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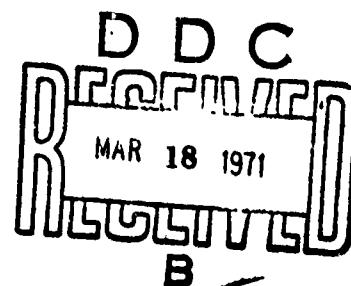
TITANIUM FUSELAGE ENVIRONMENTAL CONDITIONS IN POST-CRASH FIRES

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MARCH 1971

FINAL REPORT



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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.			
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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.

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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

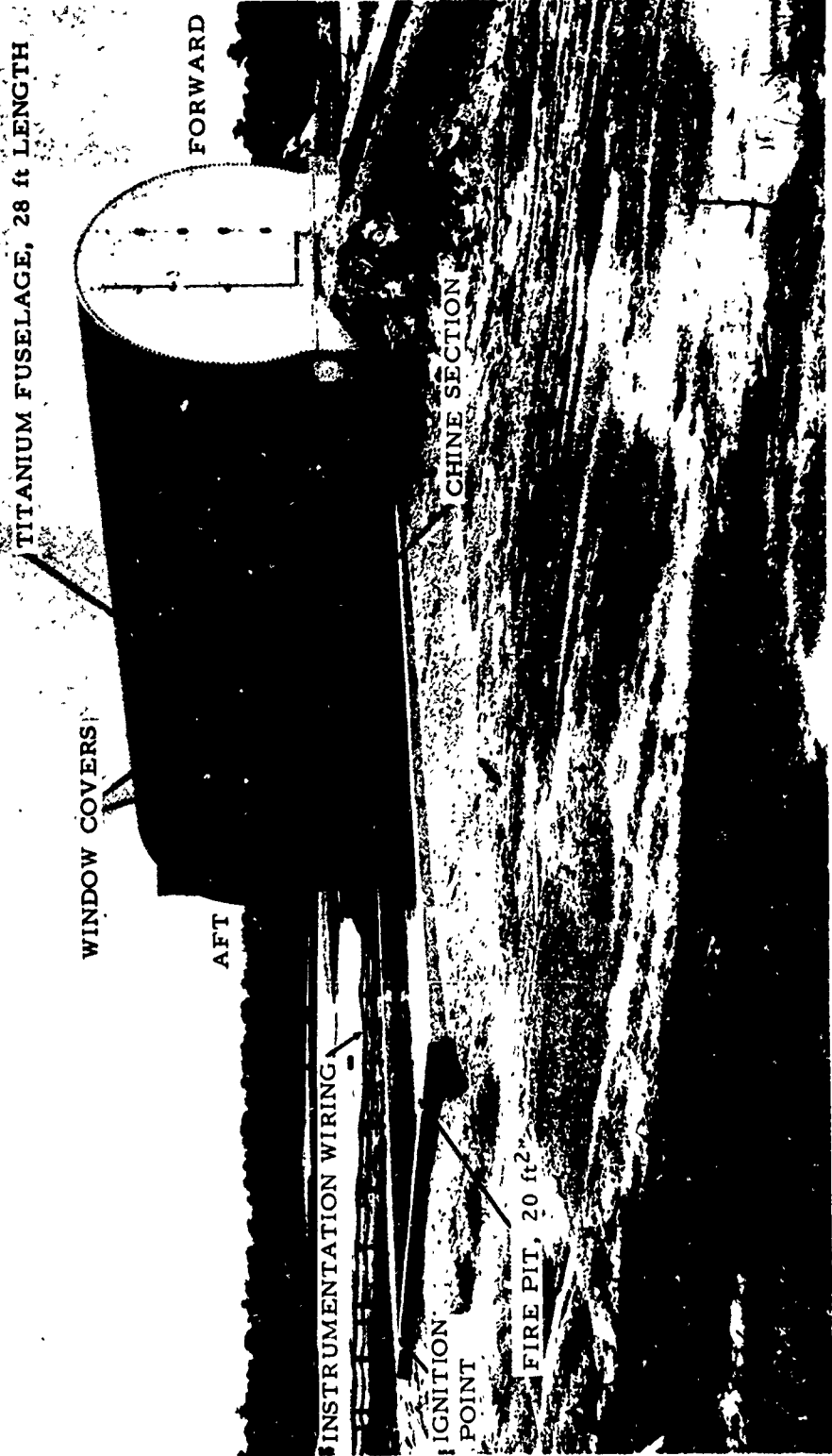


FIGURE 1 - TITANIUM FUSELAGE AND ADJACENT FIRE PIT

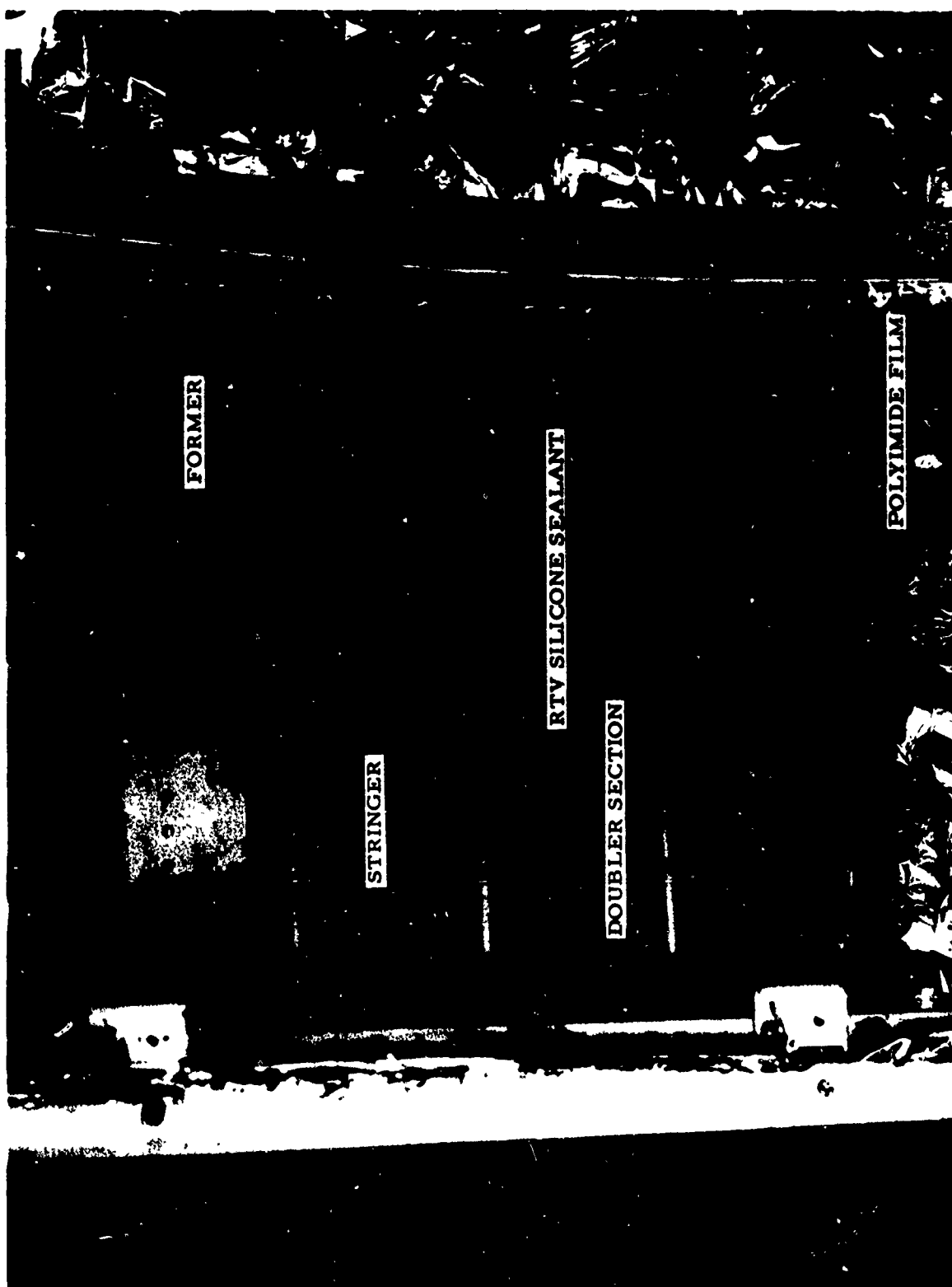


FIGURE 2 - EXTENSIVE USE OF RTV SILICONE AS CABIN
PRESSURE SEALANT

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 fiberglass 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 fiberglass 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 fiberglass 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 fiberglass 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

