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Full-Scale Test Evaluation of Aircraft Fuel Fire Burnthrough Resistance Improvements

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16. Abstract

This report summarizes the research and full-scale tests undertaken by the Federal Aviation Administration (FAA) to evaluate the fuselage burnthrough resistance of transport category aircraft that are exposed to large postcrash fuel fires. Twenty-eight full-scale tests were conducted in a reusable fuselage test rig to determine the effectiveness of thermal-acoustical insulation improvements in preventing or delaying fuselage burnthrough. The testing showed that the method of attaching the insulation to the fuselage structure had a critical effect on the effectiveness of the insulation material. In addition, the composition of the insulation bagging material, normally a thermoplastic film, was also shown to be an important factor. A number of fiberglass insulation modifications and new insulation materials were shown to be effective in varying degrees. For example, a heat-treated, oxidized polyacrylonitrile fiber (OPF) encased in a polyimide bagging material prevented burnthrough for over 8 minutes. When contrasted with current insulation materials, which were shown to fail in as little as 2 minutes, effective fire barriers such as the OPF insulation offer the potential of saving lives during a postcrash fire accident in which the fuselage remains intact.

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EXECUTIVE SUMMARY

Fuselage burnthrough refers to the penetration of an external postcrash fuel fire into an aircraft cabin. The time to burnthrough is critical because, in survivable aircraft accidents, the hazards of burning cabin materials ignited by burnthrough from an external fuel fire may incapacitate passengers before they are able to escape. There are typically three barriers that a fuel fire must penetrate in order to burnthrough to the cabin interior: the aluminum skin, the thermal-acoustical insulation, and the interior sidewall and floor panel combination. The burnthrough resistance of aluminum skin is well known, lasting between 30 to 60 seconds, depending on the thickness. Thermal-acoustical insulation, typically comprised of fiberglass batting encased in a polyvinyl fluoride (PVF) moisture barrier, can offer an additional 1 to 2 minutes protection if the material is not physically dislodged from the fuselage structure. Honeycomb sandwich panels used in the sidewall and floor areas of transport aircraft offer a substantial barrier to fire; however, full-scale testing has shown that a large fire can penetrate through other openings such as the seams between sidewall panels, window reveals, and baseboard air return grills.

The research described in this report consisted primarily of full-scale fire tests in a reusable fuselage test rig to determine the effectiveness of thermal-acoustical insulation improvements in preventing or delaying fuselage burnthrough. Twenty-eight full-scale tests were conducted on modified fiberglass batting or replacement insulation materials. The testing showed that the method of attaching the insulation to the fuselage structure had a critical effect on the effectiveness of the insulation material. In addition, the composition of the insulation bagging material, normally a thermoplastic film, was also shown to be an important factor. A number of barrier materials used in conjunction with the current insulation systems were shown to be effective in varying degrees, including the use of a ceramic fiber layer. Several new materials and combinations tested also showed vast improvements in burnthrough resistance over existing materials. For example, a heat-treated, oxidized polyacrylonitrile fiber (OPF) encased in a polyimide bagging material prevented burnthrough for over 8 minutes. When contrasted with current insulation blankets, which were shown to fail in as little as 2 minutes, effective fire barriers offer the potential of saving lives during a postcrash fire accident in which the fuselage remains intact.

INTRODUCTION

PURPOSE.

The purpose of this report is to describe the research and full-scale tests undertaken to evaluate the burnthrough resistance of a transport category aircraft fuselage and to determine the effectiveness of various improvements aimed at extending the resistance of a fuselage during a postcrash fuel fire scenario.

BACKGROUND.

In a majority of survivable accidents where there is a fire, ignition of the interior of the aircraft is caused by burning jet fuel external to the aircraft as a result of fuel tank damage during impact. One important factor to occupant survivability is the integrity of the fuselage during an accident. In an aircraft accident the fuselage can remain intact or it may rupture during the crash or emergency exits may be opened, allowing the external fuel fire flames to contact the cabin materials. Based on past accidents, experimental studies, and fuselage design, it is apparent that the fuselage rupturing or opening represents the worst case condition in a crash and provides more significant opportunity for fire to enter the cabin. [1] Past Federal Aviation Administration (FAA) regulatory actions governing interior material flammability were based on full-scale tests employing a fuel fire adjacent to a fuselage opening in an otherwise intact fuselage. This scenario, in which the cabin materials were directly exposed to the intense thermal radiation emitted by the fuel fire, represented a severe but survivable fire condition and was used to develop improved standards. However, in some crash accidents, the fuselage remained completely intact and fire penetrated into the passenger cabin as a result of a burnthrough of the fuselage shell. [2] Five transport accidents involving burnthrough have occurred in the last 20 years, in which fire penetration of the fuselage was a primary focus of the accident investigation: Los Angeles 1972, Malaga 1982, Calgary 1984, Manchester 1985, and Anchorage 1987.

During an accident involving a Continental DC-10 at Los Angeles in 1978, a large fuel fire burned for 2 to 3 minutes before it was extinguished by the Crash Fire Rescue personnel. During this interval, the fuel fire did not penetrate to ignite the cabin furnishings, although there was some evidence of heat and flame damage at panel seams and along seat back cushions. It was clear from this accident that wide-body transports (B-747, DC-10, and L-1011) could resist burnthrough for several minutes because the fuselage walls of these aircraft are constructed of thicker aluminum skin and heavy structural elements, along with thick thermal-acoustical insulation and honeycomb sidewall panels. In the DC-10 accident in Malaga, Spain in 1982, the aircraft overran the runway after an aborted takeoff, coming to rest in a field just off the airport. The right wing was torn off and a large fuel fire encompassed the aft end of the fuselage. The fire entered the aft cabin through tears in the fuselage and burnthrough of the skin. Evacuation was hampered by traumatized passengers and debris in the aisles. There were 51 fatalities of the 393 occupants.

It was believed that in narrow-body aircraft (B-727, B-737, and MD-80) burnthrough may occur much more quickly because of aluminum sidewall panels in some aircraft, thinner thermal-acoustical insulation, and in many cases, a thinner aluminum skin. [3] However, in the B-737 accident at Calgary in 1984, a fire resulted when the left engine failed and ignited the fuel released by the nearby damaged fuel tank. The fire was immediate and intensified as the aircraft was brought to rest almost 2 minutes later. The 119 passengers and crewmembers were able to evacuate in an estimated 2-3 minutes, although portions of the cabin quickly filled with smoke when the exits were opened. The same could not be said of the B-737 accident in Manchester in 1985, which had a similar fire scenario as the Calgary accident. During this accident, a B-737 was approaching takeoff when it experienced an uncontained engine failure, propelling pieces of the engine into the wing and subsequently rupturing the wing fuel access door area. The takeoff was aborted. As the airplane decelerated, leaking fuel ignited and burned, erupting into a large ground fire after the plane came to rest. Although the fire fighting response was practically immediate, 55 occupants perished from the effects of the fire. In this accident, it was believed that the external fire very rapidly burned through the lower fuselage skin and quickly ignited the cabin furnishings by gaining entry through the baseboard return air grills. [4] During an accident involving a B-727 at Anchorage in 1987, a large fuel fire developed on the ground adjacent to the aircraft when it was accidentally towed into a loading walkway causing a massive fuel spillage due to a punctured fuel tank. Although a large section of the fuselage skin melted away during the ensuing fire, it did not spread into the cabin, indicating that, in some cases, the fuselage could act as an effective fire barrier. One key difference between the Manchester accident and both the Calgary and Anchorage accidents was the presence of the wind blowing flames against the fuselage, which could have aided the rapid fire penetration.

OBJECTIVE.

Although fire can penetrate into the passenger compartment by a variety of paths including the windows, the sidewall (above the cabin floor), cheek area (below the cabin floor), cabin floor, and baseboard return air grills, there is no set pattern based on past accidents or experimental test data to indicate which areas are the most vulnerable. Testing has been performed on the individual components (aluminum skin, windows, thermal-acoustical insulation, and interior sidewall panels) but has not been done on the complete fuselage shell system in which fire penetration paths and burnthrough times could be observed. For this reason, the objective of this test program was to conduct full-scale fuselage fire tests to determine these mechanisms and the likely timeframe for burnthrough. The program was undertaken in two phases. First, a series of tests were conducted on surplus aircraft fuselages. The data from these tests were then used to develop a full-scale burnthrough test rig which was used to conduct a series of tests to quantify burnthrough rates and potential improvements.

DISCUSSION

INITIAL FUSELAGE TESTING.

To better understand and quantify the fuselage burnthrough problem, the FAA conducted a series of full-scale tests by subjecting surplus aircraft (DC-8 and Convair 880) fuselages to 400-square-feet jet fuel fires. The fuel fires were set adjacent to intact fuselage sections instrumented with thermocouples, heat flux transducers, and cameras to determine penetration locations, firepaths, and important event times. During the tests, each aircraft was divided into three sections by installing exterior barriers and internal partitions to confine the fire within the section being tested. Thus, each aircraft was tested three times in the following sequence: aft, forward, and center. [5] In the DC-8 tests, the aircraft was resting on its belly, simulating a crash with collapsed landing gear; the landing gear was extended during the tests on the Convair-880 (figure 1).

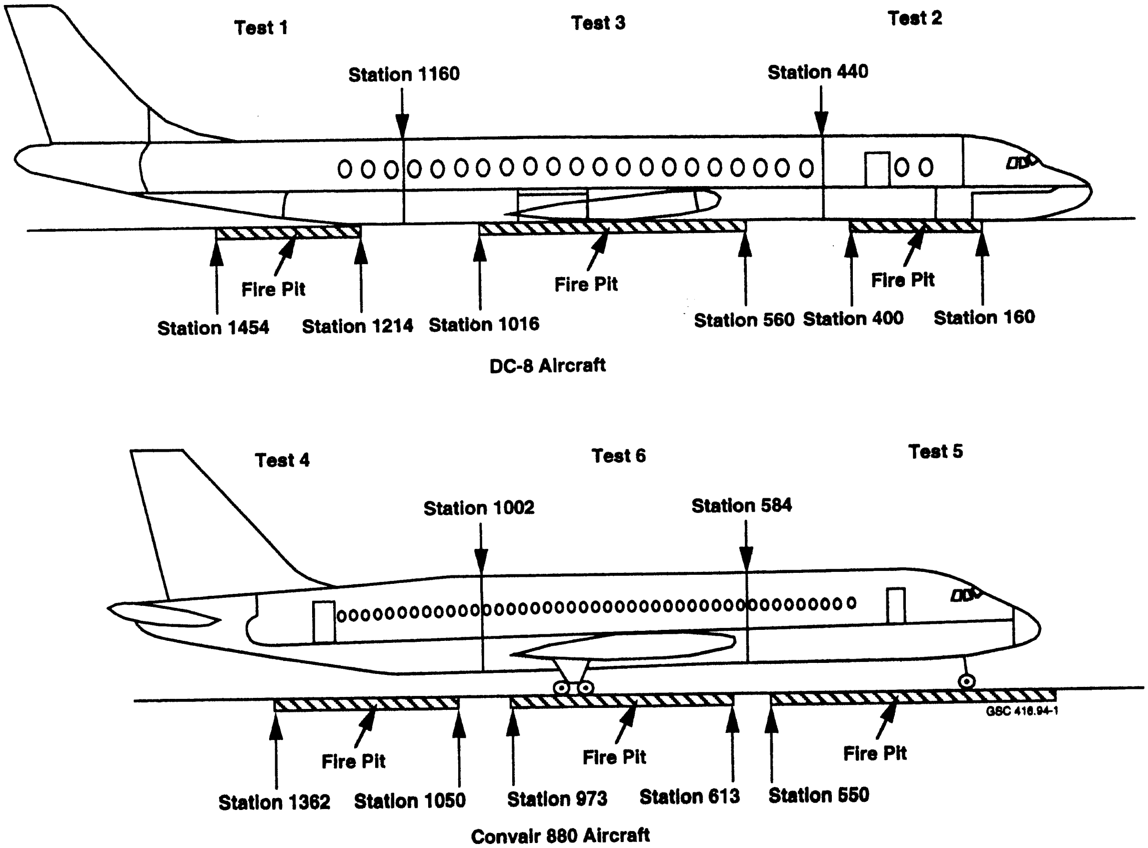


FIGURE 1. INITIAL SURPLUS AIRCRAFT TEST ARTICLES

Several observations on the likely entrance paths of the fire and the time required to involve the cabin interior materials were made. The tests indicated that the aluminum skin provides protection from a fully developed pool fire for 30 to 60 seconds and that the windows are effective flame barriers until they shrink due to the radiant heat of the fire and fall out of place allowing the flames to penetrate. These findings were consistent with data obtained during the investigation of the above mentioned accidents. The tests also highlighted the importance of thermal-acoustical insulation in preventing fire penetration. It was observed that the insulation could provide a significant delay in the burnthrough process, provided it remains in place and is not physically dislodged from its position by the updrafts of the fire. Several other findings were highlighted, including the ability of the flames to gain access to the cabin by first penetrating into the cheek area (located outboard of the cargo compartment sidewall, under the cabin floor) and then progressing upward through the baseboard air return grill system. [6] It was determined that an aircraft with its gear extended is more vulnerable to burnthrough from a ground-level pool fire than an aircraft resting on its belly, mainly because of the increased temperatures sustained at the upper flame area of the fire. The information obtained during this test project was used as a basis for the development of a full-scale burnthrough test rig.

DEVELOPMENT OF A FULL-SCALE BURNTHROUGH TEST RIG.

In the next phase of the program, a test apparatus to evaluate improvements under realistic conditions was developed. The construction of a full-scale test rig was the most practical approach that would allow repetitive testing and systematic evaluation of singular components. A 20-foot-long steel test rig was fabricated, a B-707 fuselage was cut in half to allow the test rig to be inserted between the two fuselage pieces (figure 2). This test rig had a 12- by 8-foot section of the outer skin removed which could be mocked-up with aluminum skin, thermal-acoustical insulation, floor and sidewall panels, carpet, and cargo liner. The mocked-up test rig extends beyond a 10-foot-long fire pan that was used to simulate the external fire, eliminating any edge effects or mating problems that might occur if the test rig/ B-707 fuselage seams were directly exposed to the fuel fire. Measurements of temperature, smoke, and fire gases (CO, CO_2, and O_2) were taken inside the test rig along with video coverage at several locations to determine exact burnthrough locations and times (figure 3).

