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ABSTRACT: A program of experimental fires has been carried out to determine the effectiveness and usefulness of a burner to simulate various fire loads under different ventilation conditions in an enclosure of approximately similar dimensions as an aircraft lavatory module. The objective of the program was to develop fire containment criteria of aircraft interior panels such as burnthrough time, rate of back face temperature rise, evaluation of selected combustible and toxic gases, heat flux rate, and other parameters that affect fire containment such as structural integrity. These tests are intended to evaluate fire performance of panels under relatively full-scale conditions prior to more expensive large-scale testing.

Tests were conducted to characterize a fire load consisting of three polyethylene trash bags filled with a total of 3.37 kg of paper and other polymeric materials. The total heat release and burn rate of these trash bags were used as the basis for the calibration of a gas burner ignition source. Two fire containment tests (Tests 1 and 2) were conducted using the gas burner as the ignition source and fuel load. In these tests, two adjoining walls were state-of-the-art aircraft interior panels, 2.5 cm thick; the ceiling was a 1.2 cm thick panel. The quantity of total fuel released in these tests was approximately the same; however, the fuel release rate varied slightly. Test 1, terminated in 6 min, resulted in extensive charring and damage of the panels, but there was no actual burnthrough. Test 2 was terminated in 3 min, when structural failure occurred at the ceiling-wall corner of the module. The tests were conducted with the module in a

partially open enclosure (3/4 compartment) which was utilized primarily for gas sampling and to permit exposure of animals to the combustion products of the aircraft panels.

This paper describes the methodology utilized for these tests and experimental results.

INTRODUCTION

THE PROCESS OF improving fire safety through actual accident experience in ground structures has been expensive and wasteful of human life and resources [1, 2, 3]. Now, with newly developed instrumentation and recently available facilities, it is possible to model aircraft accidents before they happen [4]. Presently, there is a capability to model in the laboratory and to examine practical alternatives of aircraft fire safety. Many factors can affect human survivability in aircraft interior fires. Each factor can be related to an objective in a systematic fire safety design methodology. Some of the key factors and objectives are as follows:

1. *Risk of fire outbreak:* The frequency of unwanted fires must be controlled before the ignition. The probability of fire must be kept as low as possible.
2. *Fire propagation within the aircraft interior spaces:* The rate of fire spread through any interior space from a given source of ignition (a certain fire threat level) should be slow enough to allow extinguishment if passengers are to survive an inflight situtation and/or evacuation.
3. *Containment of fire in aircraft interior spaces:* A fire should be contained within a predetermined space. This space must not affect the control and safe operation of the aircraft. Further, a fire in any concealed space of the airplane should have the demonstrated ability to contain fire long enough to avoid jeopardizing the passengers and crew.
4. *Structural integrity and airworthiness:* The aircraft must retain its structural integrity and airworthiness during an onboard fire long enough for the aircraft to reach the ground safely and the passengers or crew to be evacuated.
5. *Toxic threat of products of combustion:* The aircraft construction should be free from materials that produce excessive amounts of smoke or toxic gases that would threaten the life of passengers and crew under foreseeable fire conditions.

In practice, each of these objectives requires a specific test or a series of tests that can establish the differences in performance of given materials and components. This information can then be used by the aircraft designer, as well as the manufacturer of products, to evaluate alternatives.

This research project was principally concerened with establishing a test for the third objective above, i.e., containment of fire.

EXPERIMENTAL PROGRAM

Part I. Calibration Tests for Trash Bags and Burner

The test module utilized in the tests is shown pictorially in Figure 1. The outside dimensions and interior volumes closely approximate that of an actual wide-bodied jet lavatory module. Steel angle irons form the structural framework. The module was instrumented with chromel-alumel thermocouples. Placement of this instrumentation is shown graphically in Figure 2. A series of calibration tests were performed with one, two, and three trash bags as the ignition source. Each trash bag consisted of paper and polystyrene cups in a polyethylene bag with a weight of 1.1 kg each or 3.3 kg for the three bags. Time-temperature curves were calculated for burning the trash bags in the module. Figures 3–5 are predicted time-temperature curves for the module with 0.6 cm cement-asbestos board walls, floor, and ceiling. These curves were calculated for various ventilation and fuel loads. In order to produce the above and other fire loads in a reproducible manner, a gas burner was utilized, fired with propane gas and air. The burner, shown in Figure 6, consists of five cast-iron burners which can be adjusted to give premixed flames or any degree of diffusion flames. The burner can be programmed to simulate the spectrum of fuel released from various ignition sources and, therefore, reproduces a wide range of possible fire threat levels. A special module test door was constructed for the burner calibration and subsequent tests. The door, shown in Figure 7, consists of steel and cement-asbestos board construction similar to that in the module itself. The door is fitted with thermocouples, radiometers, pressure probes, and observations windows. It can be modified quickly to contain other instrumentation. An exhaust vent in the door allows the combustion products from the burner to escape in a controlled manner through the use of the damper. The burner was operated under various modes and was calibrated to reproduce approximately the fuel release rate produced from the burning of three trash bags. This program would produce a total heat release of approximately 17,500 kcal for a test duration of 6 min, as represented by curve A, Figure 8. Figure 9 shows the temperatures produced when the burner was operated in this mode (A).

Part II. Fire Containment Tests for Panels

The objectives of fire protection can be achieved by a number of methods. Figure 10 [5] shows a systematic framework to achieve the objectives given in the introduction. One of the objectives (i.e., "risk of fire outbreak") assumes that ignition has not yet occurred; one achieves this objective by taking the lefthand path in Figure 10 [5] and attempts to "prevent fire ignition." All other objectives assume that an unwanted fire has started, and one must follow the righthand branches. For containment, one follows the path through the "control fire by construction." There is always a need to know the containment qualities of walls, floors, doors and similar structures.

The primary objective of the tests conducted was to evaluate the experimental arrangement as a possible test method for fire containment. The second objective was to evaluate the toxic threat of products of combustion of the materials used in the construction of the panels. The third objective was to obtain the relative fire containment capability of these panels so that other assemblies could then be tested for comparative purposes.

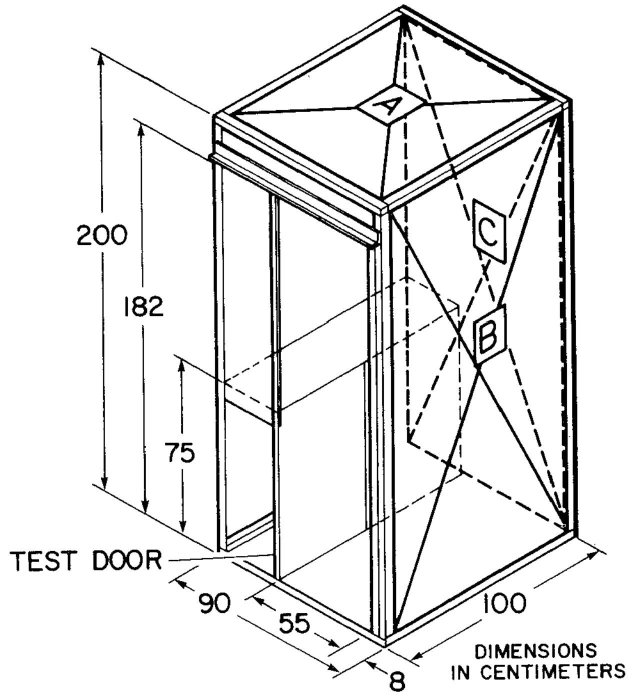

Figure 1. Module Configuration.

