Marcy

Report No. FAA-RD-71-3

TITANIUM FUSELAGE ENVIRONMENTAL CONDITIONS IN POST-CRASH FIRES

Constantine P. Sarkos
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

MARCH 1971

FINAL REPORT

Availability is unlimited. Document may be released to the National Technical Information Service, Springfield, Virginia 22151, for sale to the public.

Prepared for

FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington D. C., 20590

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FAA-RD-71-3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle TITANIUM FUSELAGE ENVIRONMENTAL CONDITIONS IN POST-CRASH FIRES		5. Report Date March 1971
		6. Performing Organization Code
7. Author(s) CONSTANTINE P. SARKOS		8. Performing Organization Report No. FAA-NA-71-2
9. Performing Organization Name and Address National Aviation Facilities Experimental Center Atlantic City, New Jersey 08405		10. Work Unit No.
		11. Contract or Grant No. Project No.503-301-01X
12. Sponsoring Agency Name and Address FEDERAL AVIATION ADMINISTRATION Systems Research & Development Service Washington, D. C. 20590		13. Type of Report and Period Covered Final Report 1968 - 1970
		14. Sponsoring Agency Code

15. Supplementary Notes

None

16. Abstract

A 28-foot titanium fuselage was exposed to a 400-square-foot JP-4 fire for about 2 1/2 minutes. The titanium fuselage remained intact, thus preventing any flames from entering into the cabin. Heating of the cabin pressure sealant and insulation caused these materials to burn. This, in turn, caused significant increases in temperature, smoke, and toxic and combustible gases within the cabin at about 1 minute after fuel ignition and a flash fire at 2 minutes. Theoretical heat transfer calculations were compared with thermocouple data from a section of the fuselage where the insulation did not burn. This comparison indicated that if the insulation and sealant were "inert," habitable conditions would have been maintained within the cabin for at least 5 minutes, and perhaps more.

17. Key Words Aircraft Fires Fire Safety Titanium Alloys Thermal Insulation Silicone Plastics	18. Distribution Statement Availability is unlimited. Document may be released to the National Technical Information Service, Springfield, Virginia 22151, for sale to the public.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	74	

Form DOT F 1700.7 (8-69)

PREFACE

A special recognition and gratitude is owed to Mr. John F. Marcy who conceived this project and was responsible for most of its planning.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

INTRODUCTION

Purpose

The purpose of this investigation was to experimentally determine the ability of a titanium fuselage to withstand a severe post-crash fuel fire and protect the cabin environment from attaining hazardous conditions for long fire durations. The results of this investigation were expected to provide some insight toward the formulation of evacuation procedures for aircraft whose fuselage is of titanium construction.

Background

Following the survivable crash of an aircraft, a fire usually results if the fuel system is ruptured. Present federal regulations specify an aircraft design which will enable all passengers to evacuate from one side of the aircraft in 90 seconds. Analysis of full-scale tests (Reference 1) has determined the sequence of events leading to a fire, and has demonstrated that, in many cases, the aircraft may become completely surrounded by flames. In this situation, and also if the fuselage is intact, the probability of passengers surviving the accident will essentially depend on two factors: the ability of the airport fire department to quickly suppress the fire, and the degree of protection afforded by the aircraft skin and insulation. The latter will depend on such variables as the size of fuel spillage, the proximity of the fire to the fuselage, the crash terrain, and the wind intensity and direction.

The fuselage of a modern subsonic airliner is constructed of an aluminum alloy which melts at a temperature range (approximate) of 900° to 1200°F (Reference 2). The temperature within a fuel fire is considerably higher (Reference 2), having an average value of about 2000°F. Therefore, a fuel fire will eventually melt any aluminum aircraft and expose the cabin to the heat and smoke from the fire. The fire will then spread into the interior and fill it with smoke, and both toxic and combustible gases from burning materials as well. In a short time, conditions within the aircraft will become fatal to any occupant. This behavior has been verified experimentally by two series of full-scale tests performed at the National Aviation Facilities Experimental Center (NAFEC). The earlier tests used five C-97 aircraft, and were reported by Conley (Reference 3). The latest tests used a 40-foot section of a Boeing 707 fuselage, and were reported by Geyer in Reference 2. These tests encompassed both complete and partial envelopment of the test article in the fuel fire environment. Geyer's results indicated that the burn-through time depended on the skin thickness and the net heating rate from the fire. During severe fire conditions, the skin is predicted to melt in about 24 seconds for a representative skin thickness of .032 inch.

The high design Mach number (M=2.7) of the U.S. supersonic transport (SST) causes significant aerodynamic friction which raises the skin temperature to as high as 420°F (Reference 4). At this temperature, the strength of aluminum is drastically reduced and, consequently, its use as a structural material is precluded (Reference 5). Titanium, with significantly superior high-temperature mechanical properties, has been selected as the structural metal for the U.S. SST. Since the melting temperature of titanium is 3035°F (Reference 6), which is significantly higher than the fire temperature, a titanium fuselage should prevent the flames of an external fuel fire from penetrating into the passenger cabin. (This behavior has been demonstrated on a small scale by Hughes, Reference 7. These tests showed that commercially pure titanium as thin as .016 inch resisted a 2000°F flame for a minimum of 15 minutes without penetration.) Therefore, the passenger survivability time will depend on such factors as the heat transfer to the cabin, and the amount of smoke, toxic and combustible gases produced by materials adjacent to the hot titanium skin; viz, the insulation and cabin pressure sealant.

DISCUSSION

Titanium Fuselage

During competition for the SST contract, one bidder constructed a 28-foot titanium mockup of the SST in order to test its proposed environmental control system. After the contract was awarded, this fuselage became surplus equipment and was eventually shipped to NAFEC for testing under this project. The fuselage was primarily constructed of two titanium alloys: the outer skin was made of Ti-8Al-1Mo-1V, and the structural members were made of Ti-6Al-4V. Figure 1 shows the fuselage at the NAFEC fire test site.

Room temperature vulcanizing (RTV) silicone sealant was originally used extensively along the interior surface of the titanium skin. It was especially thick at doubler sections and along the interface between the former and skin. Figure 2 shows a typical view between two formers. Moreover, it was applied to faying surfaces. Realizing that the pyrolysis products from the RTV would consist of smoke and both flammable and toxic gases, an attempt was made to remove the RTV from the fuselage skin. However, this was discovered to be a difficult task, and the effort was abandoned with the hope that the pyrolysis gases would have a negligible effect on the experimental results.

An SST flying at Mach 2.7 will experience aerodynamic heating which will raise the skin temperature to approximately 420°F. This, of course, will result in heat transfer toward the cabin which must be intercepted if the cabin temperature

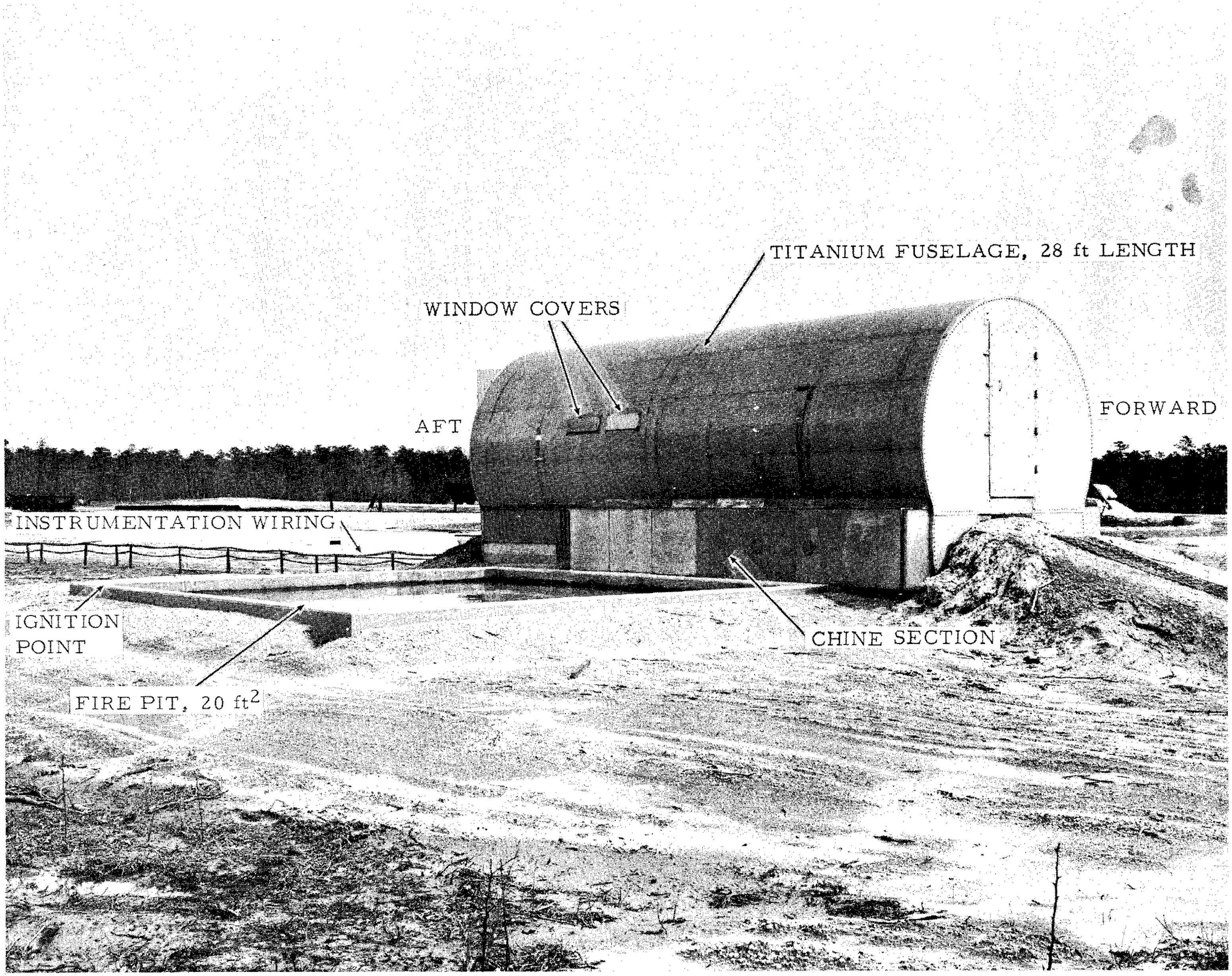

FIGURE 1 - TITANIUM FUSELAGE AND ADJACENT FIRE PIT

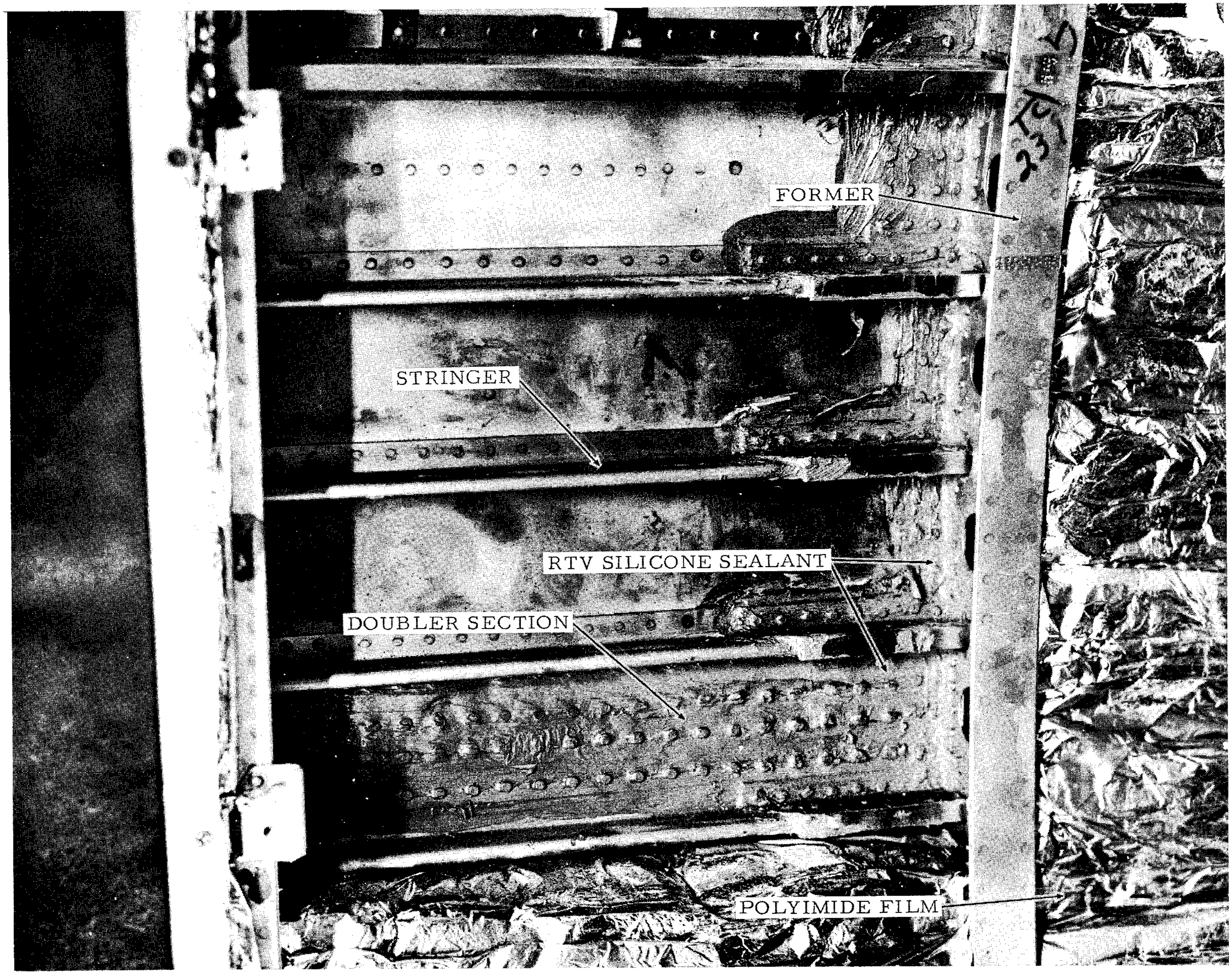

FIGURE 2 - EXTENSIVE USE OF RTV SILICONE AS CABIN PRESSURE SEALANT

is to be maintained at a pleasant level. This mockup incorporated cooling tubes using refrigerated air to solve this problem. A model of the fuselage cross section is shown in Figure 3. The design target for the insulation was a heat transfer rate of 20 Btu/sq ft-hr from the fuselage skin at 400°F to the cabin wall at 70°F (Reference 8). A silicone-bonded fiberglas with a density of 1.0 lb/cu ft was used. The insulation was heat treated at 600°F for 20 hours in a 3-5 torr vacuum in order to alleviate objectionable odors (Reference 9). It was also necessary to encapsulate the fiberglas within a polyimide film to reduce convective heat transfer (Reference 10). Radiative heat transfer from the titanium skin was lessened by aluminizing the film (Reference 11). The cooling ducts were connected to an aluminum "isothermal" wall via conductive tapes. The cabin decorative sidewall material was attached directly to the aluminum wall. A distance of 4 inches existed between the titanium skin and aluminum wall.

