Heat Shields for Aircraft—A New Concept to Save Lives in Crash Fires

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Test of the concept, which draws on research for Apollo, opens the way to considering retrofit systems and designing shields for new aircraft, where the protection system may involve little or no weight penalty

Aborted take-offs and crash landings, although not frequent because of constant attention to safety practices, nevertheless constitute a continuing hazard of aviation. Often passengers survive the impact, but in far too many cases subsequent fire kills them. A typical case occurred several years ago during a landing at Salt Lake City.[1] Because of too high a descent rate, the airliner tore off its main landing gear as it made ground contact. The impact destroyed the landing gear, but did little structural damage to the fuselage, and caused only relatively minor injuries to a few passengers. A few seconds after impact, however, fire started from a ruptured fuel line under the cabin floor. Within 90 seconds flames engulfed the entire cabin. Two airport fire trucks arrived about three minutes after impact, but they were too late to save half the passengers. Forty-three were burned to death or died from smoke inhalation.

Typically, the passengers caught in an aircraft ground accident causing fire have only a matter of seconds to escape.[2] Those failing to exit quickly probably will die from exposure to heat and fumes. Because of the fire danger, the FAA stresses rapid evacuation in such accidents. Unfortunately, as in the case cited, it is not always possible to evacuate an airliner fast enough to save everyone on board. As more of the larger airbus-type airplanes,

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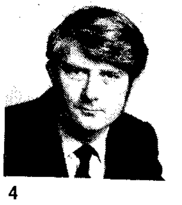

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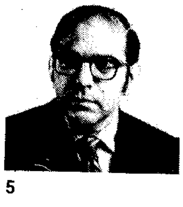

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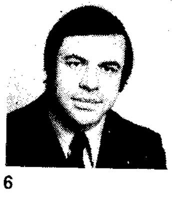

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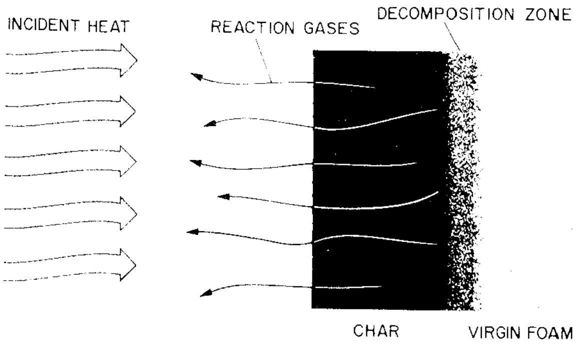
CARR B. NEEL (1), JOHN A. PARKER (2), and **RICHARD H. FISH (3)** are members of the Chemical Research Projects Office at NASA Ames Research Center. **JIM HENSHAW (4), JULIAN H. NEWLAND (5),** and **FRANCIS L. TEMPESTA (6)** are with the Systems Div. of AVCO in Lowell, Mass. AVCO performed the demonstration test described in the article under contract to Ames. Neel, as technical monitor of the contract, had over-all responsibility for the program. Parker guided the development of the fire-retardant materials used in the test and provided technical guidance in materials selection, modification, and processing. Fish performed important quality-control evaluations of the materials as systems before the test. Henshaw, as AVCO project engineer, coordinated the various activities involved in the evaluation and application of the materials and conduct of the test. Newland directed the processing and installation of the materials in the test fuselage. Tempesta was responsible for the thermal-design aspects of the test.



Thermal-protection mechanisms of ablative materials.

PHYSICAL PROPERTIES OF POLYISOCYANURATE FOAM USED IN FIRE TEST

Property	Value
Density, lb per cu ft	3.8 to 4.3
Open-cell porosity, %	1-2
Thermal conductivity, (Btu in./hr ft^2) F	0.2 to 0.3
Shear strength, psi	15-20
Compressive strength, psi	
Parallel to rise direction	30-40
Perpendicular to rise direction	35-45
Compressive modulus, psi	
Parallel to rise direction	1800-3000
Perpendicular to rise direction	1000-1500
Tensile strength, psi	36-42

capable of carrying several hundred passengers, enter service, the problem of quick evacuation in emergencies may worsen.

Some studies have been made to find ways to improve evacuation techniques.[4-5] Others have treated possible ways to prevent or control fires.[5-7] At NASA Ames Research Center, we have been taking a third approach to passenger survival: heat shielding—a passenger compartment surrounded by a fire-retardant shell able to protect the occupants long enough for the fire to burn out or for fire-fighting equipment to reach the airplane and extinguish it.