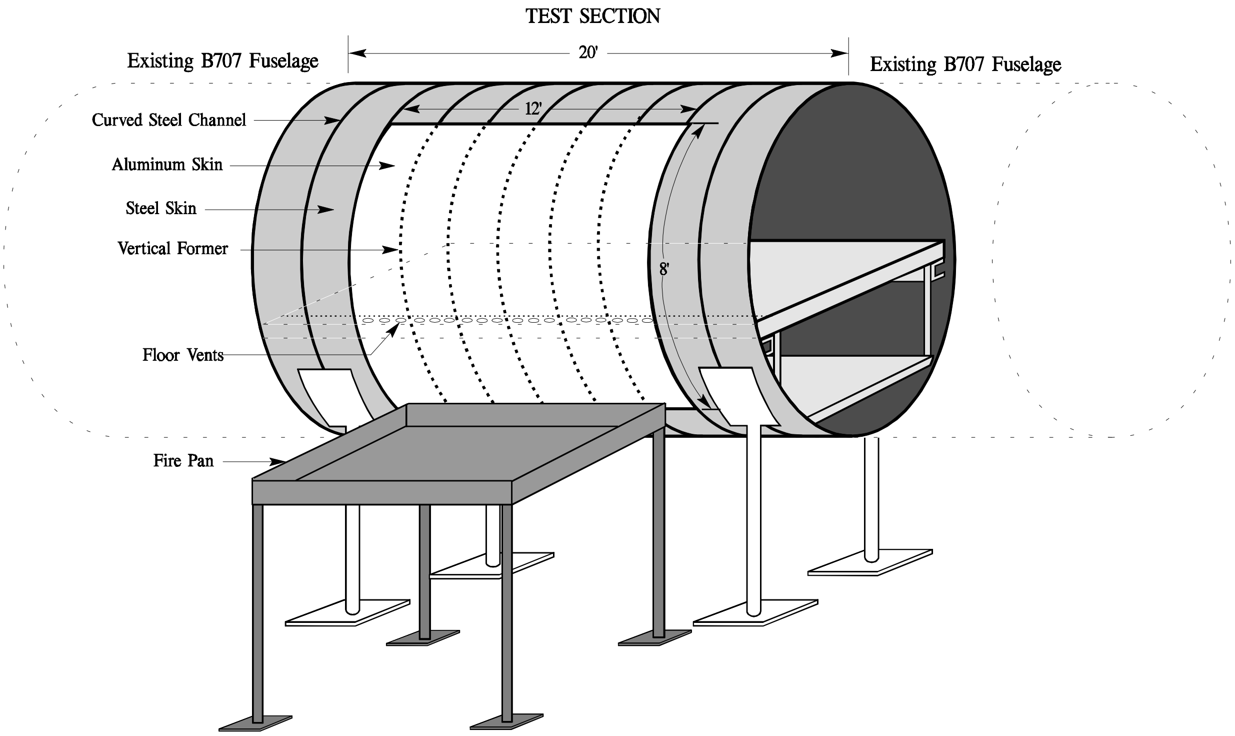


FIGURE 2. FULL-SCALE FUSELAGE BURNTHROUGH TEST RIG

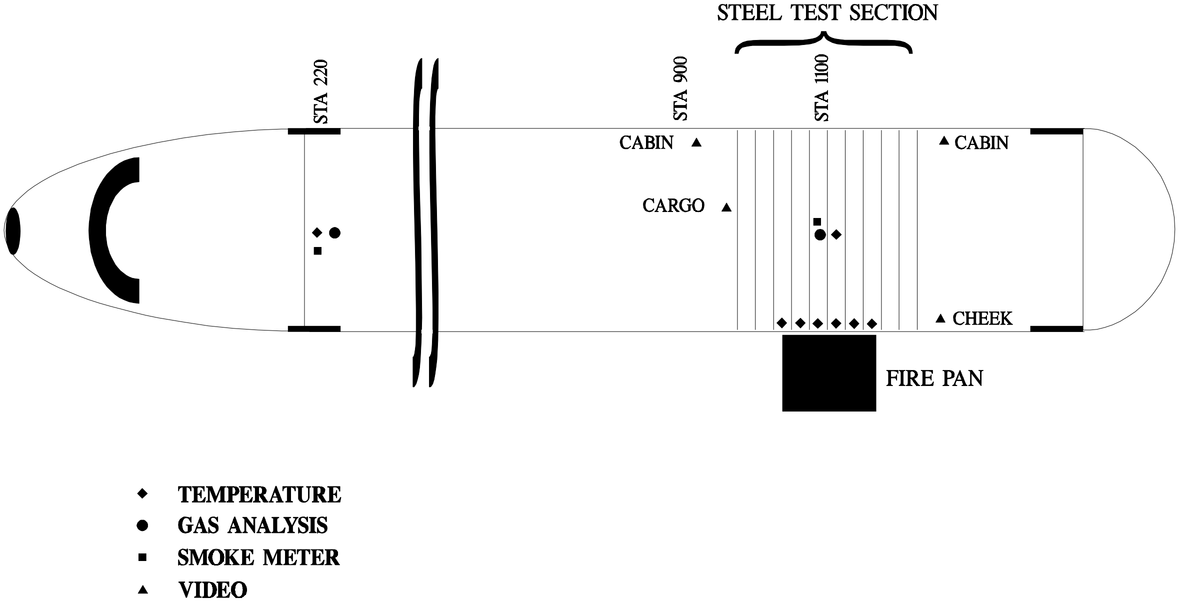
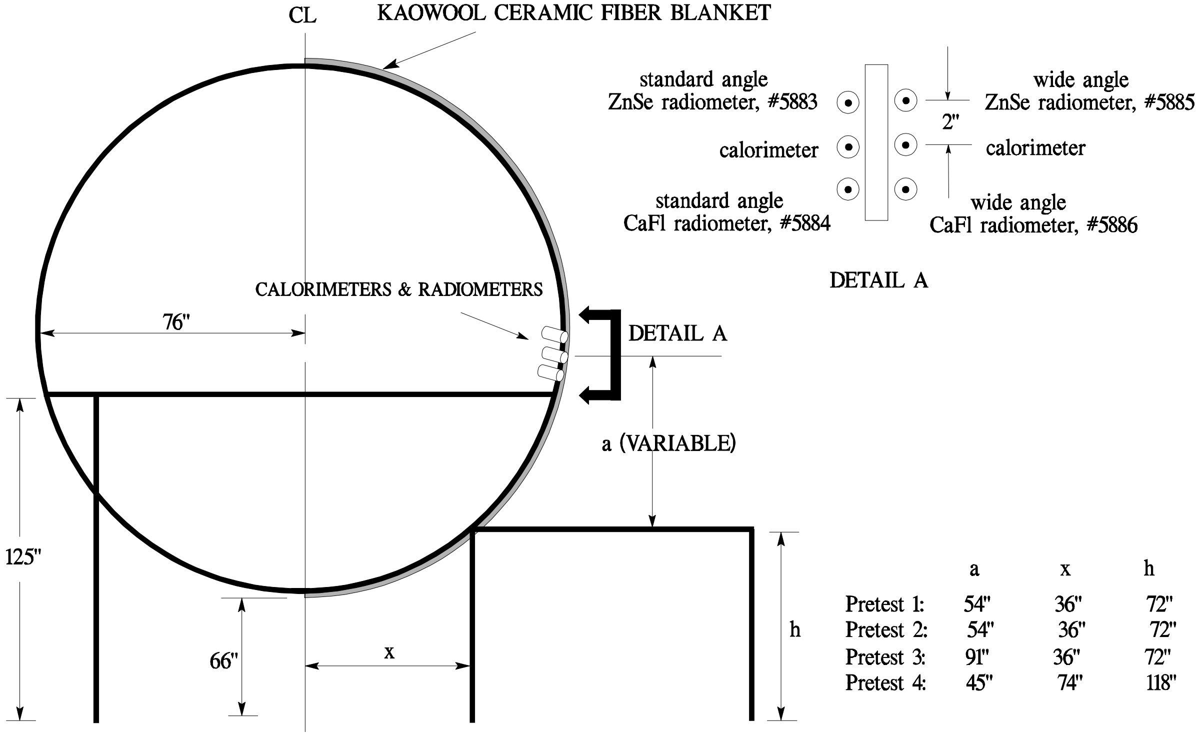


FIGURE 3. INSTRUMENTATION, FULL-SCALE TEST ARTICLE

Before beginning the mock-up tests, the fuselage exterior was covered with a Kaowool ceramic fiber blanket on the surface exposed to the fire; the Kaowool covered approximately half of the fuselage circumference, from center top to center bottom. The exterior surface was then instrumented with thermocouples, calorimeters, and radiometers to quantify test fires at different fuselage locations (figures 4 and 5). During past test programs, ground fires ranging in size from 20′ x 20′ to 35′ x 40′ were ignited next to fuselages at the cabin floor level and adjacent to a Type A opening to simulate an open escape exit or fuselage rupture. It was determined from these earlier tests, however, that from a burnthrough standpoint, a more severe condition results when the fire is beneath the fuselage, allowing the higher temperatures of the upper flame area to come in contact with the lower fuselage. Two fire pan locations were tested using an 8′ x 10′ pan filled with 55 gallons of Jet-A fuel, and the location that provided the more severe results of the two was established as the standard fire condition for future material mock-up tests. These pretests also provided information on the radiative and convective heat flux produced by this size fire. Figure 6 plots the radiative and convective heat flux as a function of time measured by a thermogauge calorimeter that measures the combined radiative and convective heat flux. As shown in figure 6, the fuselage is subjected to a maximum heat flux of between 14 and 16 Btu/ft^2-second. By comparison, a thermogauge radiometer with a 136^o angle of incidence (radiative heat flux only) reached approximately 12 Btu/ft^2-second.



	a	x	h
Pretest 1:	54"	36"	72"
Pretest 2:	54"	36"	72"
Pretest 3:	91"	36"	72"
Pretest 4:	45"	74"	118"

FIGURE 4. CALORIMETER AND RADIOMETER LOCATION, FIRE OUTPUT DETERMINATION

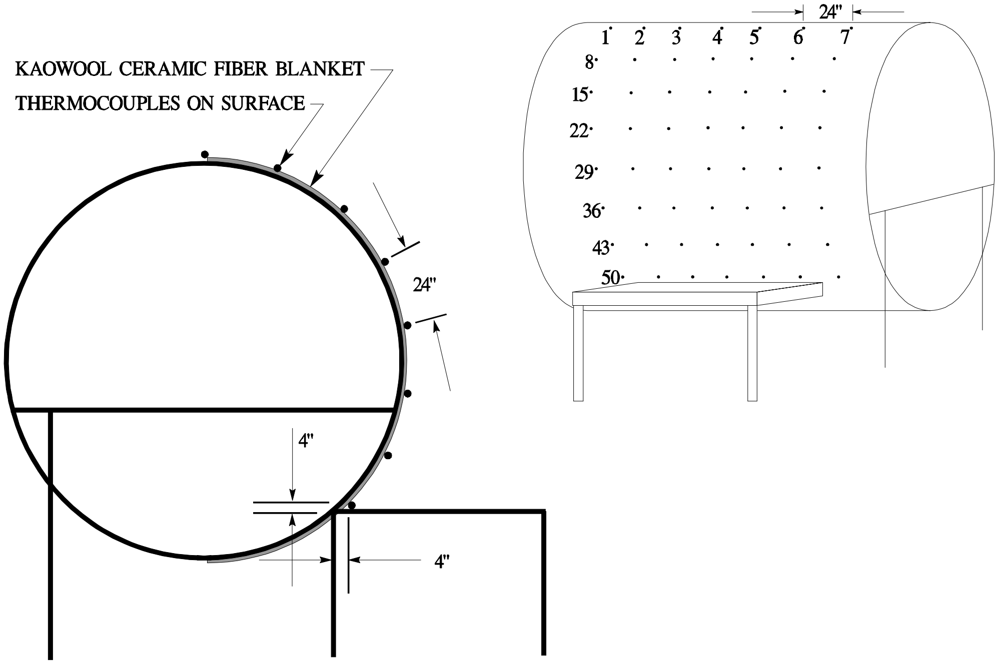


FIGURE 5. THERMOCOUPLE LOCATION, FIRE OUTPUT DETERMINATION

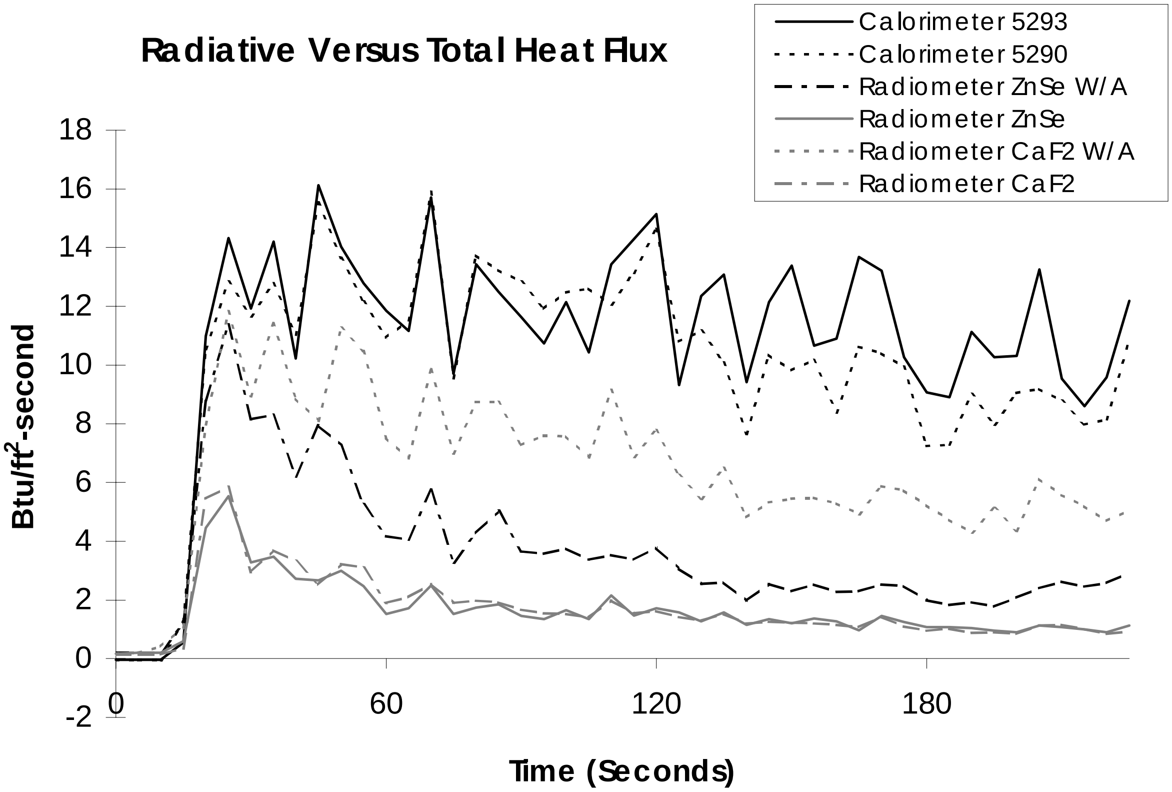


FIGURE 6. TEST RIG HEAT FLUX MEASUREMENTS

INITIAL BASELINE TEST RESULTS.

To evaluate potential improvements in materials and systems for better resistance to fuel fire penetrations, a baseline test arrangement was established using in-service materials. An aluminum skin section measuring 8 feet high by 12 feet wide was installed where the original steel skin of the test rig was removed. It consisted of two sheets of 0.063-inch-thick Alclad 2024 T3 aluminum heliarc welded together. The aluminum panel extended from the lower fuselage quadrant up to the window level and was mounted to the test rig stringers and ribs using steel rivets to reduce the potential for separation during testing. The remaining area of the test rig was covered with 22-gauge sheet metal. The first several tests used custom-made insulation batting consisting of Owens-Corning Aerocor fiberglass insulation encapsulated in Orcon brand heat shrinkable metallized polyvinyl fluoride (PVF) film (also known as Tedlar), type AN-18R. The insulation batting was sized to fit in the spaces outlined by the vertical formers and the horizontal stringers of the test rig (figure 7). The insulation batts spanned the entire area of the aluminum skin, 8 by 12 feet. In the test rig cargo compartment, 0.013-inch-thick Conolite BMS 8-2A fiberglass liners were installed in both the ceiling and sidewall areas facing the fire and held in place by steel strips of channel screwed into the steel frame of the test rig. An M.C. Gill “Gillfab” 4017 honeycomb floor panel measuring 4 by 12 feet was installed in the test rig cabin floor area and covered with FAA-approved aircraft quality wool/nylon carpet. The remaining test rig cabin floor area consisted of corrugated sheet steel. Interior sidewall panels from an

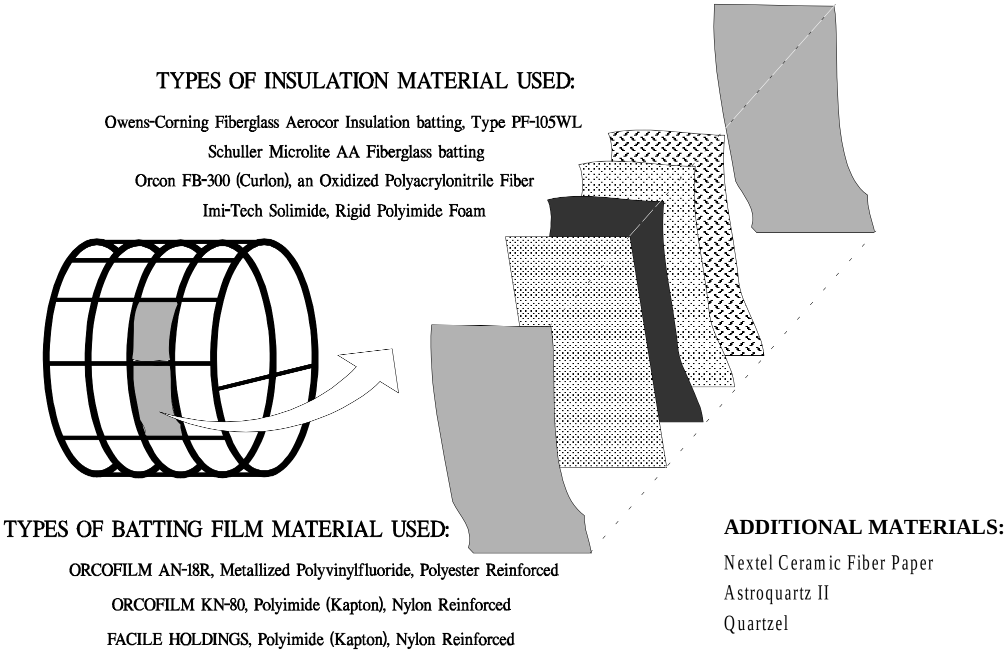


FIGURE 7. INSULATION BATTING CONSTRUCTION

MD-80 aircraft were used; these panels used an aluminum substrate that did not meet the current FAA fire test regulations regarding heat release rate. The outboard cabin floor area contained steel plating with 3-inch-diameter holes to simulate the venting area between the floor and cheek area. Additionally, an aluminum mesh was installed below the sidewall panels to simulate the baseboard air return grills (figure 8). In general, the major components of a typical aircraft fuselage were represented in the test rig (figure 9).