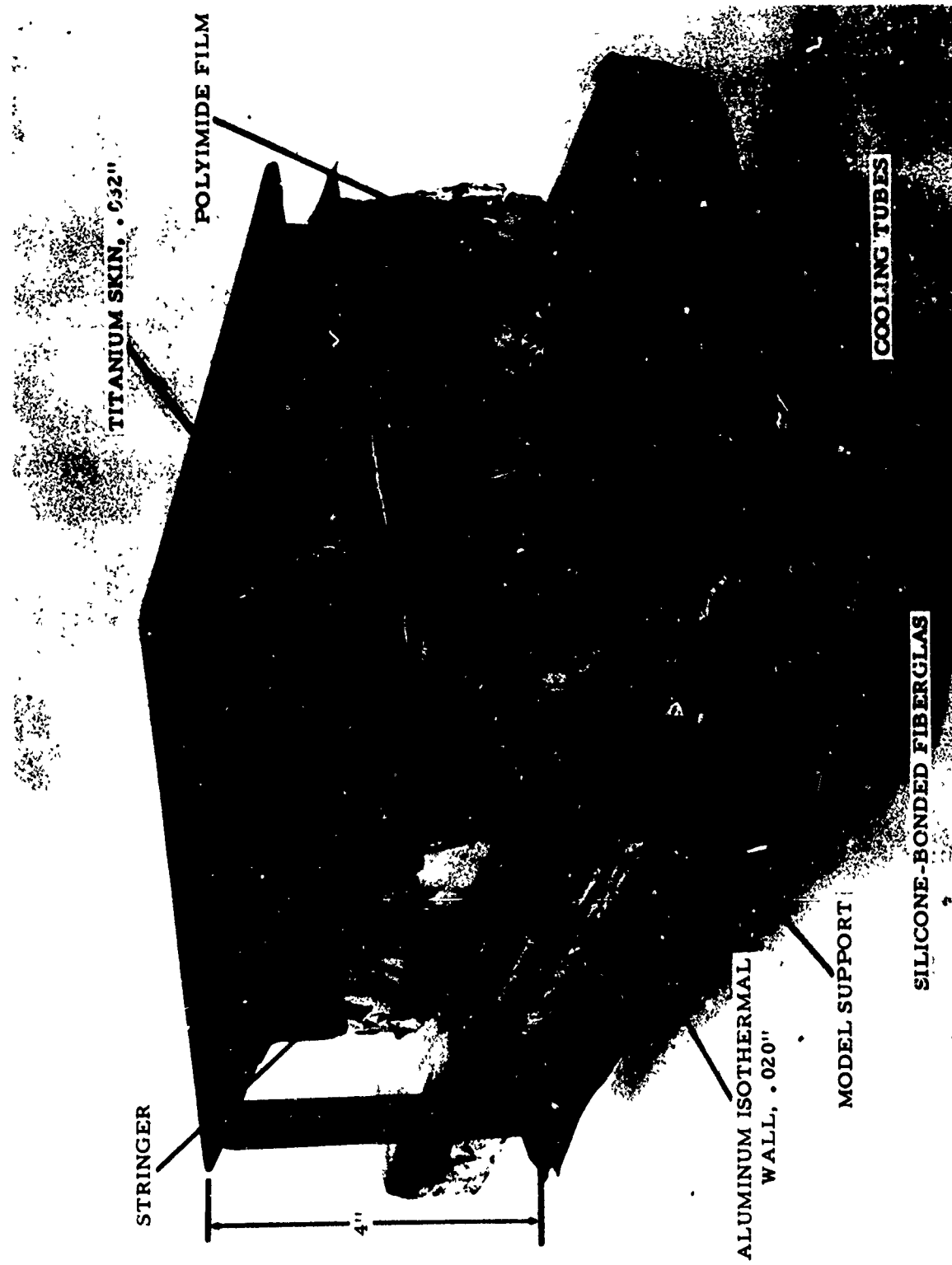


FIGURE 3 - MODEL OF TITANIUM FUSELAGE CROSS SECTION



FIGURE 4 - CABIN FURNISHINGS AND INSTRUMENTATION

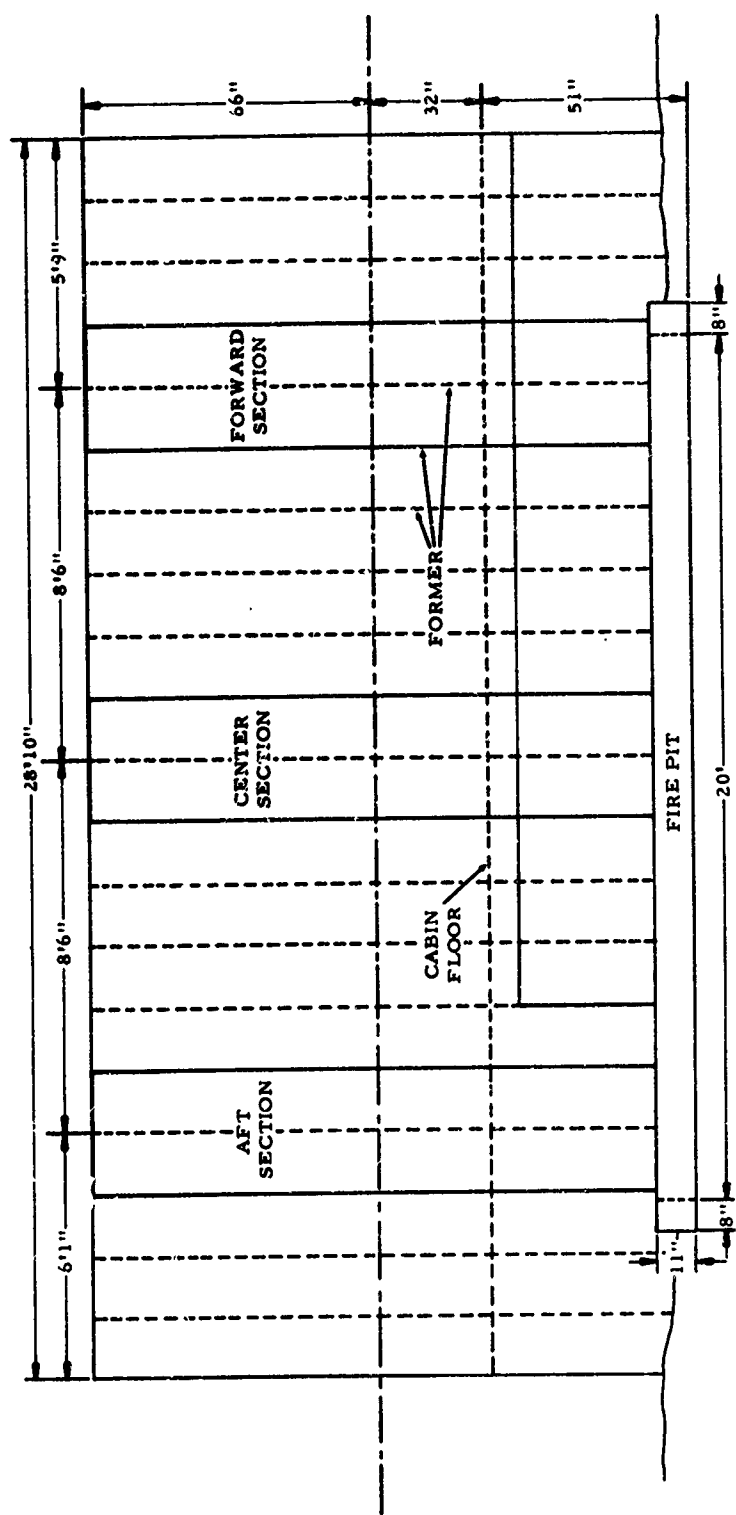
were covered with an aromatic polyamide fabric. It was necessary to face the seats toward the aft end of the fuselage in order to fit them to the curvature of the side wall. The floor was covered with an aromatic polyamide rug.