This concept has been made possible by the recent development of two new fire-retardant materials: a very lightweight foam plastic, called polyisocyanurate foam, and an intumescent paint. Exposed to heat, the intumescent paint expands to many times its original thickness and insulates the surface underneath it. The thermal-protection mechanisms of these materials operate on the same ablative principles (see diagram at the top) that protect our astronauts during re-entry of the Apollo spacecraft.[8-13]

How the Materials Work: As the diagram just above indicates, heat converts this ablative foam to a stable char and at the same time some heat is absorbed. As the temperature of the char goes up, it radiates a large amount of heat. During decomposition in the char-forming process, gases are generated that blow outward, cooling the char by transpiration. At the surface of the char, the gases block convective heating by forming an outflowing front of gas. In the case of protection against fire, the gases also chemically interfere with the flames. Thus, ablative materials do much more than ordinary thermal insulators, such as the fiber-glass-wool insulation commonly in use in the walls of present-day airliners.

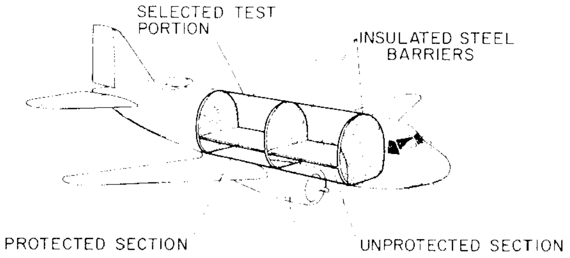
Demonstration Testing: To demonstrate this concept of passenger protection, the new fire-retardant materials were fitted into an airplane and tested in a jet-fuel fire. A 26-foot-long piece from the fuselage of a surplus McDonnell Douglas C-47 served as the test section. Shown on page 20, this section was divided in half and capped on each end by steel bulkheads, making two equal lengths typical of traditional airplane construction. One half was left essentially unchanged. The thermal-protective materials formed a shell around the passenger compartment of the other half. Thus, the test would validate feasibility of a retrofit system for existing aircraft.

Design of the test had to consider two prime factors influencing survival in a crash fire: minimizing heat penetration and preventing intrusion of smoke and toxic gases, which can be lethal even though temperature is controlled. Both of these threats in a survivable crash would be influenced by structural damage rupturing the fuselage. The test did *not* treat such crash damage or windows, which also could be a point of heat and gas penetration. The main point of the test was to explore the basic shielding concept.

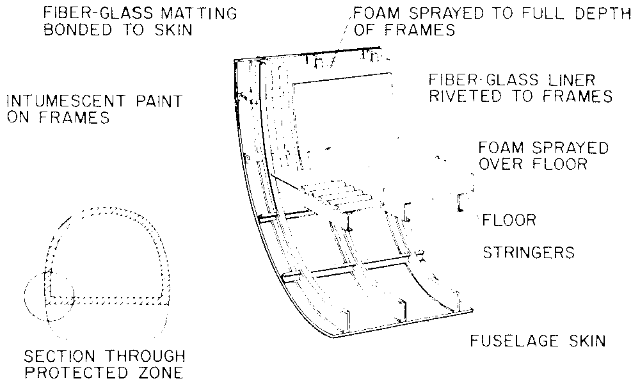
The drawing on page 20 shows the fire-protection system tested. The circular frames were first covered with intumescent paint 0.05 in. thick; it would expand and fill any voids caused by shrinkage of the foam as it charred. Next, a layer of loosely woven fiber-glass matting was bonded to the skin to reinforce the charred zone of foam. Sprayed over the matting, the polyisocyanurate foam (density, about 4 lb per cu ft—see the table above) was built up to the full 2 1/2 in. depth of the frames and 2 to 3 in. over the floor structure. Excess foam was trimmed off.

To finish the installation, a liner of fiber-glass-epoxy laminate (similar to airliner decorative interior paneling) 1/32 in. thick was cemented to the foam and then riveted to the frames. The floor foam was also covered with the laminate, and all joints were sealed to exclude smoke and gases.

In the unprotected section, the space between the aluminum skin and the interior paneling was filled with 2 in. of fiber-glass batting, a material typical of conventional aircraft insulation. The steel bulkheads that divided the protected and unprotected sections and capped the two ends were



Portion of airplane used for test.



Installation of fire-protection materials.

insulated with 1-in.-thick commercial firewall insulation covered with 3 in. of fiber-glass batting.