During the first test, the fire burned through the aluminum skin within 30 seconds and quickly displaced or penetrated the thermal-acoustical insulation batting, allowing flames to enter the cheek area within 40 seconds. The actual point of first penetration into the cabin was difficult to determine, since the fire penetrated both the sidewall panels and baseboard return air grills at nearly the same time. It was determined that there was not a complete coverage by the 1-inch-thick thermal-acoustical insulation batts, which had been attached to the test rig by loosely packing it into the spaces between the stringers and formers and then taping all edges using fiberglass tape. Since the major objective was to determine the effectiveness of the thermal-acoustical insulation batt when it is not physically displaced, efforts were made to better secure the batting material. During the next test, the insulation batts were held in place with steel spring clips that attached the film moisture barrier directly to the test rig frame. The thickness of the insulation batt was also increased for these tests since an inspection of several surplus fuselages revealed that the insulation batt was at least 3 inches thick in the sidewall area (the insulation batt actually becomes much thinner at the extreme lower section of the fuselage due to less acoustical requirements). Although the thickness of the insulation batt varies slightly between aircraft, it

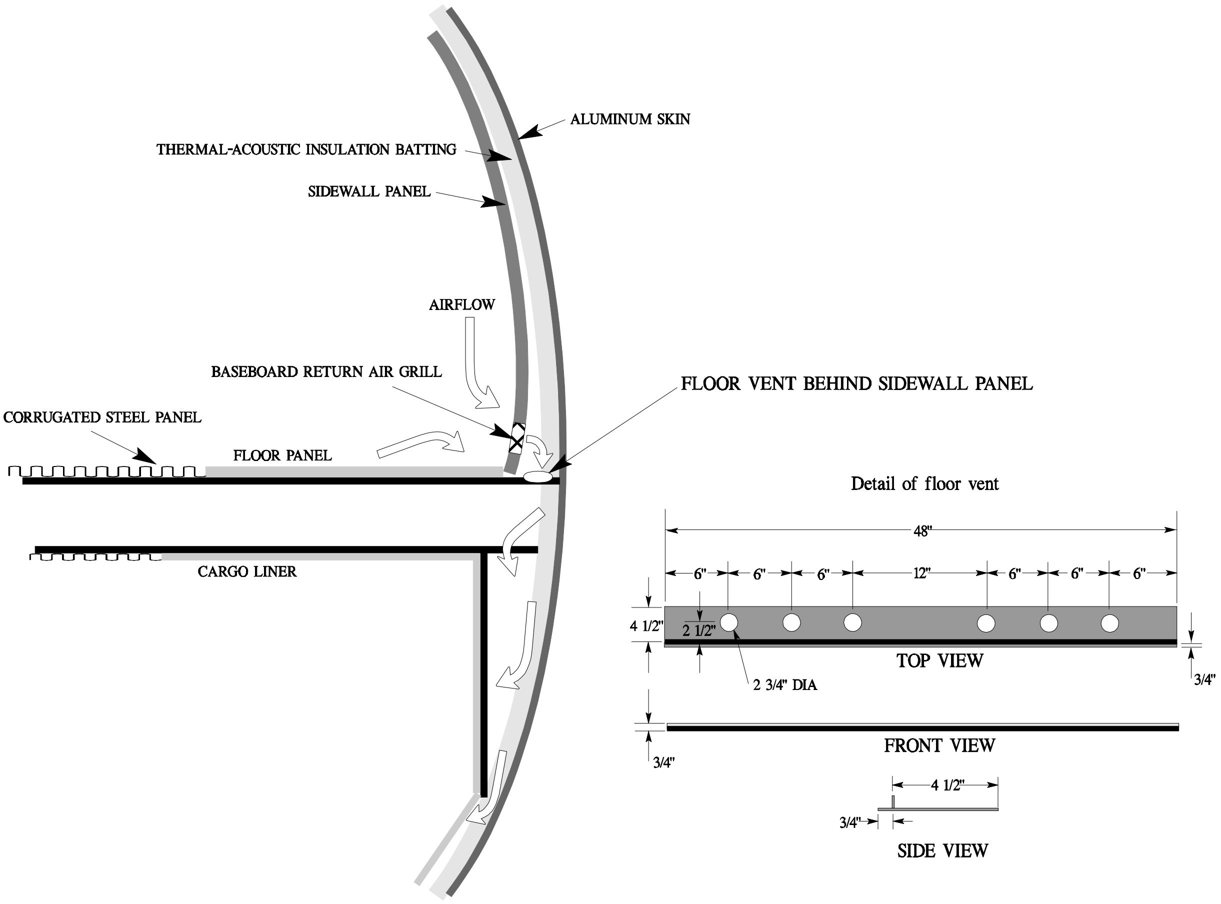


FIGURE 8. CROSS SECTION DETAIL

was found to be at least several plies thick in the corresponding areas of the surplus aircraft fuselage where the fire had penetrated during the first two tests in the steel test rig. The results of the next test were similar to the first in terms of fire propagation paths and burnthrough times, but again, it was very difficult to pinpoint the actual path taken because of the visual obstruction due to the placement of the sidewall panels and cargo liner. In order to better understand the burnthrough mechanism, the subsequent tests were conducted without sidewall panels, cargo liner, and floor panels to allow a better view of the burnthrough point and time.

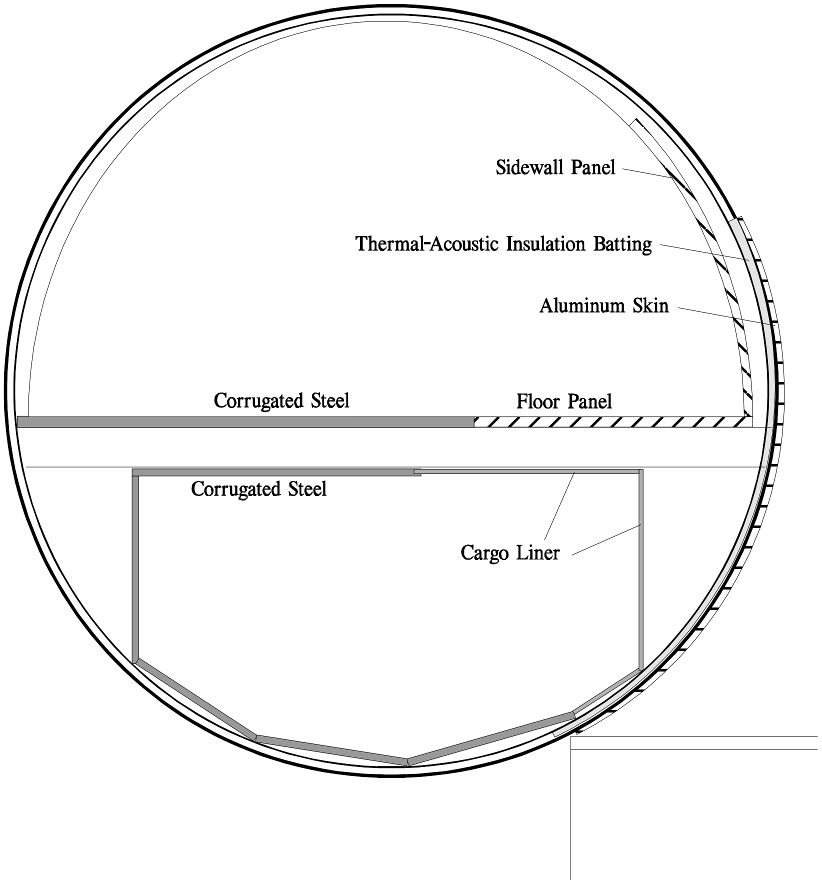


FIGURE 9. TEST RIG MATERIAL USAGE AND LOCATION DURING INITIAL BASELINE TESTS

EVALUATION OF CURRENT MATERIALS.

An evaluation of current fiberglass insulation was conducted in which the effects of the thickness and the method of installation on burnthrough time were investigated. Several tests were performed using a varying number of layers. As shown in figure 10, the first 3 Aerocor tests used 3-inch-thick insulation encased in a heat shrinkable metallized polyvinyl fluoride film. The method of insulation batting attachment was refined during each test, as the fire visibly dislodged the batting materials during the first and second tests causing burnthrough in 52 seconds and 1 minute 15 seconds respectively. During the third Aerocor test, both the moisture film barrier and the insulation material inside the film were attached to the frame. Heavier spring clips were used around the entire perimeter of each insulation batt, which proved to be a very effective attachment system. A fourth Aerocor test was conducted using an additional 1-inch layer of insulation, which provided an additional 12 seconds. Thus, a secured insulation batting provided about 45 seconds of additional protection after the aluminum skin melted. The time to burnthrough was determined by visual observation by video cameras located at various points in the test rig interior. The actual time is somewhat subjective, since the exact time and location are not always clearly defined.

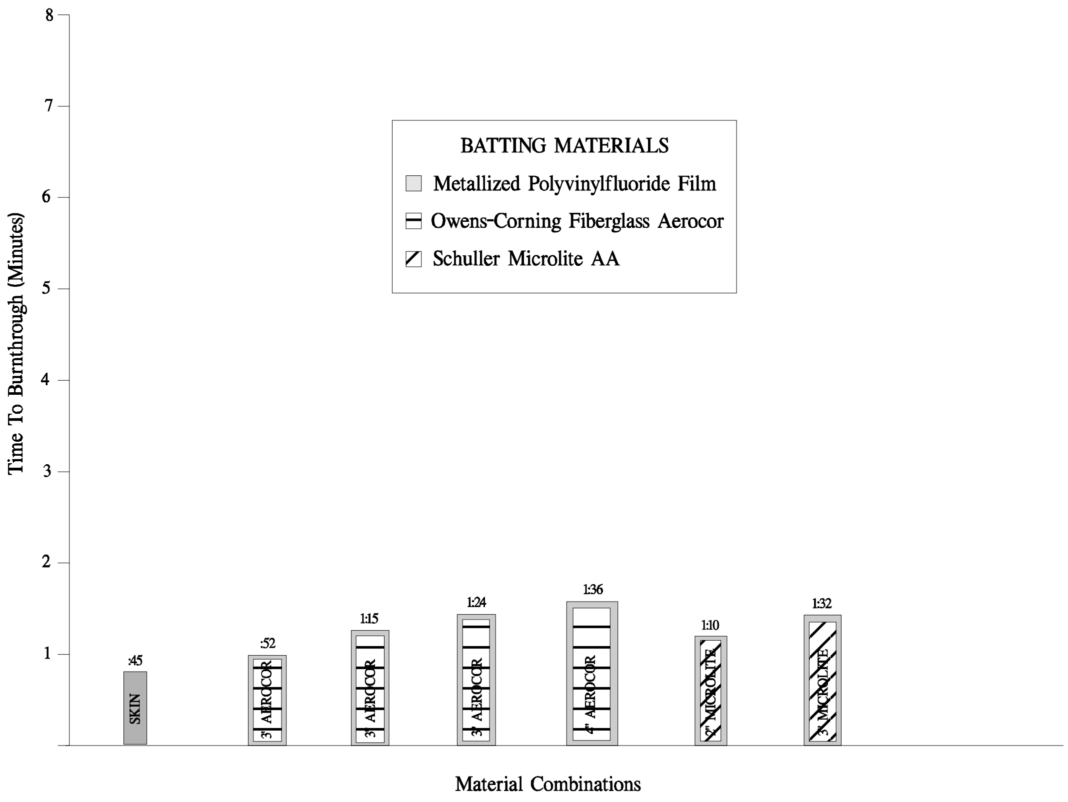


FIGURE 10. EVALUATION OF CURRENT INSULATION MATERIALS

Since the Aerocor is a somewhat older material, additional tests were conducted using Microlite AA insulation, which is currently used on most transport category aircraft. As shown, there was only a marginal increase in the burnthrough resistance offered by the 3-inch Microlite material (1 minute 32 seconds versus 1 minute 24 seconds using 3-inch-thick Aerocor). The test rig burnthrough times compared favorably with past tests using surplus aircraft where flame penetration was observed in approximately 2 minutes 30 seconds. [6] Assuming that the sidewall panels, flooring, and cargo liner in the surplus aircraft likely provided an additional minute of protection, it was concluded that the mock-up tests were a reasonable representation of actual crash fire conditions.

With a realistic and repeatable test condition and the burnthrough resistance of current materials defined, improvements in burnthrough resistance were evaluated. Considering the thermal-acoustical insulation system only, there are two possible areas for improvement (1) modification or enhancement of existing insulation materials or (2) replacement of the current fiberglass insulation with a more fire-resistant type.

EVALUATION OF MODIFIED CURRENT INSULATION MATERIALS.

The previous burnthrough evaluation of existing materials showed that with the metallized polyvinyl fluoride film, fire propagated rapidly from the outboard face of the insulation batt to the inboard face. Polyimide (Kapton), a candidate replacement film, with low flammability and smoke emission characteristics was evaluated. The use of polyimide film as a moisture barrier for commercial aircraft insulation is not new, having been introduced on the L-1011. The polyimide film displayed improved flame resistance compared to polyvinyl fluoride film as shown in figure 11. For example, comparable burnthrough times were exhibited when polyimide film was used with half the thickness of insulation (1.5 inches as compared to 3 inches of insulation used with metallized polyvinyl fluoride film). The most notable test results occurred when 3-inch-thick Microlite AA insulation was used with the polyimide film. This combination was capable of resisting burnthrough for 4 minutes or an increase of approximately 2 minutes 30 seconds over the identical thickness of insulation material used with the metallized polyvinyl fluoride film.

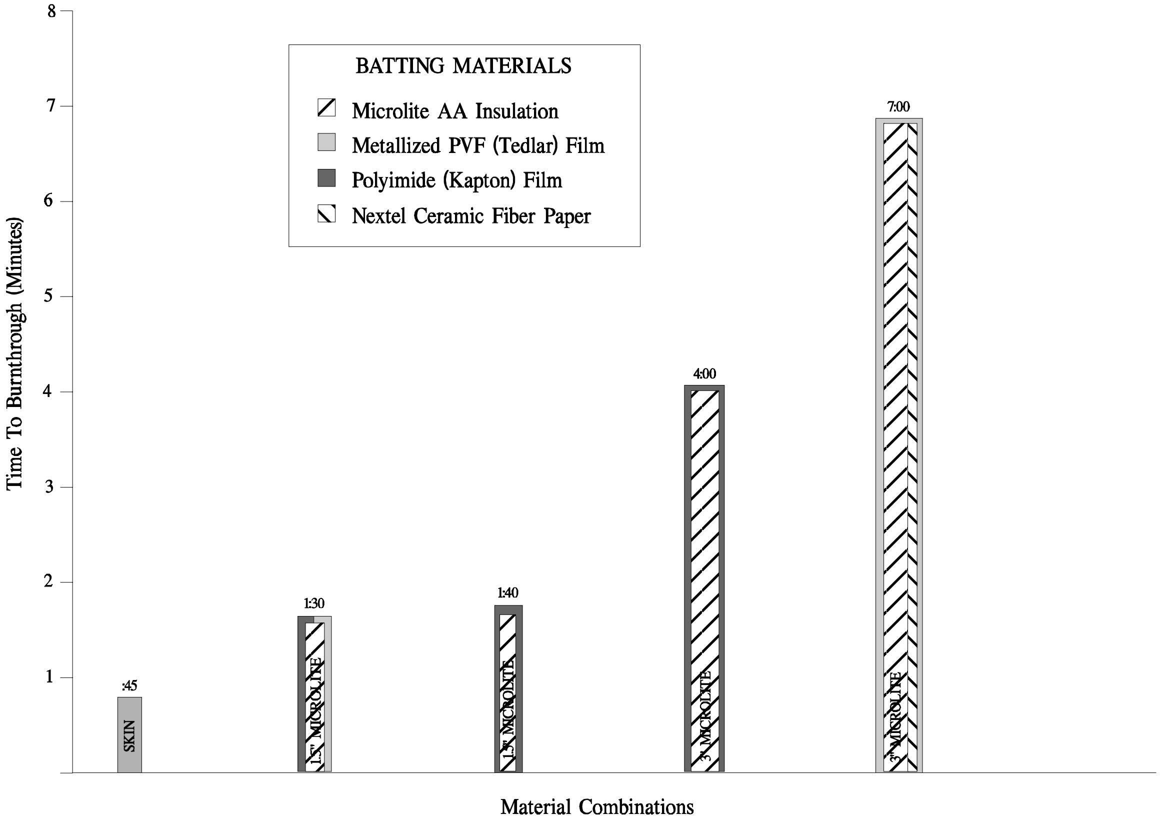


FIGURE 11. EVALUATION OF MODIFIED CURRENT INSULATION MATERIALS

A thin, fire-resistant layer of ceramic fiber material known as Nextel™ was also evaluated. Developed by the 3M, Nextel™ ceramic oxide fibers are resistant to temperatures above 2000°F, nonporous, and have a diameter of 10-12 µm. The continuous nature, strength, and flexibility of the fibers allow them to be processed into a variety of textile forms. Nextel™ fabrics are fireproof and are currently used as the firewall layer in engine thermal blankets and polymer composites on commercial and military aircraft and helicopters. In this test a dot printed, nonwoven paper of Nextel™ was tested to determine its effectiveness when used as an additional barrier to the existing insulation.

During the test, a layer of the Nextel™ was placed inside each of the insulation batts and both were then encapsulated in the standard metallized polyvinyl fluoride moisture barrier film. The Nextel™ was installed on the outboard face of the insulation batts (within the film) to form a flame propagation barrier between the external flames and the interior of the fuselage. The insulation batts and Nextel™ fiber mat were clamped in place around the perimeter; thus the clamping also held the Nextel™ in place. This arrangement was very effective, preventing burnthrough for nearly 7 minutes. Although there were visible flames on the backface of the insulation batts after approximately 4 minutes, it was difficult to determine if fuel fire penetration had occurred or if the polyvinyl fluoride film was burning due to the elevated temperatures. A posttest inspection showed that the majority of the Nextel™ had remained in place with the exception of one area approximately 20 inches by 20 inches which had been penetrated.

EVALUATION OF ALTERNATIVE INSULATION MATERIALS.

Another series of tests were conducted using an alternate insulation material known as Curlon®, a heat-treated, oxidized polyacrylonitrile fiber (OPF) produced by RK Carbon International, Ltd. RK Carbon International, Ltd. also manufactures OPF (Panox®) which is converted in a proprietary heat-treating process into the nonmelting, nonburning gray-black Curlon® fiber. The Curlon® fiber has a permanent crimp or waviness which aids in the manufacture of lightweight battings used for aircraft insulation. Curlon® contains about 70% carbon, 20% nitrogen, and 10% oxygen. It has a fiber diameter of about 8 microns and is considered nonirritating to the skin. Curlon® is also a nonconductor and chemically resistant.