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 negligible. 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, CO₂, O₂ 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



THERMOCOUPLES AND HEAT FLUX TRANSDUCER.
ALSO SMOKE METER AND GAS SAMPLING FOR
CENTER SECTION

FORMER THERMOCOUPLES

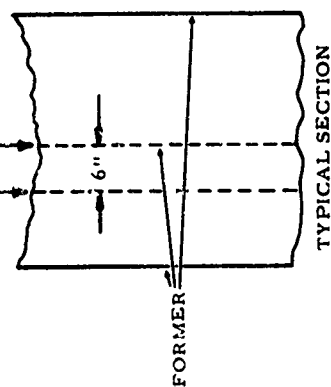


FIGURE 5 - LOCATION OF THREE INSTRUMENTATION SECTIONS

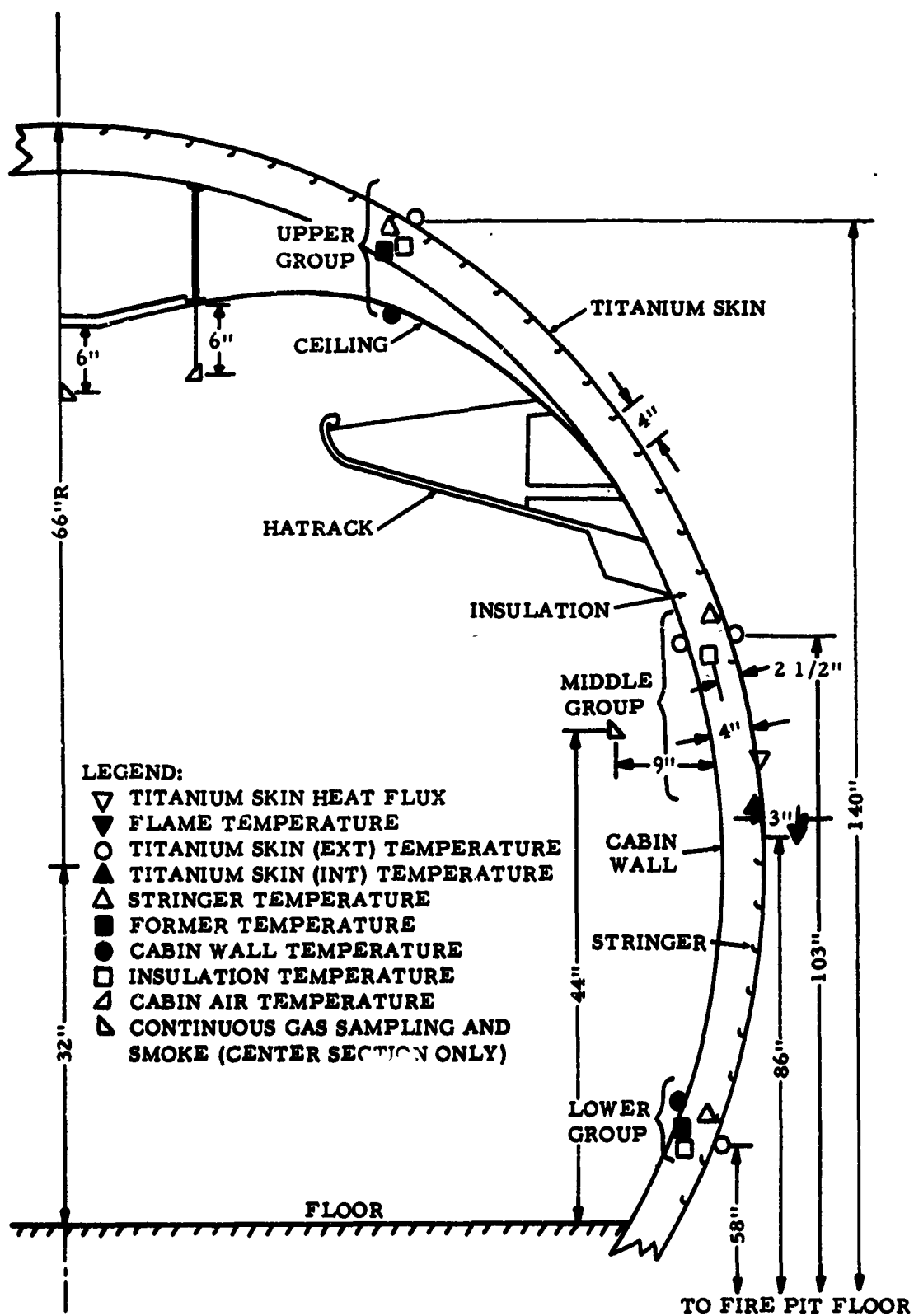


FIGURE 6 - CROSS SECTIONAL VIEW OF A TYPICAL INSTRUMENTATION SECTION SHOWING MEASUREMENT LOCATIONS

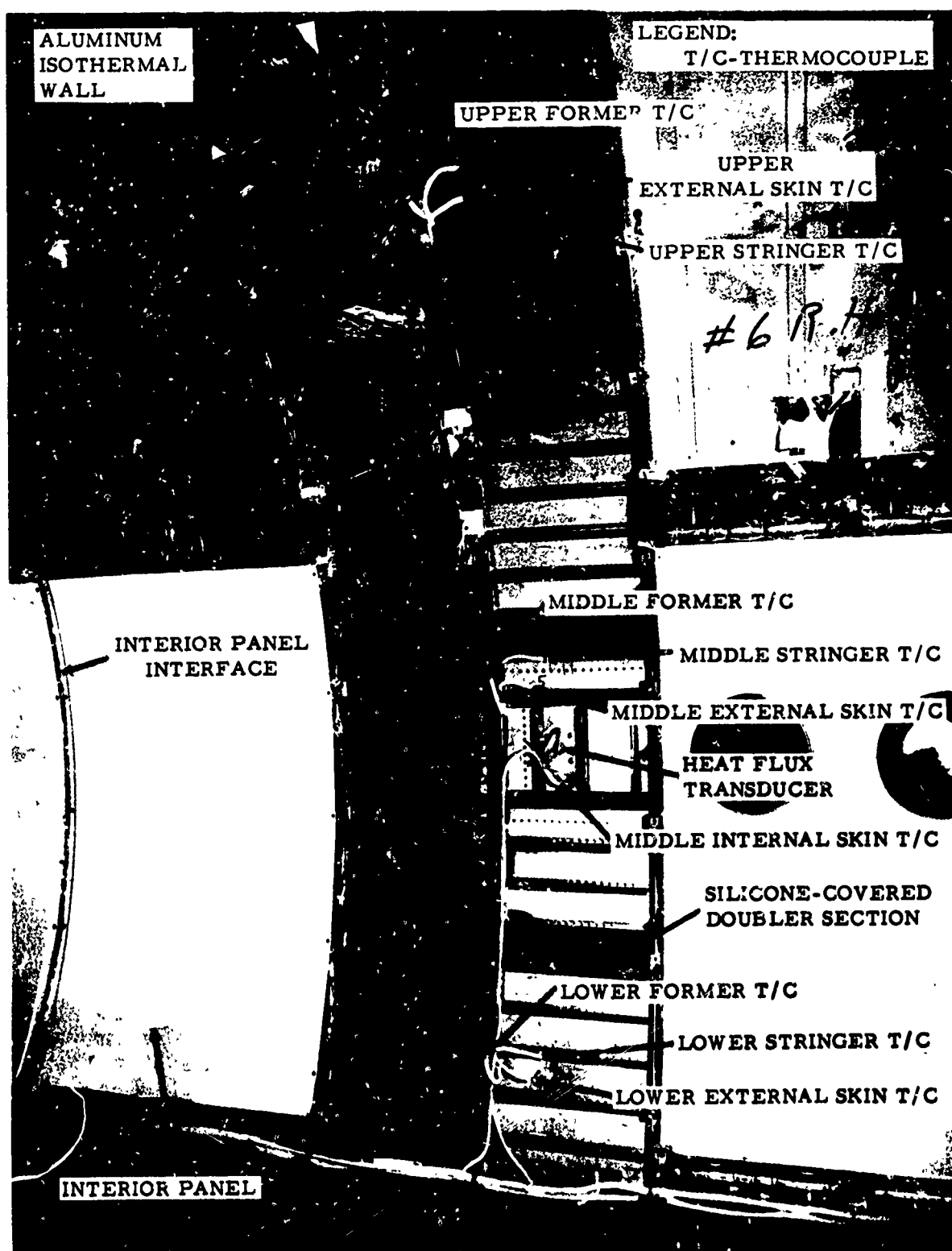