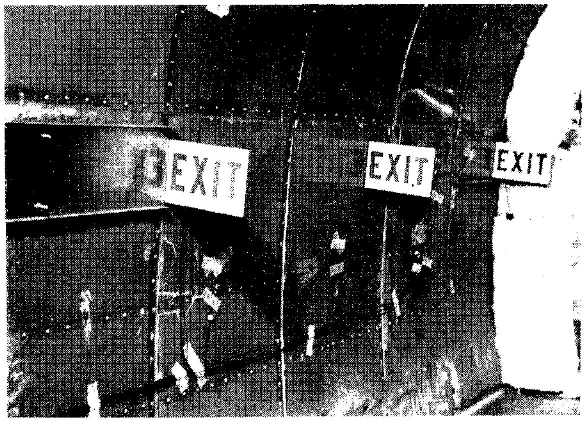
Both the protected and unprotected sections of the fuselage were instrumented to measure the exterior and the interior thermal environments. Thermocouples measured temperatures both inside and outside the cabin. Slug-type calorimeters measured the exterior heat flux.

A sketch in adjacent column illustrates the arrangement. The fuselage, placed directly on the ground, was flanked by two shallow pits, each 27 by 48 ft. Water was placed directly on the bottom of the pits, and 2500 gallons of JP-4 fuel was floated on top of the water in each pit, forming two large fuel ponds. Water-cooled probes that contain motion-picture cameras and gas-sampling equipment observed the interior of each section. The probes were arranged so that they could be withdrawn when temperatures got too high. Several cameras placed around the vehicle recorded the test.

Photos at right show the fuselage exterior and the interior of the protected section before the test. Simulated exit signs and an optical target permitted evaluation of any smoke effects. The interior of the unprotected section bore no exit signs or optical target.

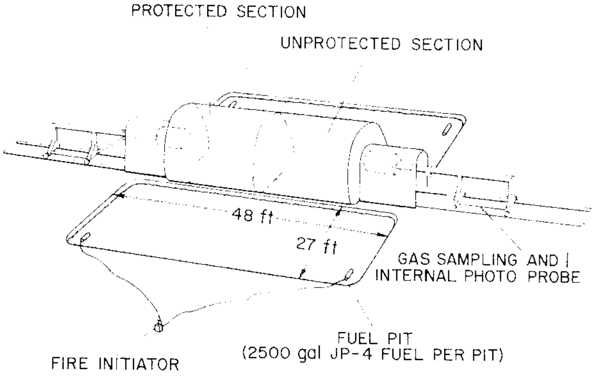
The plan was to ignite both ponds of fuel simultaneously at several points to obtain a uniform buildup of flames over the surface of each. The quantity of fuel and the configuration of the ponds, as calculated, would make the fire envelop the fuselage completely and expose it to maximum heat flux for 10 minutes. It was expected that the unprotected section would be destroyed within 1 to 2 minutes. The protected section hopefully would survive the fire.

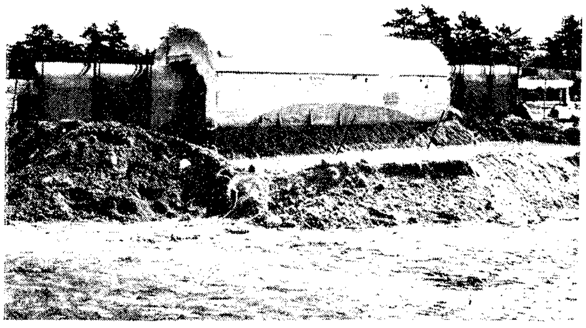
The test was made on August 13, 1970, at Otis Air Force Base. Within 1/2 minute after ignition, the fire was fully developed and smoke had already started to penetrate the unprotected section. Occupants of the unprotected cabin would have



Interior of protected section before test.

FIRE-TEST ARRANGEMENT





Fuselage section before test.

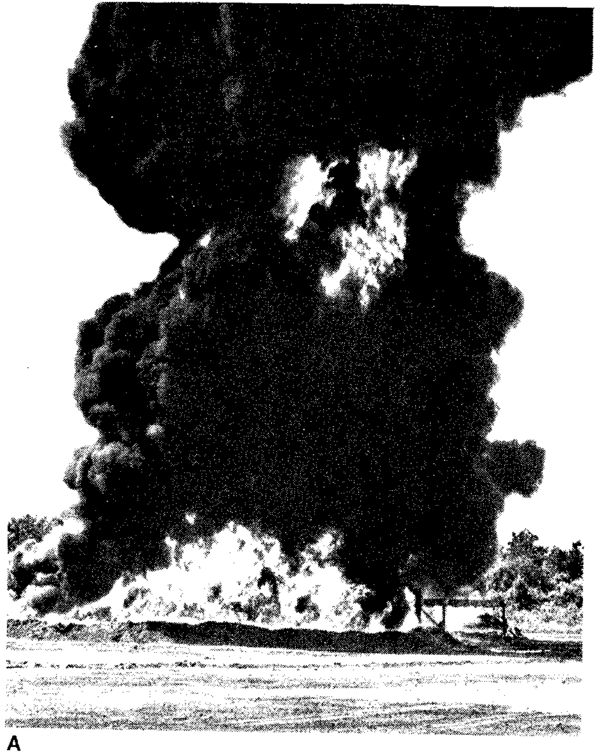
had to evacuate the vehicle by this time to have survived.