The insulation system incorporating Curlon® was originally marketed jointly by Orcon Corporation and RK Carbon International under the trade name FB-300. Orcon subsequently purchased the sole right to manufacture the insulation system under the trade name Orcobloc. The insulation system is unique in that it could potentially be used as a drop-in replacement for the current fiberglass insulation (i.e., it possesses qualities similar to fiberglass for the intended use in aircraft applications). Early versions of the FB-300 were somewhat inferior to the current fiberglass materials in terms of sound absorption and noise attenuation, which is the primary purpose of insulation in the window belt area. The fabrication process was altered slightly to produce a better performing material known as FB-300 SA (superior acoustics). Both materials were tested extensively in the full-scale test rig; the results are shown in figure 12. The Curlon® material was extremely effective at resisting flame penetration for at least 5 minutes during several tests.

Hydrogen cyanide was measured at two locations within the cabin, one close to the burnthrough area and another near the front of the test fuselage, both at heights of 5 feet 6 inches. Small amounts of hydrogen cyanide were collected during several of the tests (figures 13 and 14) indicating the decomposition products yielded when Curlon® is exposed to elevated temperatures would not inhibit passenger escape.

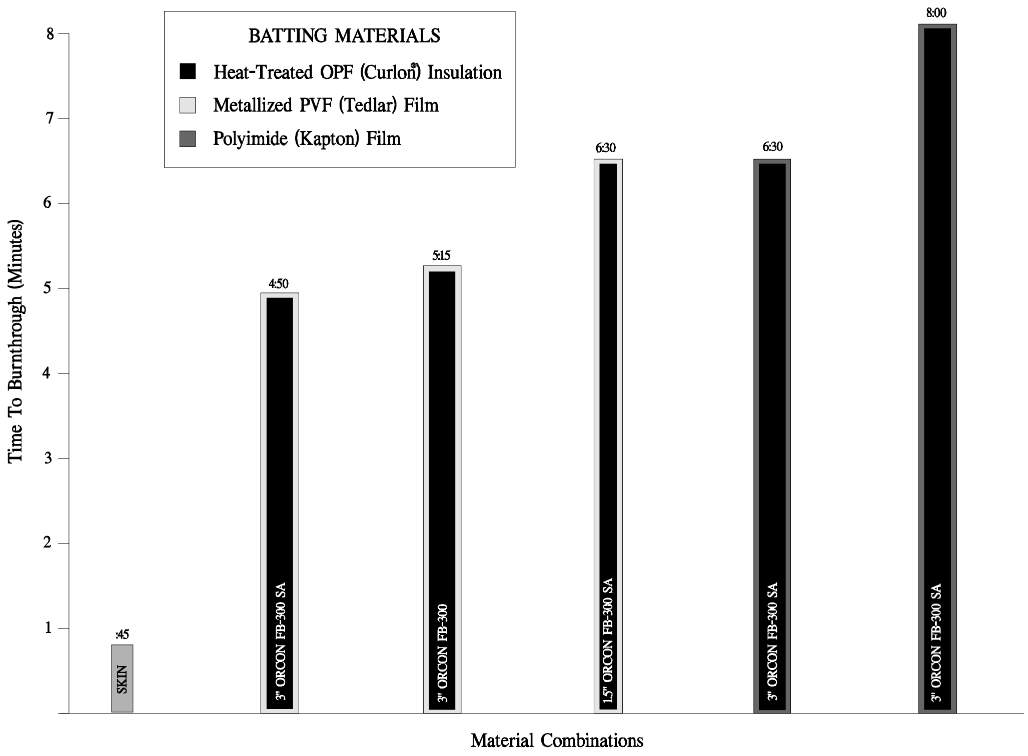


FIGURE 12. EVALUATION OF OXIDIZED POLYACRYLONITRILE FIBER

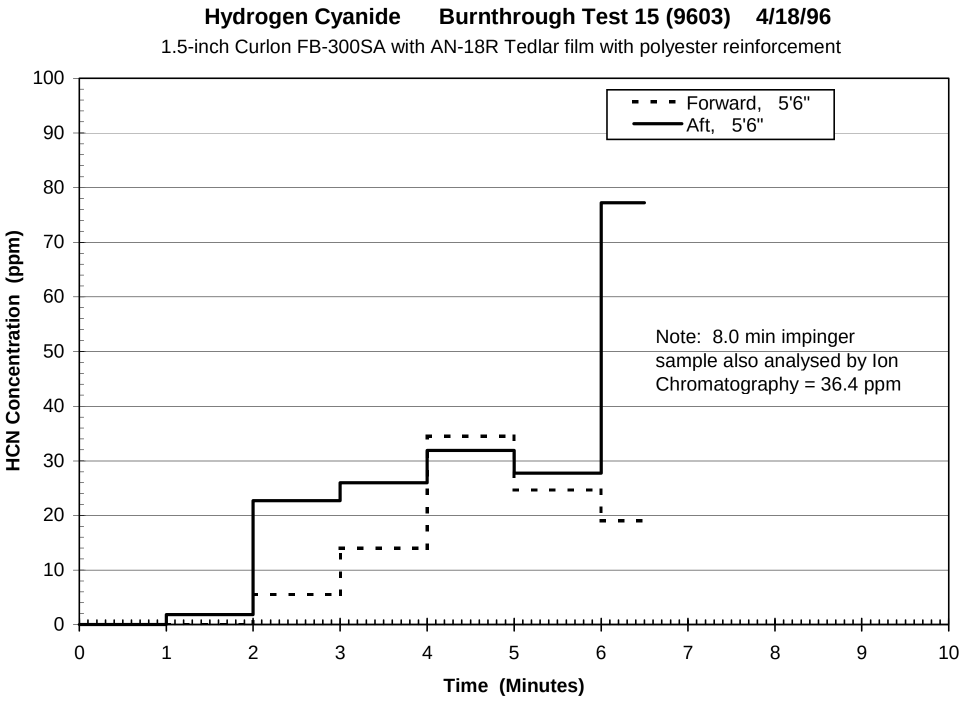


FIGURE 13. HYDROGEN CYANIDE MEASURED BY ION CHROMATOGRAPHY METHOD DURING TEST 15

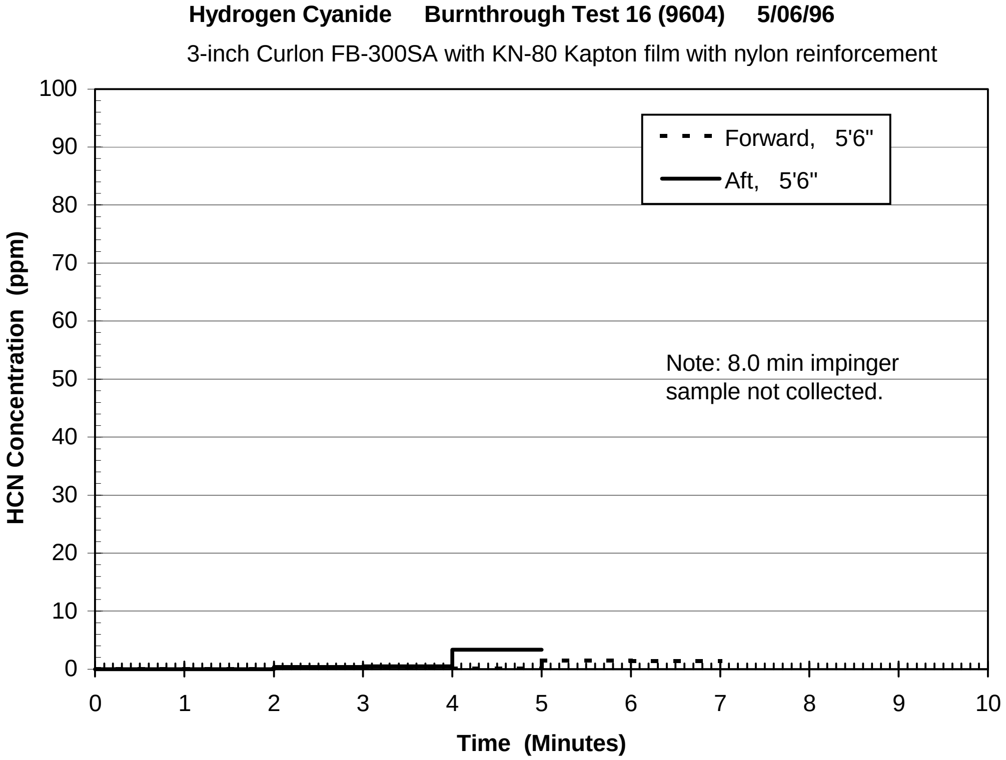
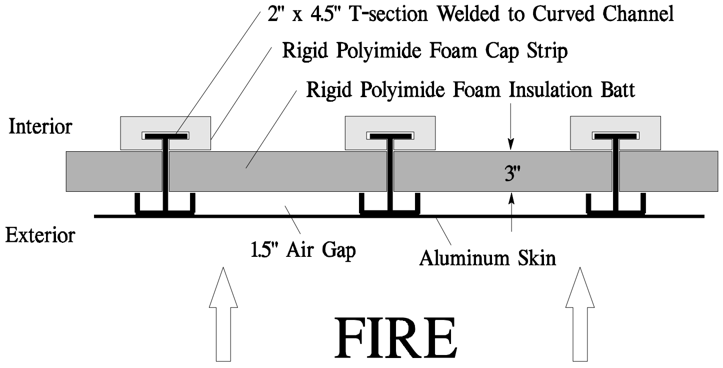


FIGURE 14. HYDROGEN CYANIDE MEASURED BY ION CHROMATOGRAPHY METHOD DURING TEST 16

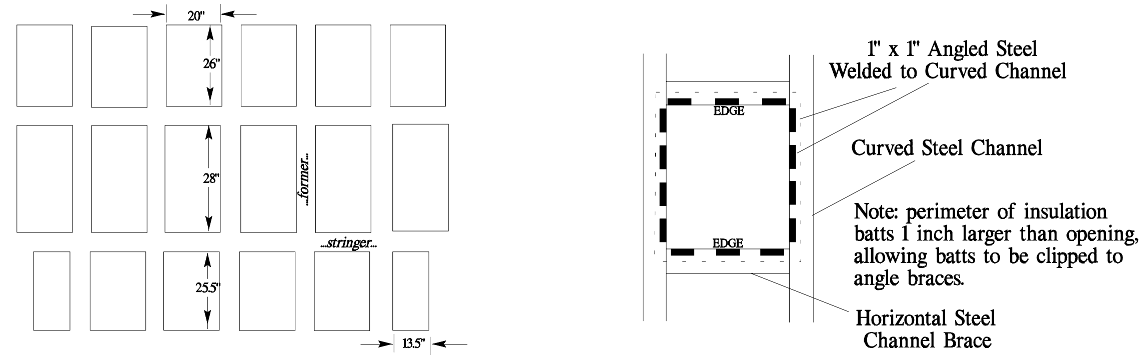
The performance of the metallized polyvinyl fluoride film moisture barriers was also more evident during these tests since the Curlon® material stayed in place for extended periods of time. In doing so, it was clear that the fire was actually propagating along the film, around the periphery of the individual batts to the backface. This could present a problem when interior sidewall panels are installed since the burning film may be enough of an ignition source to involve the panels despite the fact that the insulation had not been penetrated. Two additional tests were conducted using polyimide film with the Curlon® for an additional improvement. The backface of the polyimide film did not ignite and was clearly far superior to the metallized polyvinyl fluoride film in this respect.

Another alternate material tested was rigid polyimide foam, Solimide® AC-430, supplied by the Imi-Tech® Corporation. Solimide® AC-430 has excellent sound absorption and good thermal insulating properties but does not compress like fibrous insulation. The primary advantage of the foam is its rigidity, enabling the design of an insulation system which spans between aluminum formers (i.e., it does not allow the insulation to directly contact the inside surface of the outer skin) thereby reducing moisture entrapment from condensation. This has been a significant problem with existing insulation systems as they inevitably absorb moisture when in continuous contact with the aluminum skin. Variants of the rigid foam are currently in use in the belly area of some newer Boeing commercial aircraft.

Before the full-scale tests, the test rig was modified to hold the rigid foam, since it did not require clips to hold the batting material in place. Three steel T-sections with cross sections 2 inches wide by 4.5 inches high were installed along each of the vertical curved steel channels as shown in figure 15(a). The insulation batts were held in place by rigid foam cap strips that snapped in place over the top of the steel T-section at the edge of each insulation batt. No moisture barrier film was used.



(a) Initial Attachment Method Using Vertical Cap Strips



(b) Size and Location of Openings Between Stringers and Formers

(c) Modified Attachment Method Using Steel Perimeter Clips

FIGURE 15. RIGID POLYIMIDE FOAM ATTACHMENT METHOD

During the first test, the insulation batts were 3-inch-thick Solimide® rigid foam heat sealed in a bag of Insulfab®-reinforced polyimide film, supplied by Facile Holdings, Inc. For this insulation system, burnthrough occurred at 1 minute 8 seconds, approximately 20 seconds less than fiberglass batting. In an effort to extend the burnthrough time, a second test was run in which Quartzel®, a vitreous silica wool barrier, was placed in the insulation batts, not unlike the earlier fiberglass-enhanced tests with Nextel™. The Quartzel® improved the burnthrough resistance of the rigid foam material, but the system was less effective than the system with the Nextel™-enhanced fiberglass system and the Curlon®. The weakness appeared to be at the horizontal seam location where the individual batts matted together. The absence of an attachment system along the top and bottom edges of each batt allowed flames to propagate to the inboard face early in the test. After reviewing the video coverage, it was confirmed that the system was, in fact, failing at the top and bottom seams rather than because of burnthrough of the material. To rectify the problem, horizontal cap strips were used in addition to the vertical cap strips already used in the previous tests to hold the insulation to the test frame. A third test was conducted with this arrangement and the use of another fire-blocking material known as Astroquartz II®, a quartz fabric. The additional horizontal cap strips aided in extending the burnthrough time, but still not to the level attained by the other systems. An additional test was conducted to repeat the third test using an installation method that would allow direct attachment of the fire-blocking material to the test frame, similar to the method used during the Nextel™-enhanced test. For this test, 4 inch lengths of 1-inch angled steel were welded to the periphery of each opening in the test rig to allow the batts to be clamped around the entire perimeter (figure 15c). Each of the batts contained the previously used Astroquartz II® ceramic mat in addition to a thin layer of Nextel™ ceramic fiber paper, which was also used in a previous test with fiberglass insulation. This configuration provided the best result amongst the rigid polyimide tests, resisting flame penetration for over 8 minutes (figure 16). A summary of all tests is shown in table 1 and known properties of the materials used in the full-scale tests are included in table 2. A temperature versus time plot for all material combinations is shown in figure 17.