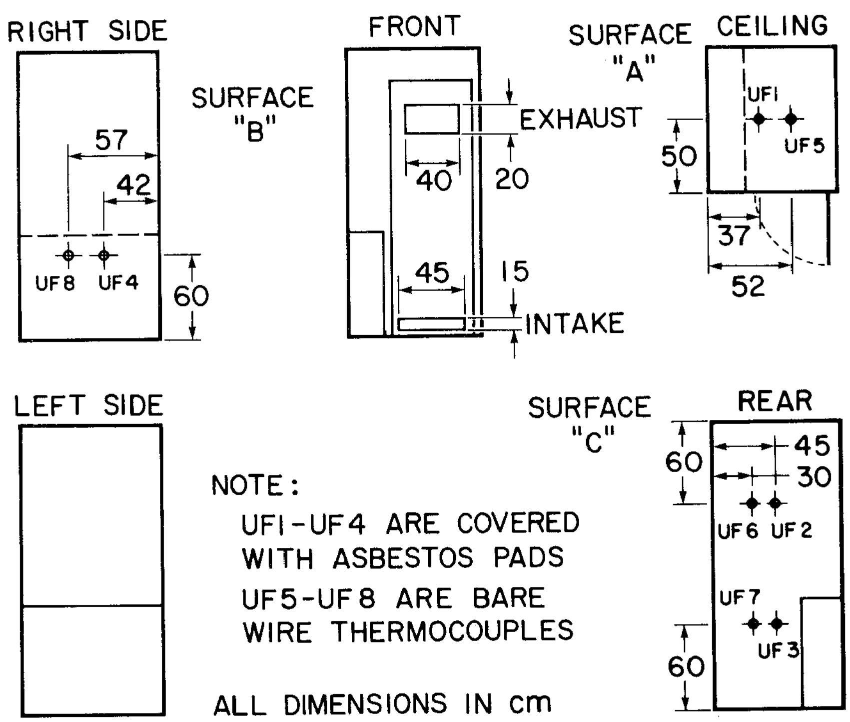

Figure 2. Unexposed Surface Thermocouple Locations.

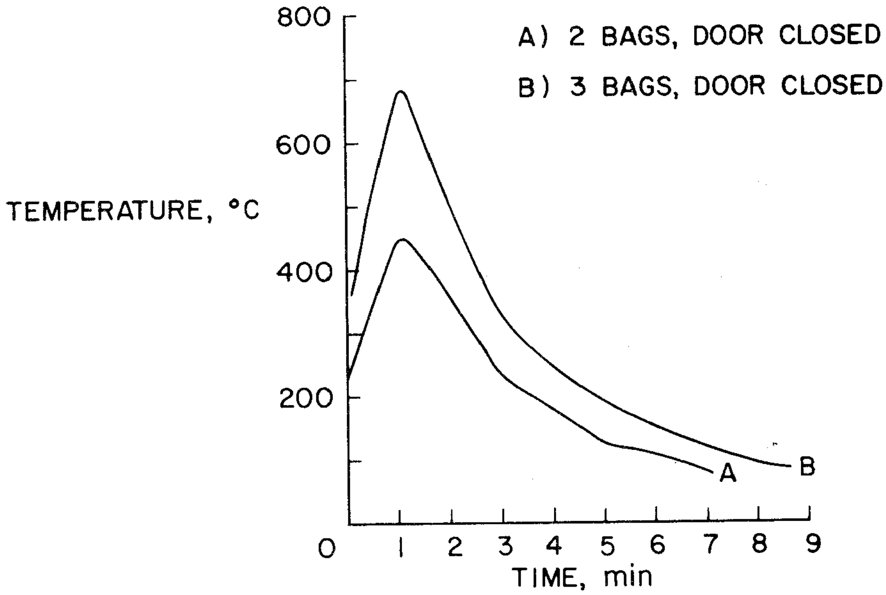

Figure 3. Surface Temperature in Module.

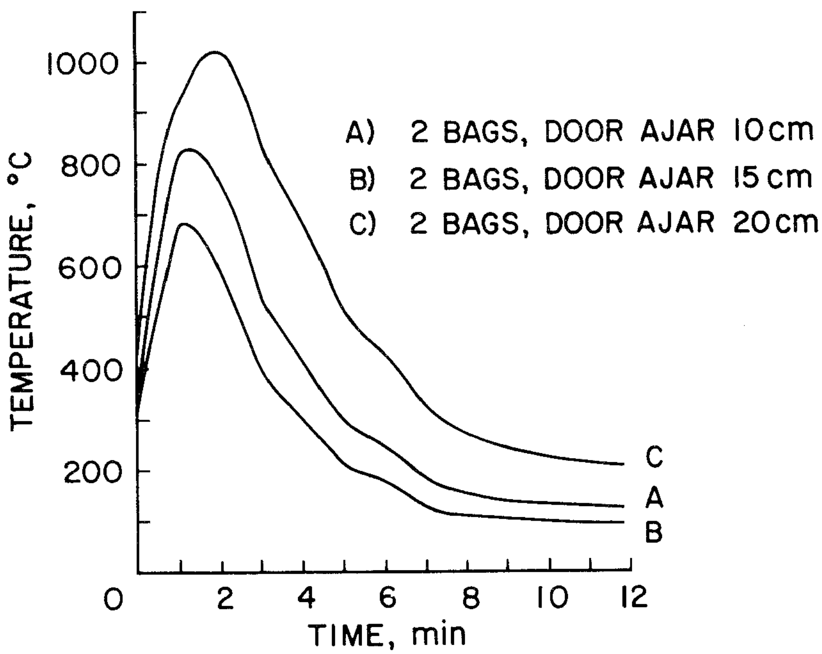

Figure 4. Surface Temperature in Module.

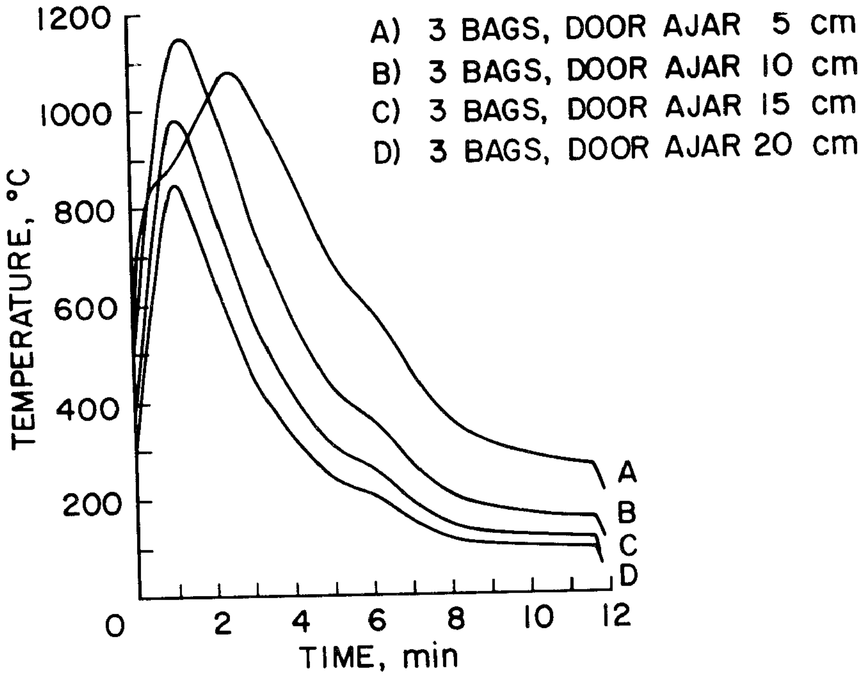

Figure 5. Surface Temperature in Module.