Photos at right show two views of the fire during the test. Throughout most of the test, flames engulfed the entire test section. Because of the volume of flames and smoke, it was hard to see by eye what was happening. About 5 min after ignition, a light wind arose from the southeast and directed the flames so that occasionally you could see the end of the protected section. A tremendous vortex of flames around the entire fuselage accompanied this wind shift. Swirling extended about 100 ft upward. Peaks of the flames reached some 200 ft high.

Motion pictures of the interior of the unprotected section showed flame penetration within 1 min of ignition. By about 2 min, the unprotected section was completely destroyed.

Meanwhile, in the protected section, the motion pictures showed no smoke, the gas-sampling probe showed no toxic gas, and the thermocouples showed no temperature change. A power failure prevented further motion pictures of the interior and necessitated removal of the probe containing the motion picture cameras and the gas-sampling equipment after 5 1/2 minutes. The last gas sample was taken 5 min after ignition and still showed no toxic gases. The fire lasted for 12 minutes. Then the ponds burned out, and only residual flames remained around the edges where fuel had soaked into dirt mounds. Soon after the fire died down, fire hoses were played on the test section, to preserve it for study, and on the remaining flames around the edges of the ponds.

Following the test, you could see a dramatic difference between the protected and unprotected sections, as shown by the photo on page 22. The photos on page 22 show the interior of the protected section. Some time during tail-off of the fire, flames reached a relatively unprotected floor seam along the top of the dirt mound supporting the test section. Heat penetrated at this point, and eventually caused a slight burn-through and considerable blackening of the interior walls. This occurred *after the main fire burned out.* It should be attributed to the design of the test and *not* to a failure of the thermal-protection system.



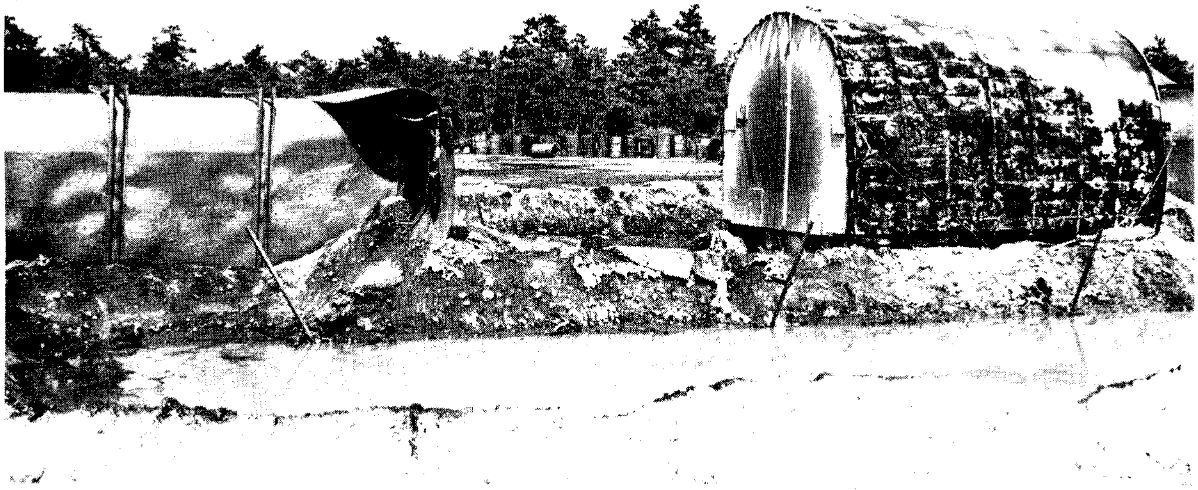
A

Fire during test. A North side of test fuselage. **B** East end of test fuselage.