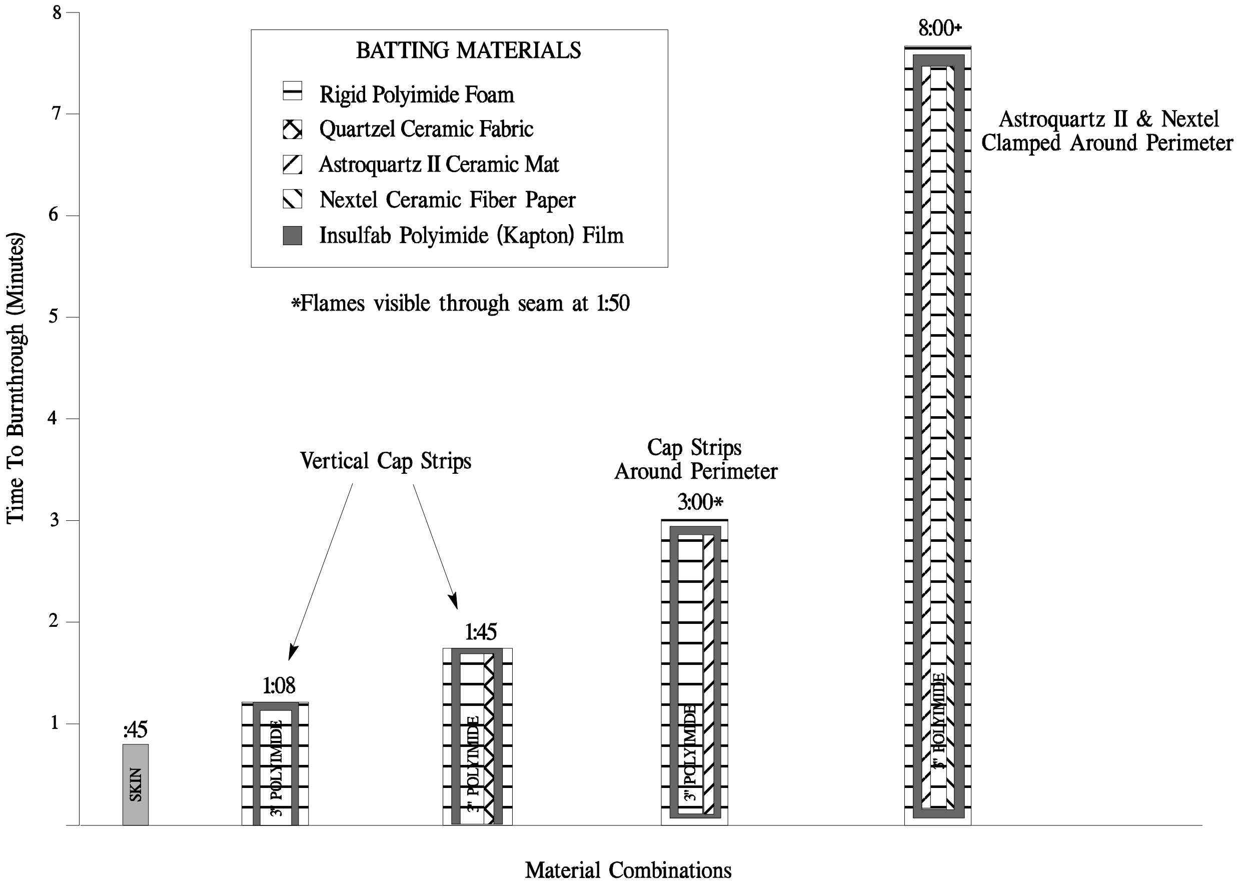


FIGURE 16. EVALUATION OF RIGID POLYIMIDE FOAM

TABLE 1. SUMMARY OF BURNTHROUGH TESTS

Test	Date	Insulation Material	Density (lb/ft^3)	Additional Barrier	Film Material	Film Reinforcement	Attachment Method	Acid Gas Data	HCN Data	Comments
1	8/23/95	1-inch OCF Aerocor	0.37	N/A	AN-18R (Tedlar)	Polyester	F/G Tape	N	N	Baseline test full cabin materials
2	9/26/95	1-inch OCF Aerocor	0.37	N/A	AN-18R (Tedlar)	Polyester	Spring Clips	N	N	Full cabin materials
3	10/10/95	3-inch OCF Aerocor	0.37	N/A	AN-18R (Tedlar)	Polyester	Spring Clips	N	N	Skin/insulation only burnthrough 52 sec
4	10/25/95	3-inch OCF Aerocor	0.37	N/A	AN-18R (Tedlar)	Polyester	Spring Clips	N	N	Skin/insulation only burnthrough 1 min 15 sec
5	11/3/95	3-inch OCF Aerocor	0.37	N/A	AN-18R (Tedlar)	Polyester	Perimeter Clips	N	N	Skin/insulation only burnthrough 1 min 24 sec
6	11/9/95	4-inch OCF Aerocor	0.37	N/A	AN-18R (Tedlar)	Polyester	Perimeter Clips	N	N	Skin/insulation only burnthrough 1 min 36 sec
7	12/7/95	2-inch Microlite AA	0.6	N/A	AN-18R (Tedlar)	Polyester	Perimeter Clips	N	N	Skin/insulation only burnthrough 1 min 10 sec
8	12/15/95	3-inch Microlite AA	0.6	N/A	AN-18R (Tedlar)	Polyester	Perimeter Clips	N	N	Skin/insulation only burnthrough 1 min 32 sec
9	12/20/95	Aluminum skin only	N/A	N/A	N/A	N/A	N/A	N	N	Skin only burnthrough 50 sec
10	1/25/96	3-inch Orcon FB-300 SA	0.34	N/A	AN-18R (Tedlar)	Polyester	Perimeter Clips	N	N	Skin/insulation only burnthrough 4 min 50 sec (clip)
11	2/8/96	3-inch Orcon FB-300	0.34	N/A	AN-18R (Tedlar)	Polyester	Perimeter Clips	N	N	Skin/insulation only burnthrough 5 min 15 sec
12	2/29/96	3-inch Orcon FB-300 SA	0.34	N/A	KN-80 (Kapton)	Nylon	Perimeter Clips	N	N	Skin/insulation only burnthrough 6 min 30 sec (clip)
13	4/4/96	3-inch Microlite AA	0.6	Nextel™ Ceramic Fiber[a]	AN-18R (Tedlar)	Polyester	Perimeter Clips	Y	Y	Skin/insulation w/barrier burnthrough 7 min
14	4/11/96	3-inch Microlite AA	0.6	N/A	KN-80 (Kapton)	Nylon	Perimeter Clips	Y	Y	Skin/insulation only burnthrough 4 min
15	4/18/96	1.5-inch Orcon FB-300 SA	0.34	N/A	AN-18R (Tedlar)	Polyester	Perimeter Clips	Y	Y	Skin/insulation only burnthrough 6 min 30 sec
16	5/6/96	3-inch Orcon FB-300 SA	0.34	N/A	KN-80 (Kapton)	Nylon	Perimeter Clips	Y	Y	Skin/insulation only burnthrough beyond 8 min (fuel)

a—Nextel™ ceramic fiber paper placed on the exterior side of the insulation, within the metallized Tedlar vapor barrier.

TABLE 1. SUMMARY OF BURNTHROUGH TESTS (Continued)

Test	Date	Insulation Material	Density (lb/ft^3)	Additional Barrier	Film Material	Film Reinforcement	Attachment Method	Acid Gas Data	HCN Data	Comments
17	5/23/96	3-inch Microlite AA, 1.5-inch Microlite AA[b]	0.42	N/A	KN-80 (Kapton)	Nylon	Perimeter clips	N	N	Skin/insulation only burnthrough 1 min 30 sec (lower)
18	6/11/96	1.5-inch Microlite AA	0.42	N/A	KN-80 (Kapton)	Nylon	Perimeter clips	N	N	Skin/insulation only burnthrough 1 min 40 sec (upper)
19	7/2/96	AF 2000 Intumescent	N/A	N/A	N/A	N/A	N/A	N	N	Skin + aluminum sidewall panels coated with intumescent paint
20	8/14/96	Rigid Polyimide Foam	0.33	N/A	Facile Kapton	Nylon	Pre-formed batts [c]	N	N	Skin/insulation only burnthrough 1 min 45 sec
21	8/21/96	Rigid Polyimide Foam	0.33	Quartzel®	Facile Kapton	Nylon	Pre-formed batts [d]	N	N	Skin/insulation only burnthrough 1 min 24 sec
22	8/27/96	Rigid Polyimide Foam	0.33	Astroquartz®	Facile Kapton	Nylon	Pre-formed batts [d]	N	N	Skin/insulation only burnthrough 1 min 36 sec
23	10/22/96	3-inch Microlite AA	0.42	N/A	An-18R (Tedlar)	Polyester	Perimeter clips	N	N	Full materials, investigation of baseboard return grill absence [e]
24	11/5/96	3-inch Microlite AA	0.42	N/A	An-18R (Tedlar)	Polyester	Perimeter clips	N	N	Full materials, investigation of baseboard return grill absence [e]
25	11/22/96	3-inch Microlite AA	0.42	N/A	An-18R (Tedlar)	Polyester	Perimeter clips	N	N	Full materials, investigation of return grill influence (blocked) [e]
26	12/19/96	Rigid Polyimide Foam	0.33	Nextel™ + Quartzel®	Facile Kapton	Nylon	Perimeter clips	N	N	Skin/insulation only burnthrough beyond 8 min (fuel)
27	2/5/97	3-inch Orcon FB-300 SA	0.34	N/A	KN-80 (Kapton)	Nylon	Perimeter clips	N	N	B-747 skin section/insulation structural failure 3 min 30 sec [f]
28	3/19/97	3-inch Orcon FB-300 SA	0.34	N/A	KN-80 (Kapton)	Nylon	Perimeter clips	N	N	B-747 skin section/insulation structural failure 4 min 30 sec [g]

b—Three-inch microlite AA blankets were installed in the sidewall area above the cabin floor, 1.5-inch blankets were installed in the cheek area below the cabin floor.

c—vertical cap strips used to attach insulation batts.

d—vertical and horizontal cap strips used to attach insulation batts.

e—outer skin burnthrough area reduced to 4 by 12 feet, centered above and below the cabin floor.

f—747 skin section melted at the upper attachment points.

g—steel I-beam used to restrain 747 skin section; skin completely melted in several areas causing loss of attachment at 4 minutes 30 seconds.

TABLE 2. PHYSICAL PROPERTIES OF INSULATION AND MOISTURE BARRIERS

INSULATION BATTING MATERIALS				
Material Name	Material Type	Density (lb/ft^3)	Fiber Diameter (um)	Tensile Strength (GPa)
Aerocor Type PF105WL	Glass fiber	0.42	1.5	
Microlite AA	Glass fiber	0.34 to 0.60	1.5	
Curlon®	Heat-treated, oxidized polyacrylonitrile fiber	0.2 to 0.4	8	0.65 x 10^{-1}
Solimide®	Rigid polyimide foam	0.33	N/A	4 x 10^{-5}
FIRE BARRIERS				
Material Name	Material Type	Density^a (g/cm^3)	Fiber Diameter (um)	Fiber Tensile Strength (GPa)
Nextel™	Ceramic fiber	2.7	10 to 12	1.7
Quartzel®	Vitrous silica wool	2.2	9	3.6
Astroquartz II®	Quartz fabric	2.2	7, 9, 14	5.9
INSULATION FILMS				
Material Name	Material Type	Film Thickness (um)	Skrim Material	Film + Skrim Weight (g/m^2)
AN-18R	Metallized polyvinyl fluoride film	50	Polyester	30 ± 5
KN-80	Polyimide (Kapton™) film	25	Nylon	46.5
Insulfab 121-KP	Polyimide (Kapton™) film	25	Nylon	68.6

a—density of individual fiber.

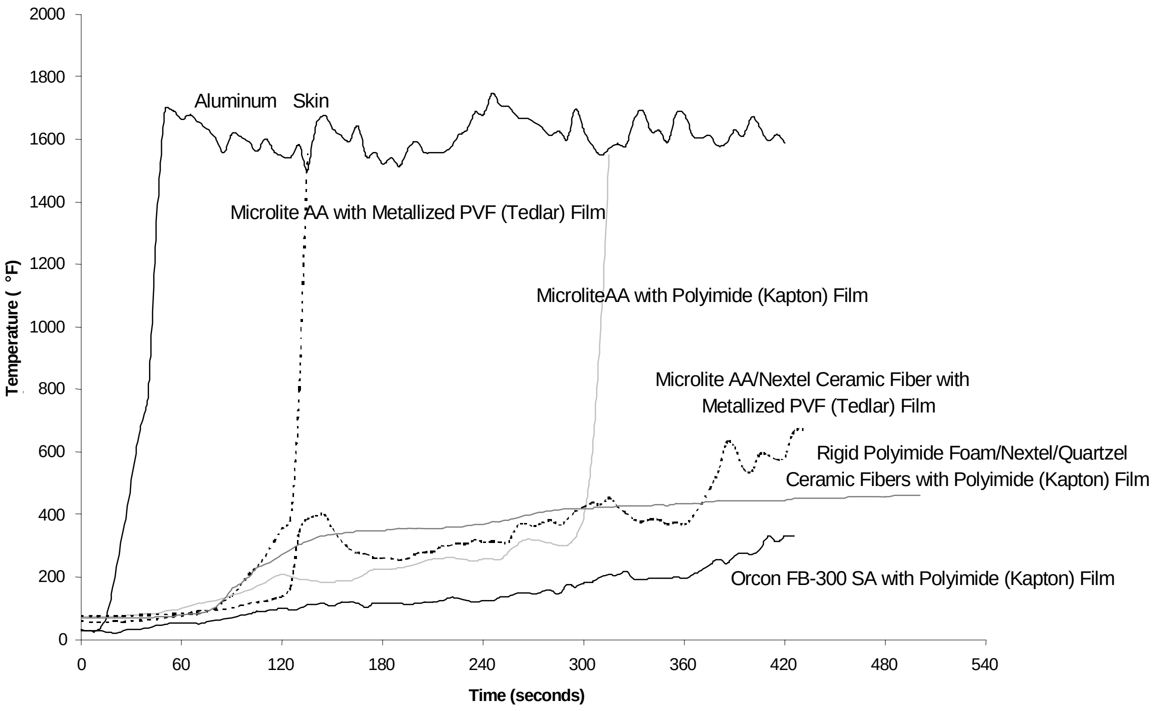


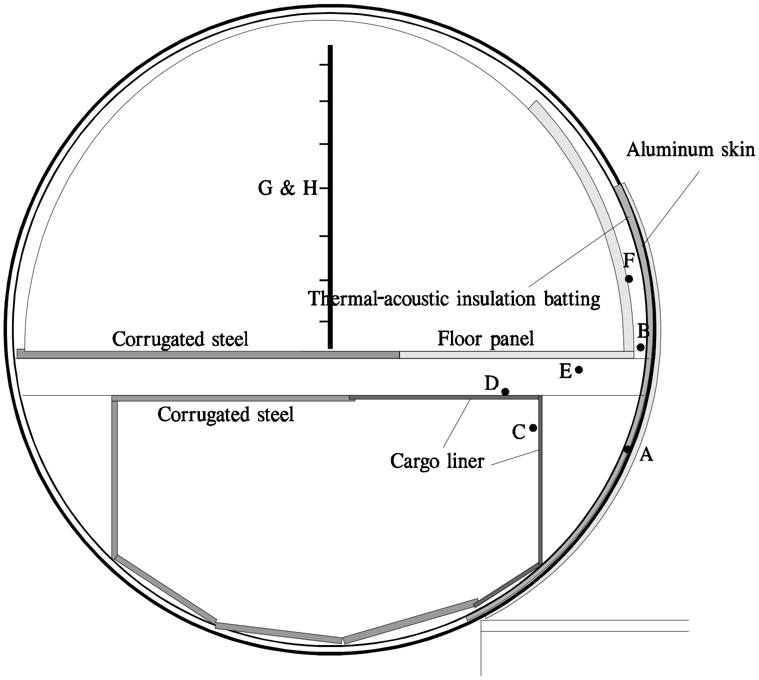
FIGURE 17. SIDEWALL AREA TEMPERATURE COMPARISON FOR VARIOUS MATERIALS

INVESTIGATION OF VULNERABILITY OF FUSELAGE CHEEK AREA.

During the initial tests using surplus aircraft, the likely areas of burnthrough were investigated. The test results indicated the cheek area below the floor line usually provided the earliest penetration of an external fire into the fuselage. Most of the vulnerability of this area was due to the location of sidewall panel-mounted return air grills used to channel cabin air through floor openings behind the sidewall panel down to the outflow valve located in the fuselage belly. These baseboard grills provide direct openings for fire propagation, and the problem is compounded by the fact that there are no interior sidewall panels located beneath the cabin floor making the fiberglass insulation batting in this area more susceptible to breakdown. The combined insulation weakness and direct flame accessibility renders the entire cheek area prone to early burnthrough. In order to more fully understand the ability of fire to penetrate this area, a brief series of blocked and unblocked air return grill tests were run to determine the degree of flame penetration in this area.

An initial baseline test was conducted in which the test rig was configured with a 4- by 12-foot burnthrough area, roughly half of the area used for most previous tests. Since the investigation focused on the cheek area only, there was no need to involve more materials than required. The 4-foot-high burnthrough area was centered above and below the cabin floor and riveted in place similar to previous tests. Insulation bags of Microlite AA with metallized polyvinyl fluoride film were installed in the cabin sidewall, above the floor only. For test purposes, there was no insulation below the floor, since it was assumed that the batts would be displaced during an actual fire. In addition to the sidewall insulation, interior sidewall panels were installed along with an M.C. Gill Gillfab 4017 honeycomb floor panel measuring 4 by 12 feet and covered with FAA-approved aircraft quality wool/nylon carpet and cargo liner in the lower compartment. Thermocouples were located in the following areas: behind the skin, inside floor openings behind the sidewall panel, behind the cargo liner (sidewall), above the cargo liner (ceiling), below the cabin floor, and behind the cabin sidewall panel (figure 18). In each of these locations, a thermocouple was placed in the area between the vertical formers; a total of four thermocouples were used in each area. Temperatures were also monitored at two tree locations inside the cabin, one near the burnthrough area and another in the forward fuselage.

Because there was no insulation below the cabin floor, flames were visible inside the cabin in 20 seconds during the initial test and quickly propagating through the floor vent holes behind the sidewall panels. A problem with the attachment of the insulation and sidewall panels led to extinguishing the external fuel fire early. A subsequent test used proper attachment methods and a more realistic mounting of the sidewall panels. During the open-grill test, the baseboard air return grill area normally located in the base of the sidewall panel was left completely open to produce a test condition offering the least resistance to flame penetration. Flames were evident in the cabin in approximately 45 seconds and flames had completely engulfed the cabin materials after 1 minute 30 seconds. The test was terminated at 2 minutes 30 seconds. During a follow-up test, the baseboard air return grill area was blocked off with sheet metal, but the cabin floor openings behind the sidewall panels were left open. After fuel pan ignition, flames were visible in the cabin after 1 minute. The interior materials were completely involved after approximately 2 minutes, approximately 30 seconds later than during the previous test.



A, Thermocouples 1-4 behind lower skin (cheek area)

B, Thermocouples 5-8 above floor vents

C, Thermocouples 9-12 behind cargo liner sidewall

D, Thermocouples 13-16 above cargo liner ceiling

E, Thermocouples 17-20 below cabin floor

F, Thermocouples 21-24 behind skin/insulation (cabin)

G, Thermocouples 25-31 on tree (burnthrough area)

H, Thermocouples 32-38 on tree (forward area)

FIGURE 18. THERMOCOUPLE ARRANGEMENT FOR BASEBOARD GRILL TESTS

A review of the temperature data indicated a similar fire development in the blocked-grill test and the open-grill test, as the temperature profiles were nearly identical behind the lower (cheek area) skin, below the cabin floor, and at the floor vent area (figures 19, 20, and 21). In each of the figures, the second and third of the four thermocouples are displayed for each test. A moderate delay in the temperature rise behind the sidewall panel was measured during the test in which the grills were blocked off (figure 22). It appeared that the grill blockage prevented the fire from propagating up behind the cabin sidewall panel. However, the temperature profiles inside the cabin were nearly identical, indicating a minimal impact on the overall test (figure 23). The minimal impact from the grills could be a result of the severity of the tests because the fire was initially allowed to progress directly into the cheek area without obstruction from insulation (insulation was not used during these tests). As a result, the flames quickly entered the cabin through seams in the sidewall panels during both tests, essentially minimizing the effect (if any) of the grill area being blocked.

