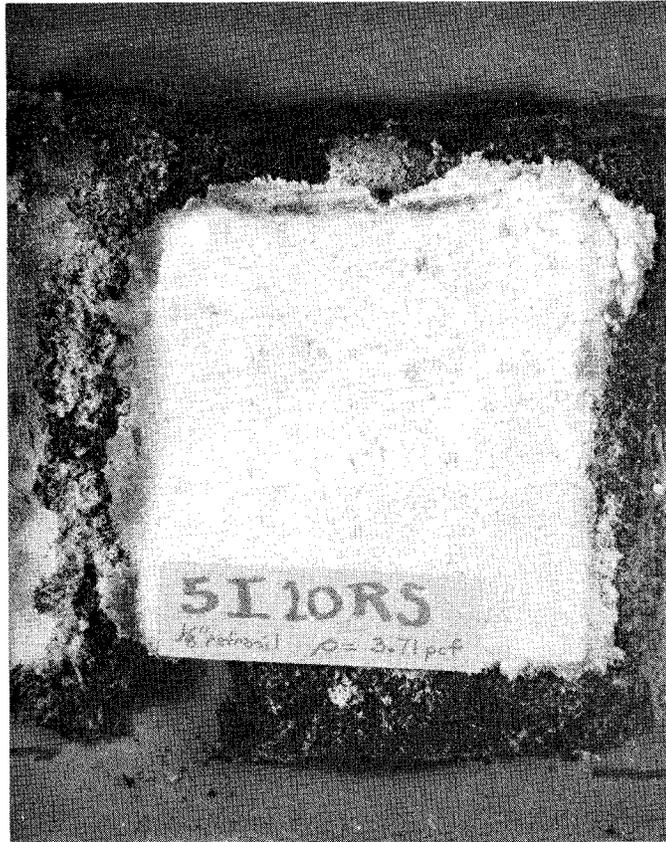


Figure 12. Fire exposed side of foam formulation 8.



Figure 13. Fire exposed side of foam formulation 9.



Figure 14. Fire exposed side of foam formulation 10.



Figure 15. Glass reinforced and silica reinforced polyurethane foam before and after pyrolysis oxidation in a high temperature furnace. Note relative difference in shrinkage effects of the two reinforcing materials.

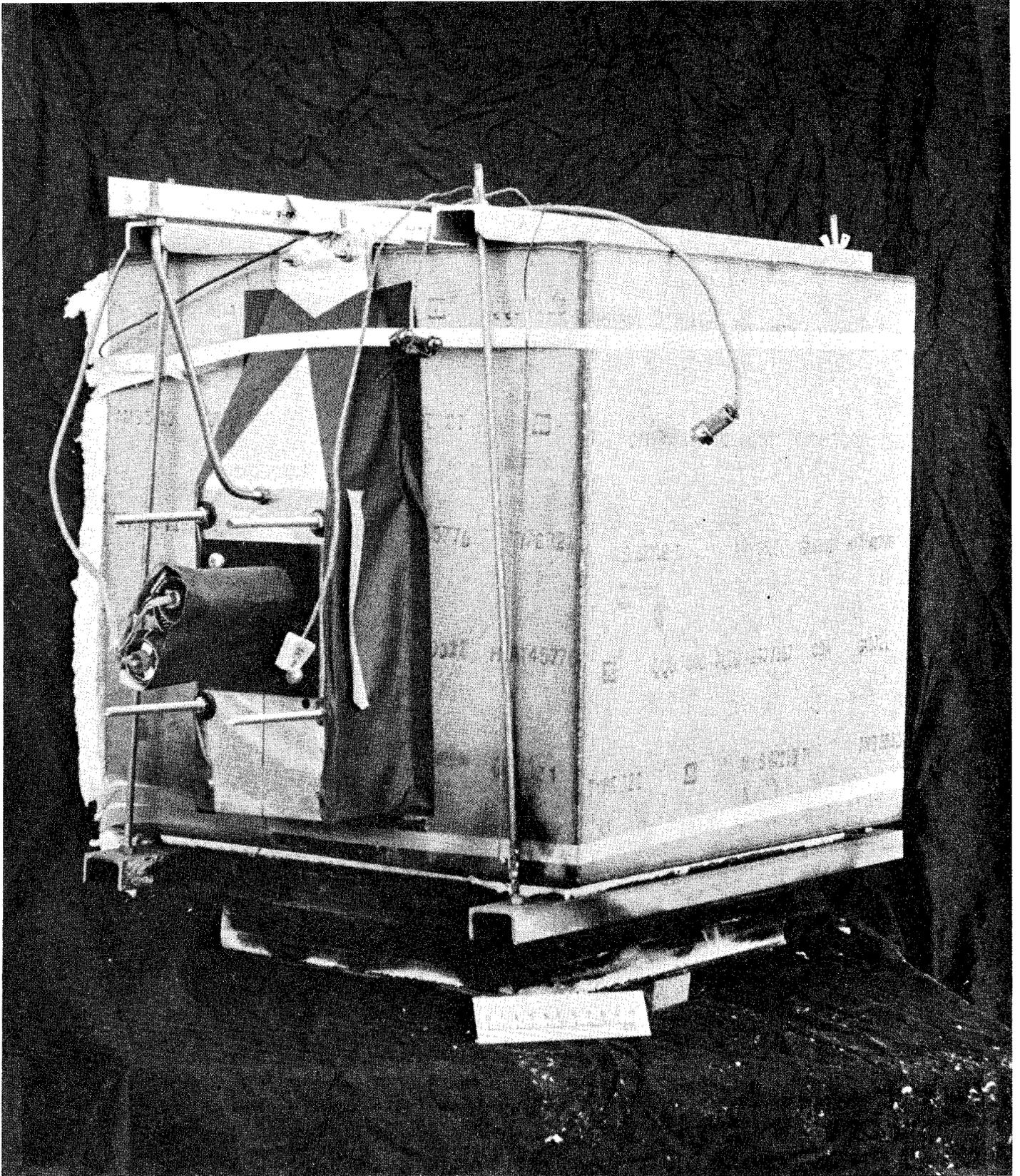


Figure 16. Specimen holder and enclosed test chamber used to determine still air temperature.