FIGURE 7 - CENTER INSTRUMENTATION SECTION WITH INTERIOR PANEL AND HALF OF INSULATION REMOVED

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 fiberglass 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 CO₂ (range 0-10 percent) analyzers were of the infrared absorption type. The O₂ (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 CO₂. 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 CO₂ for any interior fires

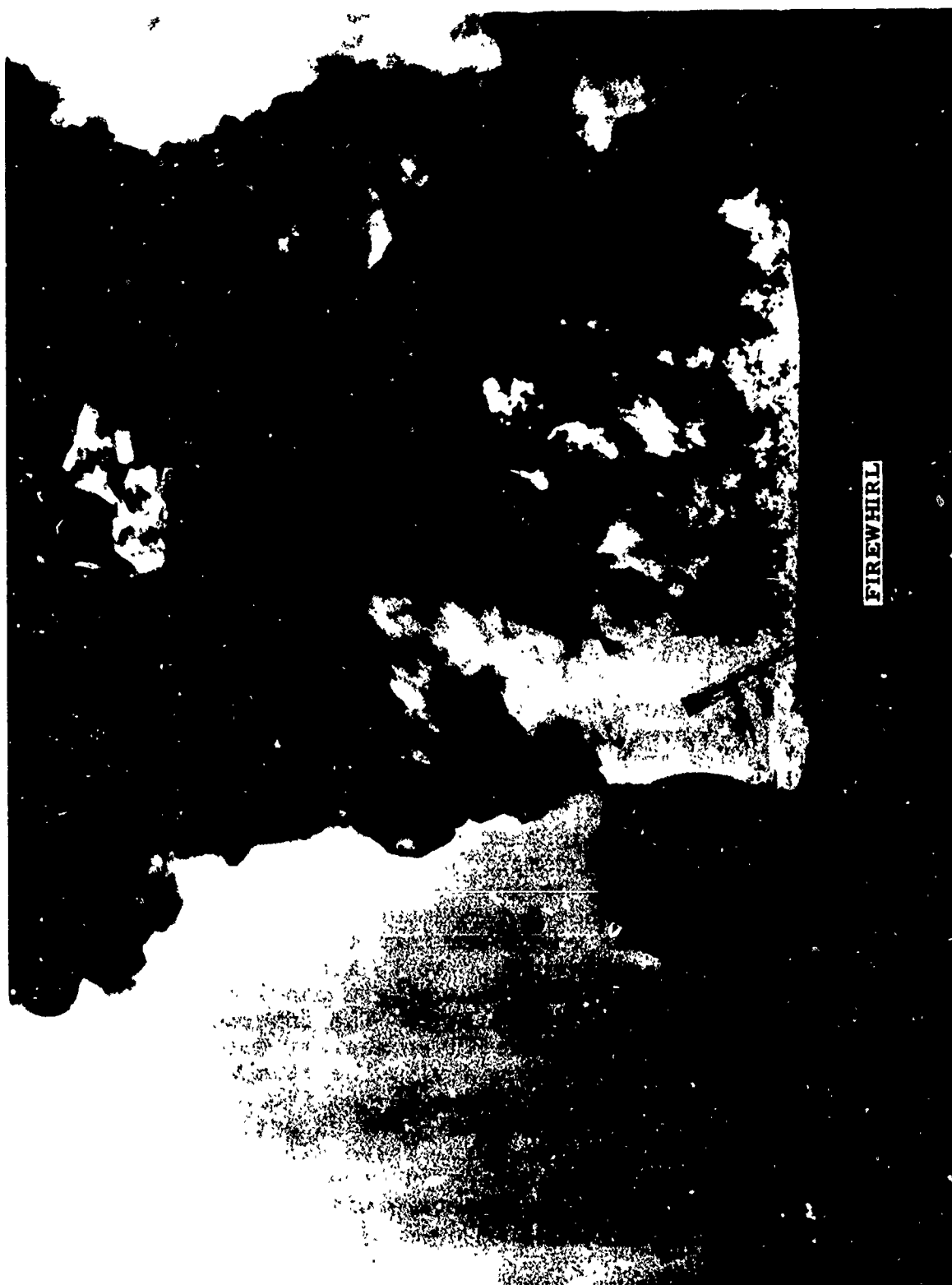


FIGURE 8 - TITANIUM FUSELAGE FIRE TEST AT 45 SECONDS
AFTER IGNITION

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.