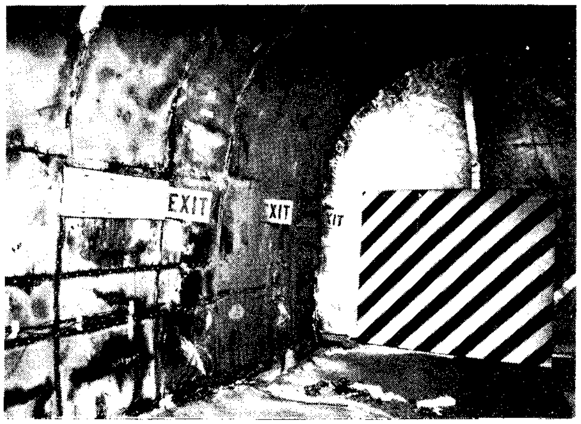
B

Cabin Air Temperatures: The cabin-air-temperature histories, shown on page 23, proved the most significant measurements made in the test. In the unprotected section, the air temperature rose to 600 F less than 2 min after the start of the fire and continued to climb rapidly. By the 2-min mark the unprotected section had been, as mentioned, destroyed. In contrast, the temperature in the protected section changed very little for the first 6 minutes. Then, as the heat finally penetrated, the temperature rose faster, reaching 300 F as the fire burned out, at the 12-min point.

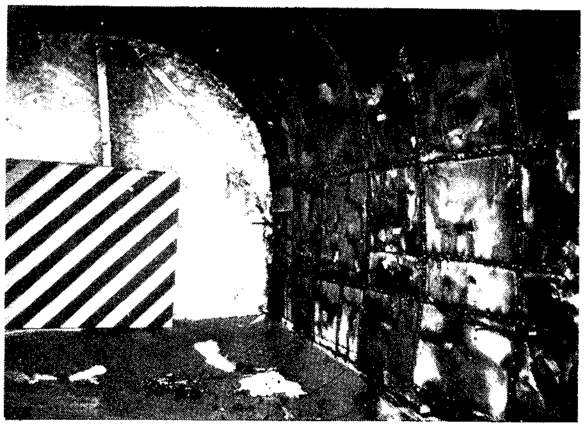
Survivability: To give an idea of the chance that passengers might have had of surviving inside the cabin, we have constructed a curve of 'human-tolerance limit' from the data of two studies treating exposure of humans to extreme heat.[14–15] The curve represents *more severe* conditions than existed in the test. It compares with the test results as shown on page 23. The chart also shows



Fuselage section after test.



Interior of protected section after test. South side.



North side.

the exposure envelope for the sauna-bath ritual, which calls for repeated exposures of 10 to 15 min at temperatures from 170 to 210 F (This is done for the health).

Temperature in the protected section just reached the human tolerance limit (for more severe conditions) in 12 minutes. If temperature were the only consideration, passengers should have been able to survive for this time.

After the fire burned out in the ponds, small flames remained along the sides of the test section. At 12 1/2 min after the start of the fire, the air temperature suddenly increased, indicating flame intrusion into the cabin, through cracks at the floor-wall intersection. (Why this happened will be discussed later.) The flame intrusion was probably rather small, being limited to the low flames remaining at the edges of the ponds. At the 14-min point, water hoses were played on the protected section and on the remaining flames, causing the air temperature in the cabin to drop rapidly.

Toxic gases kill, too. Up to 5 min into the test, no toxic gases appeared in the protected test compartment. At this point, the gas-sampling probe was withdrawn. During the last few minutes before burnout, segments of the fiber-glass-epoxy liner reached temperatures at which partial decomposition of the resin might have occurred. Gases might have been generated that could have been somewhat toxic. But we do not believe enough toxic fumes were generated to influence survivability, even at 12 minutes.

If this test represented an actual crash fire at an airport, fire-fighting equipment would likely have reached the airplane and extinguished the fire in less than 8 min, as indicated in the graph on page 23. At the 8-min point, conditions favored survival of passengers much more than at 12 min, and for the 8-min period neither heat nor toxic gases would have endangered life in the cabin.

Thus the concept of passenger protection was adequately demonstrated by this test.

Foam and Fissures: Although the system of foam, paint, and fiber-glass liner gave satisfactory protection, subsequent to this test we explored ways to improve the system, particularly to reduce the weight of protection materials while maintaining their beneficial effects.

Thermal data were analyzed to identify and evaluate the sources of heating. We plotted temperature histories at various places in the cabin for the last 5 min of the test, as shown, for example, in the graph on page 23—middle of the cabin, on the fiber-glass liner alongside of the air thermocouple, and in the foam 1/4 in. away from the liner. Note that the temperature of the air exceeded the temperature of the fiber-glass liner, and the liner's temperature exceeded the foam's. This means that the air was heating the sidewall of the cabin—an unexpected reversal in heat-flow direction. *It indicates that most of the cabin heating came from heat leaks rather than through the main area of the side walls.*

Two sources of heat leaks have been identified by the temperature histories shown at right, made over a frame and on the fiber-glass liner opposite a region of the foam that fissured. At both of these points the temperatures went well above the air temperature.