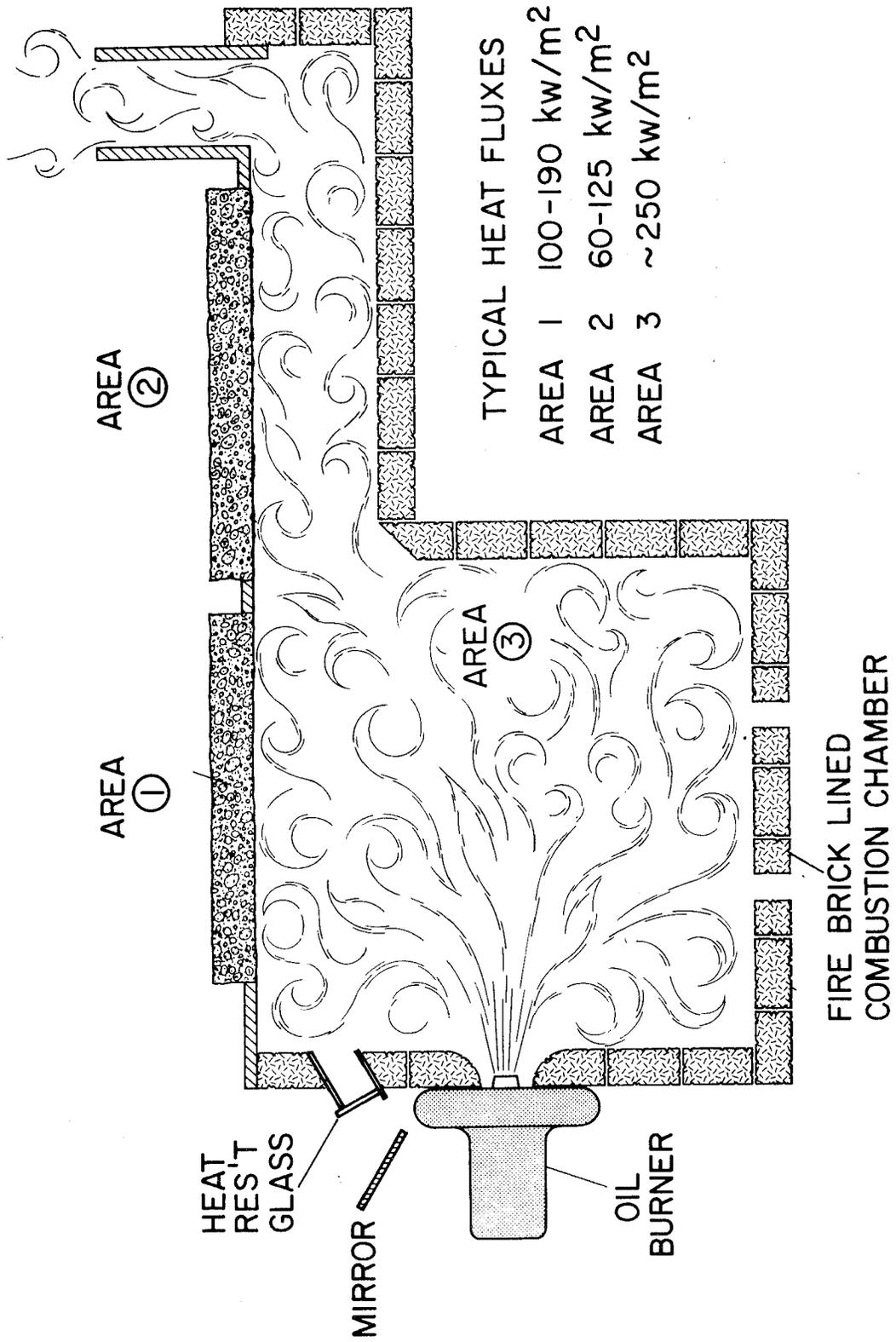


Figure 17. Cross-sectional view of the NASA Ames T-3 Fire Test Facility.

TABLE 3. SUMMARY OF THERMAL TESTS OF POLYURETHANE FOAM VARIATIONS

TEST No.	DESIGNATION	DENSITY kg/m <sup>3</sup>	DESCRIPTION	DURATION MINUTES	REMARKS
1.	5A43	53.35	Polyurethane foam, cast, reinforced with 1.91 cm "E" glass.	4.75	Initial heavy smoke generation. Specimen warpage observed at 2.0 minutes. Gap warpage initiated at 2.5 minutes. Gap thermocouple exceeded 540°C at 3.1 minutes. Escaping flame around corner seat at 3.5 minutes. Most of specimen reduced to char-like substance.
2.	5A43	64.72	Polyurethane foam, cast, reinforced with 1.91 cm "E" glass.	6.50	Initial heavy smoke generation. Warpage not as pronounced as during test 1. Some escaping flame around corner seal at 5.0 minutes followed by steady rise of backface temperature.
3.	5A43	39.57	Same as test 2	3.17	Initial heavy smoke generation. Severe warpage with evidence of corner "hot spot" at 1.5 minutes. Backface temperature rise initiated at 2.0 minutes.
4.	5F14	65.20	Polyurethane foam, cast, reinforced with 1.91 cm "E" glass, KBF <sub>4</sub> added and catalyst reduced.	6.00	Initial heavy smoke generation. Backface charring observed at 4.0 minutes. Significant backface temperature rise initiated at 5.0 minutes.
5.	5F14RS	69.20	Polyurethane foam, cast, reinforced with 0.64 cm silica fibers, KBF <sub>4</sub> added, reduced catalyst.	3.50	Excessive voids noted in specimen prior to test. Noticeable backface temperature rise observed at 1.0 minutes. Noted formation of white "blanket" of silica on exposed face. Gas flow in oven caused local failures of this "blanket".

TABLE 3. CONCLUDED

6.	5F14RS	64.56	8.67	<p>Polyurethane foam, cast, reinforced with mixture of 0.64 cm and 0.32 cm silica fibers, KBF<sub>4</sub> additive, reduced catalyst</p>	<p>No backface temperature rise until 3.0 minutes. Minimum warpage. Excellent fire exposed face "blanket", resistant to oven wind forces. Slower temperature rise than previous specimens.</p>
7.	5F14RS	45.66	5.33	<p>Polyurethane foam, cast, reinforced with 0.32 cm silica fibers, KBF<sub>4</sub> additive, reduced catalyst. Backface inclosed in box.</p>	<p>Initiation of backface temperature rise at 2.0 minutes. Good fire exposed face "blanket" but extremely weak with rapid erosion. At conclusion of test only a thin backface shell remained. Still air temperature at 5.33 minutes. was 56°C.</p>
8.	5F14RS	59.43	7.00	<p>Same as test 6. Backface inclosed in box.</p>	<p>Initiation of backface temperature rise at 3.0 minutes. Strong, erosion resistant "blanket" formation. Still air temperature at 7.00 minutes was 52°C.</p>
9.	5F14RS	56.55	8.75	<p>Polyurethane foam, cast, reinforced with mixture of 0.64 cm and 0.32 cm silica fibers, no KBF<sub>4</sub> additive, reduced catalyst. Backface inclosed in box.</p>	<p>Initiation of backface temperature rise at 4.0 minutes. Strong, erosion resistant "blanket" formed. Still air temperature at 8.75 minutes was 66°C. Post-test foam damage unrelated to test.</p>
10.	5F14RS	64.72	9.33	<p>Same as test 9.</p>	<p>Initiation of backface temperature rise at 4.0 minutes. Strong, erosion resistant "blanket" formed. Still air temperature at 9.33 minutes was 85°C.</p>