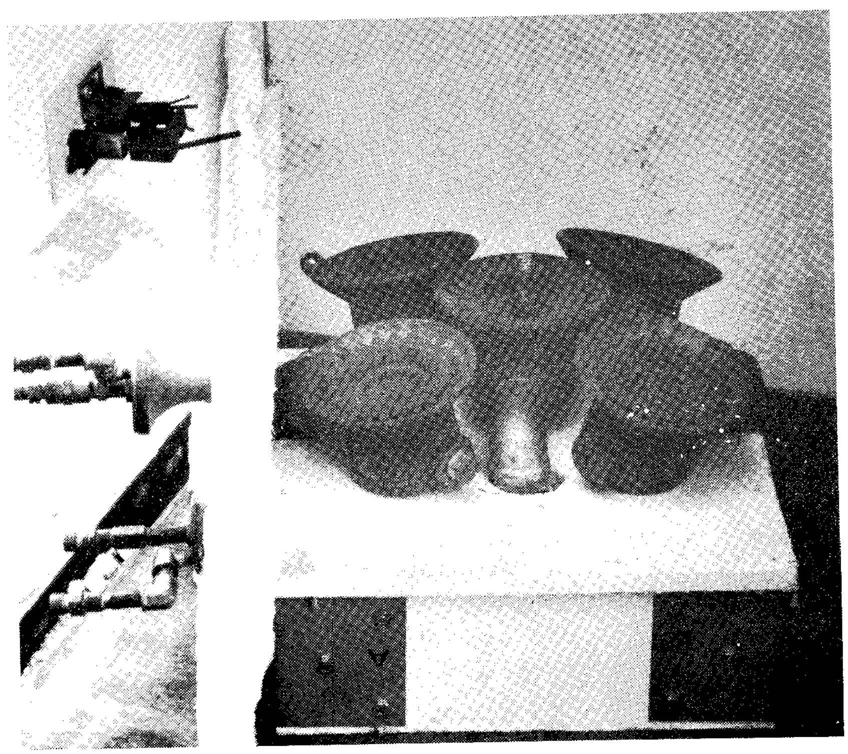

Figure 6. Gas Burner.

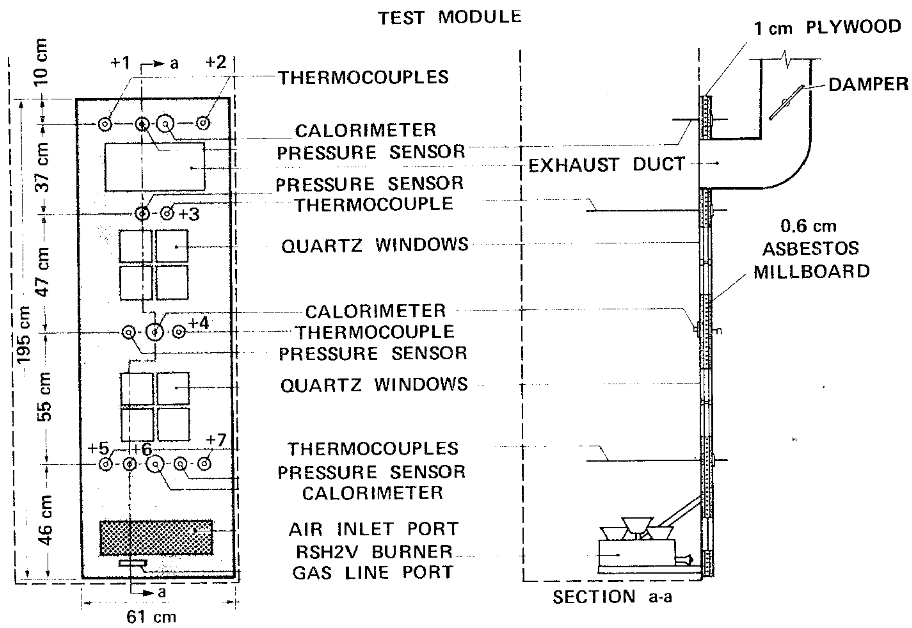

Figure 7. Module Fire Test Door.

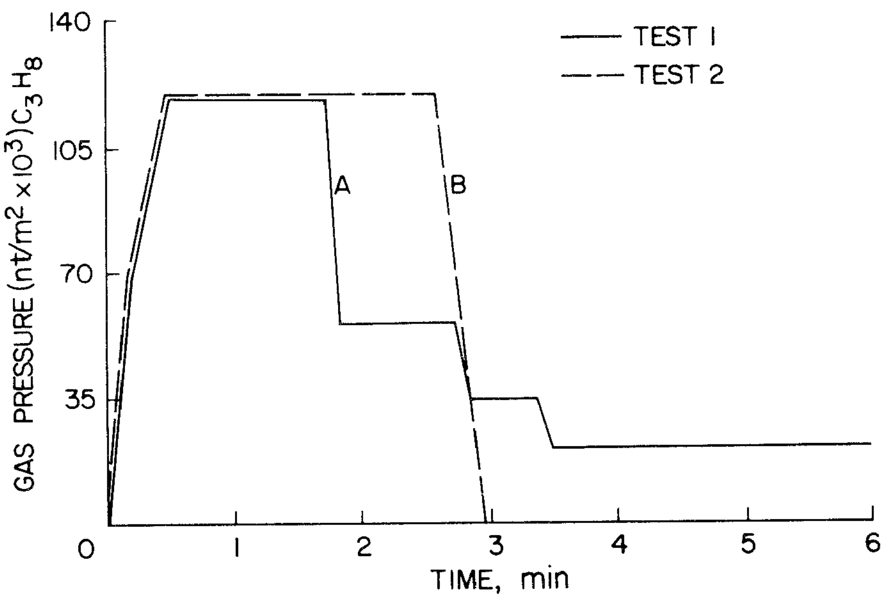

Figure 8. Burner Operating Parameters (Ideal).

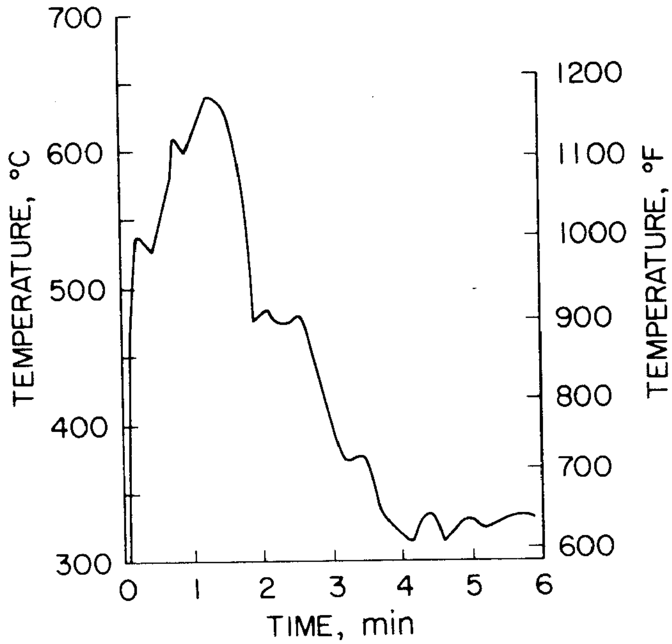

Figure 9. Approximate Temperature Above Gas Burner.