These temperature histories typify the two primary sources of heat leak. The frames formed highly conductive heat-flow paths through the foam. Calculations indicate that about a third of the total heat input to the cabin for the last 5 min of the test came through the frames. Fissuring of the foam also introduced heat. The sudden increase in fiber-glass-liner temperature indicates the appearance of a fissure in the foam.

Apparently fissures were the chief cause of heat leaks into the cabin. According to calculation, they contributed over half the heating of the cabin.

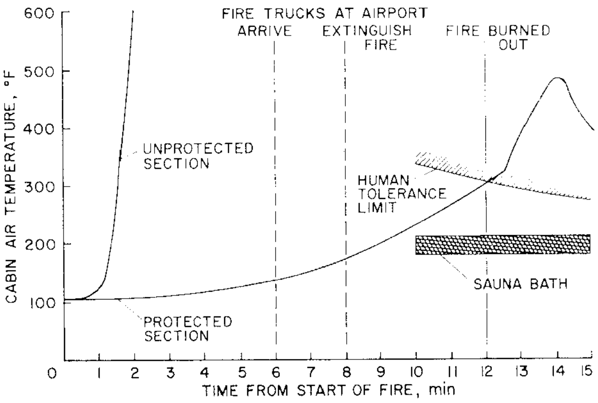
The photo at bottom shows examples of fissures after the test. The deep cracks, some of which penetrated clear to the fiber-glass liner, obviously mark heat-flow paths to the liner.

To minimize heating from the frames, the obvious solution would be to insulate the fiber-glass liner from the frame flanges. Because of its low thermal conductivity, isocyanurate foam would be a good material for this. Calculations indicate that 1/2 in. of foam placed between the frame flanges and the fiber-glass liner would cut the heat input from the frames 80% (from value with no insulation).

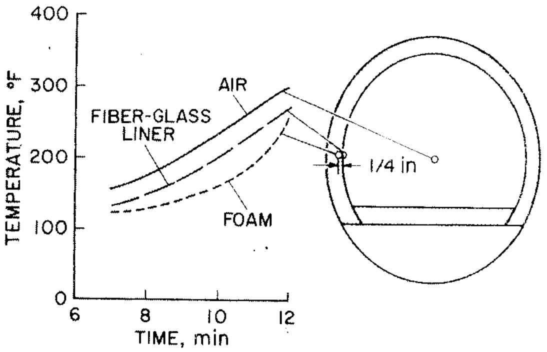
Fissuring of the foam needs further study. Tests have shown that isocyanurate foam in the lower-density range (2-2.5 lb per cu ft) has less tendency to fissure than higher-density foam, such as that installed in the protected section.

There are several possible explanations for the fissuring. The most likely one: higher density means greater stresses upon heating of the foam.