Preparation of Test Article

A considerable number of modifications were made to the titanium mockup in preparation for the fire test. One purpose of the experiment was to determine the degree of protection afforded by the titanium skin; this necessitated the use of stainless steel covers to protect the windows. Also, several aluminum end plates on the chine section facing the fire pit were replaced by steel plates.

All interior materials were laboratory tested to show compliance with federal regulations, and materials which failed were either removed or replaced. The sidewall material was replaced by a fiberglas fabric. Air-conditioning manifolds and lighting fixtures were removed. In order to reduce the amount of flammable material, a 4-foot plywood floor section was replaced by aluminum honeycomb, and plywood hatrack partitions were removed.

Care was taken to assure a relatively airtight test article so that any smoke produced by the fuel fire would not be misconstrued as being generated by interior materials. All ducts were packed tightly with fiberglas material. The end doors were provided with asbestos gaskets. The forward end door was permanently bolted closed, while the aft end door, which was used for entering the fuselage, was closed with spring-loaded fasteners.

The fuselage interior was furnished with three rows of used seat frames upholstered with fire-retardant materials (Figure 4). Each frame was thoroughly stripped of any foam or adhesive material which was part of the original seat. Only the armrests and rigid foam supports were retained. The cushions were made of a fire-retardant polyurethane foam and

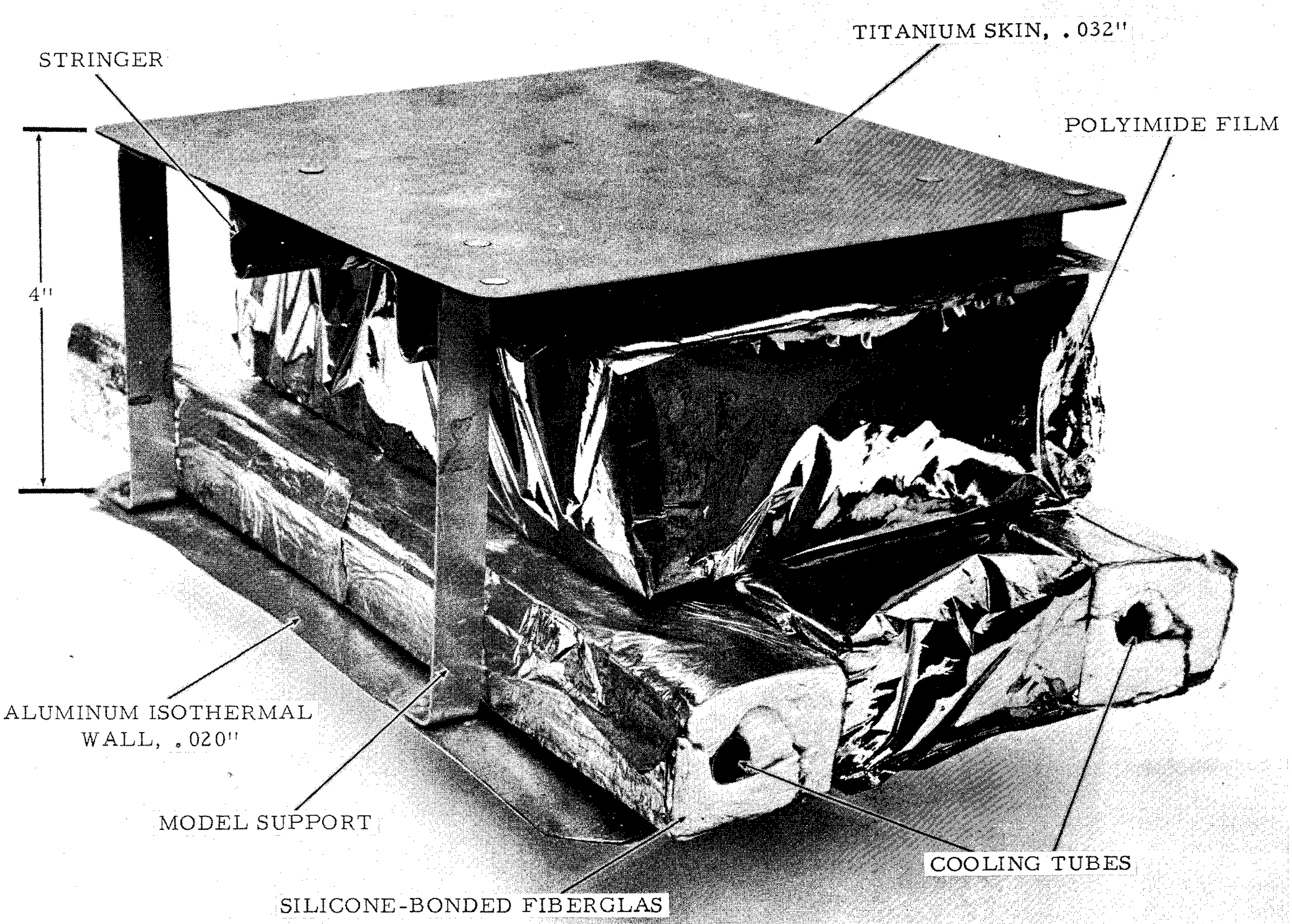

FIGURE 3 - MODEL OF TITANIUM FUSELAGE CROSS SECTION

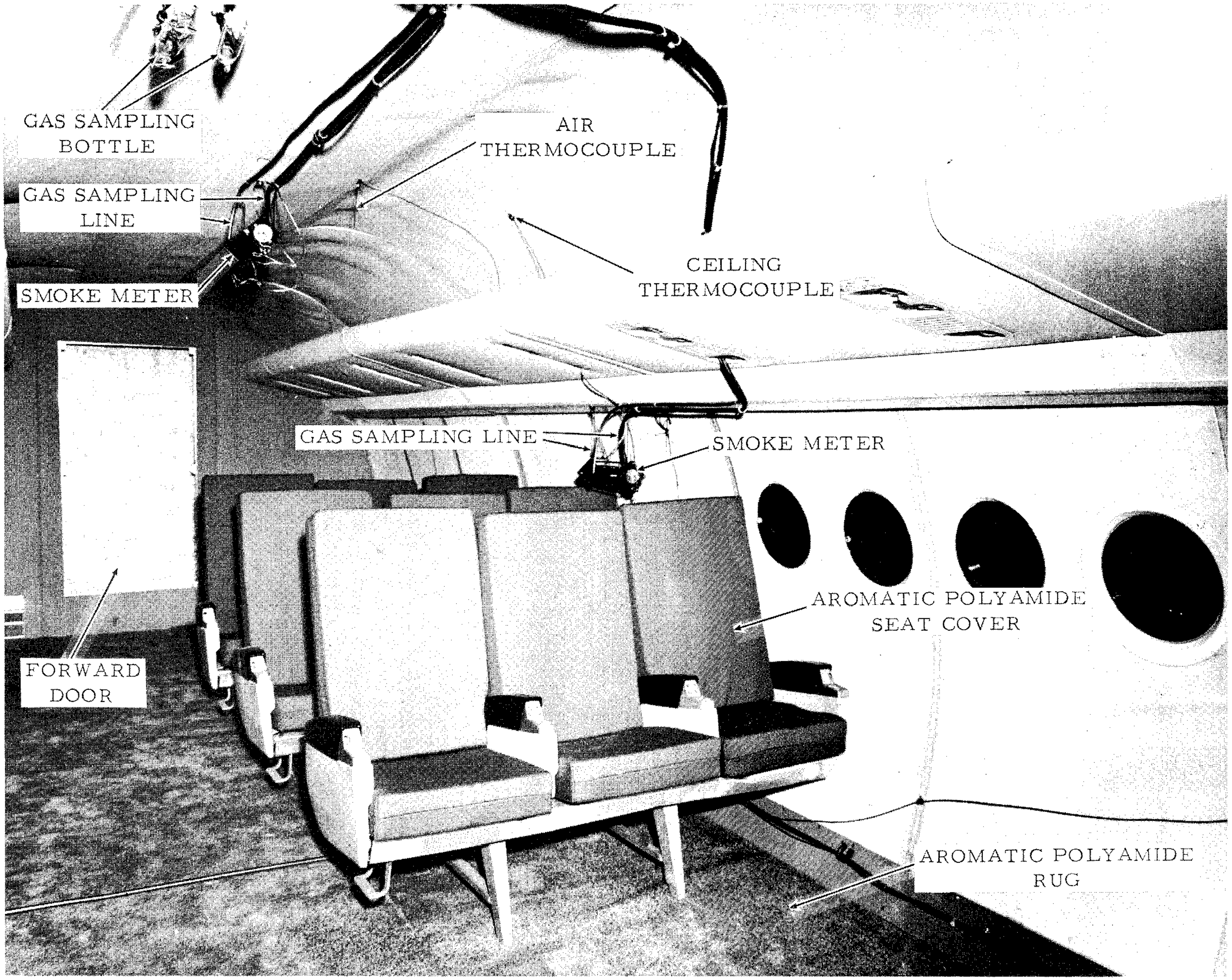

FIGURE 4 - CABIN FURNISHINGS AND INSTRUMENTATION

were covered with an aromatic polyamide fabric. It was necessary to face the seats toward the aft end of the fuselage in order to fit them to the curvature of the side wall. The floor was covered with an aromatic polyamide rug.

The fuselage was buried to the level of the wing in order to simulate a crash landing with collapsed landing gear and some burrowing of the fuselage into the ground. Actually, a landing of sufficient force to crush to such a level would result in breakup to the extent that the crash landing would not be survivable (Reference 11). However, this test configuration was selected since it resulted in the majority of the heat being transferred through the sidewall and, thus, was probably a worse case condition. If the airplane were still on its landing gear, the cabin fire hazard would not be as severe, due to multiple layers of protection isolating the passenger compartment from the flame. Moreover, the worse case configuration lends itself to easier theoretical analysis, since the majority of the heat transfer is through the sidewall and the floor contribution is neglible. In order to help guarantee this worse case behavior, several additional modifications were made to the original fuselage: sand was packed against the inside fuselage sidewall below the floor level and facing the fire, and insulation was attached to the end plates.

A 20-foot-square fire pit was constructed of reinforced concrete adjacent to the fuselage. The outer surface of the concrete wall abutted against the end plates of the chine section, positioning the fire pit as close to the fuselage as possible.

Instrumentation

The instrumentation was essentially confined to three sections on the side of the fuselage facing the fire pit (Figure 5). A cross sectional view of a typical instrumentation section showing each transducer location is shown in Figure 6. Each section corresponded to a removable interior panel (Figure 7). Fifty-three of the 66 transducers recording during the test were thermocouples. Three heat flux transducers mounted flush to the titanium skin measured the total heat transfer (convection and radiation) from the fire to the fuselage. The gas composition, as indicated by the concentration of CO, CO_2, O_2 and combustible gases, was continuously measured at two locations at the center of the fuselage: 6 inches below the ceiling and at the head level of a seated passenger. An indication of the smoke density at these locations was afforded by the measurement of light transmission across a distance of 1 foot. Additional instrumentation was