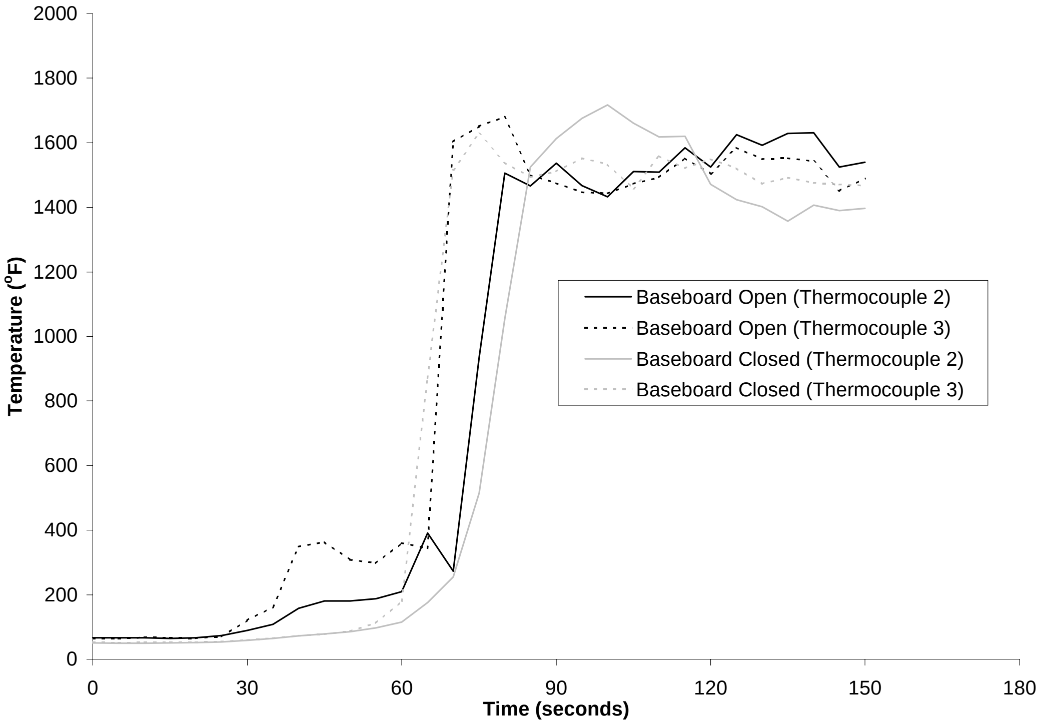


FIGURE 19. TEMPERATURE COMPARISON BEHIND LOWER SKIN

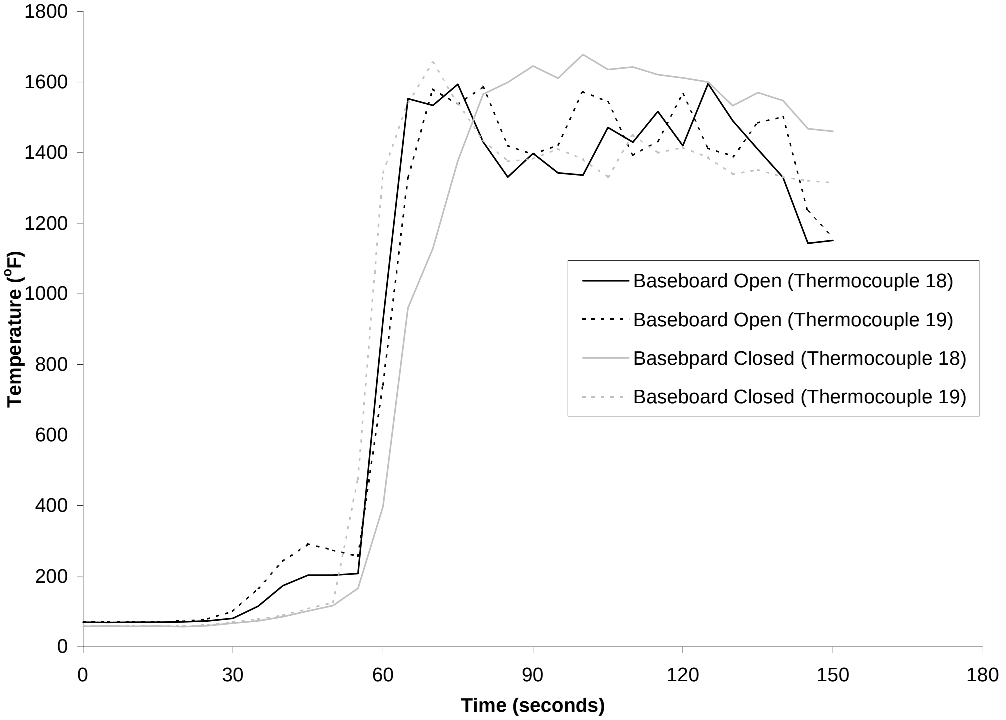


FIGURE 20. TEMPERATURE COMPARISON BELOW CABIN FLOOR

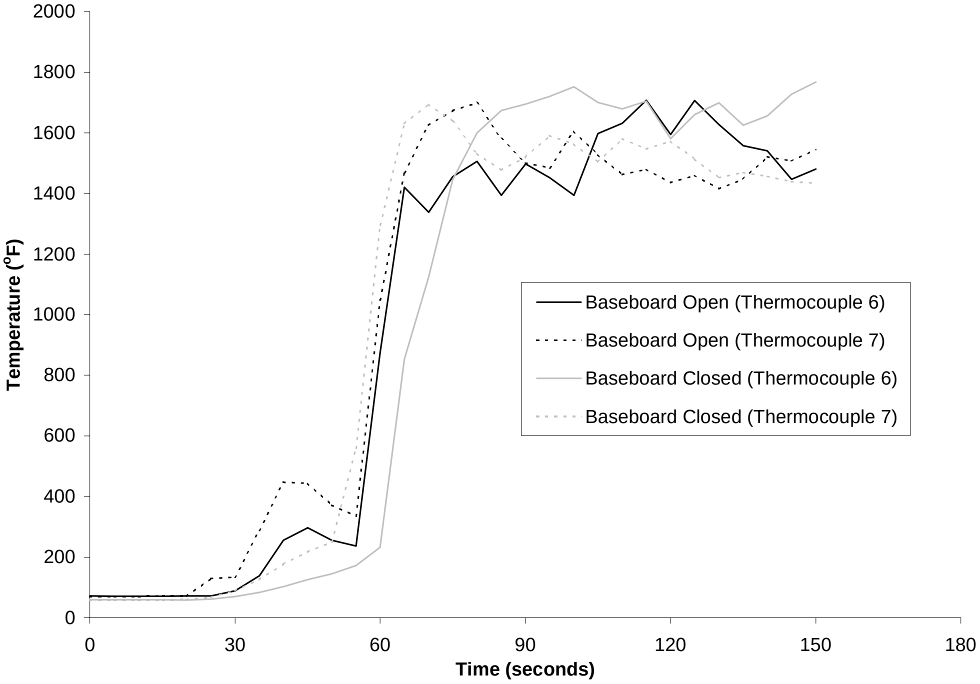


FIGURE 21. TEMPERATURE COMPARISON AT FLOOR VENT AREA

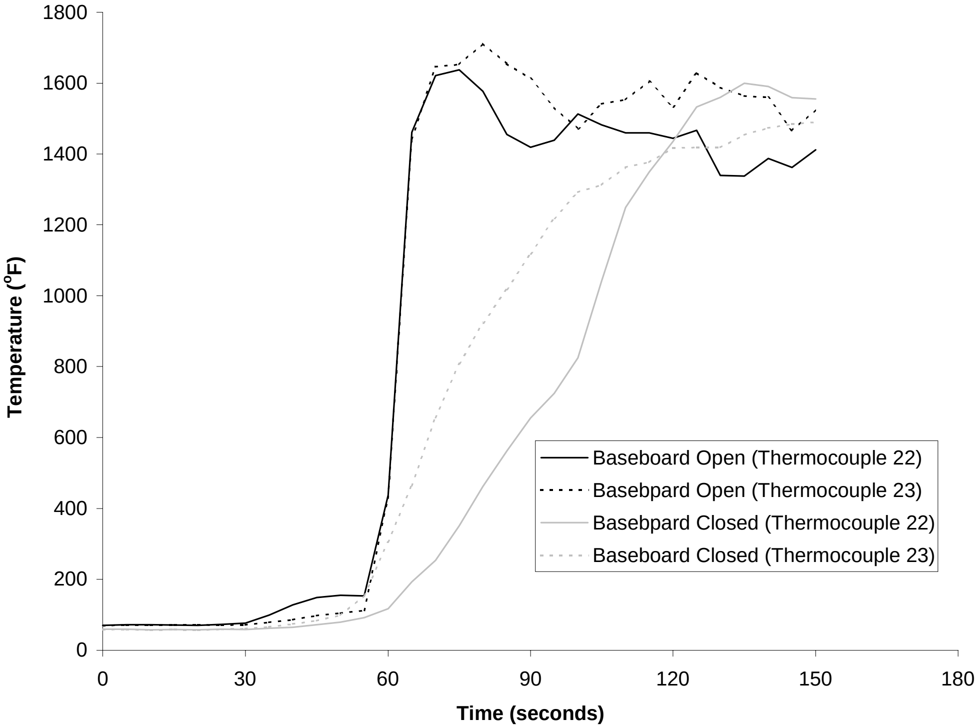


FIGURE 22. TEMPERATURE COMPARISON AT SIDEWALL LOCATION

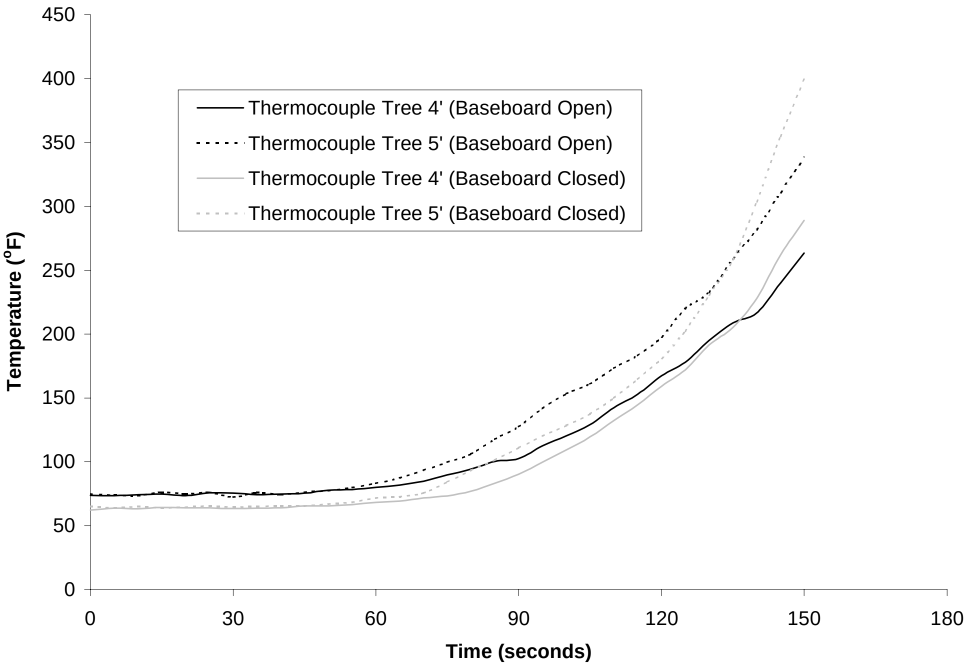


FIGURE 23. THERMOCOUPLE TREE TEMPERATURE COMPARISON IN FUSELAGE

EVALUATION OF ALTERNATE INSULATION SYSTEM ON AN ACTUAL FUSELAGE SKIN SECTION.

A final series of tests were run to determine the effectiveness of the heat-treated OPF when mounted in an actual aircraft fuselage section. Until this point, all material evaluations had taken place using the steel channel test rig. This had raised concern over the validity of the results since steel has a melting point in the area of 2600°F, which is well above the 1850°F temperature of the fuel fire flames. During most of the tests, the materials were attached directly to the test rig, which eliminated the possibility of burnthrough due to structural failure. In an actual aircraft fire, aluminum fuselage materials will melt at approximately 1100°F and lose their structural integrity at even lower temperatures. If an external fuel fire was large enough, a significant portion of the fuselage could fail, causing the insulation materials to be pulled out into the fire. If this were to occur, the burnthrough resistance of the materials would be considerably less important.

The heat-treated OPF was chosen for these tests since it could be considered a drop-in (direct) replacement for the current insulation systems, and it exhibited favorable burnthrough resistance qualities during full-scale tests. In order to evaluate the material under realistic conditions, the steel test rig was modified considerably. First, large sections of 5 of the 11 curved-steel channels were removed from the area that faced the fuel fire to provide an opening. This area was then reinforced from the inside and also around the perimeter to prevent collapse of the structure (figure 24). Next, steel mounting pads were attached at six points around the periphery of the opening in order to accept an actual fuselage section (figures 24 and 25).