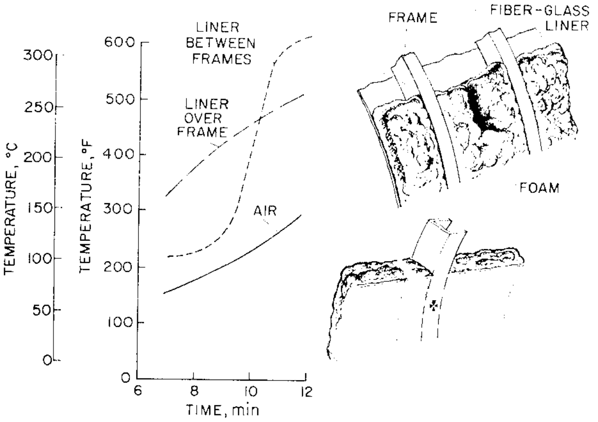
CABIN-AIR TEMPERATURE DURING FIRE



TEMPERATURES INSIDE CABIN

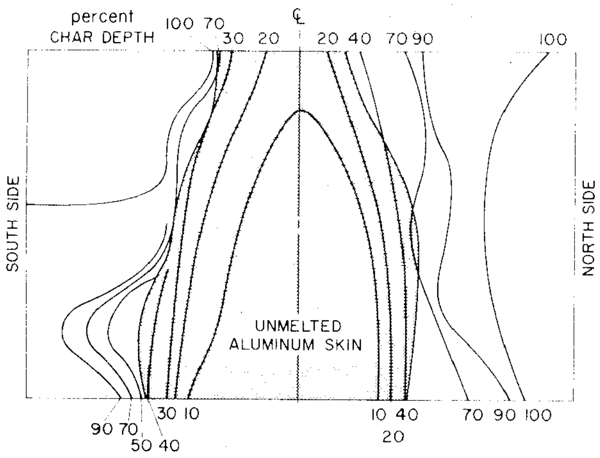


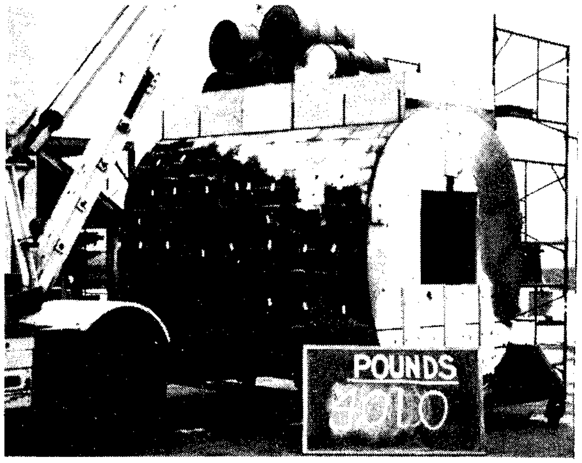
SOURCES OF HEAT LEAKS



FISSURES IN FOAM AFTER TEST

AREA OF UNMELTED SKIN AND CHAR DEPTH OF FOAM





Loading of charred fuselage.

Additionally, spraying the foam—which undergoes an exothermic reaction upon curing—against cold aluminum structure might create built-in stresses that, with heat, cause fissures. Other processing problems could also induce fissuring. These various possibilities must be studied to eliminate it.

One technique, studied recently, involves reinforcing the foam with glass fibers 1 to 1 1/2 in. long as it is being sprayed in place. This foam has much less tendency to fissure upon charring. Furthermore, weight for weight this composite apparently gives more protection than the non-reinforced foam used in the test.

Analysis of Char and Strength of Structure: As expected, the foam was extensively charred over a large part of the protected section. Most of the aluminum skin had melted; but, as can be seen in the photo on page 22, a surprisingly large section of skin was still intact on top of the fuselage. The chart at the top indicates the extent of char and unmelted aluminum skin. It shows that about half of the foam on the top and sides was charred to at least 70 percent of its depth (based on final thickness) and that this heavily charred region was in the lower part of the walls. The upper walls and top, on the other hand, were charred only to a small percentage of foam depth. *Because the char-depth pattern reflects the intensity of heating, it can serve as a guide in establishing the optimum distribution of fire-protective foam for future installations.* Clearly, the upper walls and top of a fuselage need much less protection than the lower walls.

The fire-retardant foam forms a *tough* insulative char upon exposure to a flame. To permit analysis of the char, samples were cored from the foam at various places on the sides and top of the fuselage. Analysis of five of the charred samples showed an average compressive strength of about 10 lb per sq in.—about one-fourth of the strength of the virgin foam, and sufficient to reinforce the remaining structure.

To illustrate the strength of the remaining structure, and to some extent to reflect char strength, the protected section of fuselage was loaded on the top with weights—sandbags and waterfilled drums (see photo at left)—until the structure deformed slightly. In this condition the fuselage supported 4010 lb.

This test demonstrated that the remaining structure would have had sufficient integrity to protect passengers while they awaited rescue. The inner fiber-glass liner, along with the foam, undoubtedly contributed greatly to the post-fire strength of the structure, as well as serving as the last barrier to prevent flame intrusion through fissures in the foam.

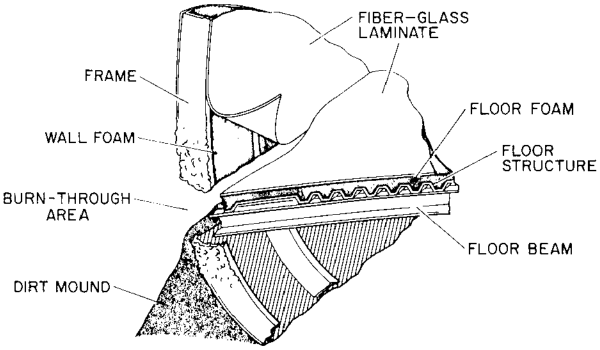
Floor-Line Failure: Because cracks developed in the floor seam during tailoff of the fire, the design of floor-line protection must be improved. The drawing on page 25 describes how the failure developed. Dirt had been banked part way up the fuselage wall to create a mound that formed one side of the fuel pond. The mound stopped just below the floor line. This protected the bottom part of the fuselage from the fire, but left exposed a portion of the structure just below the floor line. Heat from the fire finally melted the exposed frames to which the floor beams were fastened, causing the floor to sag just as the fire was burning out. This sagging opened the floor-line cracks and then flames entered the cabin.