TABLE 4. PHYSICAL PROPERTIES OF CANDIDATE FIRE BARRIER POLYURETHANE FOAMS

TYPICAL VALUE

PROPERTY	ASTM	UNITS	SF43	SF14	SF14RS
Density (Apparent)		kg/m <sup>3</sup>	39.73	42.13	41.65
Comp. Strength ↓ 10%	D-1621	N /m <sup>2</sup> × 10 <sup>3</sup>	194.6	103.4	48.27
Modulus ↓	D-1621	N /m <sup>2</sup> × 10 <sup>3</sup>	6205.5	2068.5	1034.25
Comp. Strength II 10%	D-1621	N /m <sup>2</sup> × 10 <sup>3</sup>	199.95	213.75	117.22
Modulus II	D-1621	N /m <sup>2</sup> × 10 <sup>3</sup>	6895.0	7929.3	5860.75
Tensile Strength ↓	D-1623	N /m <sup>2</sup> × 10 <sup>3</sup>	248.2	303.38	144.80
Tensile Strength II	D-1623	N /m <sup>2</sup> × 10 <sup>3</sup>	165.48	144.80	55.16
Limiting Oxygen Index	D-2863	%	19.75	22.5	23.25
Friability (wt. Loss @ 10 Min.) Oak Block		%	2	2	16

### Thermal Screening Test Conclusions

When this class of polyurethane foams is initially exposed to a fire, it resists heat transfer by a combination of low thermal conductivity, transpiration cooling, sensible heating of off-gassing by-products, boundary layer convection blockage, and opaque outgassing which scatters optical radiation. During this process the reinforcing fiber matrix serves to maintain the structural integrity of the charring barrier. Selection of reinforcing matrix material also determines the foam resistance to warpage and its mechanical strength while exposed to the fire. After depletion of the gases, heat flow through the barrier is dependent on the conductive heat transfer coefficient of the remaining char structure, about 10 times that of the virgin foam.

Heating of the air space beyond the barrier unexposed face occurs through a combination of convective and radiative heat transfer. Radiation, being a function of temperature to the fourth power, rapidly becomes the primary mode of heat transfer providing that burn-through does not occur. Emissivity and view factors both regulate radiation heating rates; however, the still air temperature data indicate that 205°C, 15 centimeters from the barrier materials, cannot be attained during the 10-minute test for any of the formulations evaluated.

Conclusions about the foams tested are as follows:

- a. Thermal insulation capability increases directly with increasing density.
- b. Silica fiber reinforcement reduces foam warpage during heating by at least 50 percent when compared to glass fibers.

- c. After depletion of gases, glass reinforced foam allows a backface temperature rise of approximately 100°C per minute, while the silica fibers allow a rise rate of about 30°C per minute.
- d. Addition of potassium fluorborate increases the silica fiber backface temperature rise rate to approximately 60°C per minute, until 150°C is achieved, then reduces the rise rate to about 15°C per minute.
- e. The potassium fluorborate additive increases the limiting oxygen index from 22.5 percent to 23.25 percent, thus increasing the foam resistance to combustion and flame spread.
- f. Substitution of silica fibers and addition of potassium fluorborate reduces the polyurethane foam mechanical strength by about 50 percent.

Either of the two basic foam formulations will meet the thermal acceptance criteria. Except for mechanical strength the 5F14RS formulation is clearly superior to the 5F14 formulation. Mechanical strength requirements have not yet been determined; however, the 5F14RS foam appears adequate and it is recommended for additional testing and evaluation.

#### AIRCRAFT FIRE SIMULATOR TEST

##### General

An aircraft fire barrier test simulator was designed and fabricated at the Naval Weapons Center, China Lake, California, to be used as a realistic screening apparatus for candidate fire barrier system. The test specimen mounting fixture was designed so that it could accept a wide geometry range of proposed concepts. Both organic and inorganic materials were evaluated. Most of the organic approaches required a building block assembly with lap

or butt joints and clearance gaps of up to 0.95 cm (3/8 inch) to accommodate penetrating aircraft parts. Two additional problem areas investigated were the penetration of an electrical wire bundle and a thin-walled aluminum tube (simulating an aircraft fuel vent line) through the barrier.

#### Materials Tested

Intumescent coatings were used to close clearance gaps. These intumescent coating materials, when exposed to fire, swell forming a carbonaceous porous matrix which functions as a thermal barrier (thus closing gaps) while, simultaneously, flame-quenching gaseous breakdown products are produced during the degradation process.

Organic materials investigated consisted of various formulations of polyurethane, closed cell, rigid foams. Inorganics tested were flexible silicone and alumina-silica mat. Table 5 presents a detailed listing of all materials and combination of materials tested.

#### Test Setup

The fire barrier test simulator was designed to generate a temperature, pressure, airflow, and heat flux environment which duplicates fire conditions in an inflight aircraft. Figure 18 details this simulator. The simulator consists of a tunnel with a controlled airstream directed through it. The downstream section of the tunnel is angled at 30 degrees to the forward section. The airflow passes over a fire pan and the flame is carried downstream to impinge on the angled test specimen which forms one wall of the tunnel. A buffer plate upstream of the fire pan acts as a flame holder and shapes a uniform flame across the specimen. Airflow velocity across the specimen was approximately 5 meters/second (10 knots), provided by a half

meter diameter axial flow fan powered by a universal motor with speed control. A pressure differential of up to  $35\text{gms/cm}^2$  (0.5 psc) was obtained with a cowled exhaust fan mounted over the unexposed side of the test specimen. For general specimen backface temperature measurements the thermocouples were mounted to 2cm by 0.16cm aluminum disks which were then bonded to the specimen with high temperature adhesive. Clearance gap thermal data were obtained with thermocouples attached directly at the gaps. Burner pan fuel flow was regulated to stabilize heat flux at  $11.35 \times 10^4$  watts/cm<sup>2</sup> (10 Btu/ft<sup>2</sup>-sec) with thermal buildup according to the schedule shown in figure 19. Documentary data were obtained with a still photographic camera.

During the initial series of tests the heat rate sensor was mounted in the test specimen just protruding past the fire exposed face. However, outgassing of the foam volatiles and migration of the intumescent coatings used interfered with this sensor and it was necessary to relocate it just upstream from the specimen mounting location. Reference air temperature was obtained with a mercury-in-glass thermometer. Time reference was obtained through the synchronous motor drive of the recorder.

TABLE 5. MATERIALS EVALUATED IN AIRCRAFT FIRE SIMULATOR TESTS

ORGANIC MATERIALS

5A43 polyurethane, glass reinforced, semi-rigid foam, cut (no outer skin), 5.1cm thickness,  $40 \text{ Kg/m}^3$  density, manufactured at NWC with ingredients supplied by AVCO, mixed to NASA specifications.