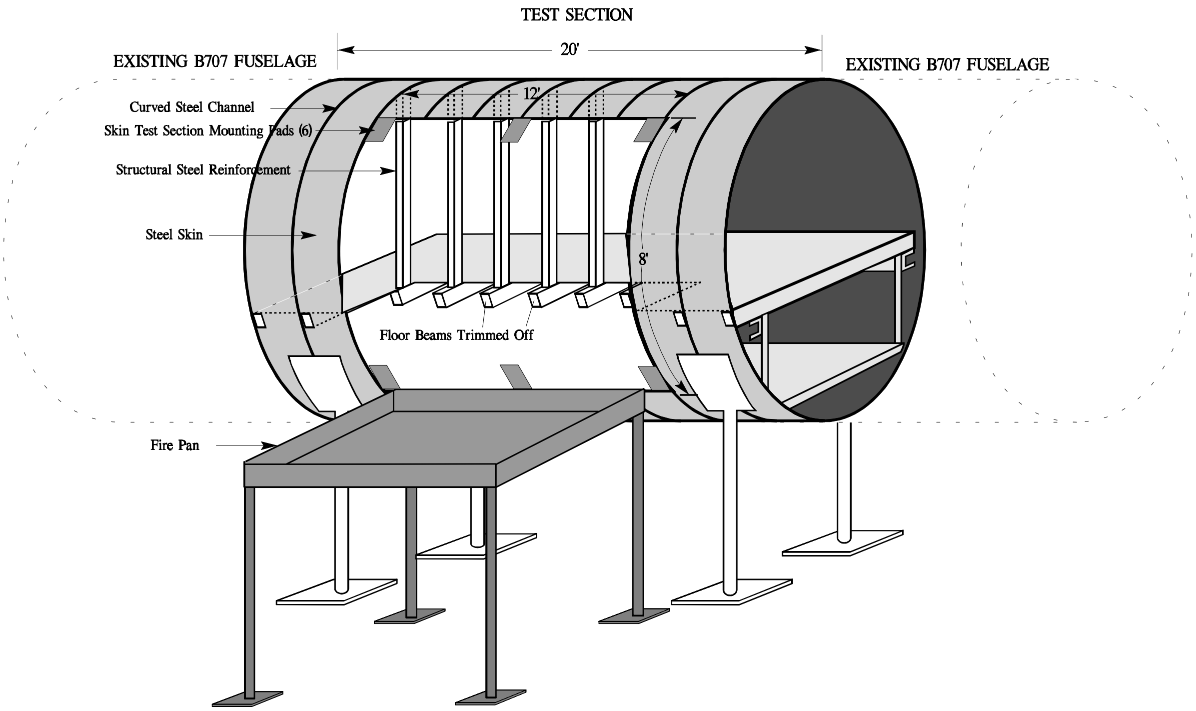


FIGURE 24. MODIFIED TEST RIG USED TO EVALUATE ACTUAL SKIN SECTION

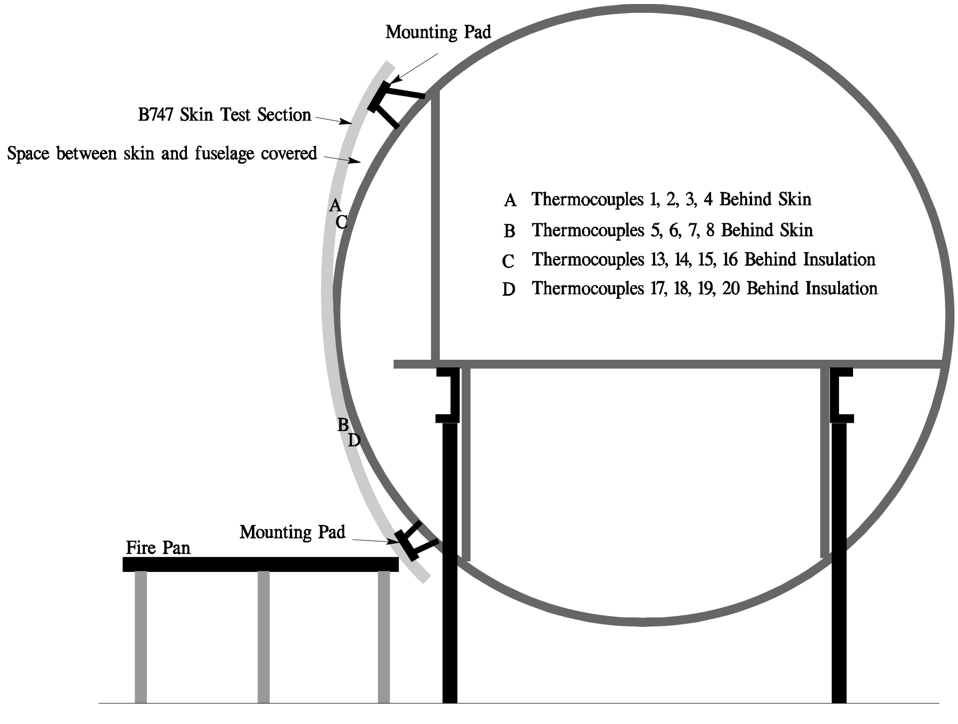


FIGURE 25. END VIEW OF MODIFIED TEST

During the initial test, a large section of a Boeing 747 aircraft skin was hoisted into place and attached to the mounting pads. The skin section was trimmed 140 inches wide by approximately 100 inches high to fit onto the test rig. The section was taken from an aircraft undergoing a passenger-to-freighter conversion and contained the area from just below the floor line to a point close to the fuselage crown. The trimmed section used in the fire test did not contain any of the window belt area or floor bracing but consisted only of vertical formers, horizontal stringers, and skin. Because the Boeing 747 skin section had a much larger diameter than the narrow-body test rig, the section did not fit perfectly against the face of the test rig, causing an opening along the vertical sides and bottom edge. The spaces between the skin section and the test rig were sealed using thin-gauge sheet metal and a Kaowool ceramic fiber blanket to minimize the amount of fuel fire flames wrapping around the test skin. The seal at the upper edge was left open. The skin section was then insulated with seven one-piece batts that fit snugly between the vertical formers. To prevent burnthrough due to an attachment failure, the tests used the identical heavy-duty spring clips used to attach insulation batts to the curved steel channel in previous tests. Approximately 30 clips were used for each bay with an overlap of insulation at each common vertical former. The insulation extended from the bottom of the skin edge to approximately 4 inches from the top edge. Sixteen thermocouples were positioned in the test section, eight behind the skin and eight behind the insulation. In each group of eight thermocouples, four were above the floor and four were below the floor (figures 25 and 26).

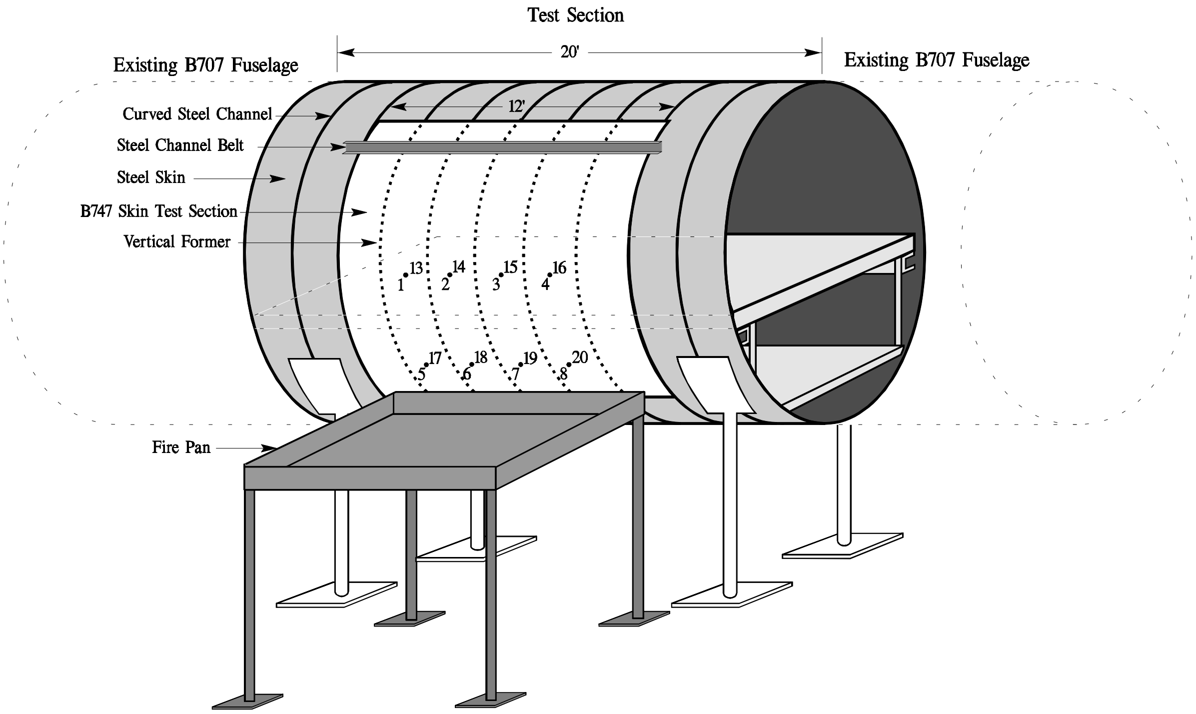


FIGURE 26. MODIFIED TEST RIG WITH STEEL CHANNEL RESTRAINT BELT

After fuel pan ignition, penetration occurred after approximately 2 minutes. At this point flames appeared along the upper edge surface, which was not insulated. At 3 minutes 30 seconds, the upper area began to break free from the mounting pads. The lower attachment pins remained intact during the entire test. For the next 30 seconds, the entire skin section slowly rotated outward into the fuel pan, allowing ever-greater flame penetration into the test fuselage. By 4 minutes, flames had completely engulfed the backside of the skin section, which was nearly horizontal at this point. The fuel fire flames were extinguished at 4 minutes 30 seconds. A subsequent investigation of the test section revealed that a large portion of the outer skin had been consumed by the fire, and a discernible horizontal failure line was observed near the upper edge of the skin, which had caused the rotation into the fire. The insulation remained nearly intact, as it was held in place by the remaining stringers and steel spring clips.

A second test was conducted in which the upper attachment points were fortified with a steel channel belt used to hold the skin section in place if the three mounting-pad attachments failed (figure 26). This also created a more realistic test condition, since an actual continuous fuselage skin would not likely fail along a horizontal line near the upper fire impingement area, as confirmed by the previous tests using the surplus fuselage sections. After fuel pan ignition, the test progressed normally until 1 minute 30 seconds when flames were again noticed at the upper edge surface, which was not insulated on the uppermost 4 inches. At approximately 3 minutes, there was a noticeable separation between the upper three mounting pins and the test rig, but the skin section was restrained from further movement by the steel channel belt. At approximately 4 minutes 15 seconds, the upper section of the two center insulation batts began to pulsate and give way to the fire. By 4 minutes 30 seconds, large flames were penetrating near the seam of the center insulation batts, but the batts remained attached along the seam at a lower location. All other insulation batts remained in place, preventing flame penetration in other areas. This pattern continued until the pan fire was extinguished at 9 minutes. The temperature data shown in figures 27 and 28 indicate that the fuselage skin was penetrated in approximately 60 seconds by the fuel fire. Maximum flame temperatures were 2000 and 1800^{o}F above and below the cabin floor, respectively. In spite of the high flame temperatures, the inboard temperatures of the heat-treated OPF batting never exceeded 500 and 400^{o}F above and below the cabin floor (figures 29 and 30) while it remained in place. Figure 29 shows a rapid temperature rise over a 2-minute period approximately 4 minutes after the test began due to the opening of a seam between adjacent batts in the upper section. A subsequent inspection revealed that not only was the skin largely consumed, but the vertical formers had been depleted in the center area as well. The center insulation batts were actually suspended between adjacent batts and stringers and held in place by the aid of the spring clips only. Inspection of the insulation material following both tests showed that the materials remained intact, confirming initial observations of flame penetration occurring along the seams. If properly restrained, the tests demonstrated that improved insulation blankets can be effective burnthrough barriers when installed in actual aluminum fuselage structures. The results were consistent with the findings in the reusable steel-framed test rig. Again, the importance of securely fastening the insulation blanket and protecting the seams was evidenced.

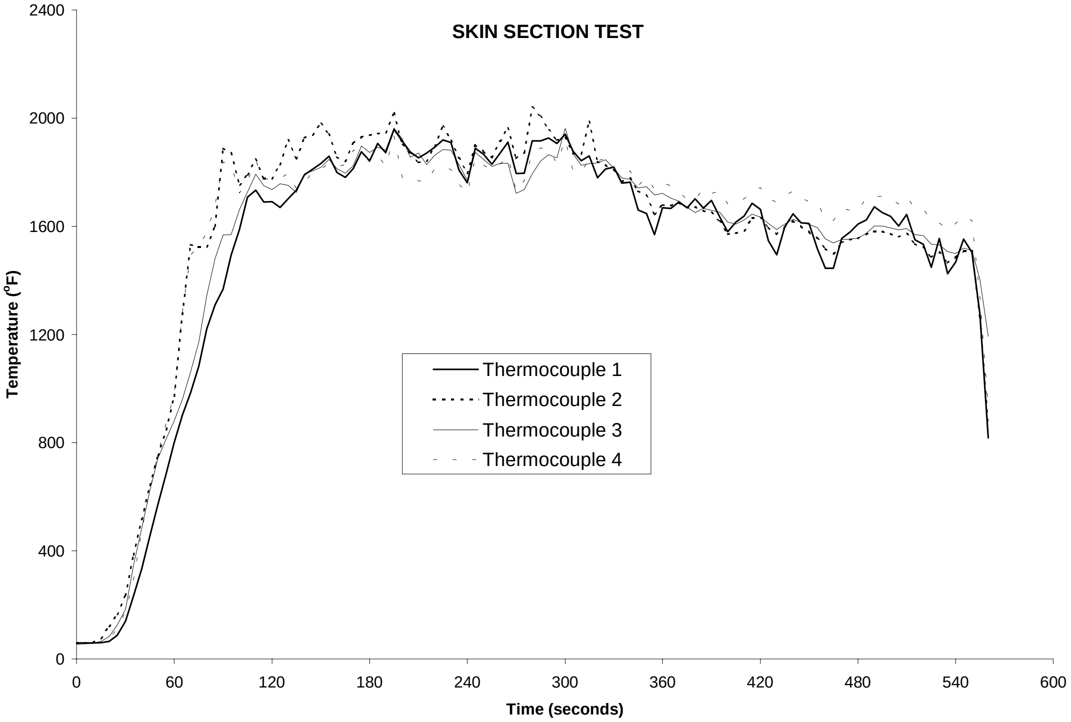


FIGURE 27. TEMPERATURES BEHIND SKIN, ABOVE CABIN FLOOR

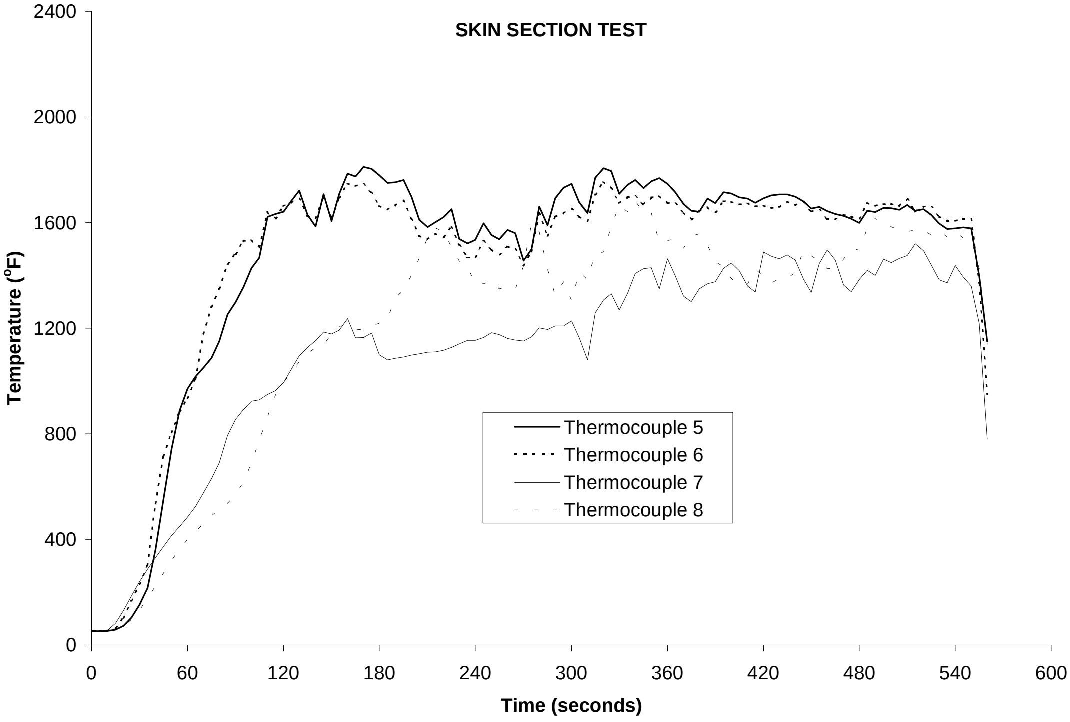


FIGURE 28. TEMPERATURES BEHIND SKIN, BELOW CABIN FLOOR

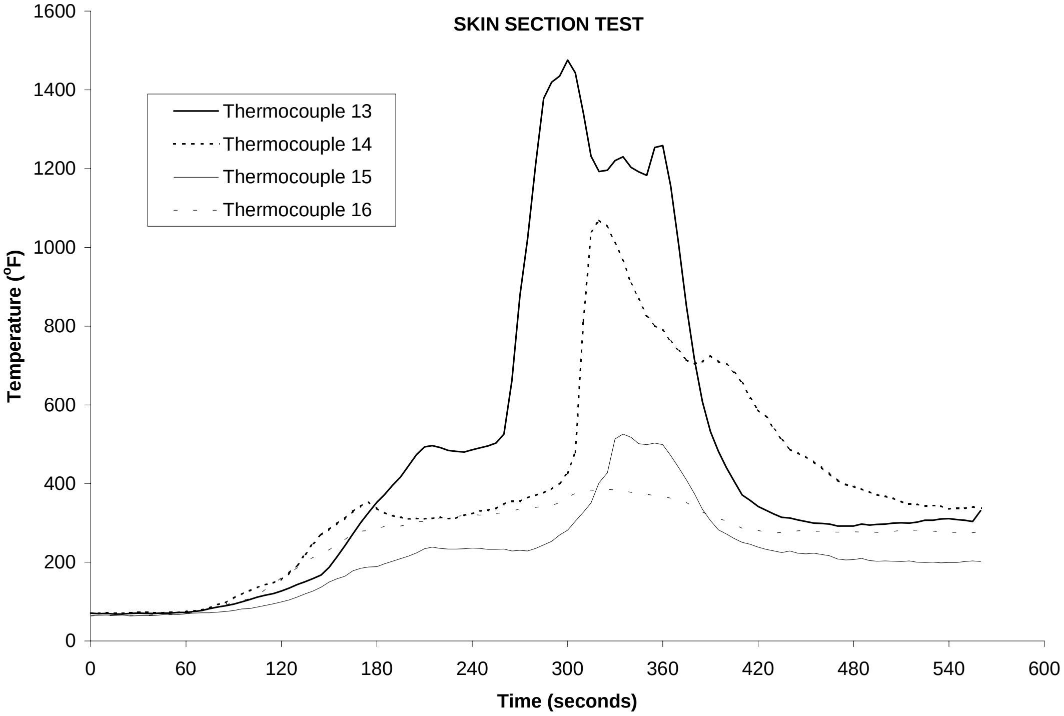


FIGURE 29. TEMPERATURES BEHIND INSULATION, ABOVE CABIN FLOOR

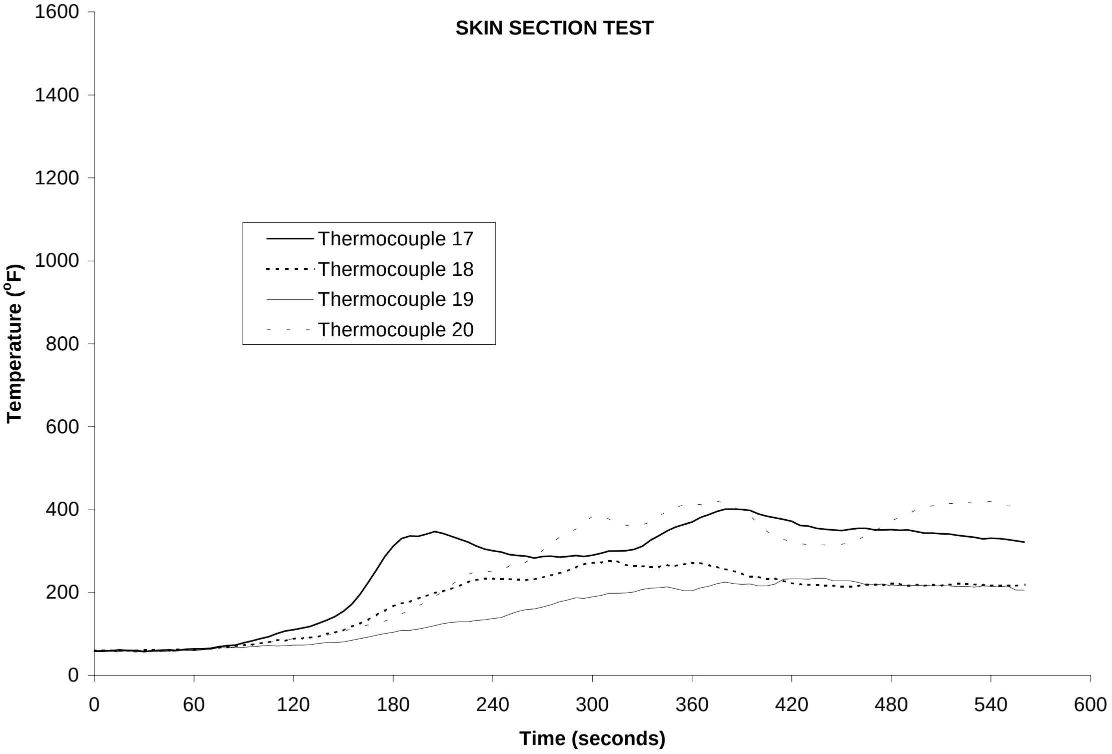


FIGURE 30. TEMPERATURES BEHIND INSULATION, BELOW CABIN FLOOR

DEVELOPMENT OF A MEDIUM-SCALE TEST RIG.