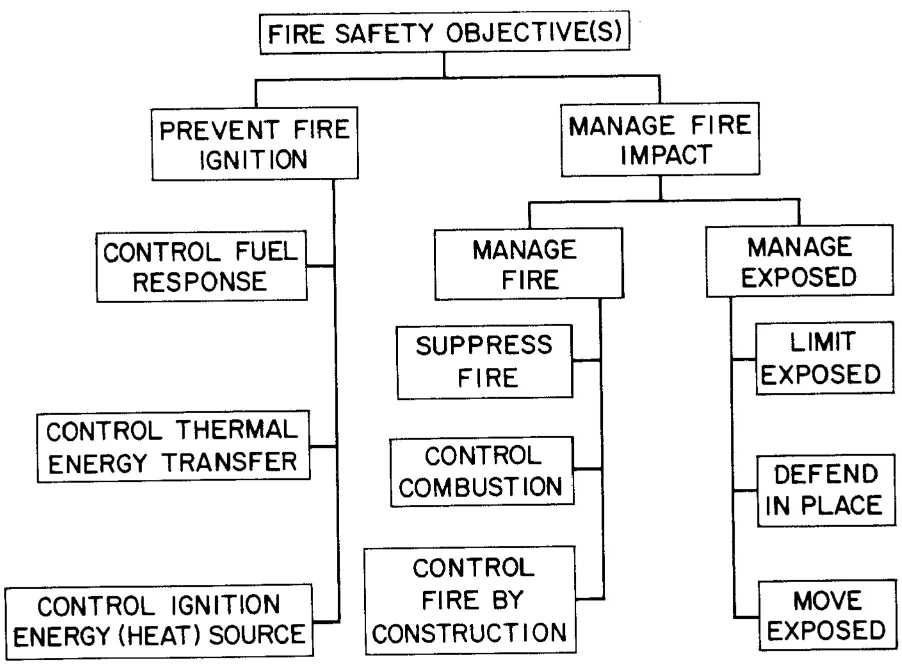

Figure 10. Fire Safety Objectives.

The composition of the panels that were used in this test is shown in Figure 11. For these tests the asbestos millboard ceiling and walls (shown as surfaces A, B, and C in Figure 1) were removed and replaced with the current aircraft interior panels. Panel A was 1.25 cm thick; the rest of the panels were 2.5 cm thick.

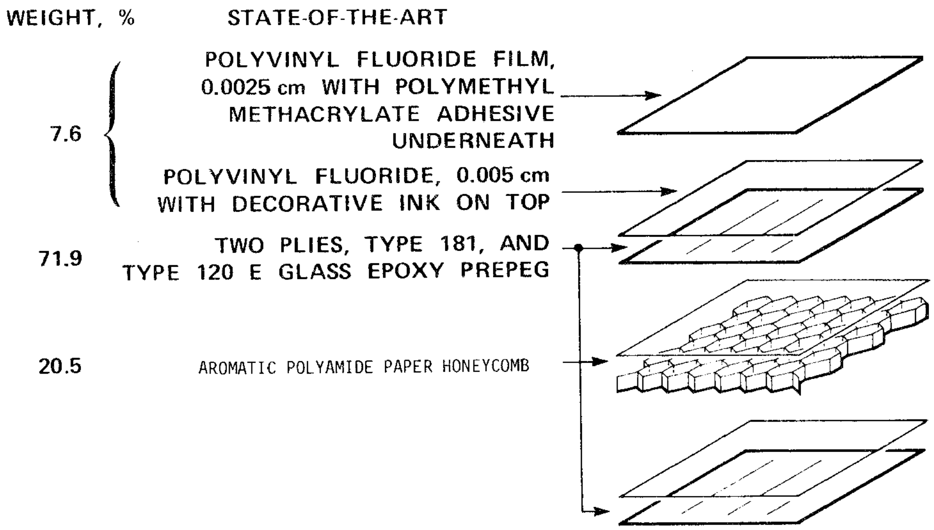

Figure 11. Composite configuration of aircraft interior panel.

Note that the panel edges were protected by a thermo-protection barrier so that the joining techniques in the test did not affect the results. A detail of this is shown in Figure 12. Obviously, in a future test, various joining techniques also could be tested, but it was felt that only the "land" of the panels would be tested in these experiments. The experimental arrangement for these tests is shown in Figure 13.

The module was placed in a surrounding compartment as shown in Figure 14. The compartment simulates the surrounding area in an airplane environment and its principal role is to catch the smoke, heat, and toxic gases that could be released by the panels in the module. The high ceiling and the "weir" at the open doorway allow experiments on the fresh smoke without obscuring the visual observations of the module itself. This can be thought of as separating the smoke cloud from the module, as schematically shown in Figure 15.

The fire inside the test module was exhausted out of the compartment as shown in Figure 14. This leaves the plenum area above the module for the gas sampling and the animal experiments.

Instrumentation – All instrumentation in the module (except exposed and unexposed face thermocouples) was contained within the module test door as shown

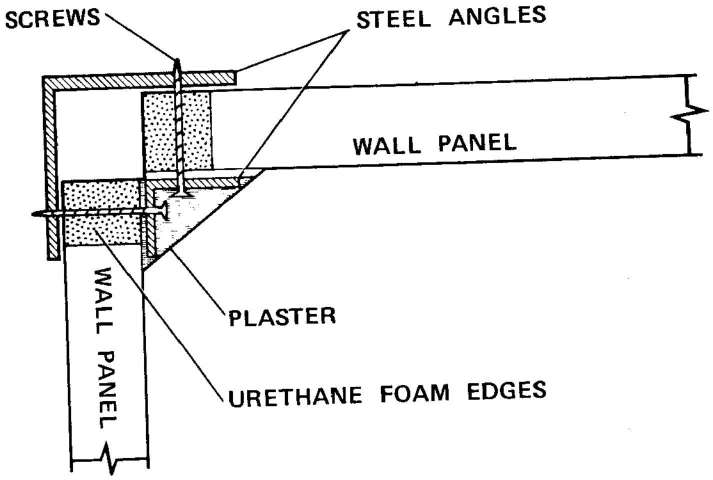

Figure 12. Corner Joint Detail.

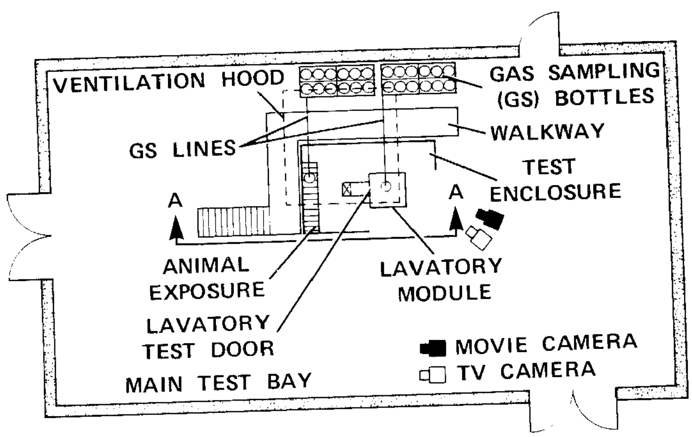

Figure 13. Plan Test Layout.

in Figure 7. This includes thermocouples, calorimeters and pressure sensors.

Thermocouples to measure temperature rise on the unexposed side of the aircraft test panels were both covered and uncovered. Covered thermocouples represented places where some object prevents adequate ventilation. Location of thermocouples is shown in Figure 2.

Air temperatures in pertinent areas of the test enclosure were monitored with chromel-alumel thermocouples as shown in Figure 16.