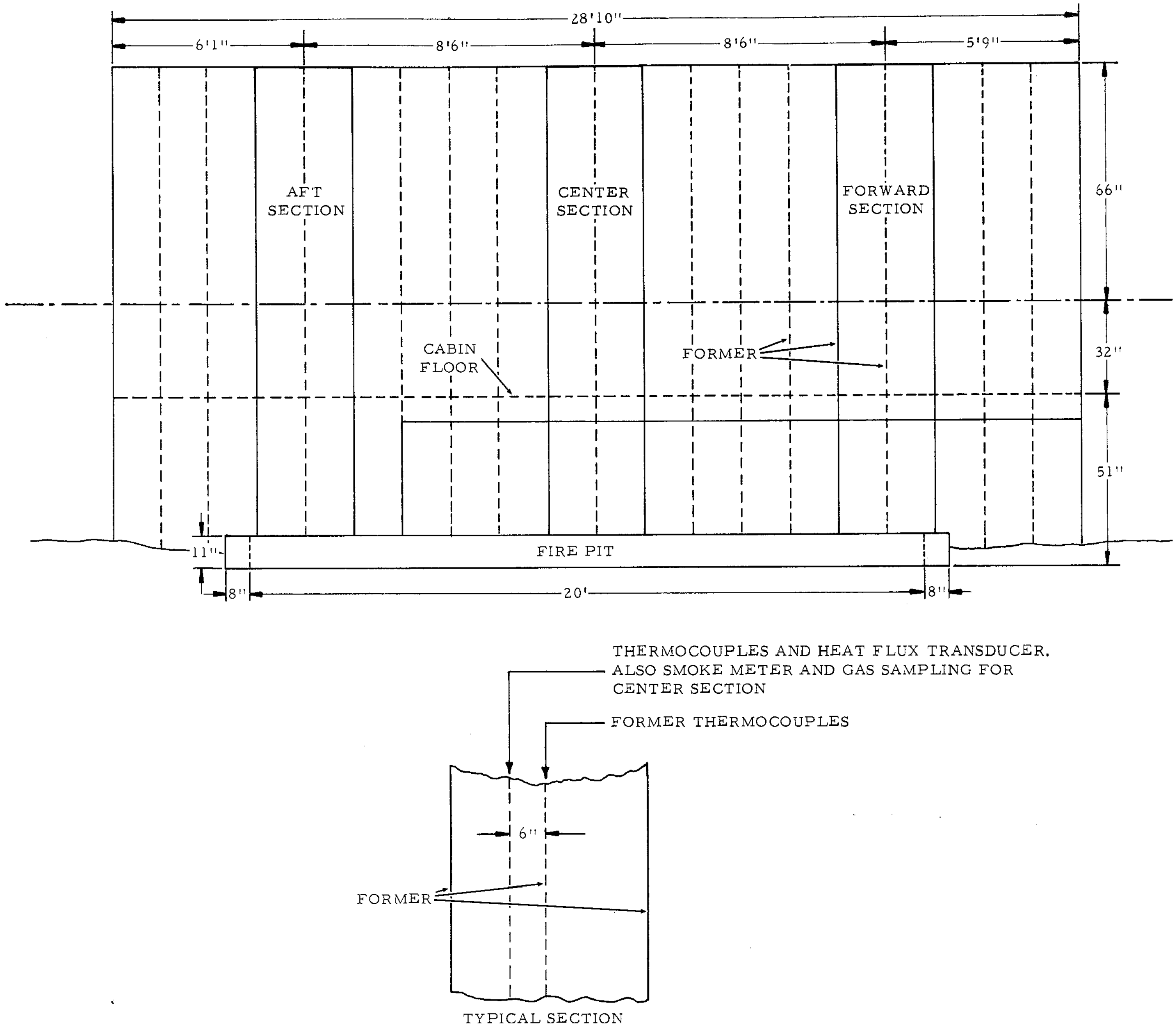

FIGURE 5 - LOCATION OF THREE INSTRUMENTATION SECTIONS

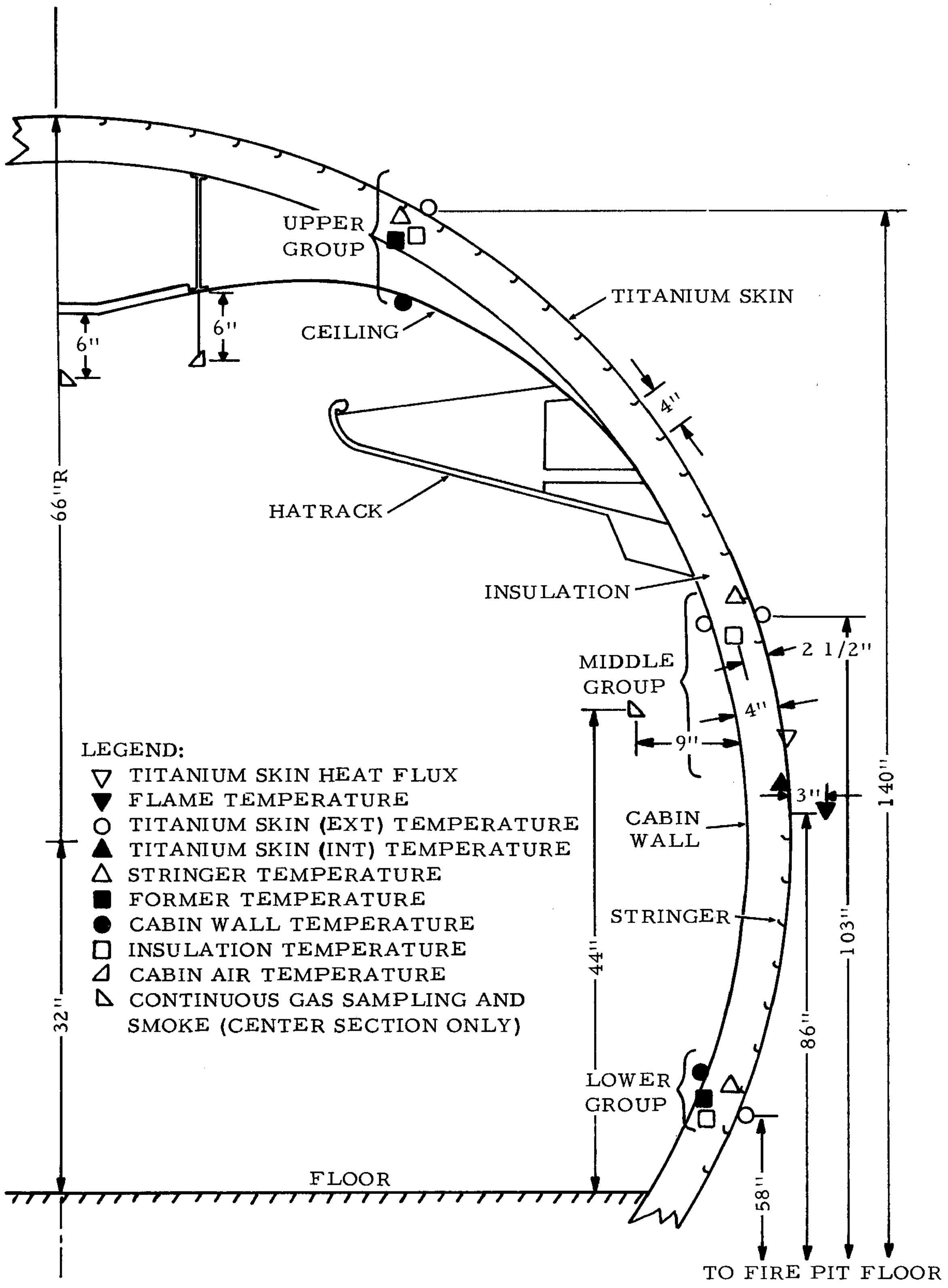

FIGURE 6 - CROSS SECTIONAL VIEW OF A TYPICAL INSTRUMENTATION SECTION SHOWING MEASUREMENT LOCATIONS

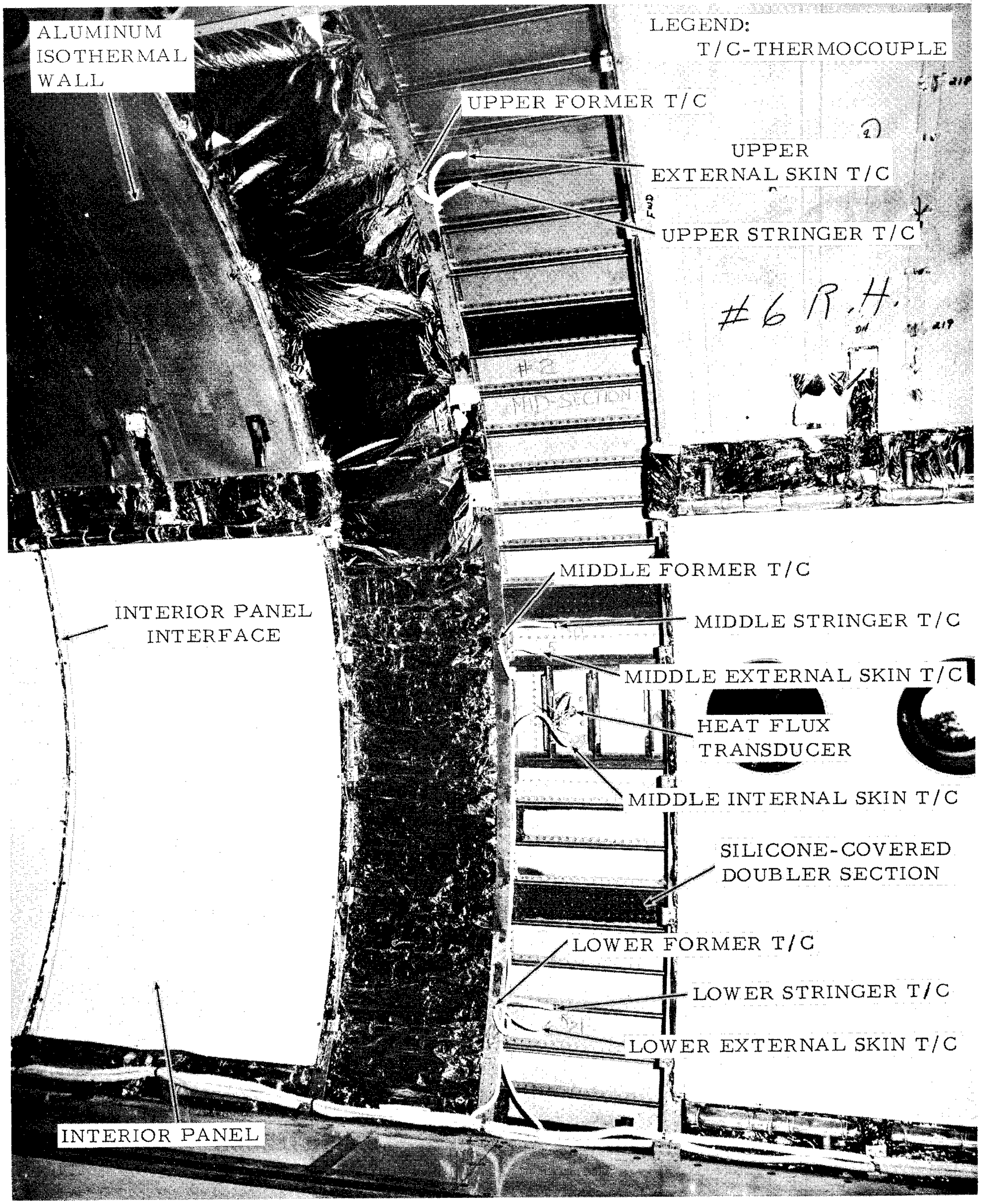

FIGURE 7 - CENTER INSTRUMENTATION SECTION WITH INTERIOR PANEL AND HALF OF INSULATION REMOVED

provided by motion picture cameras located both inside and outside the fuselage; temperature-indicating crayons applied to the outer titanium skin at the center of the fuselage; and gas-sampling bottles located 6 inches below the ceiling and slightly aft of the center section (Figure 4).

The flame thermocouples were fabricated of 20 AWG chromel-alumel wire, the titanium skin, former and stringer thermocouples of 30 AWG chromel-alumel wire, and the remaining thermocouples of 30 AWG iron-constantan wire. Ceramic sleeves insulated the external thermocouple wires from one another and from the titanium skin, while fiberglas covering provided protection from the titanium structural components which, like the titanium skin, were expected to become very hot during the test. Measurement junctions on titanium surfaces were made by spotwelding both wires to the surface, separated by a distance of about one-sixteenth inch. The remaining measurement junctions were made by spotwelding the two wires together.

The three heat flux transducers were of the Gardon Gauge design, a steady-state, differential-thermocouple type of instrument. An asbestos jacket housed the transducer and provided insulation from the titanium skin. Cooling water circulating through the transducer protected it from the fire. A favorable feature of this instrument was that the output signal was independent of the flow rate of cooling water.

All gas analyzers were housed in a double-walled metal structure, protected from any radiation by gravel piled against the top and sides, and located on the side of the fuselage opposite the fire pit. The CO (range 0-1.5 percent) and CO_2 (range 0-10 percent) analyzers were of the infrared absorption type. The O_2 (range 0-21 percent) and combustible gas (range 0-3 percent) concentrations were determined by a single unit using the paramagnetic and catalytic combustion techniques, respectively.

The smoke meter consisted essentially of an incandescent light source and a Weston 856 photocell separated by a distance of 1 foot. A housing of three concentric cylinders with staggered openings allowed for the relatively free movement of smoke between light source and photocell but, at the same time, prevented any external light from impinging upon the photocell.

All transducer data were recorded by two 24-channel, Model 1108, Minneapolis-Honeywell Oscillograph Recorders and one 18-channel, Type 5-124, CEC Oscillograph Recorder. A calibration check was made on all instrumentation immediately before the test.

Test Description

The fire pit was first filled with about 8-9 inches of water so as to provide a level reference plane which guaranteed a uniform fuel depth. Approximately 0.72 inch, or 180 gallons, of JP-4 fuel was then deposited into the pit. This amount of fuel was calculated to give a fire duration of 5 minutes. The following ambient conditions were recorded prior to the test:

Temperature = 59°F
Relative Humidity = 90%
Wind Velocity = 0-3 mph (variable)

The fuel was ignited with a torch at the outside corner of the fire pit nearest the aft end of the fuselage (Figure 1). In a matter of a few seconds the flames completely engulfed the entire pit. However, the fire did not reach full intensity until about 10-15 seconds after ignition. At about this time, or shortly thereafter, a firewhirl developed adjacent to the fuselage near the aft end. Figure 8 shows the test at 45 seconds after ignition. The firewhirl was displaced away from the fire pit and extended to the aft end of the fuselage. (Some evidence of the low wind velocity is provided in this figure by the vertical column of smoke.) At approximately 80 seconds after ignition, the firewhirl unexpectedly moved to the forward end of the fuselage, remained there for 5-10 seconds, and then shifted back to the aft end where it remained until cessation of the test. A pop was heard at 1 minute 55 seconds after ignition, and was accompanied by a sudden egression of smoke from around the edges of the door. This was then interpreted (and later demonstrated by both data analysis and examination of the test article) as resulting from a flash fire within the fuselage. Twenty seconds later the firemen were signaled to extinguish the pit fire. Complete extinguishment was accomplished by 3 minutes 50 seconds after ignition; however, because of the high cabin temperatures, the fuselage was not entered until a later time. The fuselage gas composition was drawn into the sampling bottles at 5 minutes after ignition. At 15 minutes after ignition the aft door was opened, releasing a considerable amount of smoke from within the fuselage. The interior motion picture camera, which was positioned near the aft door, was removed from the fuselage. Unfortunately, the film was destroyed. A small fire broke out beneath the floor near the aft end of the fuselage at about 27 minutes after ignition and was quickly extinguished with CO_2. Three minutes later ignition recurred, this time resulting in severe flaming, and making it necessary to extinguish the fire with water. (Originally it was decided to only use CO_2 for any interior fires