The research on fuselage burnthrough was a joint effort between the FAA and the United Kingdom Civil Aviation Authority (CAA). The FAA was responsible for the development of the full-scale test apparatus described above, while the CAA had tasked Darchem Engineering to develop a medium-scale laboratory test apparatus. A laboratory test facility that replicates the full-scale conditions allows for quick and inexpensive testing of improved materials and systems and also serves as a screening device for evaluating new materials. [7] Darchem has developed the medium-scale test apparatus and has logged hundreds of hours of testing at the Faverdale Technology Centre (FTC) in Darlington, England (figures 31 and 32). The medium-scale facility has proven to be an effective screening tool for materials under consideration and enables new protection systems to be developed. The apparatus compliments research conducted in the FAA full-scale test rig in improving the burnthrough resistance of fuselages.

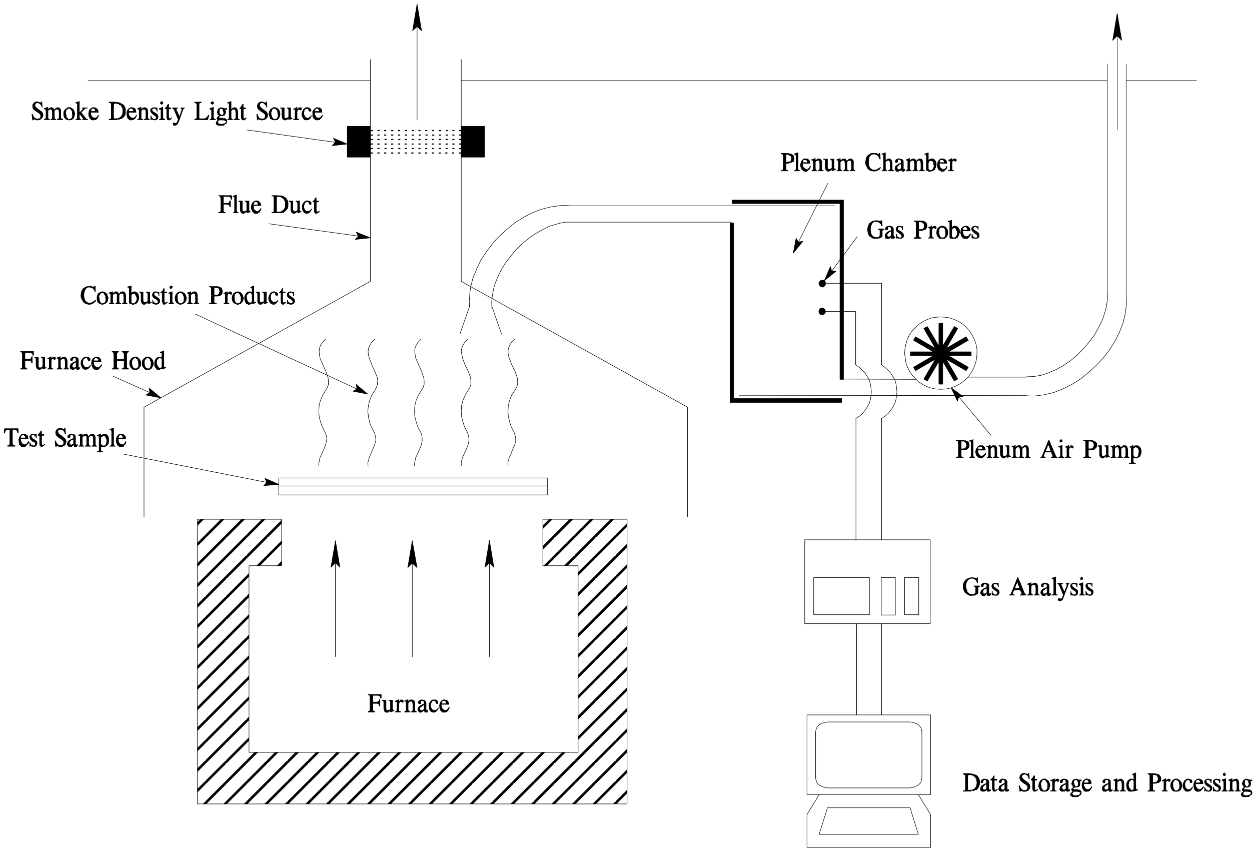


FIGURE 31. MEDIUM-SCALE RIG DEVELOPED BY DARCHEM

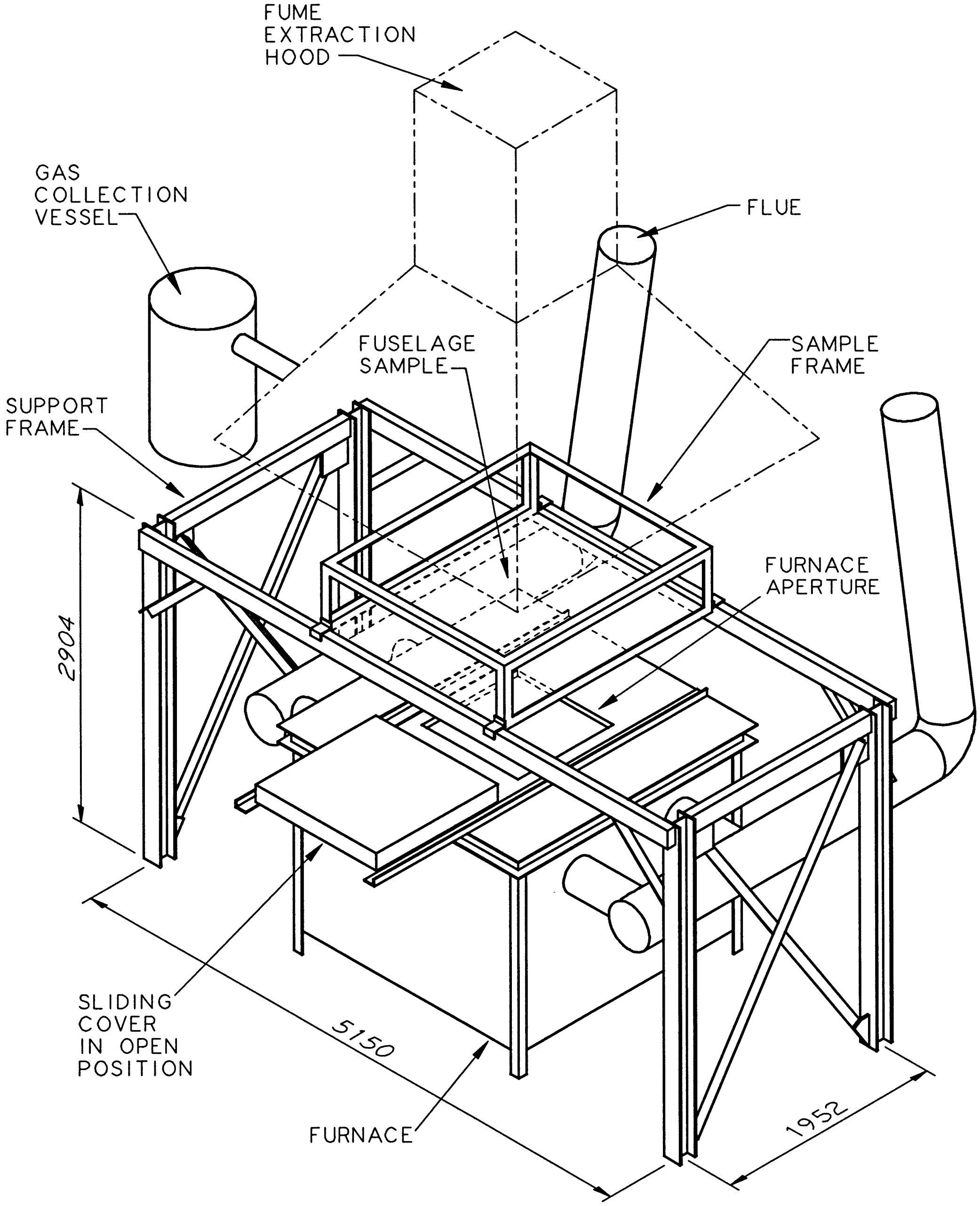


FIGURE 32. MEDIUM-SCALE RIG DEVELOPED BY DARCHEM

DEVELOPMENT OF A SMALL-SCALE TEST RIG.

In addition to the medium-scale apparatus, the FAA and the DGAC/Centre d'Essais Aeronautique de Toulouse (CEAT) in France are conducting research and tests using a small-scale rig that uses a kerosene-fired burner. The test apparatus developed by CEAT uses a 7-gallon per hour kerosene burner adjusted to yield a flame of 2000°F and 17.60 Btu/ft^2-second. The flame impinges on a 24- by 24-inch specimen that is mounted to a test box. The test box is

36 inches deep and allows for the collection of gases that may be produced during tests (figure 33). It is anticipated that the small-scale test rig could be the basis for a fire test standard, provided further tests demonstrate correlation with the results obtained in the full-scale test rig.

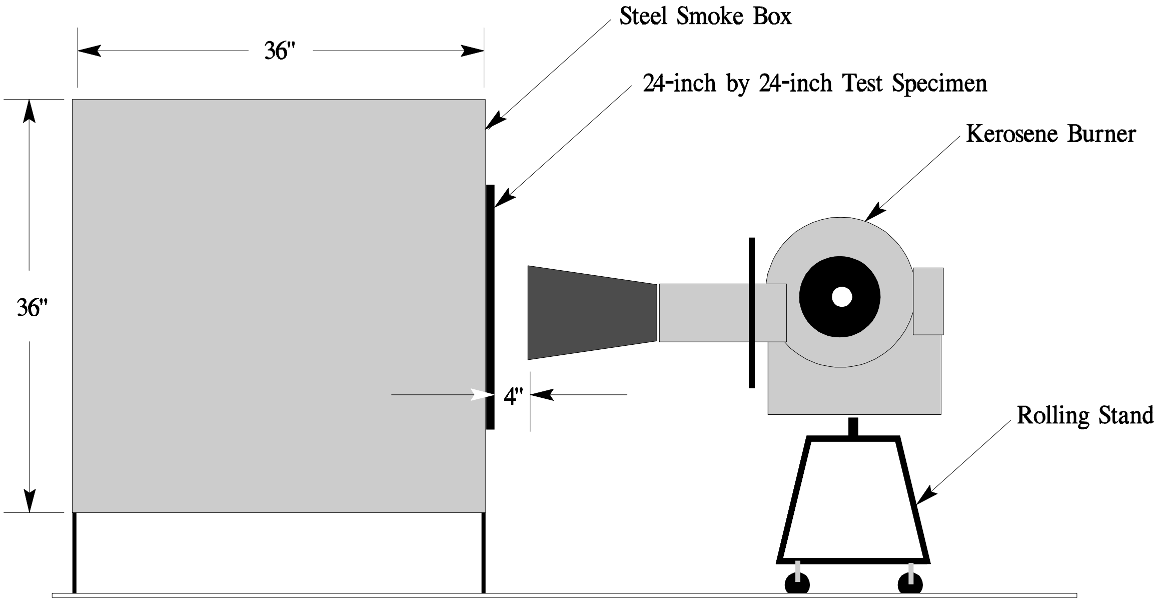


FIGURE 33. SMALL-SCALE BURNTHROUGH TEST APPARATUS

SUMMARY OF RESULTS

From the results of the initial full-scale surplus aircraft tests, as well as the several series of tests completed in the burnthrough test rig, it is evident that an aluminum skin can provide 30-60 seconds of protection prior to melting and allowing flames to impinge on the thermal-acoustical insulation. Since aluminum skin offers little opportunity for fire hardening and will likely be used in next generation aircraft to a large extent, focus has been on the thermal-acoustical insulation and, to a lesser extent, the floor and sidewall panel combination and related components. Full-scale fire tests have shown that appreciable gains in burnthrough resistance can be achieved by either protecting or replacing the current fiberglass thermal-acoustical insulation. Additionally, polyimide (Kapton) film bagging material in place of the widely used metallized polyvinyl fluoride (Tedlar) film alone may provide an additional 3 minutes of protection. Also, a lightweight Nextel™ ceramic fiber paper placed on the outboard face of the fiberglass insulation prevented burnthrough over a nearly 7-minute test duration. Superior results were also achieved using rigid polyimide foam sandwiched between ceramic fiber mats on both the external and inboard face, which provided burnthrough resistance for over 8 minutes. The most effective and practical replacement combination was a heat stabilized, oxidized polyacrylonitrile fibrous material (Curlon®) encased in a polyimide film. This combination resisted burnthrough for over 8 minutes. The Curlon® did not ignite or burn when subjected to the fuel fire and the polyimide film prevented any flame spread on the inboard face. Moreover, the Curlon® may be a direct drop-in replacement for the currently used fiberglass material.

Final tests carried out using an actual aircraft skin section of a B747 mounted in the test rig largely confirmed the results of previous tests. Although the aluminum B747 skin section was nearly consumed during the test, the heat-treated OPF/polyimide film insulation batt prevented fuel fire penetration for over 4 minutes. The insulation largely remained intact and flames penetrated only when the structural integrity of the section was lost. By comparison, fuel fire flames penetrated an actual aircraft cabin interior in only 2 minutes 30 seconds during several tests on surplus aircraft, which had the added protection offered by the sidewall and floor panels (no such panels were used in the skin section test).

An investigation of the vulnerability of the cheek area and related components, namely the baseboard return air grills, showed that improvements are possible. Temperature comparisons indicated an approximate 30-second delay in temperature rise behind the sidewall panel area when the baseboard grill area was blocked. This observation was confirmed after reviewing the videotape of the test. Despite the delay in temperature rise behind the sidewall and reduced flames into the cabin, a comparison of the temperatures of the cabin area trees revealed nearly identical temperatures between the two tests. This suggests the grills had little overall impact on the conditions inside the cabin, at least during this particular test scenario. If insulation was used behind the lower skin, a less severe test condition would have resulted, and it is likely that a more appreciable benefit would have been realized during the blocked-grill tests.

FUTURE CONSIDERATIONS

ATTACHMENT METHODS.

Additional tests using aircraft skin sections should be conducted with a thorough investigation of the attachment methods. The method of attachment is critical if the burnthrough resistance is to be improved. It may be possible to obtain additional protection against burnthrough using current materials by simply using attachment clips that resist melting and subsequent failure during exposure to external fires. Currently, there are several different mechanisms for attaching the insulation batts to the fuselage structure. These include thermoplastic studs that penetrate the batts and secure them using washer-type fasteners. Other metallic spring-type fasteners are placed over the insulation batt at each vertical former. In addition, many of the current insulation batts are attached directly to the backface of the fuselage skin by fasteners mounted using pressure sensitive adhesives which will quickly fail when heated from fuel fire exposure.

AIR GRILL PROTECTION.

A delay in flame propagation into the passenger cabin through air return grills could also equate to additional time available for escape during a postcrash fuel fire. A mechanical system capable of physically shutting off the grills may be too cumbersome, but the use of intumescent coatings may offer a simple means for delaying grill penetration. When applied directly to the grills, the intumescent would expand in the presence of heat/flames, swelling up and blocking flames into the cabin. Intumescent coatings could also be used in the seam area and backface of interior panels to prolong their burnthrough capabilities.

TOTALLY COMPOSITE FUSELAGE.

Another issue that should be considered is the burnthrough resistance of a composite skin fuselage. The use of composites in transport category aircraft has grown steadily due to their high strength and low weight. The fuselage skin of the High-Speed Civil Transport (HSCT) will likely be constructed of a composite material which requires an assessment of its performance when exposed to a large fuel fire. From a burnthrough standpoint, a composite fuselage would likely offer greater burnthrough protection than aluminum. However, there is concern over the potential toxic and combustible gases released during flame exposure, which could accumulate in the cabin and present a hazard to escaping occupants. Whether or not this is a real concern could be determined in the full-scale test rig by replacing the aluminum skin with composite structure and measuring the resultant gases within the cabin.

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