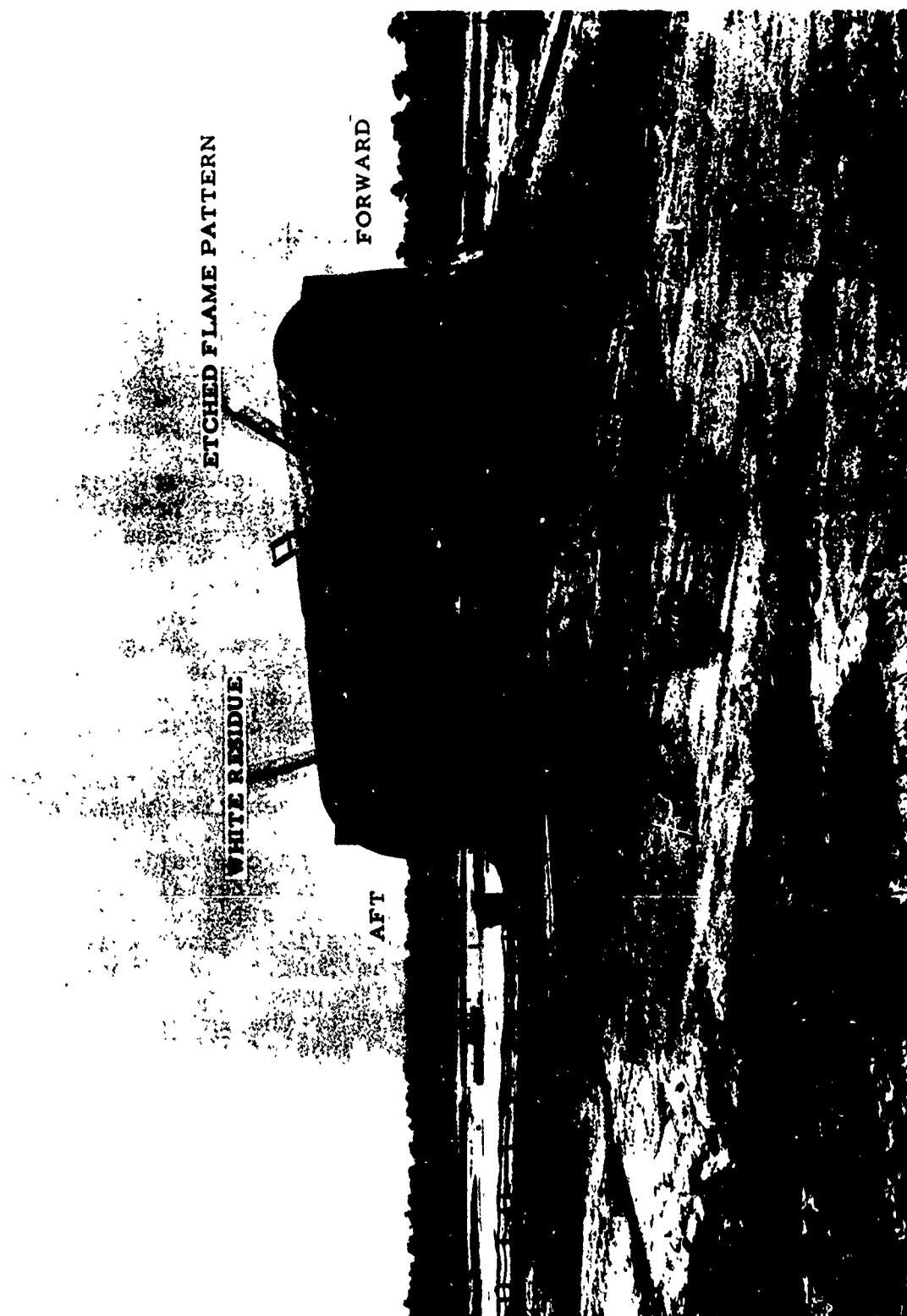


FIGURE 9 - TITANIUM FUSELAGE AFTER FIRE TEST

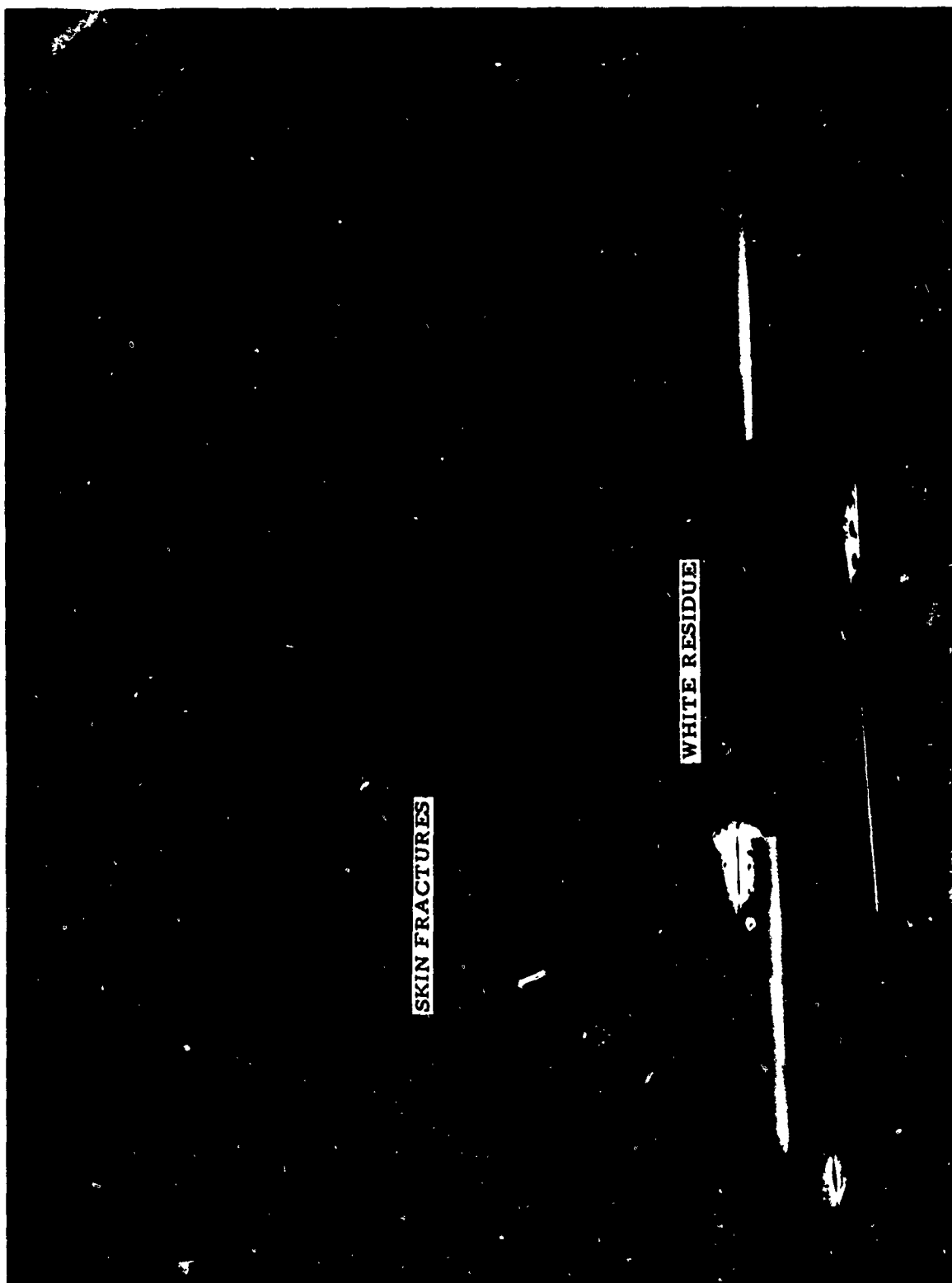


FIGURE 10 - SKIN FRACTURES NEAR LOWER AFT END

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 fiberglass 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