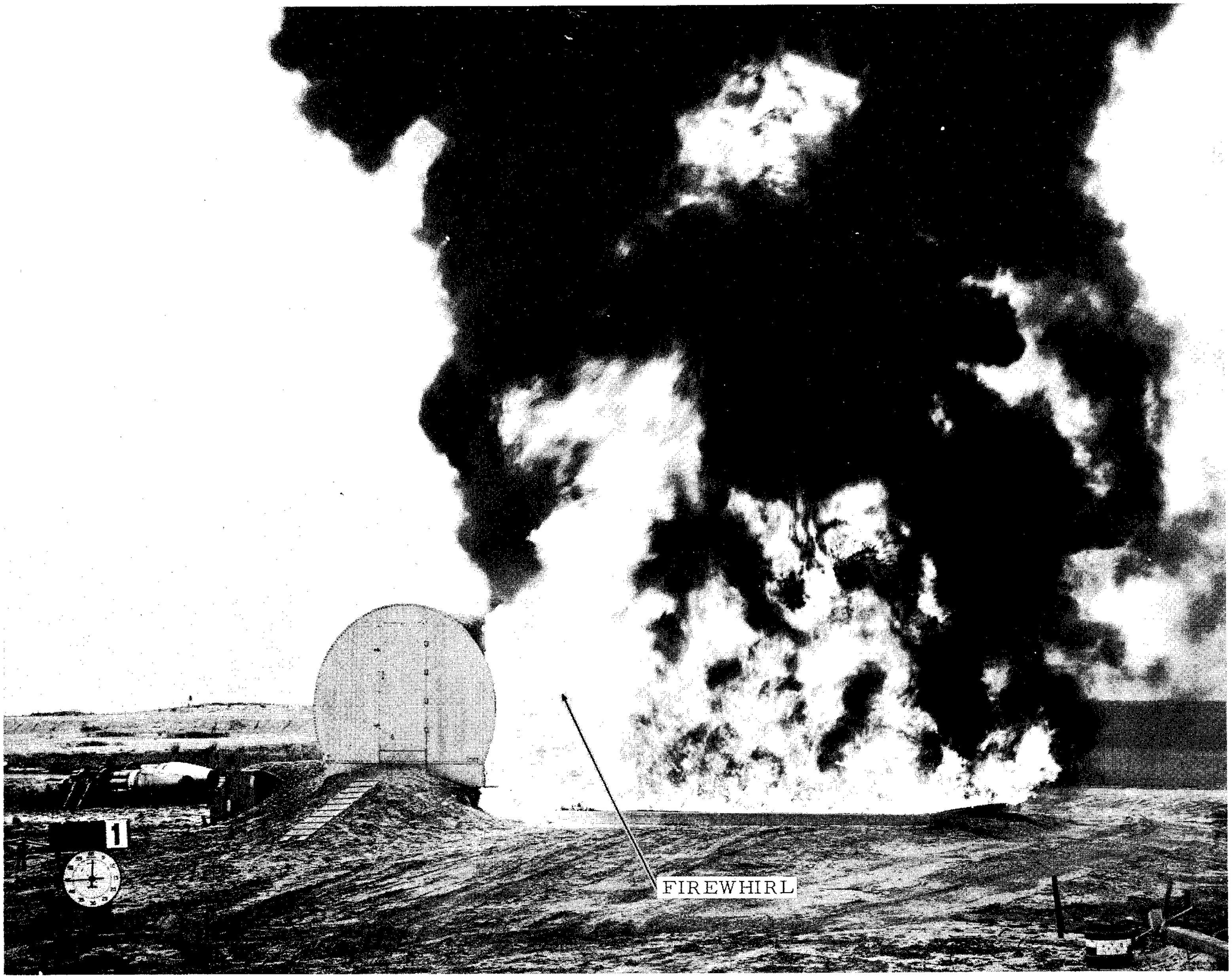

FIGURE 8 - TITANIUM FUSELAGE FIRE TEST AT 45 SECONDS AFTER IGNITION

with the hope of saving the furnishings for later tests.) The fire broke out for the third time at 39 minutes after ignition. This time the floor board was ripped out, exposing the burning insulation which was then removed from the fuselage. The forward door was opened 2 minutes later, and there were no recurrences of interior flaming.

Test Article Diagnosis

The side of the fuselage exposed to the fire presented considerable evidence of flame exposure, as is shown in Figure 9. This is quite a contrast to Figure 1, which shows the same view of the fuselage before the test. The flame pattern was etched on the titanium skin, demonstrating that the fuel flames had been drawn towards the firewhirl at the aft end of the fuselage. Because of the thermal stresses generated during the test, the titanium skin was permanently deformed and had a wrinkled appearance, especially at the areas which experienced the most severe heating. However, this deformation was insignificant in that it did not produce any gaps which could have allowed the fuel flames to come directly in contact with the interior materials within the fuselage. The fuselage skin near the lower aft end developed 12 fractures during the cooling-down period following the extinguishment of the pit fire (Figure 10). The length of tear ranged from 1 to 6 inches. An increase in the cooling of the skin because of the inadvertent application of extinguishing agent appears to have aided, if not caused, the formation of these fractures.

The first clue as to the probable cause of the flash fire was provided by the appearance of a white ash-like residue along the seams of the titanium skin (Figure 9). This residue is a characteristic product of RTV silicone combustion and had previously been observed when burning this material in a test tube. During the fuselage test, the RTV silicone applied to faying surfaces was pyrolyzed, producing combustible gases which egressed from the seams and were ignited by the fuel flames, thus producing the white residue along the seams. The pyrolysis and eventual combustion of the RTV silicone applied to the interior titanium surfaces then loomed as the possible cause of the cabin flash fire.

Frequently a system which experiences an unexpected severe fire gives the first impression as offering no evidence as to the origin of the fire or the means by which it spread. However, this information can often be obtained if one scrutinizes the system's components. This was true in the case of the titanium fuselage cabin. The following discussion describes the acquisition of this information in, more or less, the order that it was learned.

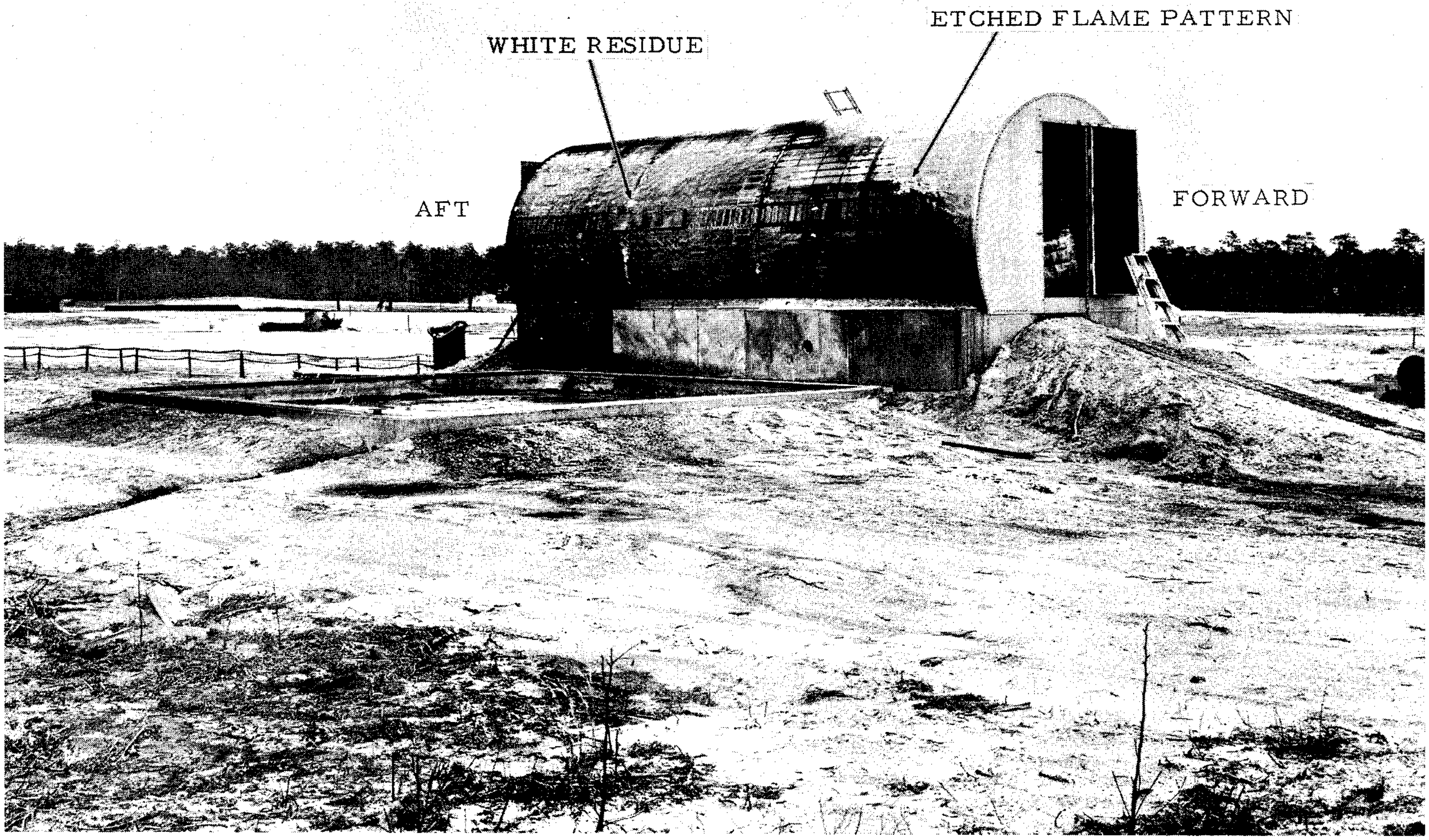

FIGURE 9 - TITANIUM FUSELAGE AFTER FIRE TEST

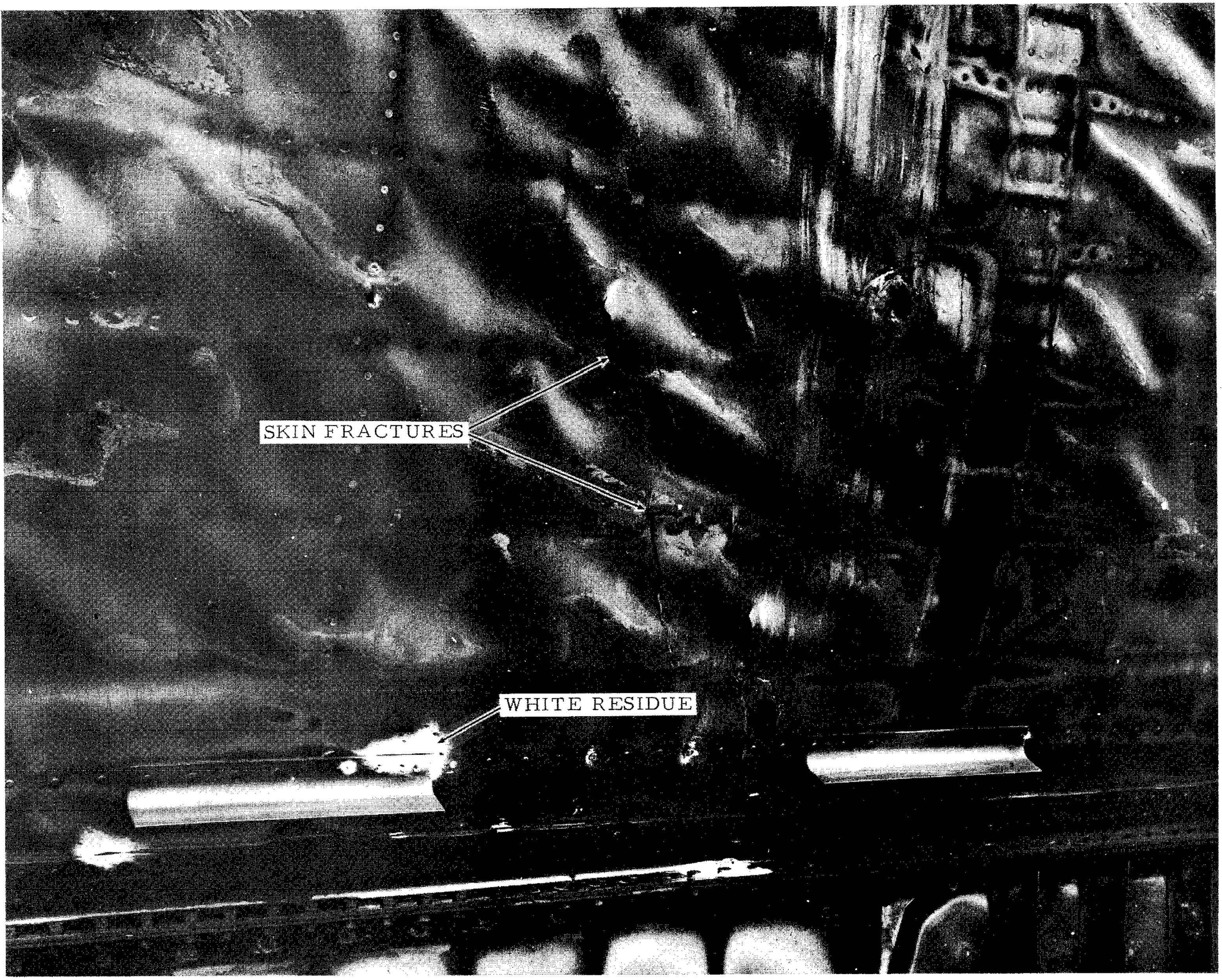

FIGURE 10 - SKIN FRACTURES NEAR LOWER AFT END

A view of the cabin after the test is shown in Figure 11, and, when compared with Figure 4, exhibits considerable damage. Note the large amount of foam extinguishing agent accidentally discharged during the initial extinguishment of the floor fire. The hatrack and ceiling damage indicated that the flash fire originated at the aft end of the fuselage (the seats are facing aft) and, as expected, was more severe near the top of the cabin. Molten aluminum, splattered against the seats during the extinguishment of the floor fire, did not ignite the seat upholstery. A closeup of the locality of the floor fire is shown in Figure 12. Sections of the aluminum honeycomb floorboard and the flammable insulation were removed during the fire extinguishment. Special notice should be given to the presence of burn marks in the vicinity of the interior panel interfaces (this will be discussed subsequently in greater detail).