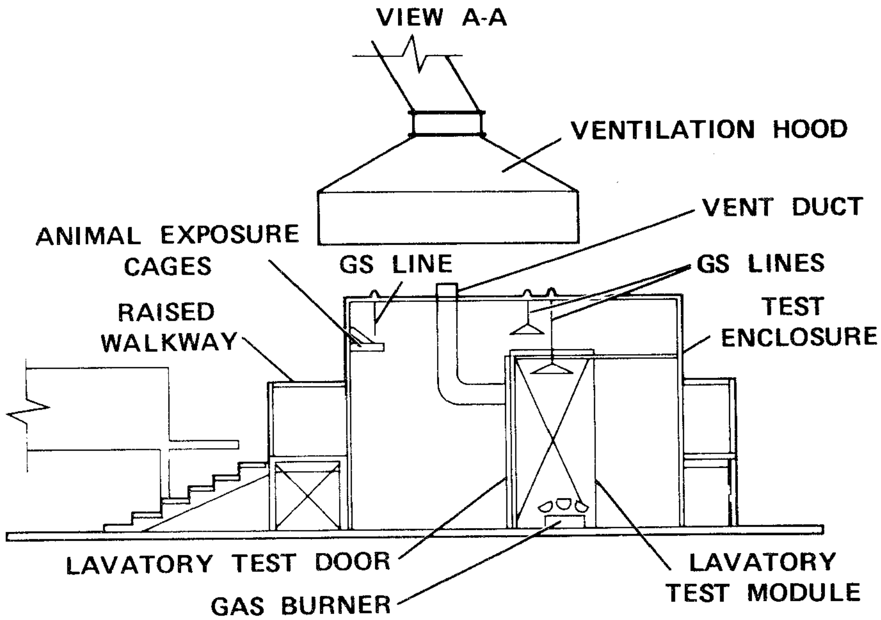

Figure 14. Elevation of Test Layout.

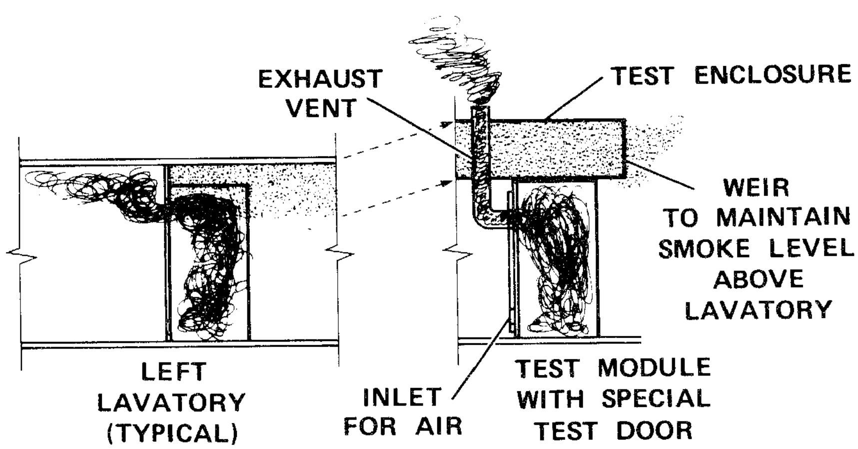

Figure 15. Arrangement for Smoke Entrapment.

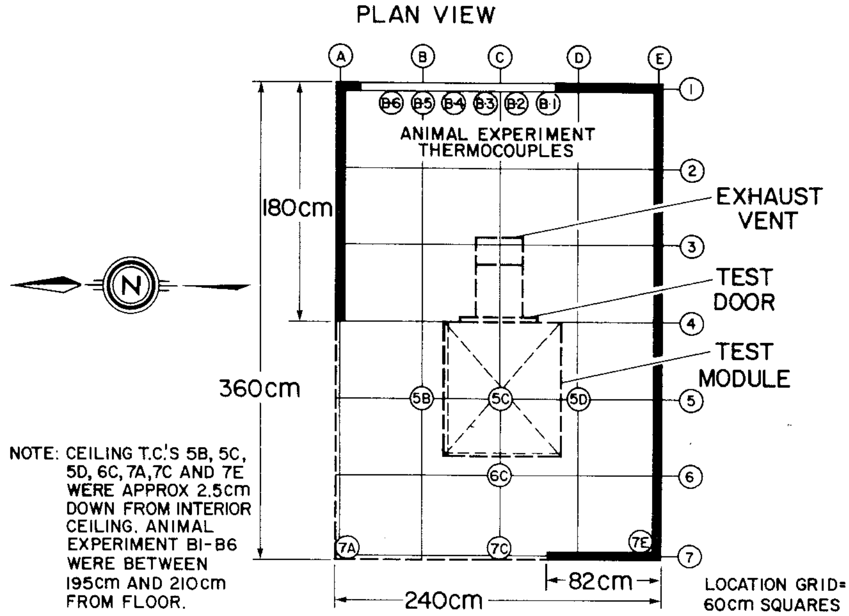

Figure 16. Location of Thermocouples in Compartment.

All instrumentation was monitored by a medium speed (2 data points/second) data scanner. Data was recorded on paper tape, which was then reduced by a digital computer.

Gas analysis and animal exposure — Smoke and gases were captured in the test enclosure plenum space above the lavatory module for analysis. Samples were withdrawn at intervals during the test period. Two collection ports were utilized for sampling the smoke and gases that escaped from the test module. Two sets of bottles were utilized for collection of (a) dry gases, (b) gases for ion-specific electrode analysis at each of the two ports. The approximate locations of the gas sampling (GS) ports are shown in Figures 13 and 14.

The methods of analysis for the gases are infrared analysis for CO, CO_2, CH_4 and NO_x.

In addition to the sampling of gases for semiquantitative analysis, rats were placed in the plenum space above the test module for characterizing the toxicity of the gases produced from the combustion of the test panels. The gases tested were pyrolysis effluents from the panels and not burner combustion products.

The apparatus for exposing the animals consisted of a test unit approximately 150 cm wide and 30 cm high, which could be mounted in an appropriately-sized opening in the wall of any test enclosure. The test unit contained six cage assemblies, each assembly holding six rats in horizontal wire mesh cylindrical cages, with their heads toward the center of the test compartment. All cages were positioned away from the wall in which the test unit is mounted, with a clearance of at least 15 cm to ensure free movement of the gases around the cage assemblies. A chromel-alumel therocouple was placed in the center of each assembly, in the same plane as the rats' noses, to monitor the temperature of the gases being inhaled. Since the rats' noses were essentially upstream from the cage assemblies in the dynamic conditions of a full-scale fire test, the gas composition inhaled was essentially independent of the material of construction of the test unit. Stainless steel was selected as the construction material for durability and ease of cleaning.

The animals used were Sprague-Dawley rats, averaging 225 grams each at the time of test. For each test, an order of 50 rats was delivered four days prior to the test, to permit adequate observation. Defective animals were separated, and 42 rats providing the narrowest weight distribution were divided into 7 groups of 6 rats each, 1 group as a control group and the other 6 groups to be exposed in the test.

The six exposure groups provide the option of six exposure periods, with one cage assembly containing six rats being withdrawn from the test enclosure at each desired time interval. Half of each group were kept for observation, and the other half sacrificed and autopsied and blood samples taken. The organs preserved were lungs, trachea, liver, kidney, and spleen. The blood samples were analyzed for carboxyhemoglobin and cyanide within 4 hr after death.

Determination of the percent carboxyhemoglobin (% COHb) in rat blood was carried out using the method of Drabkin [6] with the following modifications by Blackmore [7]: the blood was diluted with 0.4% ammonium hydroxide instead of distilled water and the ratio of the 576/590 absorbance was established to indicate the presence of interfering pigments.