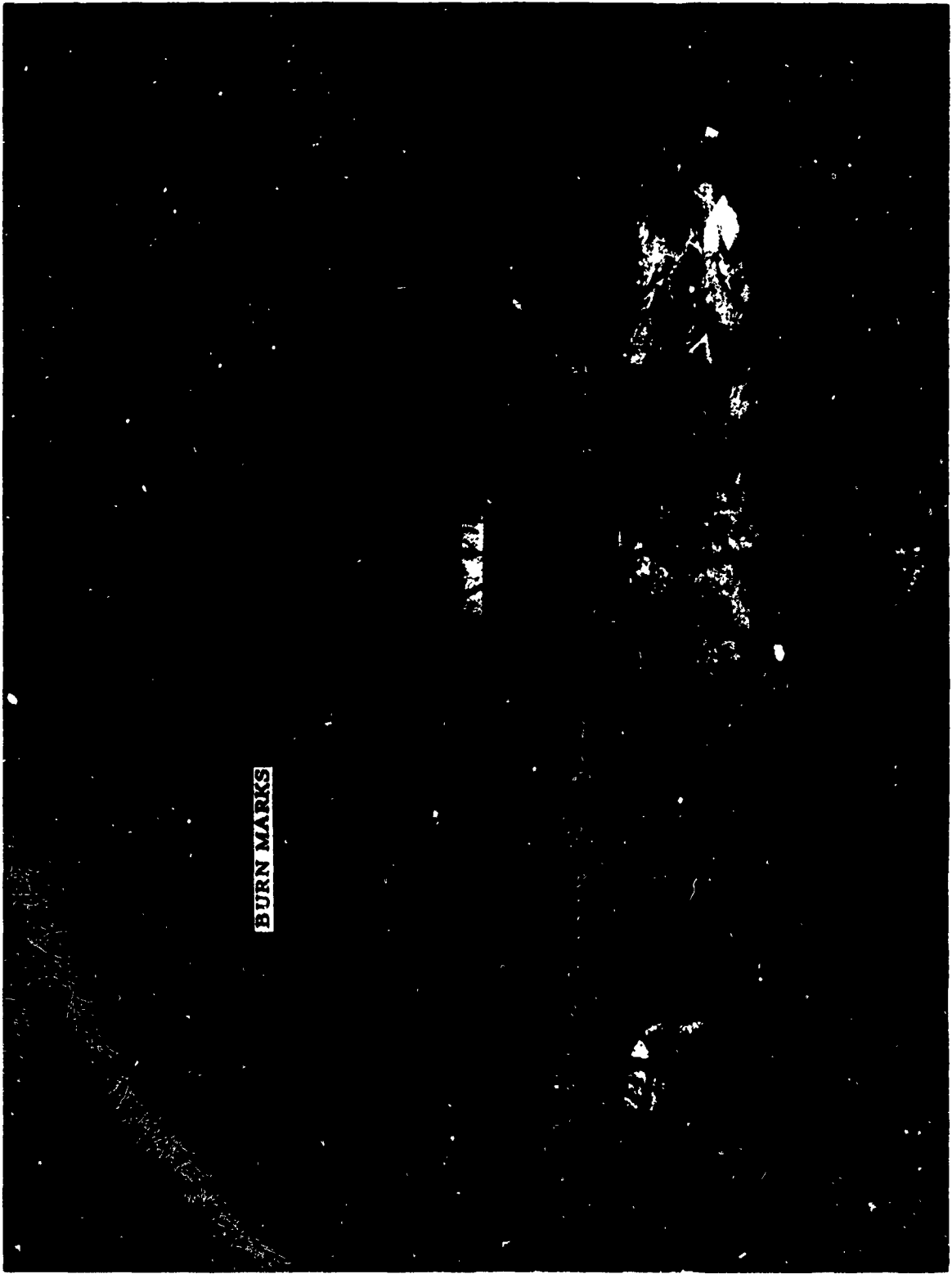


FIGURE 12 - AREA OF FLOOR FIRE



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

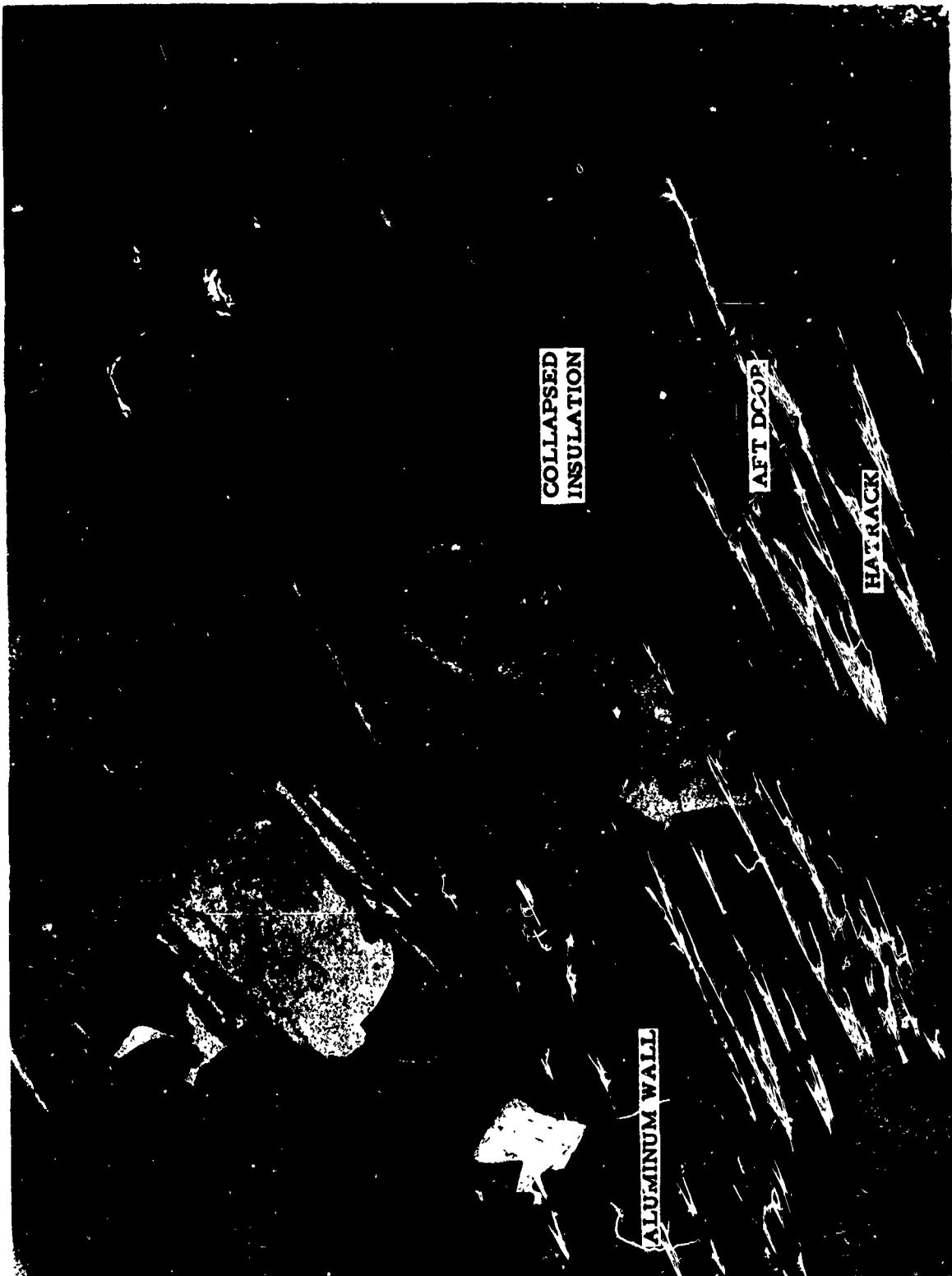


FIGURE 14 - RUPTURED ALUMINUM WALL

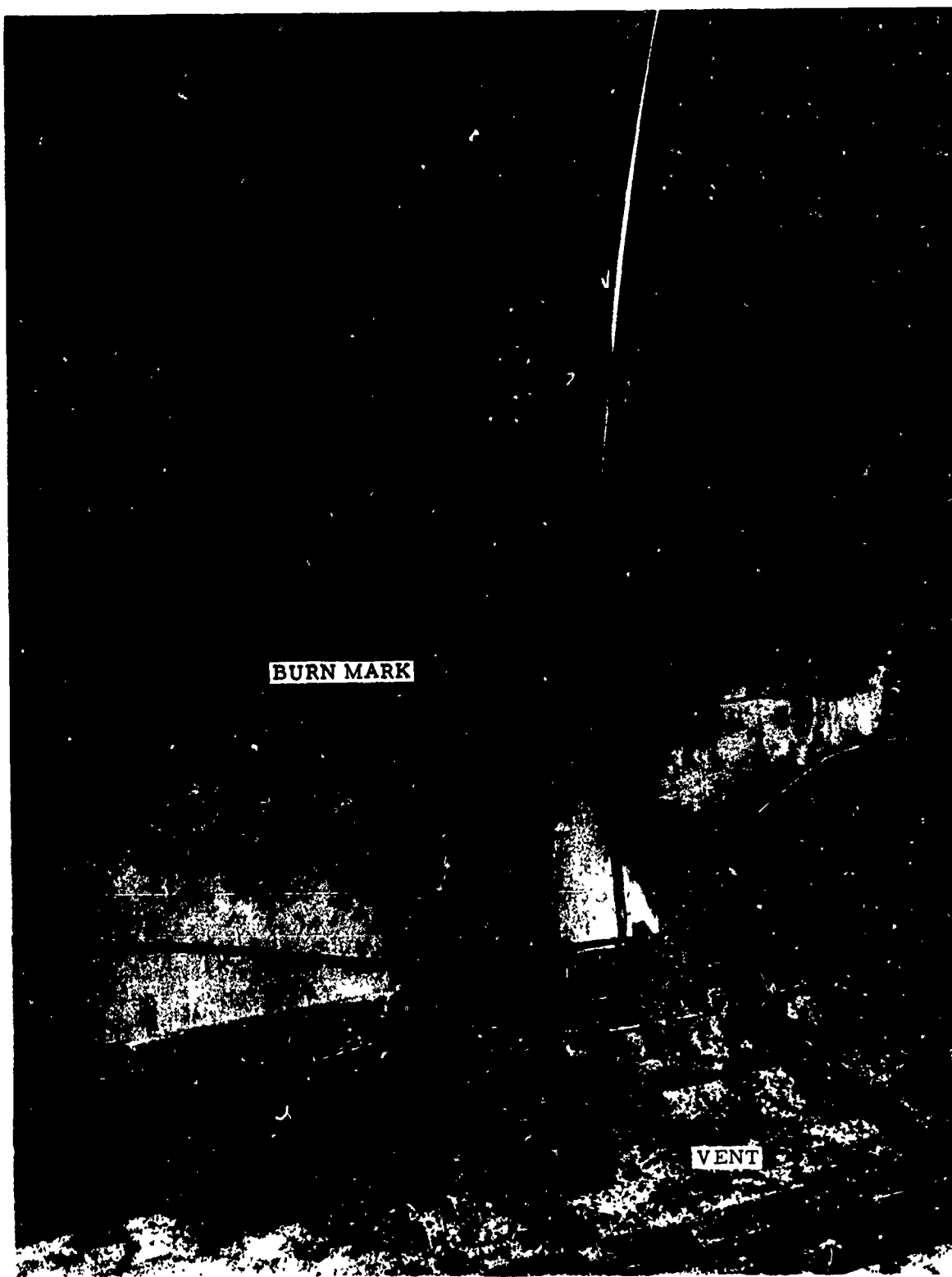


FIGURE 15 - BURNED AREA ABOVE VENT STUFFED WITH
INSULATION

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 fiberglass 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 fiberglass 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 fiberglass (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 severely 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 16 - DAMAGED CABIN NEAR AFT END