The first items removed from the fuselage were the seats and rug. Examination of the aft-most seat adjacent to the interior wall revealed evidence of flame impingement upon its side (Figure 13). The flame came from an interior panel interface which was adjacent to the burned seat area and burned away a small area of the seat cover; however, the fire did not spread from the area of flame impingement. Both the elastomeric armrest and the rigid foam siding also showed evidence of burning without any apparent flame spreading. The rug was burned away at the area immediate to the floor fire, but also without any noticeable flame spreading. This was also true of the rug areas struck by molten aluminum. The condition of the rug displayed the same trend as the hatrack and ceiling in that the damage to it decreased toward the forward end of the fuselage.

The false ceiling was next removed from the fuselage, revealing evidence of a pressure rupture above the hatrack near the aft end (Figure 14). Note the jagged appearance of the aluminum "isothermal" wall. Apparently, the space bounded by the inner aluminum and outer titanium walls was fairly airtight so as to allow a pressure buildup which eventually ruptured the aluminum. This failure probably initiated the flash fire--witnessed as a distinct pop and sudden outflow of smoke from the aft door's edges--which occurred at 1 minute 55 seconds after ignition.

Figure 15 shows a closeup of the interior panel located slightly forward of the fuselage center. The area above the floorboard vent, which was the outlet for a duct stuffed tightly with fiberglas insulation, exhibited severe burn marks. It appeared as if the volatiles from the insulation's silicone binder were released during pyrolysis and ignited upon entering the cabin environment.