5A43 foam, spray molded (with outer skin), 2.5cm, 7.6cm thicknesses, 50 to  $65 \text{ Kg/m}^3$  density, supplied by AVCO.

BX 352-P polyurethane, glass reinforced semi-rigid foam, spray molded, 7.6cm thickness, 50 to  $60 \text{ Kg/m}^3$  density; supplied by GRUM MAN

5F14RS polyurethane, silica fiber reinforced, semi-rigid foam, molded, 5.1cm thickness, 55 to  $65 \text{ Kg/m}^3$  density; supplied by NASA/Ames.

INORGANIC MATERIALS

WRP-X-AQ ceramic felt, 2.5cm thickness,  $320 \text{ Kg/m}^3$  density dry (up to  $1,120 \text{ Kg/m}^3$  wet), supplied by GRUM MAN.

Silicon foam, flexible, 5.1cm thickness,  $320 \text{ Kg/m}^3$  density, supplied by GRUM MAN.

INTUMESCENT COATING

AVCO supplied: 1000, 1000 modified, 1010, 1200 (flexible sheet), 1600 B, 313

GRUM MAN supplied: 477 GF

NASA supplied: Lacquer-type (p-nasa salt in nitrocellulose lacquer), M-30 semi-flexible sheet

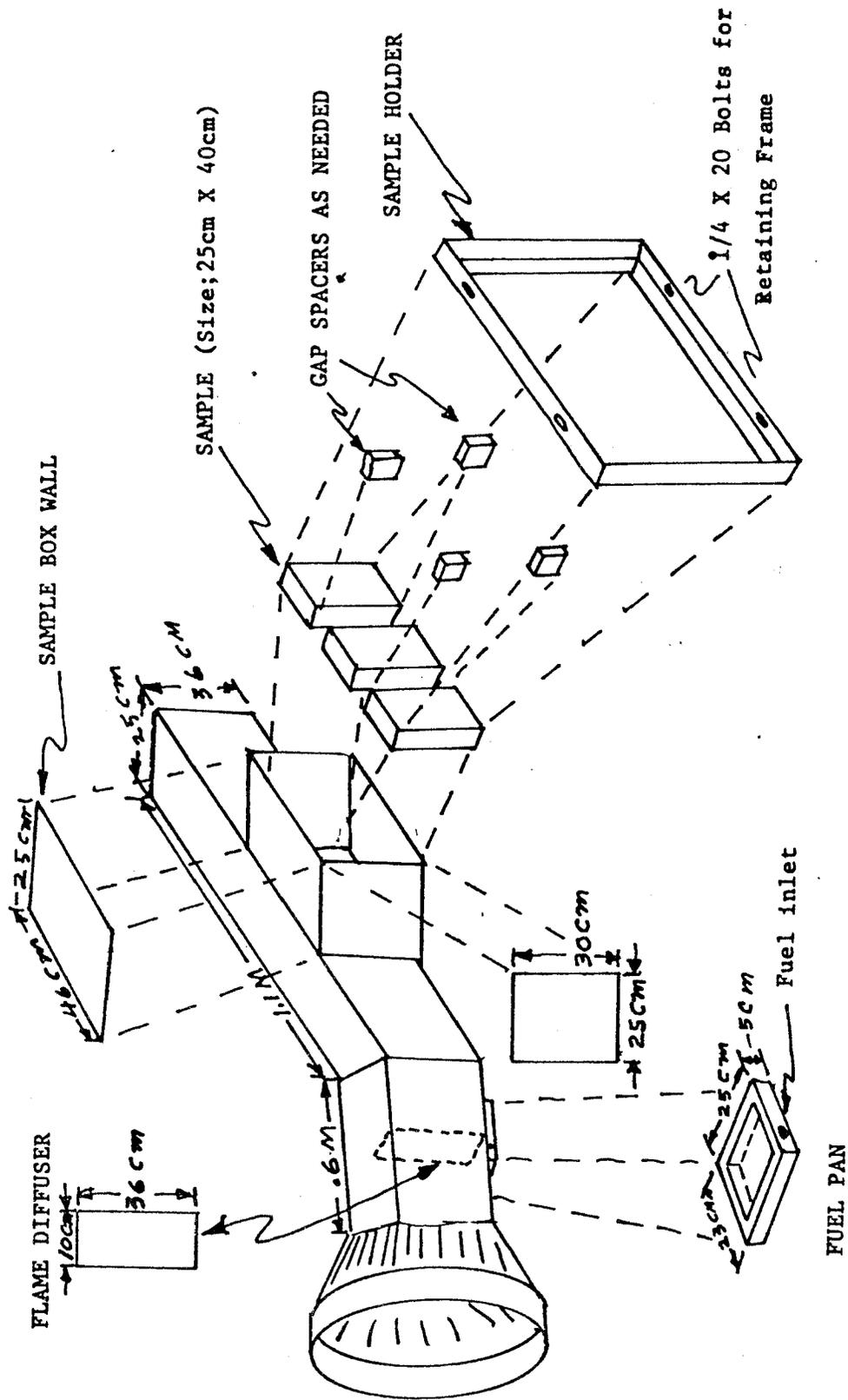


Figure 18. Aircraft fire simulator test device.