In the installation, foam was placed on top of the floor, where it did not protect the primary structure. This installation proved satisfactory for the test of the protective concept, but an improvement in design of the system would be required for an operational installation. To protect the floor structure properly, the foam should be placed under the structure, as shown by the drawing on page 25. The foam should surround the primary structure to protect it from melting.

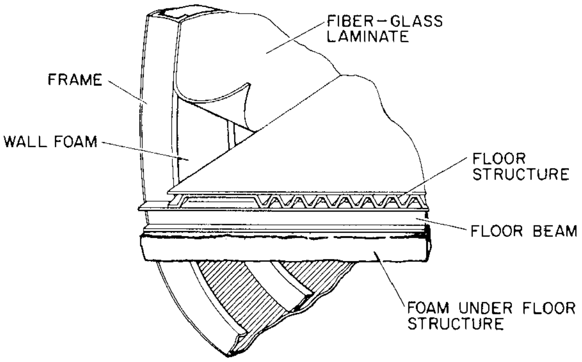
Weight Penalties: Because of its ablative character, the fire-retardant foam generally increases fire protection with increase in density. So the foam for the test fuselage had been made heavier than usual, with the intent of providing protection equal to what would have been obtained from a thicker application of lower-density foam in a larger airplane. Analysis of the data from the test indicates that the foam installation was heavier than it need be for adequate fire protection.

Various factors should permit a reduction in its weight. First, by minimizing the heat leaks, we should expect better thermal performance and hence a reduction in weight. Reinforcing the foam with glass fibers, as mentioned previously, would permit reducing foam weight from 4 to about 2.5 lb per cu ft without sacrificing protection. The required protection (weight) could be reduced further by correlation with the time fire-fighting equipment arrives and puts out the fire (8 rather than 12 min).

BURN-THROUGH AT FLOOR SEAM



PLACEMENT OF FOAM TO PROTECT FLOOR STRUCTURE



EXTENSION OF FIRE-PROTECTION TECHNIQUES

The materials described in this article may find their way into a variety of civil and military uses.

Engine compartments for autos and boats, for example, could be lined with foam or intumescent paint for fire protection. A European car manufacturer already installs foam in body cavities around the engine compartment for insulation and sound deadening; the new fire-retardant foam could readily be substituted to gain the advantage of fire protection. The intumescent coating is being considered for fire protection of the engine compartment of a cabin cruiser; the paint renders nonflammable the otherwise highly flammable polyester laminate enclosing the gasoline engine.

Operators of petroleum refineries are constantly seeking materials that could give long-term protection to storage tanks and transfer pipes to minimize the spread of a fire.

Likewise, railroad tank cars containing liquid petroleum must be protected to prevent recurrence of past holocausts started by accidental spilling of the contents of a single car. The intumescent paint, sprayed with long glass fibers for char reinforcement, may well give the protection needed in these cases.

Exposed steel-building structures, which characteristically warp and collapse when surrounded by fire, might also be protected with the new intumescent paint.

In the military area, use of the materials is being investigated to protect aircraft structures from onboard fires in combat. Protection of explosives exposed to fire is another potential use of the intumescent paint. —C.B.N.

Based on these considerations, then, we have estimated the weight penalty for installation of a fire-protection system in a typical modern-day airplane—an airliner with a gross weight of 400,000 lb. The increase in weight: 0.3 lb per sq ft of protected surface area. This would increase the gross weight 1700 lb. Structural-weight fraction would increase correspondingly from 30.0 to 30.4 percent.

It should be pointed out that the protective system proposed here would be essentially a retrofit installation for airplanes currently in service or in production. The foam would be added for the *single purpose of fire protection.* No advantage would be taken of its other useful characteristics, such as high compressive strength and compressive modulus or acoustical-damping properties.

To utilize it most effectively, foam and structure should be integrated at the beginning of structural design for a new airplane. With this approach, it is conceivable that the structural gain would permit the addition of foam with no weight penalty.

Concluding Remarks: We have seen the results of a test to demonstrate a heat-shield *concept* for protecting airline passengers in a fuel fire. This test must be regarded as only the *first step* in developing an effective system to increase the chances for survival. Many problems, such as preventing fuselage rupture and protecting windows, must be solved before such a system can be used. Nevertheless, even this one test gives promise that a heat shield can save passengers and so would help raise the reputation of air travel in the eyes of the public.

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