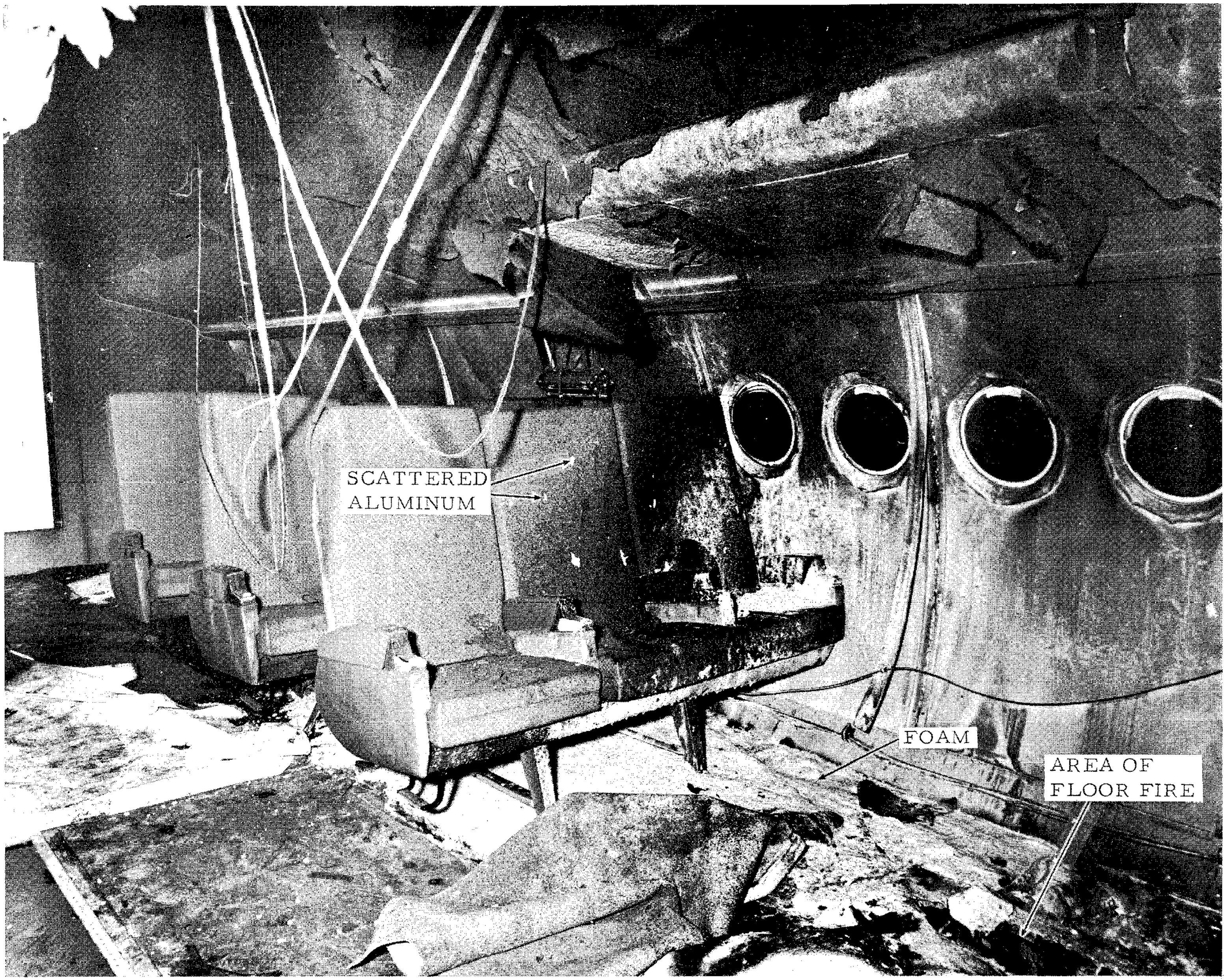

FIGURE 11 - CABIN DAMAGE AFTER FIRE TEST

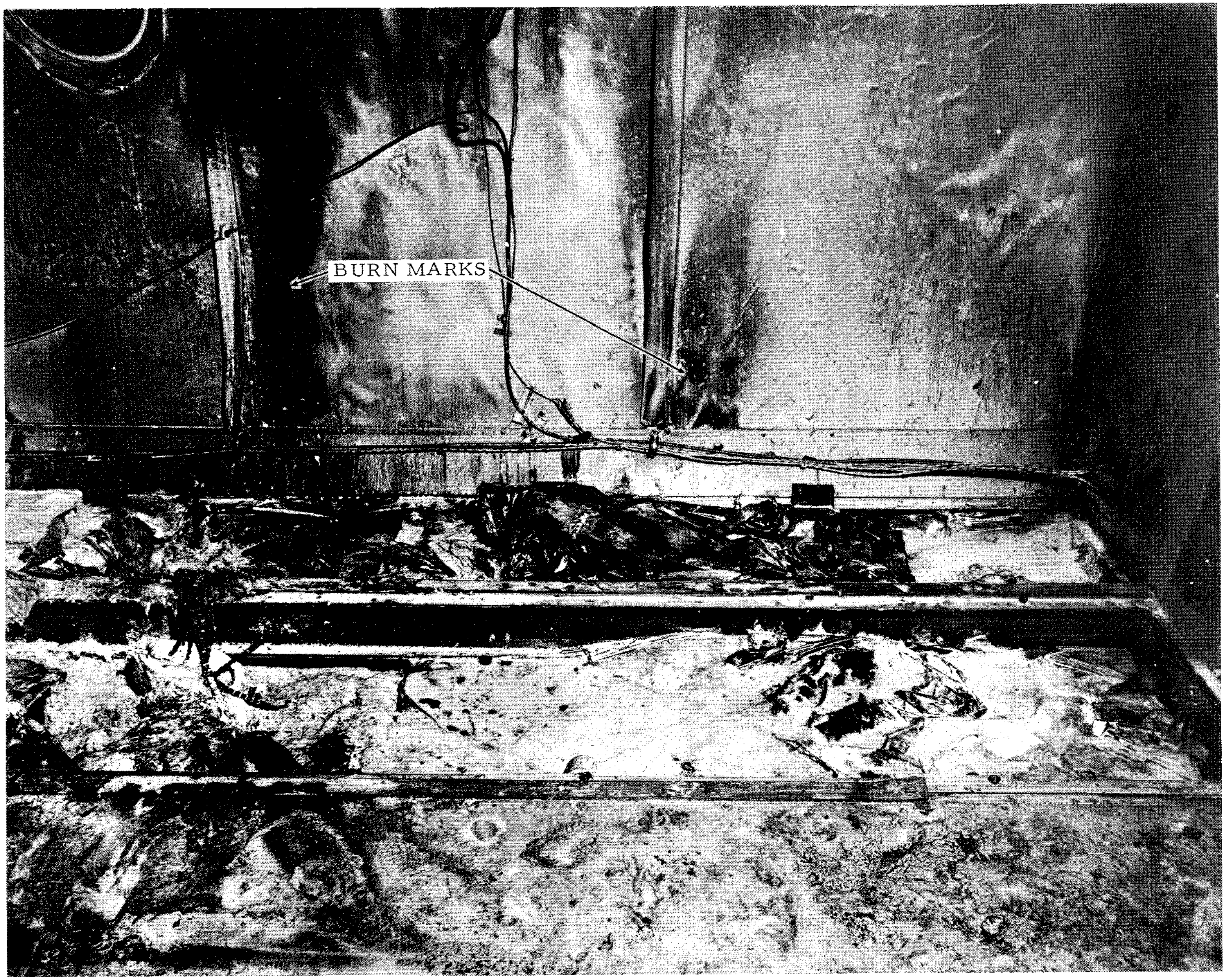

FIGURE 12 - AREA OF FLOOR FIRE

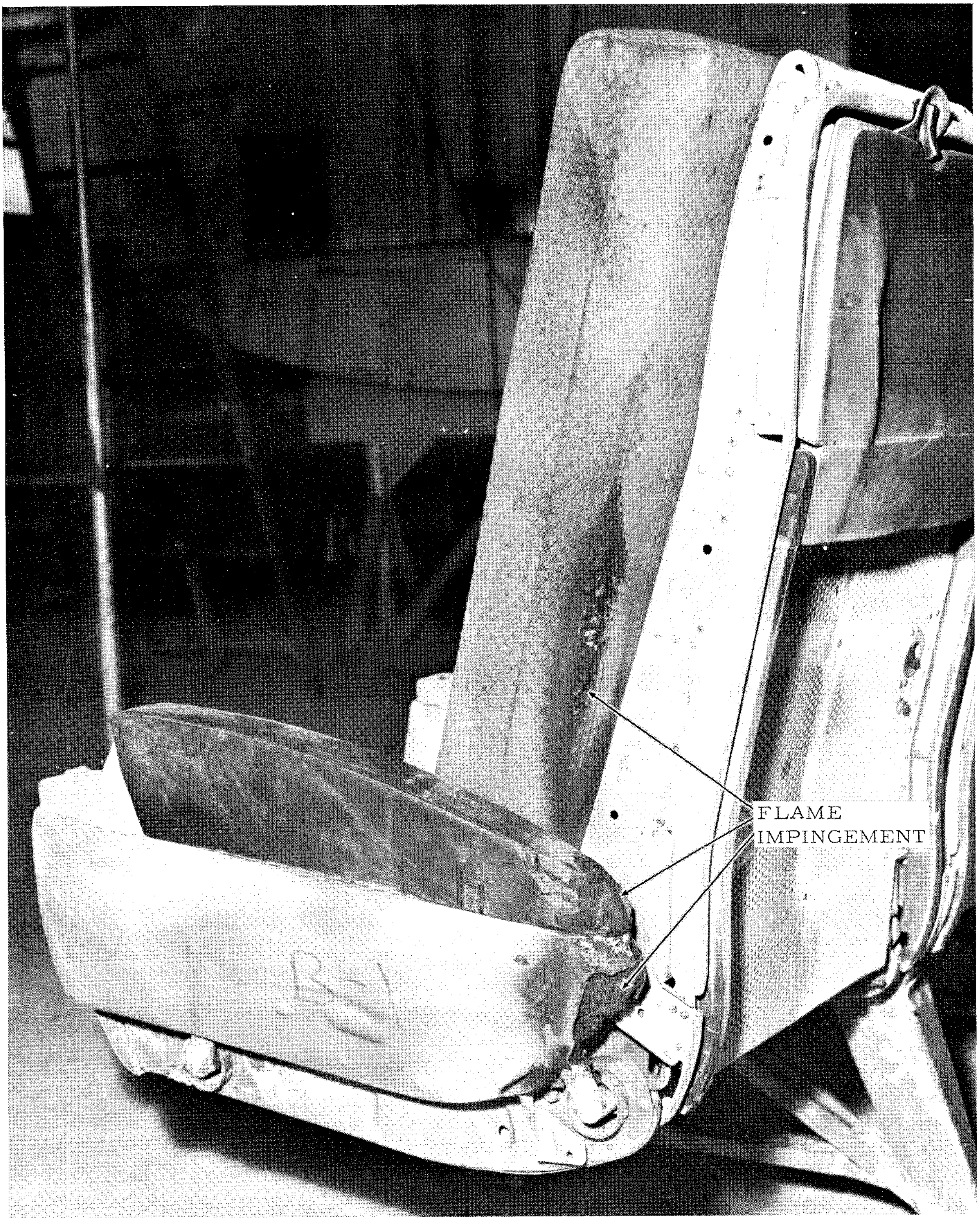

FIGURE 13 - DAMAGE TO AFT-MOST SEAT ADJACENT TO INTERIOR WALL

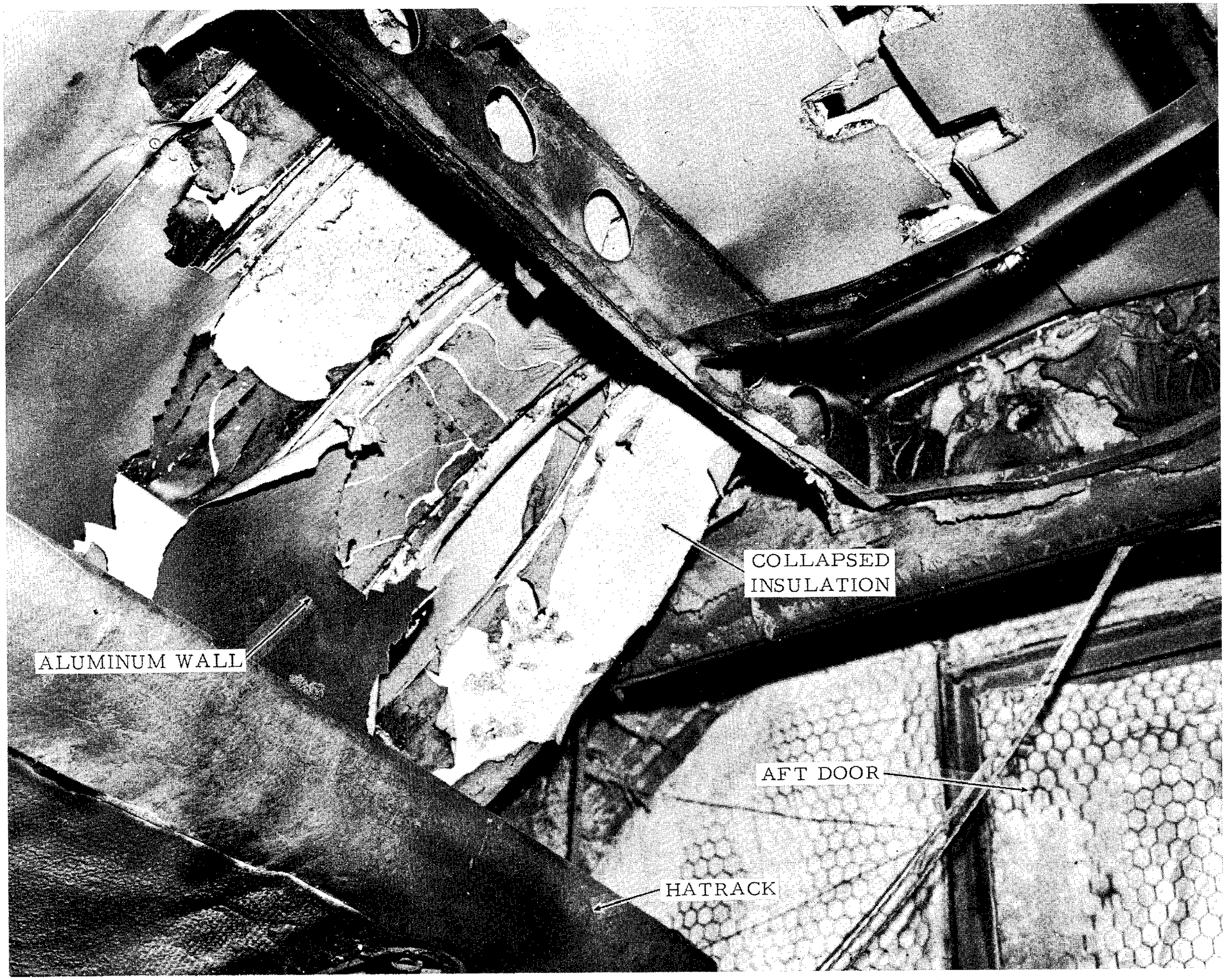

FIGURE 14 - RUPTURED ALUMINUM WALL

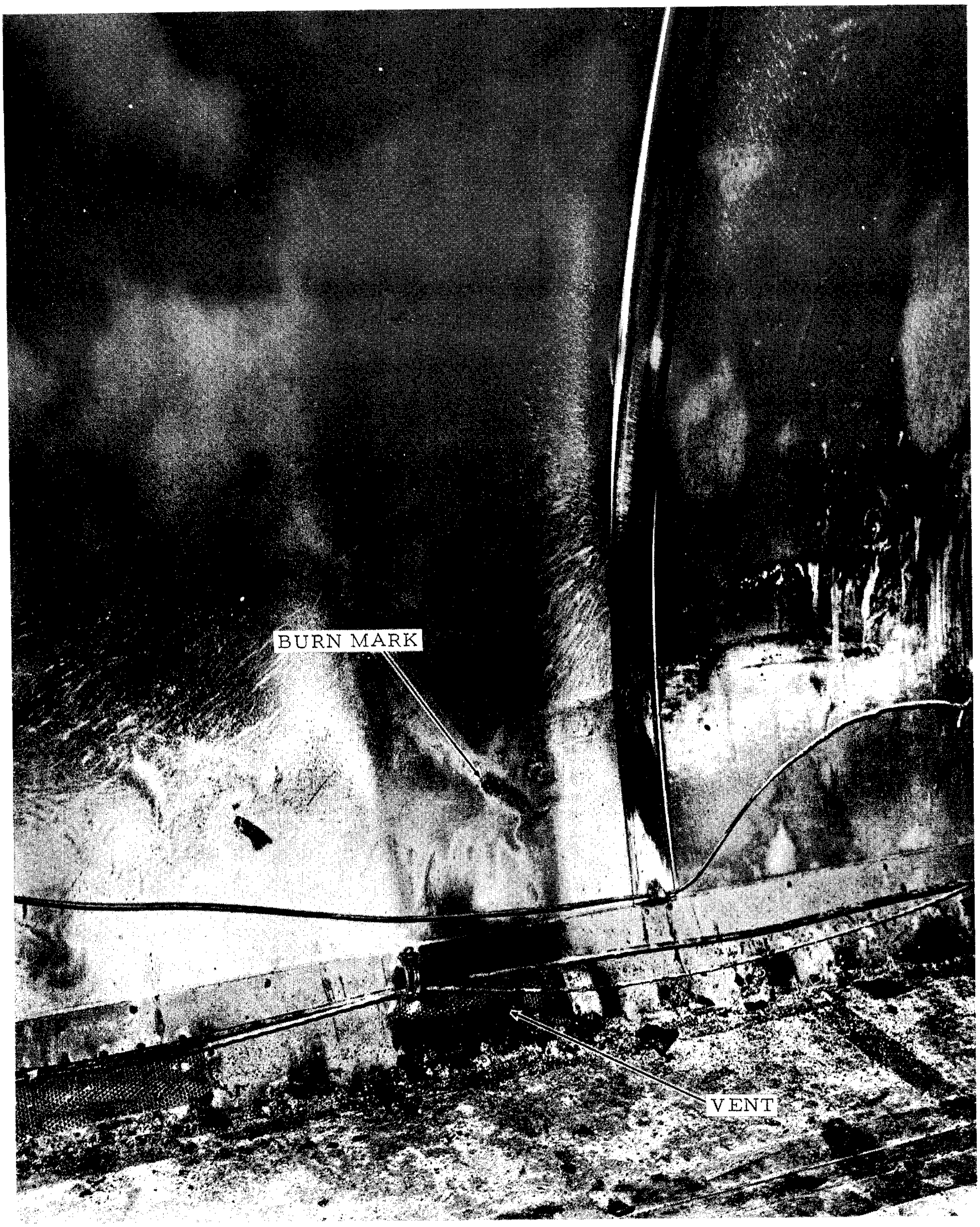

FIGURE 15 - BURNED AREA ABOVE VENT STUFFED WITH INSULATION

The short length of fuselage sidewall extending from the end plate to each partition was not insulated in the original titanium test article. It was necessary to insulate this area with fiberglas supported by chicken wire. As is noticeably evident in Figure 16, the insulation mounted at the aft end of the fuselage collapsed at some time during the test. This then allowed for a significant increase in heat transfer from the adjacent firewhirl which may have contributed (in addition to the panel interface and vent flaming) to the early heating of the cabin environment. The partition experienced fire damage alongside the interior panel from flames which, as will be subsequently demonstrated, originated from burning RTV sealant and fiberglas insulation.

The next step in the examination of the test article was to remove the interior panels. Figure 17 shows the same section near the aft end as Figure 16, but with the interior panels removed. It was evident that severe burning of the RTV sealant and fiberglas (binder) insulation had occurred during the test. The degree of fire damage followed four trends: it was most severe (1) toward the aft end, (2) toward the cabin floor, (3) in the vicinity (especially above) of the RTV-covered doubler sections, and (4) toward the interior panel interfaces. The first two trends are clearly discernible in Figure 17, while the third trend is better illustrated by the closeup shown in Figure 18. Immediately above the RTV-covered doubler section the insulation was burned away, especially near the panel interface where the oxygen necessary for combustion could be obtained from the cabin air. It appears as if the RTV ignited first and acted as an ignition source for the burning of the insulation. Another closeup better displays the fourth trend (Figure 19). Although it is not clearly distinguishable in this black and white photograph, the insulation adjacent to the center former was unburned, while the insulation near the outer formers (panel interfaces) was severly damaged. Also, the RTV used on the formers as an adhesive was burned off the outer former, but that attached to the center former was unscathed. Clearly, the combustion occurred at the panel interfaces where oxygen was readily accessible from the cabin air.

Figure 20 shows the interior panel removed from the center instrumentation section. The amount of burned insulation was considerably less than that at the aft end. The insulation immediately above the floor was almost completely burned, while that above the window level, except for a small area adjacent to an RTV-covered doubler section, was unburned. This behavior follows the previously outlined second and third trends. Examination of the insulation batt adjacent to the doubler section