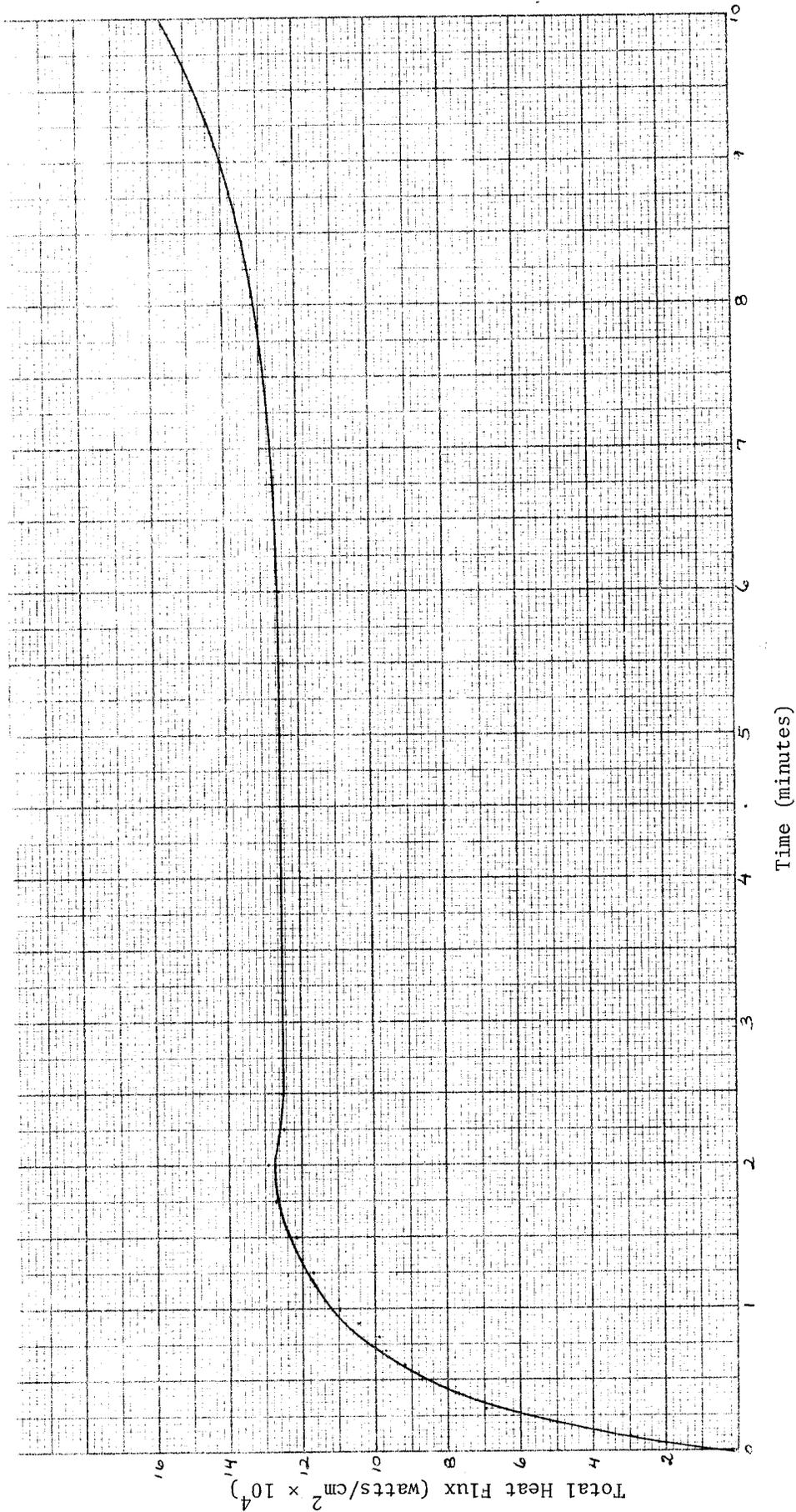


Figure 19. Typical heat flux schedule for the aircraft fire simulator.

## TEST SPECIMEN PREPARATION

Specimens as received came in various sizes and thicknesses. The materials were cleaned, cut to fit the test fixture, and the appropriate intumescent coating applied and cured as required.

Four basic mounting techniques were employed. Thermal resistance of the candidate specimens were obtained using continuous blocks; effects of butt joints were determined using three smaller blocks installed in the mounting fixture such that each block firmly contacted the other; effects of clearance gaps (to be closed by intumescent swelling) used three blocks sized such that when installed in the mounting fixture, gaps of 0.64 cm (1/4-inch) or 0.95 cm (3/8-inch) could be established between each block. Steel spacers were placed at the bottom and top of a gap to hold the desired spacing.

## TEST PROCEDURE

A given test specimen was mounted in the Aircraft Fire Simulator and thermocouples installed. Instrumentation calibration was conducted on the amplifier-recorder combination using a suitable substitute voltage source followed by photographic documentation of the pretest configuration. Next, fuel was introduced into the fire pan, ignited, airflow turned on, and fuel flow rate adjusted to give a full flame over the sample. Recorder time zero was noted when flame first reached the test specimen. In tests with gapped specimens, intumescent initiation was aided by back pressuring the exhaust or by lowering the unexposed specimen face pressure using the intake side of a high pressure blower. Tests were continued for 15 minutes or until specimen burnthrough, whichever occurred first. During one series of tests, specimen

strength while exposed to fire was determined by conducting the standard burn test for five minutes, then initiating and gradually increasing the pressure differential across the specimen until failure occurred.

## TEST RESULTS

Results of all testing are summarized in Table 6. In the first series of tests, continuous specimens were evaluated to determine thermal "toughness" with no pressure differential loading being applied. Normalizing the results to installed weight (grams per square centimeter) required for each minute of thermal protection showed that the 5F14RS material can provide a given level of protection at the lightest weight for the materials tested. These data are shown in Table 7.

The second series of tests measured specimen strength while exposed to fire. Clearance gap intumescent seal strength evaluation was included to determine overall system resistance to pressure loading. Intumescent chars of 477 GF and 1600 failed at 3.56 cm-H<sub>2</sub>O and 7.62 cm-H<sub>2</sub>O pressure differential, respectively. The AVCO 5A43 and the NASA 5F14RS foam chars failed at 15.24 cm-H<sub>2</sub>O pressure differential, respectively, without reaching the failure point for the 313 intumescent char. These data are presented in Table 8.

Resistance to burnthrough for gap filling intumescent char under no load conditions is shown in figure 20. The M-30 material was not tested under these conditions; however, results of the load tests indicate that the M-30 is comparable to the 1200 intumescent flexible sheet. Additionally, several combination intumescent coating schemes were investigated: 1000 modified applied over 1200 burned through in 6.0 minutes at 5.1 cm foam thickness; 1000 over 1200 burned through in 10.0 minutes at 5.1 cm thickness.

In later tests, the operating procedures were modified to include forcing flame through foam block gaps to accelerate the gap sealing rate. Figure 21 shows a typical example of the temperature measurement profile. Intumescent action initiation was rapid but as the gap closed, outgassing inhibited final closure rate.