Initially two aliquots of the same, normal, whole rat blood were obtained. One aliquot was saturated with oxygen while the other was saturated with carbon monoxide, then both were diluted 1/200 with ammonium hydroxide. Using these 100% solutions, a serial dilution of the blood was made to give 50%, 25%, 12.5%, 6.25%, and 3.125% COHb rat blood. The absorbance of each of these solutions were determined at 562, 576, 578, and 590 nm. A calibration curve was drawn using these blood solutions by plotting the ratio of the absorbance values at the wavelengths 578/562 versus the known % COHb. These determinations were made using a Model 25 Beckman spectrophotometer.

From the calibration curve direct values of % COHb in sample rat blood were read by determining the absorbance ratios.

Cyanide in whole rat blood was determined using the procedure of Bruce et al. [8] with the following minor changes: All volumes used were reduced 50% for the pyridine/benzidine which was reduced from 3.6 to 1.0 ml. Conway diffusion dishes were used instead of the bubbling apparatus described. A 3.5 hr diffusion time was allowed for the HCN to be trapped by the 0.1 N NaOH solution.

Test 1 — The test was initiated by lighting the burner and following a rapid increase of fuel flow such as that shown as curve A in Figure 8. This simulates the rapid growth of the fire to full involvement with the door open. The temperature rise of the unexposed faces of the panels was used as one quantitative criteria of performance.

Temperature rise on the backface of the panels is shown in Figure 17. Air temperatures in the test module are shown in Figure 18. Air temperatures adjacent to the animal experiment are shown in Figure 19 and air space and weir temperatures are shown in Figure 20. The test was terminated after 6 min by shutting off the burner.

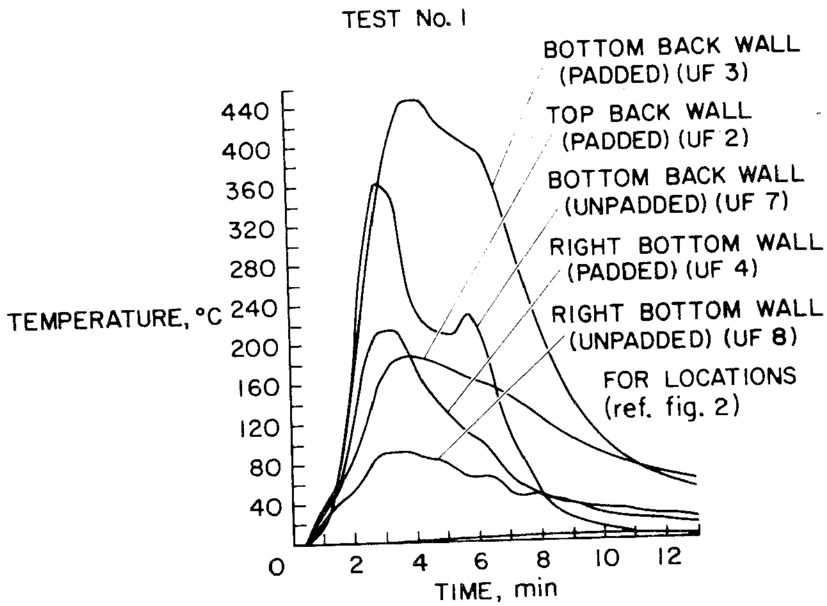

Figure 17. Unexposed Surface Temperatures on Panels.

There was no actual burnthrough of the flames in this test; however, the panels were completely charred and delaminated on the interior and extensive charring was sustained on the exterior surfaces of the walls. This charring was observed within 1 min after ignition. The rats were exposed in this test and results are given in the following section. No gas samples were taken in this test.

Test 2 – This test was similar to Test 1 except the fuel flow of the burner followed curve B on Figure 8. The total fuel released in the module was essentially the same as Test 1 except that the time of maximum fuel release was slightly longer, as indicated by curve B. Instrumentation was similar to Test 1 except that pieces of cotton waste were placed at selected places on the exterior of the panels to give an indication of ignition of clothing adjacent to a surface subjected to a fire

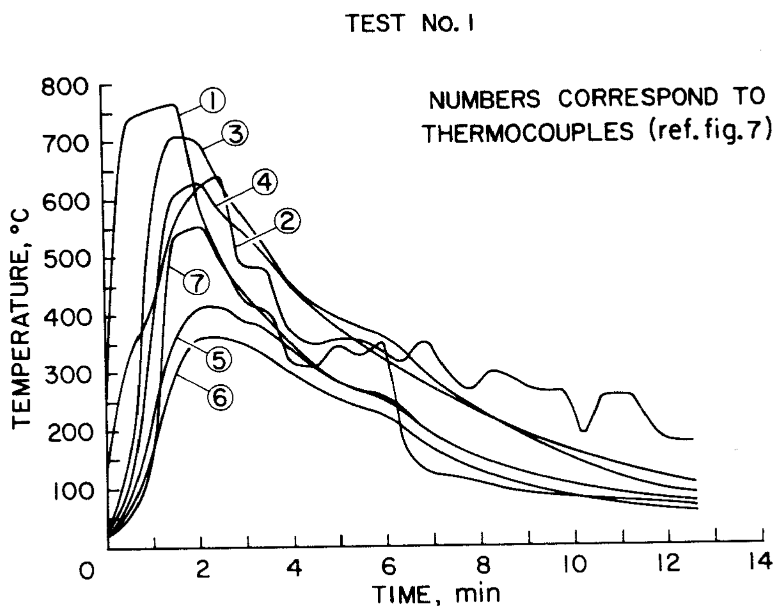

Figure 18. Air Temperature in Module.

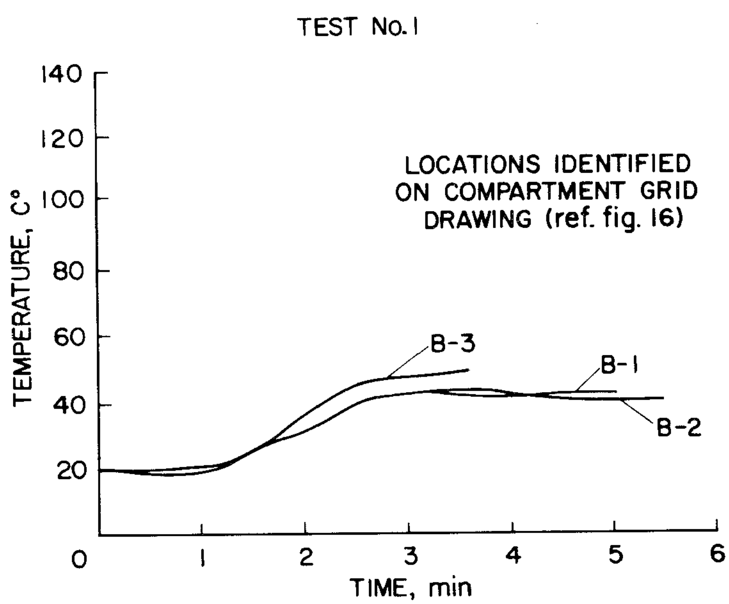

Figure 19. Air Temperatures in Enclosure

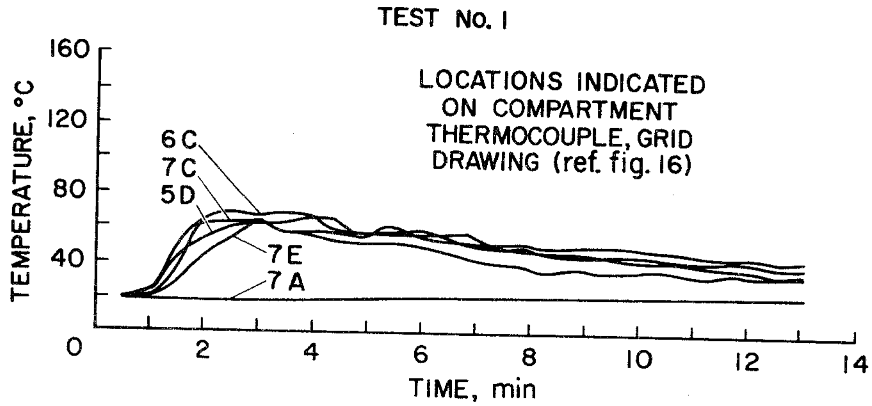

Figure 20. Air Space and Weir Temperatures.