FIGURE 17 - BURNED SEALANT AND INSULATION NEAR AFT END

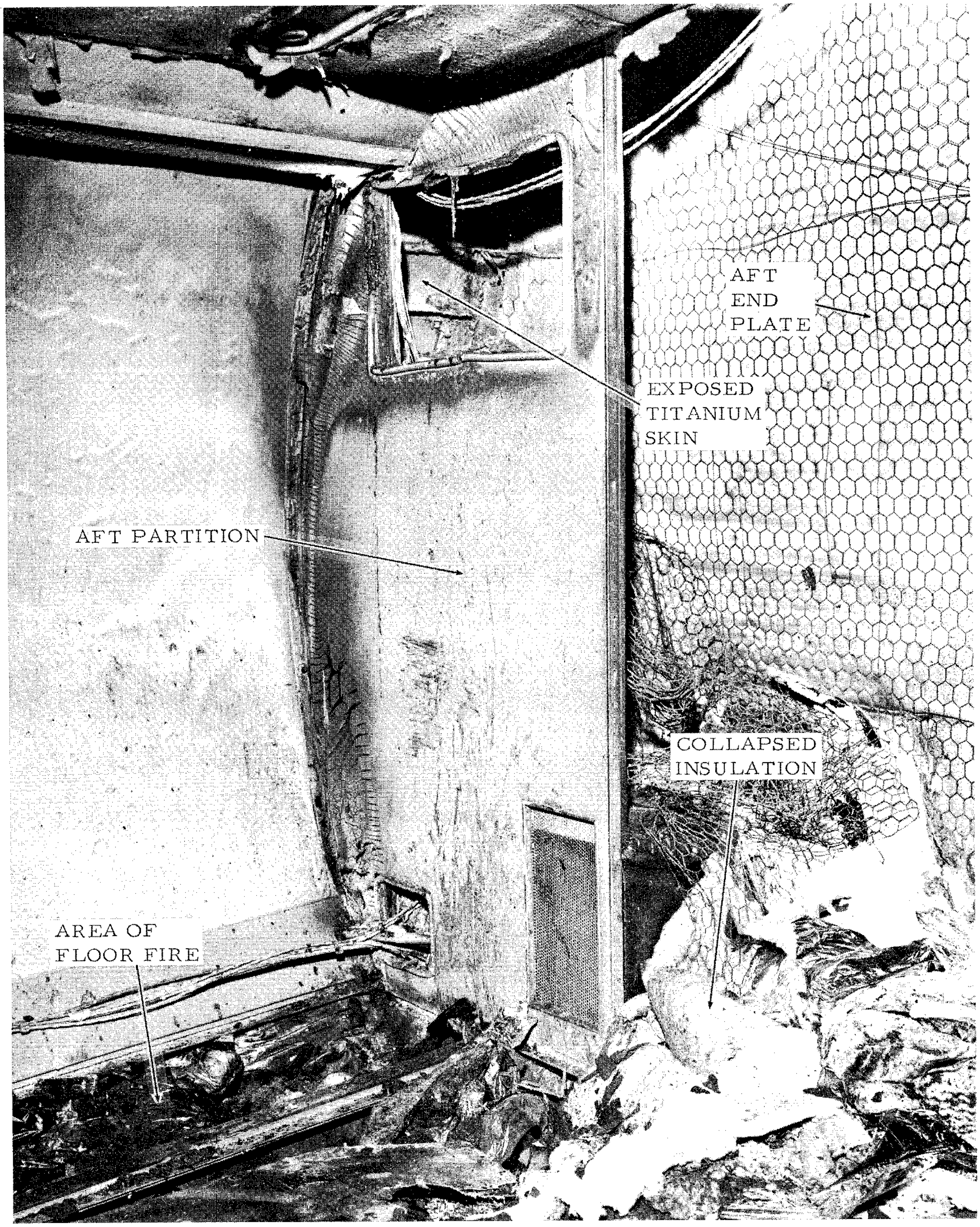

FIGURE 16 - DAMAGED CABIN NEAR AFT END

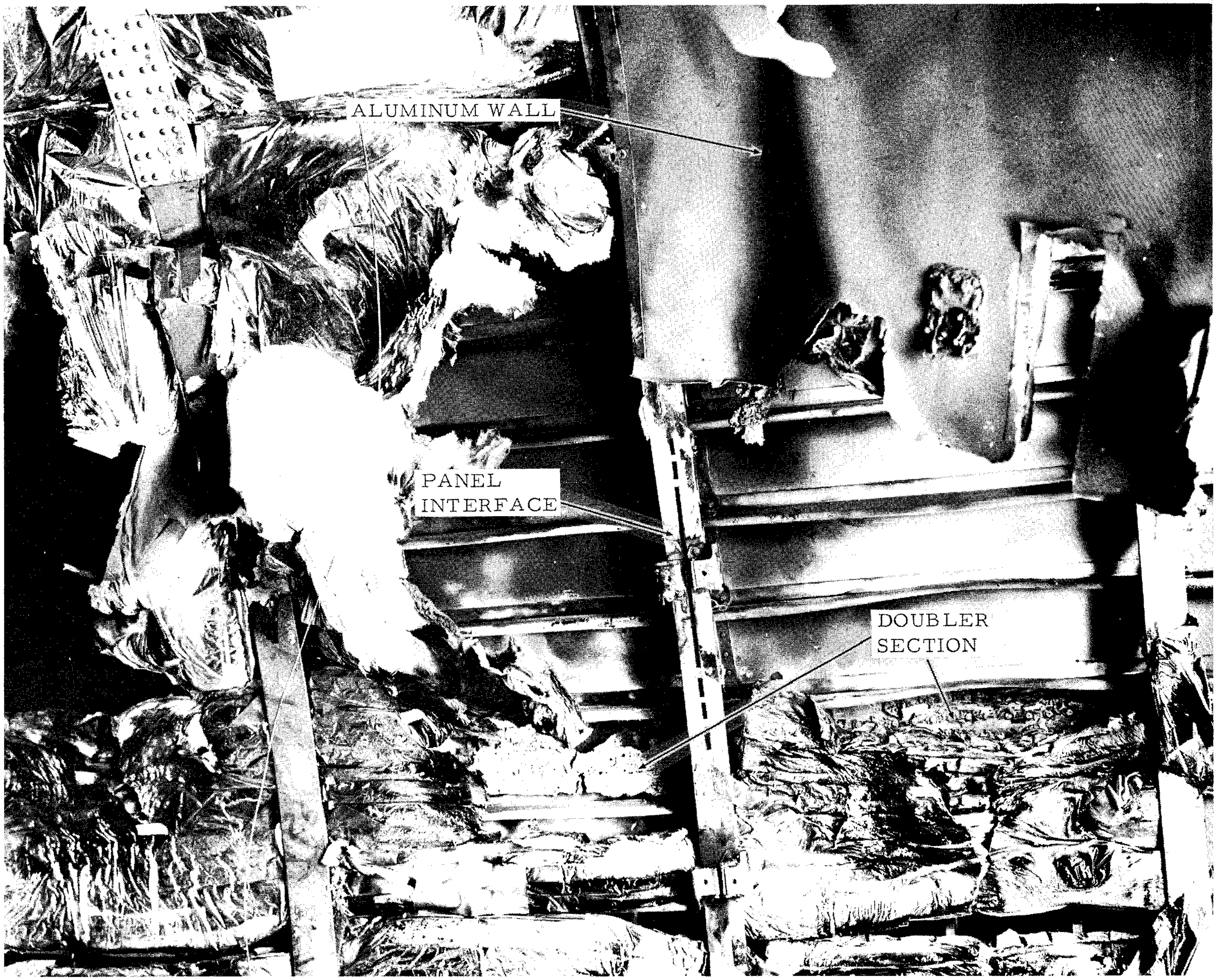

FIGURE 18 - BURNED INSULATION ABOVE DOUBLER SECTION

FIGURE 19 - BURNED INSULATION NEAR INTERIOR PANEL INTERFACES

FIGURE 20 - CENTER INSTRUMENTATION SECTION WITH INTERIOR PANEL REMOVED

revealed that the polyimide film facing the titanium skin was severely charred, while the adjacent fiberglas was not damaged. The RTV coating on the doubler section was completely decomposed, with only an insignificant amount of flake remaining. The RTV sealant decomposed and burned more readily than the fiberglas insulation, and was probably the major contributor to the cabin flash fire. Removal of the interior panel from the forward instrumentation section revealed that all of the insulation and RTV sealant were unburned. Thus, examination of the three instrumentation sections indicated that the fire damage to the RTV sealant and fiberglas insulation occurred in proportion to the severity of the external fire.

Data Analysis

Four of the 66 transducers malfunctioned during the test: two former thermocouples and, unfortunately, the two combustible gas analyzers. Analysis of the data generally corroborated the observations made during and after the test.

The intensity of the fuel fire was measured by three heat flux transducers and three thermocouples. Figure 21 compares the total heat flux impinging upon the fuselage at each instrumentation section. Each data point represents the average of five readings taken every one-half second. It was necessary to reduce the data by this procedure in order to eliminate the large, rapid fluctuations in heat flux characteristic of a turbulent fire of this size, thus making it possible to simultaneously compare the heat flux at each section. As was observed during the test, Figure 21 demonstrates that the fire did not reach full intensity until about 10-15 seconds after ignition. Also, it is apparent that the heat flux distribution was governed largely by the location of the firewhirl which, except for its movement at 80 seconds after ignition toward the forward end of the fuselage, was always adjacent to the fuselage near the aft end. Even though the center heat flux transducer was positioned at the center of the fire pit, the heat generated by the firewhirl was great enough to cause the aft total heat flux to exceed that at the center for most of the test. Convective flame bending toward the firewhirl caused the aft and forward heat flux, which were measured equidistant from the center of the fire pit, to differ by as much as a factor of ten. Data were abruptly terminated when the shielded cables connected to the heat flux transducers developed short circuits. Fortunately, temperature data were recorded throughout the test since all thermocouple wires were protected by asbestos insulation. Figure 22 shows the flame temperature at each instrumentation section. A comparison with the heat flux data revealed that the flame temperature closely followed the trends exhibited by

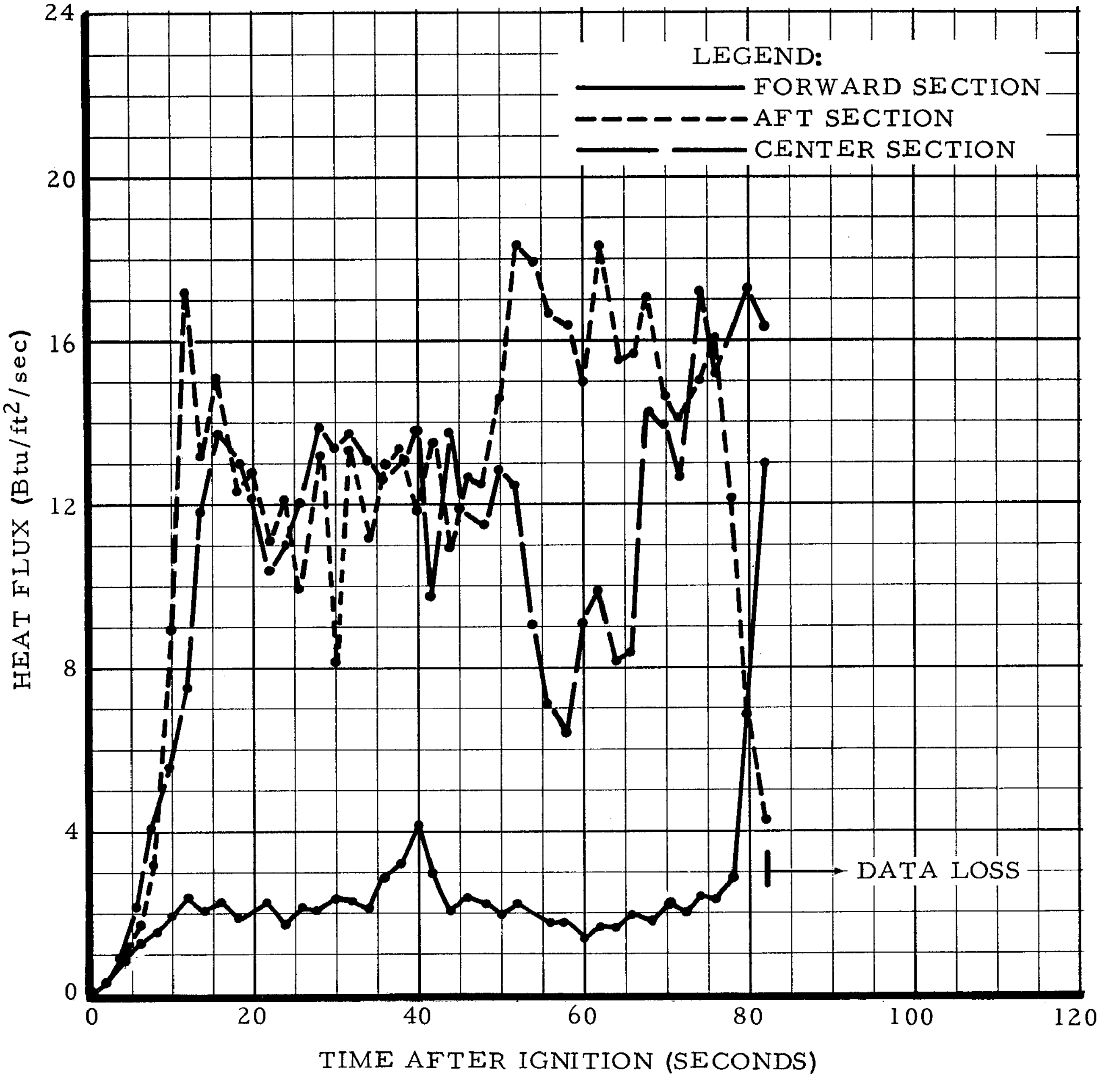

FIGURE 21 - HEAT FLUX UPON TITANIUM FUSELAGE DURING AN EXTERNAL FUEL FIRE

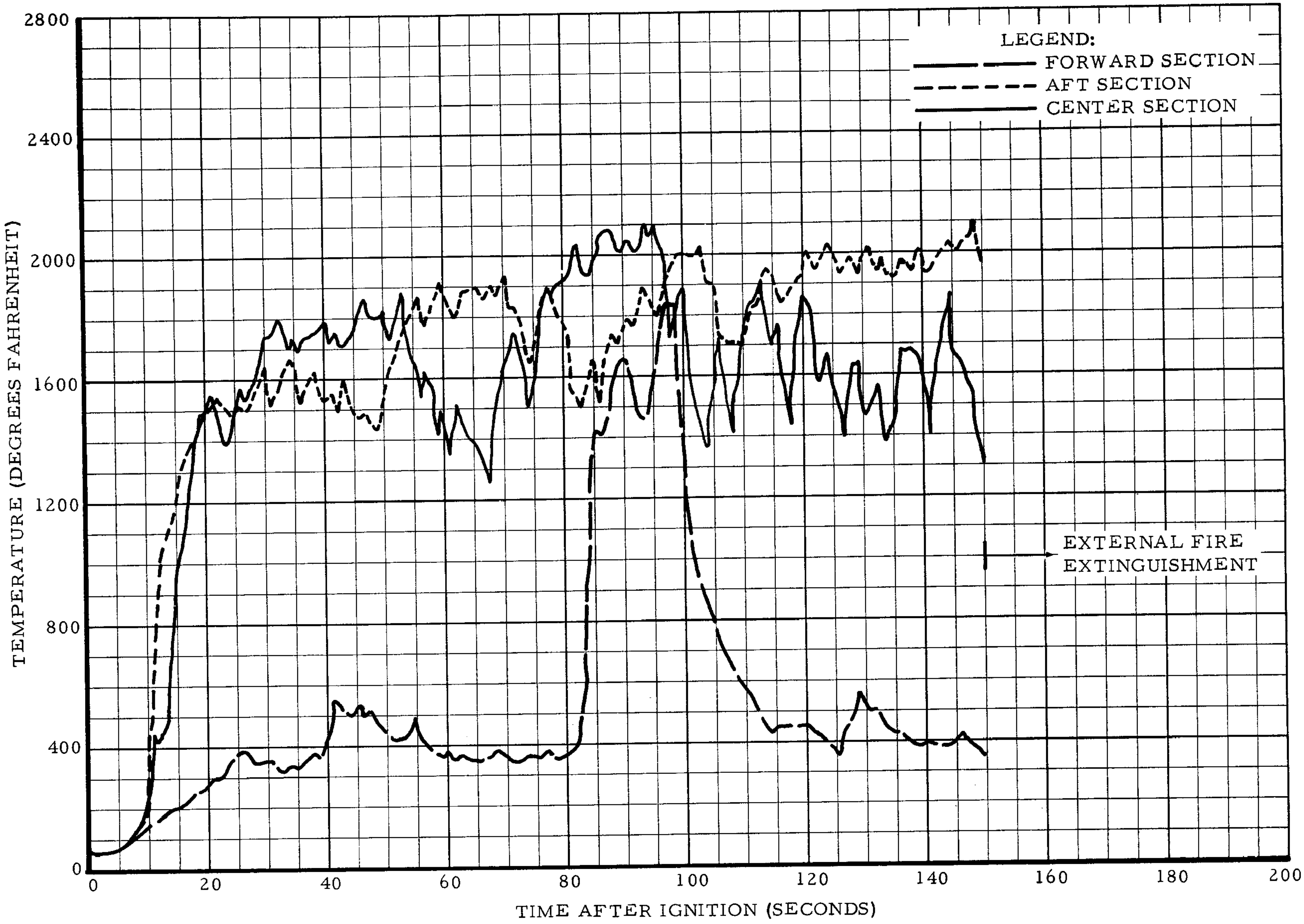

FIGURE 22 - EXTERNAL FUEL FIRE FLAME TEMPERATURE

the heat flux. The highest flame temperatures were encountered during the presence of the firewhirl which has a higher combustion temperature because of its vortical nature and resulting higher air to fuel ratio. That is to say, the amount of air injected into the firewhirl was greater than that injected into the undisturbed portion of the fire.

The titanium skin temperatures at the center section are shown in Figure 23 for the three measurement levels. The middle and lower temperatures were fairly similar, while the upper temperature was substantially lower, indicating that flame bending around the fuselage was not significant enough to raise the upper fuselage skin temperatures to the values experienced by the areas adjacent to the fire. This trend was also exhibited by the aft and forward sections, although the forward temperatures were significantly lower than either the center or aft temperatures. Since an aluminum alloy melts over a temperature range extending from about 900° to 1200°F (Reference 2), the skin of a conventional subsonic aircraft experiencing the same temperature history shown in Figure 23 would melt in less than 30 seconds at some areas and allow fire entry into the cabin interior.

The structural members of the titanium fuselage did not heat up nearly as rapidly as the skin. In fact, the maximum increase in former temperature was only 30°F. This was due to the large heat capacity of the former and somewhat, perhaps, due to the location of the thermocouple on the inside flange of the former (Figure 7). Since the stringers were not nearly as massive as the formers, they were heated much more rapidly than the formers were, and the stringer temperatures eventually reached the titanium skin temperature by the end of the test. Figure 24 compares the measured stringer temperatures at the center section and is representative of the trend exhibited by the other two sections; i.e., the stringers located closest to the fire pit experienced the greatest heating. The temperatures of the three instrumented stringers increased towards the aft end of the fuselage, except for the upper stringer at the center section where the temperature exceeded that at the aft end. Since a comparison of the stringer temperatures gives a relative indication of the amount of heat transmitted through the titanium skin, it is not surprising that the location of the highest stringer temperatures coincided with the fuselage areas which experienced the most severe burning of RTV sealant and insulation.