TABLE 6. SUMMARY OF EXPERIMENTS CONDUCTED IN AIRCRAFT FIRE SIMULATOR

SPECIMEN DESCRIPTION		FACE COATING		GAP		GAP COATING		BURNTHROUGH TIME (min.)	COMMENTS
TYPE	THICKNESS (cm)	DENSITY (kg/m <sup>3</sup> )	TYPE	THICKNESS (mm)	(mm)	TYPE	THICKNESS (mm)		
WPR Felt	2.54	400	None	-	None	-	-	20 +	Continuous specimen
Silicone	5.08	320	None	-	None	-	-	14.0	"
5A43	7.62	77	1200	0.51	None	-	-	13.1	"
5A43	5.08	69	None	-	None	-	-	4.5	Edge failure
SFI4RS	5.08	67	313	0.25	None	-	-	13.2	Continuous specimen
SFI4RS	5.08	71	None	-	None	-	-	6.7	Edge failure
SFI4RS	5.08	75	None	-	None	-	-	15 +	No burnthrough
5A43	5.08	55	1200	0.51	9.5	M-30	5.59	5.0*	Load test $\Delta p = 15.24$ cm-H <sub>2</sub> O
Silicone	5.08	320	None	-	butt	None	-	8.0	$\Delta p = 0$ failed joint
BX352-P	7.62	60	1600	0.51	6.3	1600	1.5	5.0*	$\Delta p = 7.62$ cm-H <sub>2</sub> O
BX352-P	7.62	60	477 GF	0.51	6.3	477 GF	1.5	5.0*	$\Delta p = 3.56$ cm-H <sub>2</sub> O
SFI4RS	5.08	60	1200	0.51	9.5	M-30	5.59	5.0*	$\Delta p = 19.05$ cm-H <sub>2</sub> O
WRP Felt	2.54	400	None	-	butt	ceramcoat	-	10.0*	$\Delta p = 12.7$ cm-H <sub>2</sub> O
5A43	2.54	59	1000 mod	0.25	butt	1000 mod	1.52	4.0	Edge failure
5A43	2.54	62	1000 mod	0.25	butt	1000 mod	1.52	4.75	
5A43	5.08	59	1000 mod	0.25	butt	1000 mod	1.52	8.0	
5A43	7.62	48	1000 mod	0.25	butt	1000 mod	1.52	7.5	
5A43	2.54	61	1010	0.25	butt	1010	1.52	4.5	
5A43	5.08	52	1010	0.25	butt	1010	1.52	5.75	
5A43	7.62	55	1010	0.25	butt	1010	1.52	8.5	
5A43	2.54	63	313	0.25	butt	313	1.52	3.0	
5A43	2.54	63	313	0.25	butt	313	1.52	2.5	
5A43 cut	5.08	40	lacquer	0.25	butt	lacquer	1.02	3.5	
5A43 cut	5.08	40	lacquer	0.25	butt	lacquer	2.03	4.0	
5A43	2.54	56	1000	0.25	butt	1000	1.52	2.75	
5A43	5.08	63	1000	0.25	butt	1000	1.52	2.9	
5A43	7.62	51	1000	0.25	butt	1000	1.52	3.5	
5A43	7.62	54	1000	0.25	butt	1000	1.52	5.0	
5A43	5.08	52	1000 mod	0.25	butt	1000 mod	1.52	6.0	
5A43	7.62	58	1000 mod	0.25	butt	1000 mod	1.52	8.5	Edge failure
5A43	2.54	61	1010	0.25	butt	1010	1.52	3.0	
5A43	5.08	53	1010	0.25	butt	1010	1.52	2.5	
5A43	7.62	53	1010	0.25	butt	1010	1.52	4.75	

\* Pressure differential applied after 5 minutes.

TABLE 6. CONCLUDED

TYPE	SPECIMEN DESCRIPTION		FACE COATING		GAP (mm)	GAP COATING		BURNTHROUGH TIME (min.)	COMMENTS
	THICKNESS (cm)	DENSITY (kg/m <sup>3</sup> )	TYPE	THICKNESS (mm)		TYPE	THICKNESS (mm)		
5A43	5.08	53	313	0.25	6.35	313	1.52	5.0	Edge failure
5A43	7.62	49	313	0.25	6.35	313	1.52	8.5	
5A43	5.08	73	1000	0.25	6.55	1200	1.52	7.75	1000 over 1200
5A43	5.08	50	1000	0.25	6.35	1200/1000	4.57	10.0	
5A43	2.54	57	lacquer	0.25	6.35	lacquer	1.02	2.25	3.6
5A43	2.54	58	1000	0.25	9.53	1000	1.52	3.6	
5A43	5.08	54	1000	0.25	9.53	1000	1.52	4.75	5.5
5A43	7.62	58	1000	0.25	9.53	1000	1.52	5.5	
5A43	5.08	62	1000 mod	0.25	9.53	1000 mod	1.52	3.75	6.5
5A43	7.62	48	1000 mod	0.25	9.53	1000 mod	1.52	6.5	
5A43	7.62	71	1000 mod	0.25	9.53	1000 mod	1.52	11.75	2.25
5A43	2.54	64	1010	0.25	9.53	1010	1.52	2.25	
5A43	7.62	50	1010	0.25	9.53	1010	1.52	5.0	Gap never closed completely
5A43	5.08	59	313	0.25	9.53	313	1.52	3.5	
5A43	7.62	53	313	0.25	9.53	313	1.52	7.25	5.75
5A43	7.62	-	1600B	0.25	9.53	1600B	1.52	5.75	
5A43	7.62	-	1600B	0.25	9.53	1600B	1.52	7.2	4.0
5A43	2.54	-	1200	0.25	9.53	1200	1.52	4.0	
5A43	5.08	86	1000 mod	0.25	9.53	1000 mod/1200	2.03	6.0	3.5
5A43	5.08	57	1010	0.25	9.53	1010/1200	2.54	3.5	
5A43	5.08	-	1200	0.25	9.53	1200	2.03	10.1	No burnthrough
5A43	7.62	-	1200	0.25	9.53	1200	2.03	20 +	
5A43	2.54	-	1200	0.25	9.53	1200	2.03	5.5	