environment on the other side. Flame burnthrough occurred at the ceiling-wall corner primarily due to structural (joint) failure at approximately 2 min and 50 sec after ignition, at which time the burner was turned off and the test terminated by extinguishing the fire with a fire extinguisher. The temperature on the unexposed face of the panels is shown in Figure 21. The air temperature in the module, as measured by the thermocouples on the door is shown in Figure 22. Air space and weir temperatures are indicated in Figure 23. Air temperatures adjacent to the animal experiment are shown in Figure 24. One set of gas samples was collected and the animal experimental procedure was similar to Test 1.

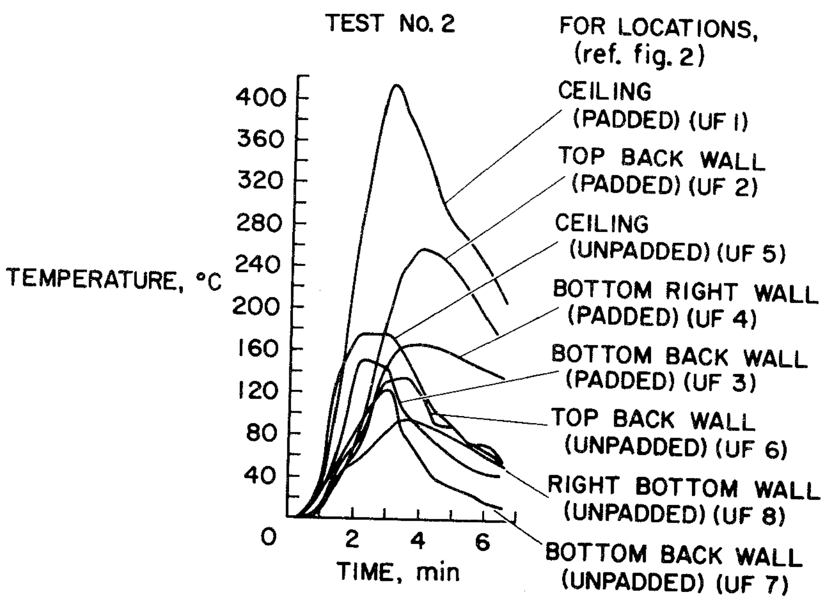

Figure 21. Surface Temperatures in Panels.

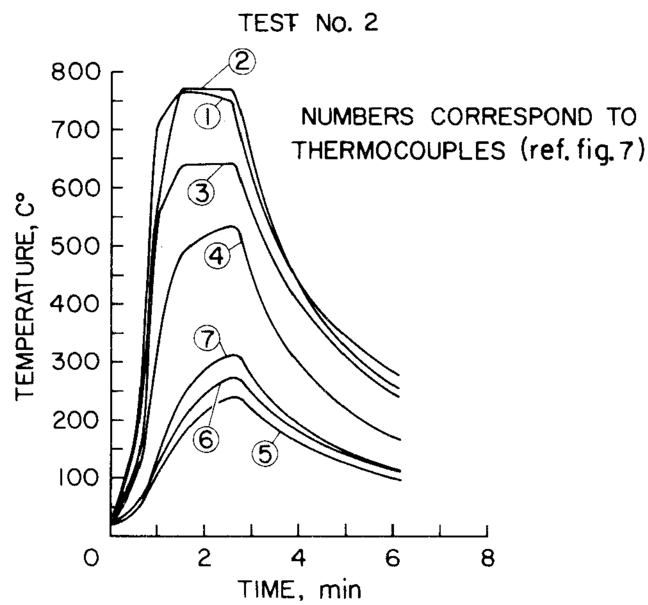

Figure 22. Air Temperatures in Module.

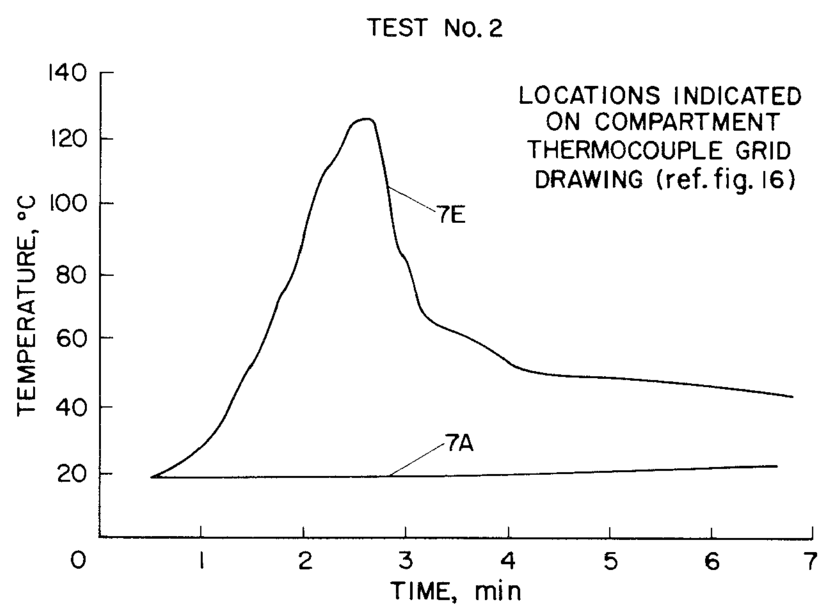

Figure 23. Air Space and Weir Temperatures.

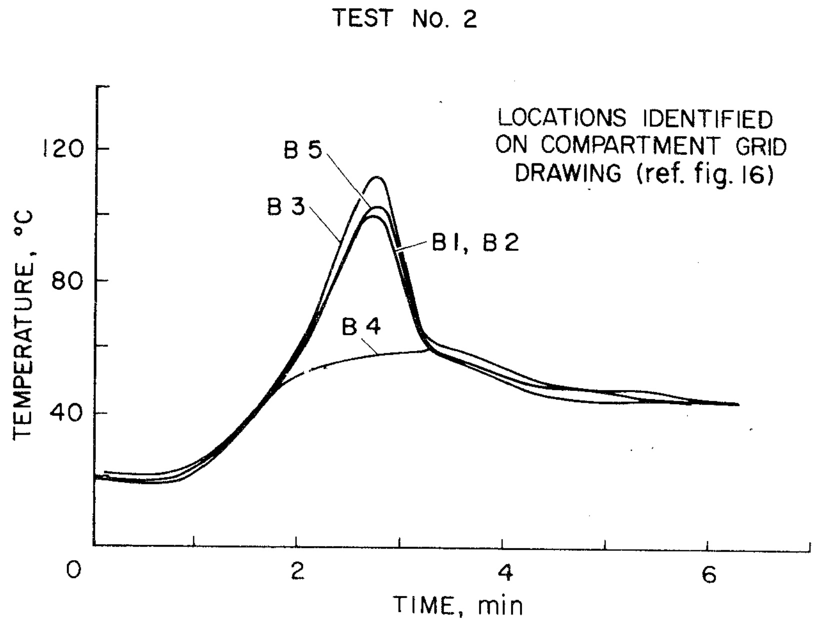

Figure 24. Air Temperatures in Compartment.