FIGURE 17 - BURNED SEALANT AND INSULATION NEAR AFT END



FIGURE 18 - BURNED INSULATION ABOVE DOUBLER SECTION



FIGURE 19 - BURNED INSULATION NEAR INTERIOR PANEL INTERFACES

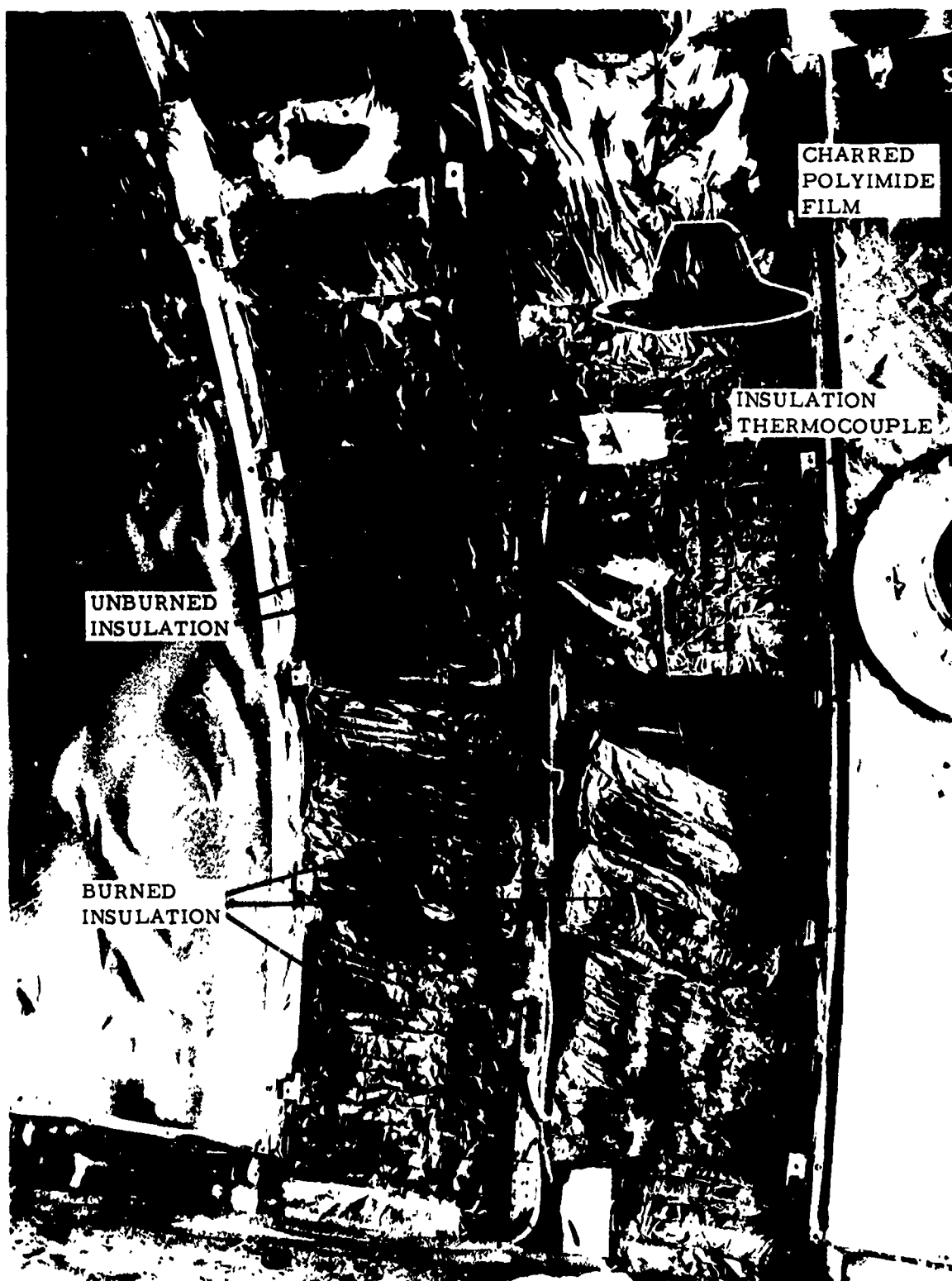


FIGURE 20 - CENTER INSTRUMENTATION SECTION WITH INTERIOR
PANEL REMOVED

revealed that the polyimide film facing the titanium skin was severely charred, while the adjacent fiberglass 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 fiberglass 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 fiberglass 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