TABLE 7. AIRCRAFT FIRE SIMULATOR DATA ON THERMAL RESISTANCE OF CANDIDATE MATERIALS WITHOUT PRESSURE DIFFERENTIAL LOADING

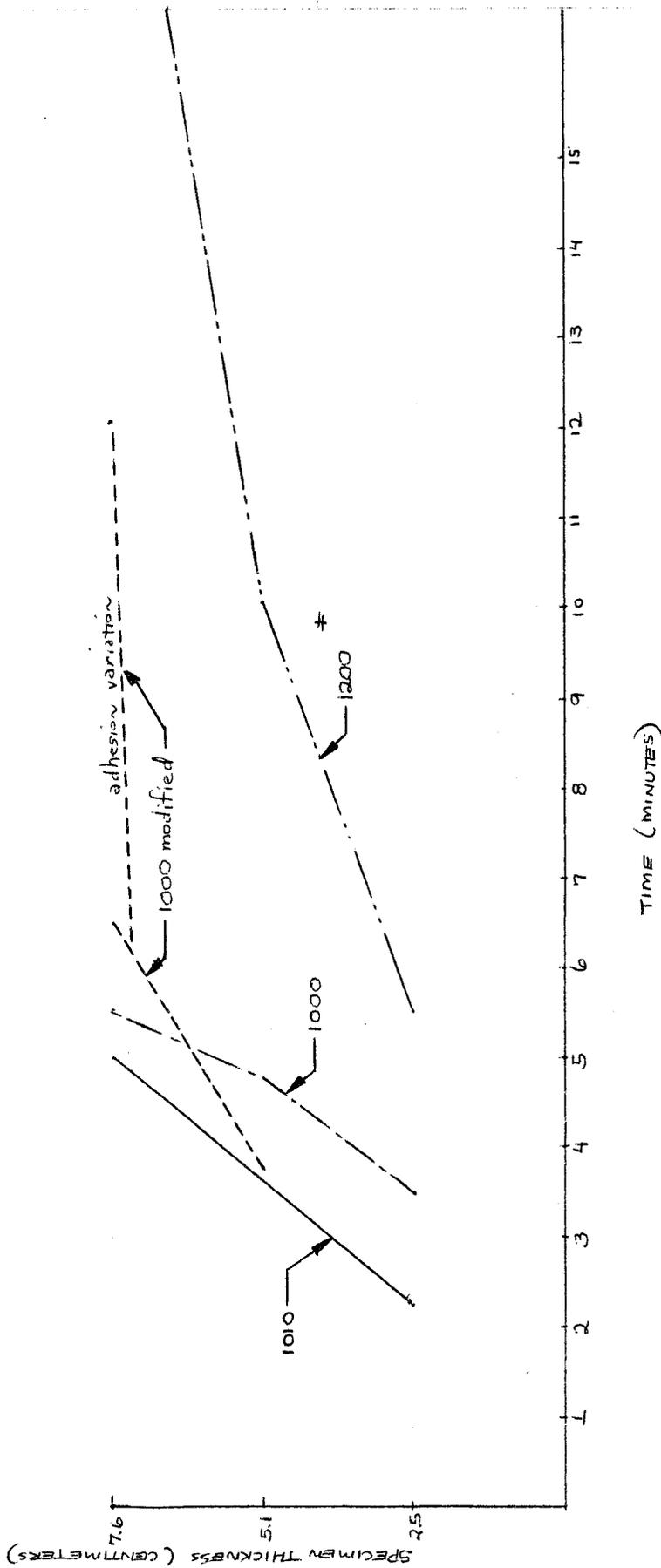
TEST SPECIMEN DESIGNATION	SPECIMEN DESCRIPTION		FACE COATING		BURN THROUGH TIME (MIN.)	MATERIAL REQUIRED PER MINUTE PROTECTION (g/cm <sup>2</sup> -min)	PERCENT WEIGHT PENALTY
	THICKNESS (cm)	DENSITY (kg/m <sup>3</sup> )	TYPE	THICKNESS (mm)			
5A43	5.08	69	NONE	-	4.5*	-	-
5A43	7.62	77	1200	0.51	13.0	0.045	42
SILICON	5.08	320	NONE	-	14.0	0.125	79
WPR FELT	2.54	400	NONE	-	20 +	0.041	34
5F14RS	5.08	71	NONE	-	6.8*	-	-
5F14RS	5.08	75	NONE	-	15 +	0.026	0
5F14RS	5.08	67	313	0.25	13.3	0.026	0

\* Edge failure rather than actual burnthrough

TABLE 8. GAP FILLING INTUMESCENT CHAR STRENGTH DURING BURN TEST

SPECIMEN DESCRIPTION		GAP COATING		MAXIMUM PRESSURE * DIFFERENTIAL (kg/cm <sup>2</sup> )
DESIGNATION	THICKNESS (cm)	TYPE	THICKNESS (mm)	
5A43	5.08	M-30	5.59	0.42
BX 352-P	7.62	1600	1.50	0.21
BX 352-P	7.62	477GF	1.50	0.10
5F14RS	5.08	M-30	5.59	0.53

\* Load applied 5 minutes after burn initiation and gradually increased to failure.



\* Initial intumescent coating total thickness at gap was 0.152 centimeters (0.060 inches).

‡ 0.203 centimeters (0.080 inches) initial coating thickness at gap.

Figure 20. Burnthrough time for intumescent materials filling a 0.95 cm gap of 5A43 foam.\*

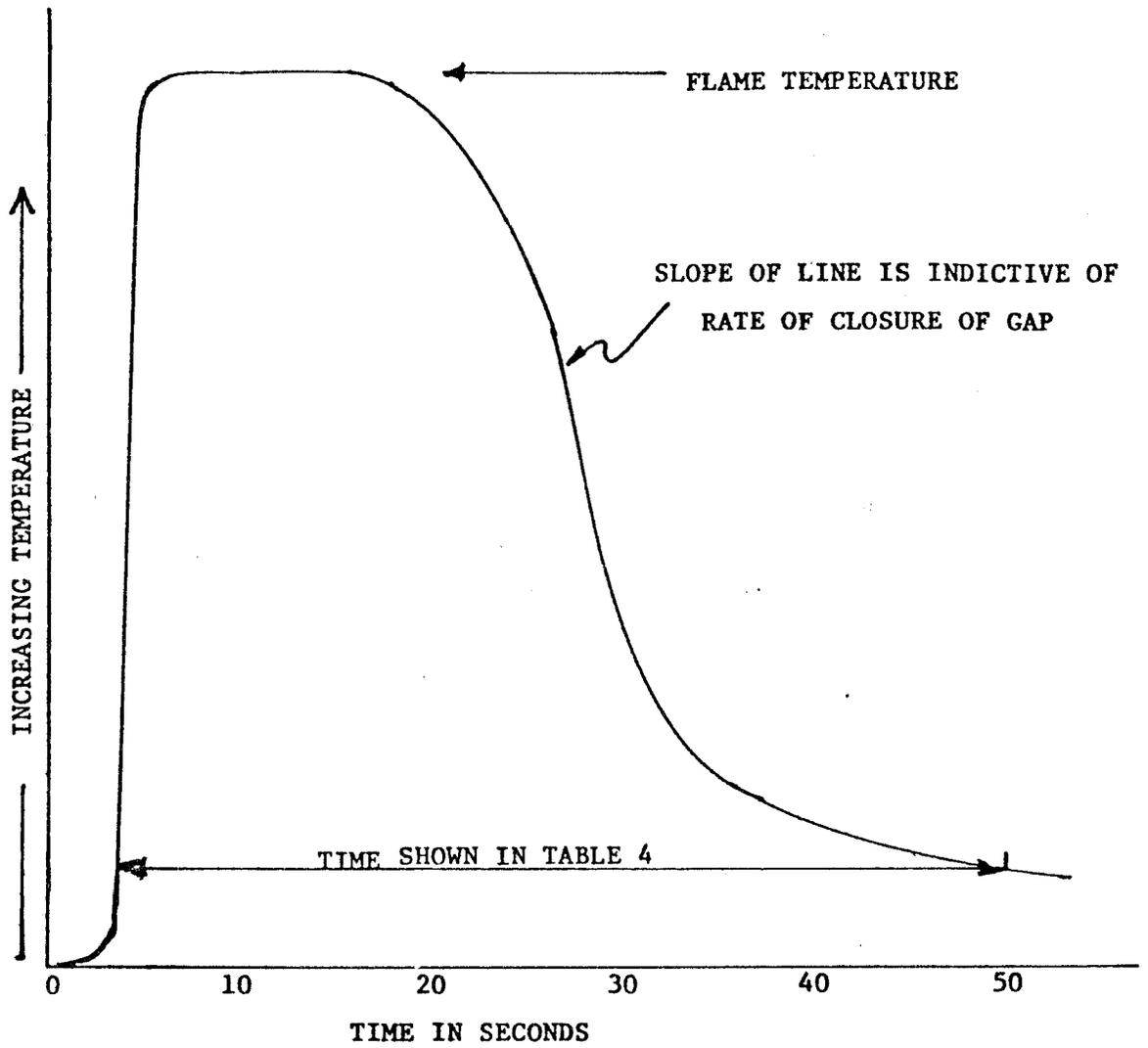


Figure 21. Typical temperature trace associated with closure of gap.