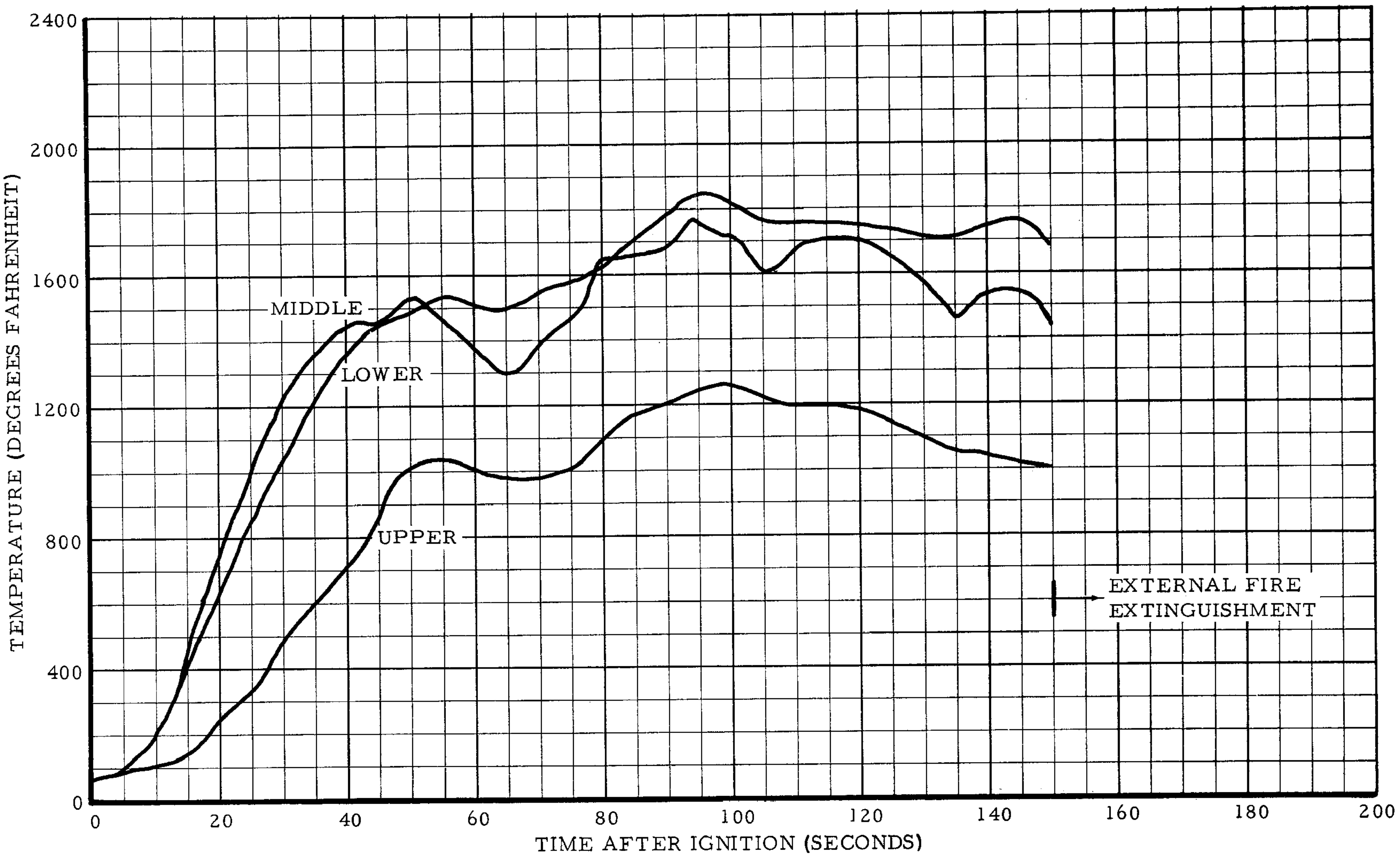

FIGURE 23 - TITANIUM FUSELAGE SKIN TEMPERATURE (CENTER SECTION) DURING AN EXTERNAL FUEL FIRE

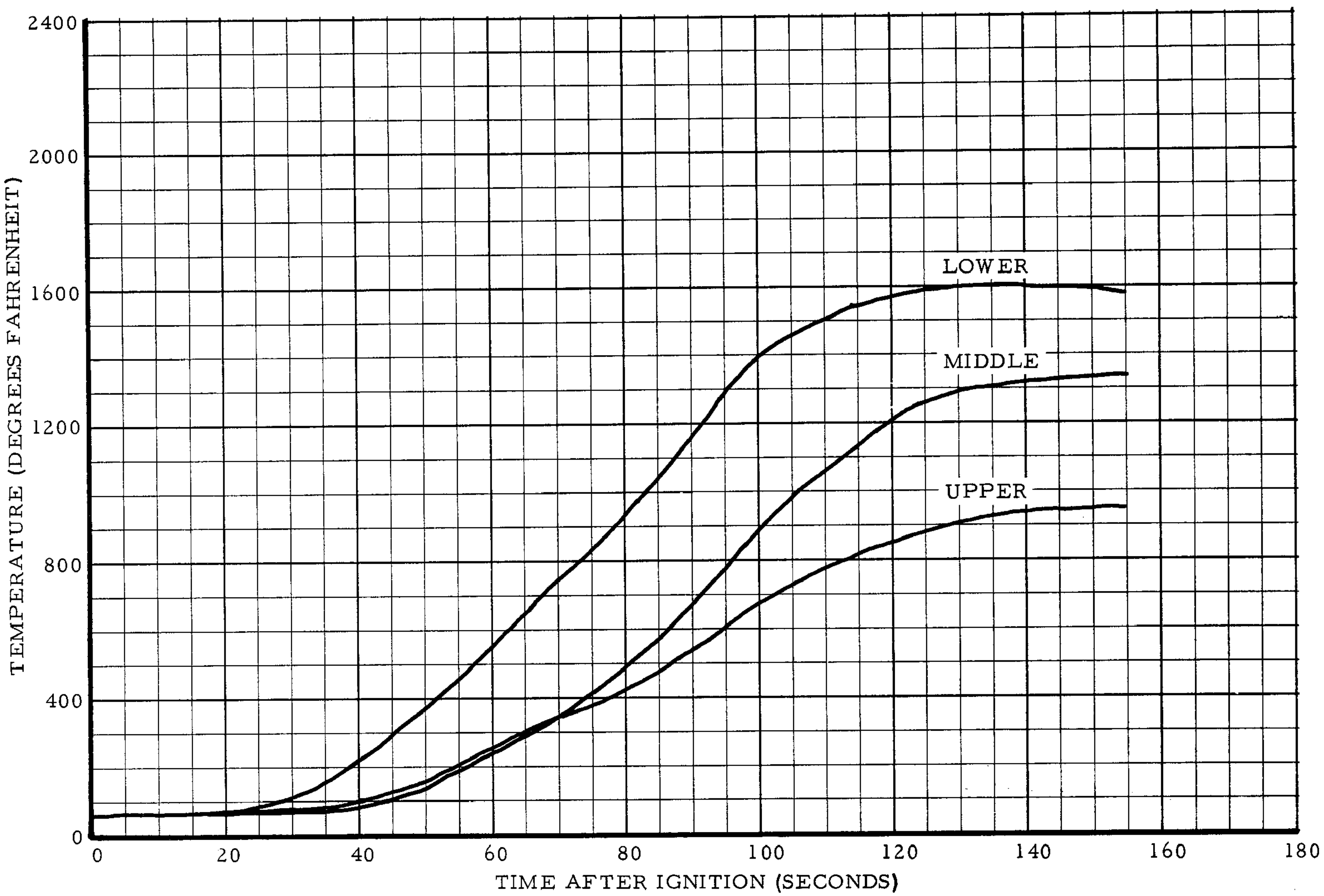

FIGURE 24 - TITANIUM FUSELAGE STRINGER TEMPERATURE (CENTER SECTION) DURING AN EXTERNAL FUEL FIRE

The heat transmitted through the titanium skin was impeded by the insulation batts, and from the preceding discussion, one would expect the insulation temperature at different levels to follow the same trends as the stringer temperature. Figure 25 shows that this was not the case. The middle temperature unexpectedly exceeded the lower temperature until about 130 seconds after ignition, probably because the middle thermocouple was feeling the heat from the combustion of the RTV silicone sealant. (The middle insulation thermocouple was located adjacent to an RTV-covered doubler section, while both the lower and upper thermocouples were not.) Because of the greater heat transfer at the lower level, the insulation there eventually ignited and burned, as indicated by the sharp and initially erratic increase in temperature starting at 125 seconds after ignition. Since both the middle and upper thermocouples did not experience any sharp increases in temperature which are characteristic of flaming, the thermocouple data were thus consistent with the appearance of the center section (Figure 20). All three aft insulation thermocouples showed sharp increases in temperature indicative of burning insulation, the remnants from which were observed in Figure 17. The insulation temperature of the forward section did not change throughout the test.

Thermocouple data at the cabin wall of the center section are shown in Figure 26. At about 65 seconds after ignition all three thermocouples began to detect heat. During the initial heating, when the increase in cabin wall temperature was fairly gradual, the highest temperature was near the ceiling and decreased toward the floor. Also, a comparison of these data with Figure 25 indicates that the cabin wall temperature always exceeded the insulation temperature. This behavior was also observed at the other two sections. Both observations tend to prove that the cabin wall was being heated by the cabin air--not by heat transfer from the external fuel fire. The rapid increase in wall temperature was caused by the flash fire within the cabin. Figure 27 shows the cabin air temperature measured by the three thermocouples located 6 inches below the ceiling. The early and swift heating of the cabin environment was believed to have been caused primarily by flaming at the panel interfaces, with vent flaming and heat transfer through the uninsulated area at the aft end being minor contributions. The air temperatures were highest toward the aft end of the fuselage, as was the degree of damage to interior materials.

A better perspective of the heating of the titanium fuselage is provided by Figure 28 which shows temperature data from the middle group of thermocouples at the aft section. The titanium

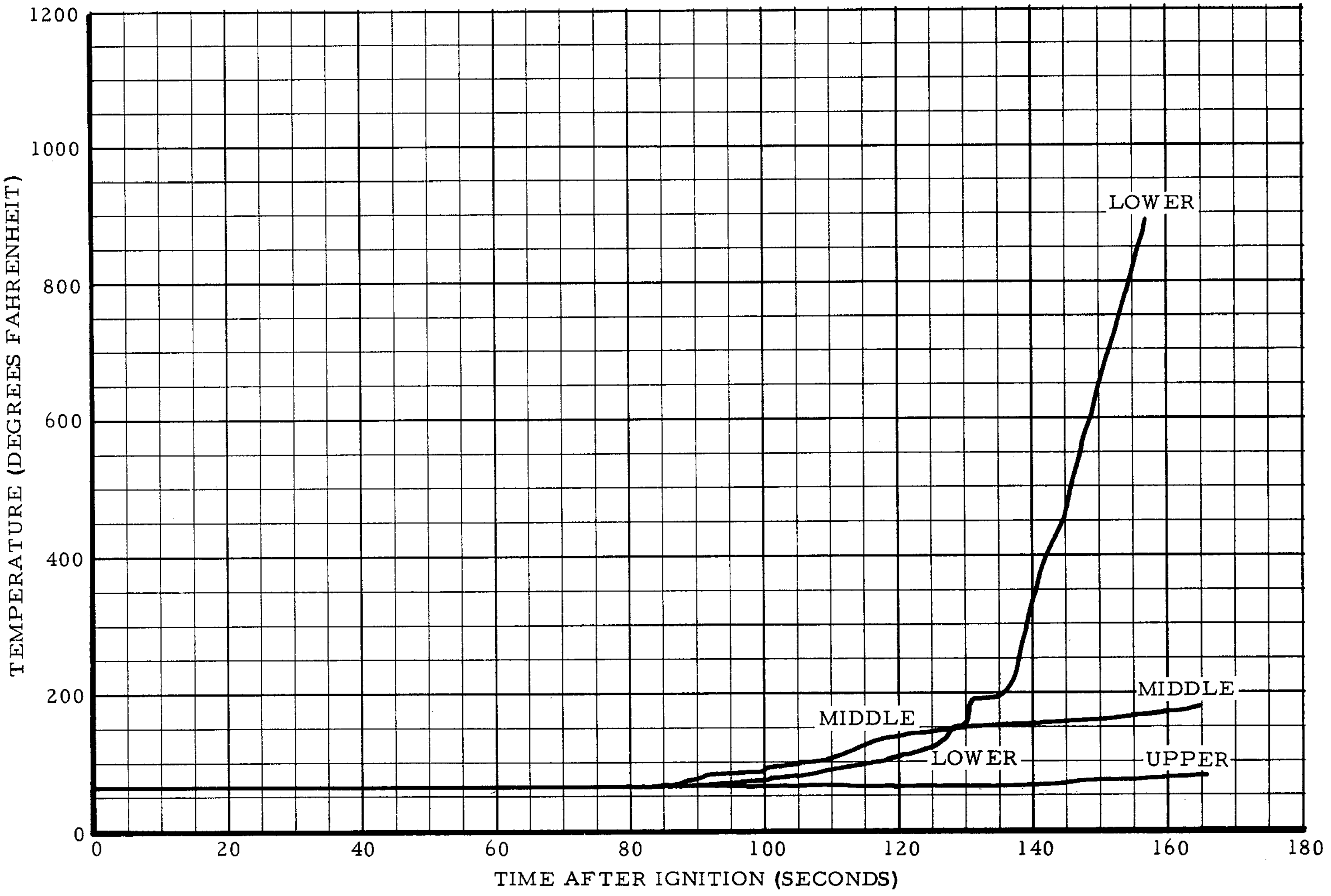

FIGURE 25 - TITANIUM FUSELAGE INSULATION TEMPERATURE (CENTER SECTION) DURING AN EXTERNAL FUEL FIRE