Part III. Results of Analysis of Gas Sample and Animal Exposure

Gas analyses – The results indicated below are from the gas sample collected during the first 2 min of the test inside the test module and adjacent to the animal experiment in the compartment. The table below lists the gases found and the parts per million of the sample that they constituted. Water was also observed, but it is not listed in the table because its infrared spectra was not an accurate measure of its concentration in the collection tank. Several samples were taken from each tank so a standard deviation from the mean is also given.

	CO, ppm	CO_2, ppm	CH_4, ppm
Inside module	2800 ± 300	60000 ± 5000	1000 ± 200
Near animals (compartment)	420 ± 70	4600 ± 100	420 ± 10

Only CO_2, CH_4, H_2O, and CO were observed. These are relatively unreactive gases. No other hydrocarbons were observed in the infrared spectrum. It is not known how long corrosive gas such as NO_2, NO, and HCN may be stored in the presence of moisture in stainless steel cylinders such as those used and therefore their presence could not be ascertained.

Animal exposures – The tests differed principally in that cotton waste was placed on top of the module in Test 2 to indicate one criterion of failure. Since cotton has been reported as producing carbon monoxide and cyanide in fires, and the cotton ignited about 2 min into the test, it is impossible to determine the material causing the elevation of blood carboxyhemoglobin and cyanide, in the rats in Test 2. The results are presented in Table 1.

Table 1. Carboxyhemoglobin (COHb) and Cyanide (CN) Concentrations in the Blood of Sprague-Dawley Male Rats Exposed in Tests 1 and 2.

TOTAL TIME OF EXPOSURE, min	CARBOXYHEMOGLOBIN CONCENTRATION IN BLOOD, percent COHb		CYANIDE CONCENTRATION IN BLOOD, μg/ml NaCN EQUIVALENT	
	TEST No. 1	TEST No. 2	TEST No. 1	TEST No. 2
0	1.8	1.2 ± 0.4	0.376	0.415 ± 0.073
1	2.3 ± 1.8		0.492 ± 0.041	
2	3.7 ± 1.5		0.498 ± 0.064	
3	4.9 ± 1.6	21.5 ± 7.4	0.525 ± 0.087	1.019 ± 0.44
4	3.3 ± 1.3	24.0 ± 5.0	0.533 ± 0.099	0.950 ± 0.424
5	2.8 ± 2.0	20.3 ± 4.5	0.515 ± 0.067	0.498 ± 0.112
6	3.5 ± 1.4	19.7 ± 2.9	0.429 ± 0.065	0.506 ± 0.185
7		18.2 ± 5.0		0.509 ± 0.201
8		15.0 ± 2.8		0.364 ± 0.054

Based on the work of Stewart [9] the carboxyhemoglobin data from Test 2 would indicate inhalation of high concentrations of carbon monoxide before the first animal withdrawal at 3 min, and significantly lower carbon monoxide concentrations thereafter, which permitted some elimination of carboxyhemoglobin.

Of the animals from Test 1, 2 out of 18 had lower body weights on the day after the test than on the day of the test, but these had recovered their original weight by the second day after the test. Of the animals from Test 2, 17 out of 18 had lower body weights on the day after the test than on the day of the test; 13 out of 18 still had lower body weights on the second day after the test; 5 out of 18 still had lower body weights on the third day after the test. All animals under observation eventually resumed apparently normal weight increase with age. Selected data are presented in Table 2.

An attempt was made to measure the effects of exposure on one type of behavioral response: exploratory behavior as determined by the time for individual animals to look over the edge of a 25 cm^2 platform suspended in midair after being

Table 2. Body Weights of Sprague-Dawley Male Rats Exposed in Tests No. 1, No. 2.

ANIMAL No.	BODY WEIGHT, g TEST -3	TEST DAY	TEST +3	TEST +7	TEST +14
TEST No. 1 CONTROL GROUP					
1	192	224	237	270	301
2	180	207	223	254	284
3	188	221	241	270	311
4	189	204	225	256	300
5	190	227	248	286	336
6	187	219	235	266	295
TEST No. 1, 1 MINUTE EXPOSURE					
1	175	205	218	253	283
2	186	210			
3	196	227			
4	185	215	229	252	295
5	185	211	225	260	294
6	178	211			
TEST No. 1, 3 MINUTE EXPOSURE					
1	186	217			
2	177	203	215	256	302
3	180	214	228	258	292
4	178	206			
5	177	202			
6	183	224	237	272	325
TEST No. 1, 6 MINUTE EXPOSURE					
1	205	237			
2	186	217	237	267	310
3	176	208	229	258	296
4	177	202			
5	186	218	239	264	310
6	195	227			

ANIMAL No.	BODY WEIGHT, g TEST -3	TEST DAY	TEST +3	TEST +7
TEST No. 2 CONTROL GROUP				
1	185	210	234	264
2	175	201	224	250
3	175	203	215	258
4	168	200	220	253
5	190	207	224	257
6	173	197	219	252
TEST No. 2, 3 MINUTE EXPOSURE				
1	185	230	206	235
2	192	223		
3	175	202	212	242
4	178	209	224	253
5	166	197		
6	178	207		
TEST No. 2, 6 MINUTE EXPOSURE				
1	169	194	199	224
2	170	204		
3	183	218		
4	178	201	202	225
5	171	206	224	263
6	184	220		
TEST No. 2, 8 MINUTE EXPOSURE				
1	179	206	200	228
2	183	208		
3	173	205	222	244
4	184	210		
5	171	199		
6	190	224	245	277

placed in the center of the platform. The results are presented in Table 3. The only conclusion that can be made from these data is that the number of animals was insufficient, and that significant increase in the number of animals is needed to be able to detect significant differences.

CONCLUSIONS

1. The burner could be utilized to represent various fire load conditions. The heat release rate produced from the burner is fairly reproducible.
2. Elements of fire containment criteria include temperature rise on the backface of the composite panels, as a function of time, flame burnthrough either through decomposition of the material or severe distortion and toxicity of the combustion gases evolved. Additional tests are required to quantify these parameters in more detail.

Table 3. Behavioral Response of Sprague-Dawley Male Rats Exposed in Test No. 2.

TEST EXPOSURE CONDITIONS	EXPLORATORY BEHAVIOR TIME TO OVERLOOK EDGE OF 25.0 cm^2 PLATFORM, SEC	NUMBER OF ANIMALS IN GROUP
BEFORE EXPOSURE	1.9 ± 1.4	12
3-min EXPOSURE	2.8 ± 1.4	3
4-min EXPOSURE	3.4 ± 2.2	3
5-min EXPOSURE	2.5 ± 1.4	3
6-min EXPOSURE	2.3 ± 1.2	3
7-min EXPOSURE	0.7 ± 0.1	3
8-min EXPOSURE	2.0 ± 1.8	3

3. The methodology developed for fire containment could be useful in evaluating the fire resistance of large-sized composite panels prior to conducting more expensive large-scale tests.
4. The apparatus and methodology developed for toxic material characterization could be useful in studying the biological effects of fire gases in the critical first 10 min of large-scale fire.

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