## OBSERVATIONS AND CONCLUSIONS

Foam specimen anomalies had a noticeable effect on results. In casting relatively large blocks of fiber reinforced polyurethane-type foams the mixed ingredients are injected into the bottom of a mold and then allowed to free rise to the top. This process not only tends to orient the reinforcing fibers with the rise direction, but also creates homogeneity variations, foam density being greatest at the bottom of a casting block and gradually decreasing towards the top. Color variations in some of the specimens indicated that some of the isocyanate had not completely reacted. These process variations allowed for the presence of excessive voids in some of the samples which resulted in premature failures. No technique was applied to nondestructively measure foam homogeneity. "Soft" X-rays or acoustical techniques may have this capability.

Intumescent paint performance was also influenced by quality control of the particular coating and in its application process. Intumescent characteristics found desirable for thermal barrier application included formation of a mechanically strong insulating char (but of not especially large volume) of the exposed foam surfaces and rapid initial rise followed by maximum paint adhesion in the gap filling application. Improper adhesion was sometimes noted by detachment of portions of the coating upon initial application of heat. Residual traces of releasing agent of the virgin foam blocks, from the casting operation, prior to coating application, was the suspected fault for this failure mechanism.

Of the polyurethane foam types investigated, the 5F14RS foam (basically the 5A43 formulation modified by reduced catalyst, substitution of silica fibers for glass ones, and addition of a high temperature reacting additive)

was clearly superior in terms of thermal resistance. Indeed, it could often prevent burnthrough for in excess of 10 minutes with no supplemental intumescent coating protection. However, it must be noted that this was a special laboratory hand-mixed foam with no production experience behind it. Any of the other tested polyurethane foams could be made to resist burnthrough under the tested conditions with the aid of a proper intumescent coating.

In the exposed foam surface application, 1000 modified (with good adhesion) and the 1200 flexible sheet were found to be clearly superior to the other coatings tested. The M-30 semiflexible sheet, though not tested for this application, has laboratory proven performance indicating that it is at least equal to the 1200 type coating. The sheet format is desirable because thickness and bonding quality control are greatly simplified when compared to spray applied coatings.

In the gap filling application, M-30 followed by 1200 sheet were the most efficient. However, initial swelling action for both of these materials is relatively slow and the application of a thin outer coating of a fast rising material, such as 1000 modified, is recommended. Many of the intumescent materials suffer from an environmental "leaching out" effect which tends to stain adjacent structures. While this staining agent is noncorrosive, and the performance of the material is not measurably effected by this process, it is undesirable and can be protected by application of a thin outer coating (10 mils) of Saran.

Thermal Protection Paint 313 exhibited erratic performance. Prior laboratory testing indicated that this was a high efficiency material, and while no effort was made to determine why this irregular performance

occurred, it is suspected that insufficient mechanical mixing of the ingredients combined with incomplete removal of releasing agent from the foam specimens combined to cause it.

In applications where a predominant flow direction exists for the fire exposed side of polyurethane foam type barriers, the foam located most upstream will receive the greatest heat load. This occurs because foam smoke outgassing, when exposed to fire, travels downstream forming a thickening boundary layer of protection.

Even with intumescent coating protection the polyurethane foams burn down to their basic carbonaceous char form within about 5 minutes after exposure to fires of the tested intensity. Little actual test or measurement data of the physical characteristics of these chars at temperature exist. Their ability to withstand internal aircraft airflow generated and vibrational type loads is unknown and must be determined prior to any actual incorporation into aircraft. In the limited tests conducted with pressure differential applied loads, the foams failed at relatively low levels. This suggests that metallic backface reinforcement would probably be required to meet environmental criteria during an actual fire.

Sizing for aircraft installation and methods of mechanical fastening of the foams were not investigated in this effort, but either of these factors could seriously affect the practicality of a given installation design. However, bounding of the foams to thin metal sheets, with all mechanical fastening being accomplished through the sheets, would appear to simplify this problem area.

Limited testing was conducted with two inorganic materials: a flexible silicone foam and a rigidized ceramic felt (designated WRP-X-AQ). Although

high in density when compared to polyurethane foams, both materials exhibited high thermal resistance. The silicone foam did suffer from significant distortion prior to burnthrough and continued to burn for a number of minutes after test shutdown. This vigorous self-combustion characteristic indicates that the silicone could act as a fire re-light source aboard an aircraft. The ceramic felt (visual inspection suggests that it is a dense mat of silica fibers rigidized with a ceramic-type binder) proved almost totally inert in the tested thermal environment. Steam generation during the first 5 minutes of fire exposure indicated that the felt had absorbed a significant amount of water. Later laboratory tests showed that after oven drying the ceramic felt density was  $320 \text{ kg/m}^3$  but could be increased to  $1,120 \text{ kg/m}^3$  by water immersion without changing dimensions. These two inorganic materials represent but a sample of a family of such insulators currently available. As such they are indicative of thermal resistance but do not necessarily represent the most efficient nor optimum inorganic material to be used for this particular application.

In the test conducted to determine effects of aluminum tubing and electrical wire bundle penetration through a fire barrier, the "weak link" failure mode predominated. The thin-wall aluminum tube was protected with 1.27 mm of 313 intumescent paint where it protruded into the fire stream. Once fire penetrated a weak spot in the tube, flame propagation from the inside rapidly melted out the rest of the tube thus defeating all other thermal protection, and acted as a conduit for breaching the fire barrier. This phenomenon did not occur with the wire bundle. Although it melted where it was directly exposed to the fire stream, flame failed to penetrate the barrier.

## RECOMMENDATIONS

In any fire barrier scheme, all elements of the barrier and adjacent equipment and structure must be considered in order to realize an effective system. Selection of actual materials for use in fire barriers is a complicated decision based on space and weight allowances, cost availability of materials, fabrication and quality control requirements, environmental considerations, installation, inspection, and removal procedures, as well as thermal resistance capability.

It is recommended that a comprehensive program be conducted to evaluate a broad range of organic, inorganic, and composite fire barrier materials under a wide variety of application conditions and the results be presented in a design guideline format.