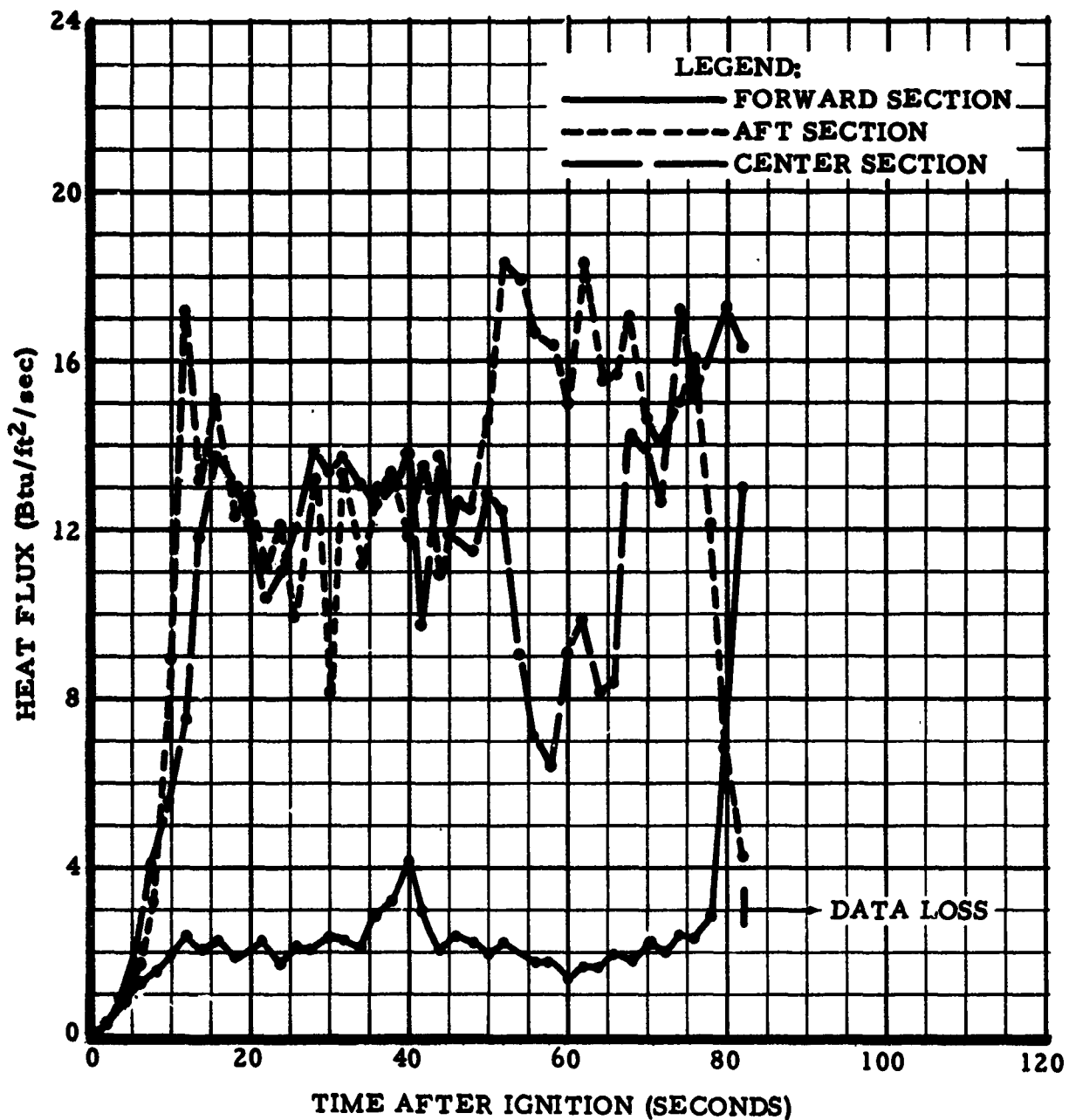


FIGURE 21 - HEAT FLUX UPON TITANIUM FUSELAGE DURING AN EXTERNAL FUEL FIRE

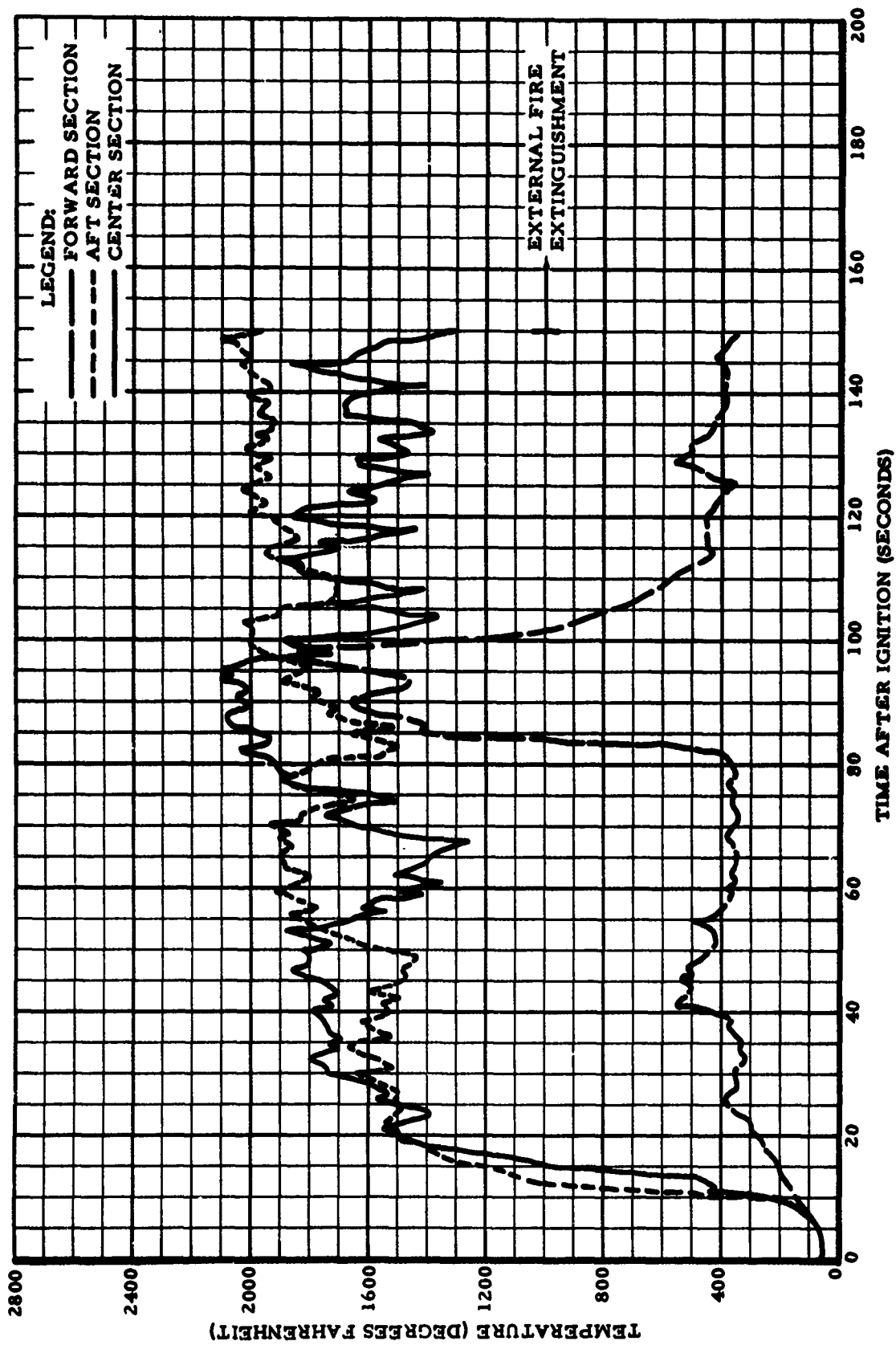


FIGURE 22 - EXTERNAL FUEL FIRE FLAME TEMPERATURE

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.

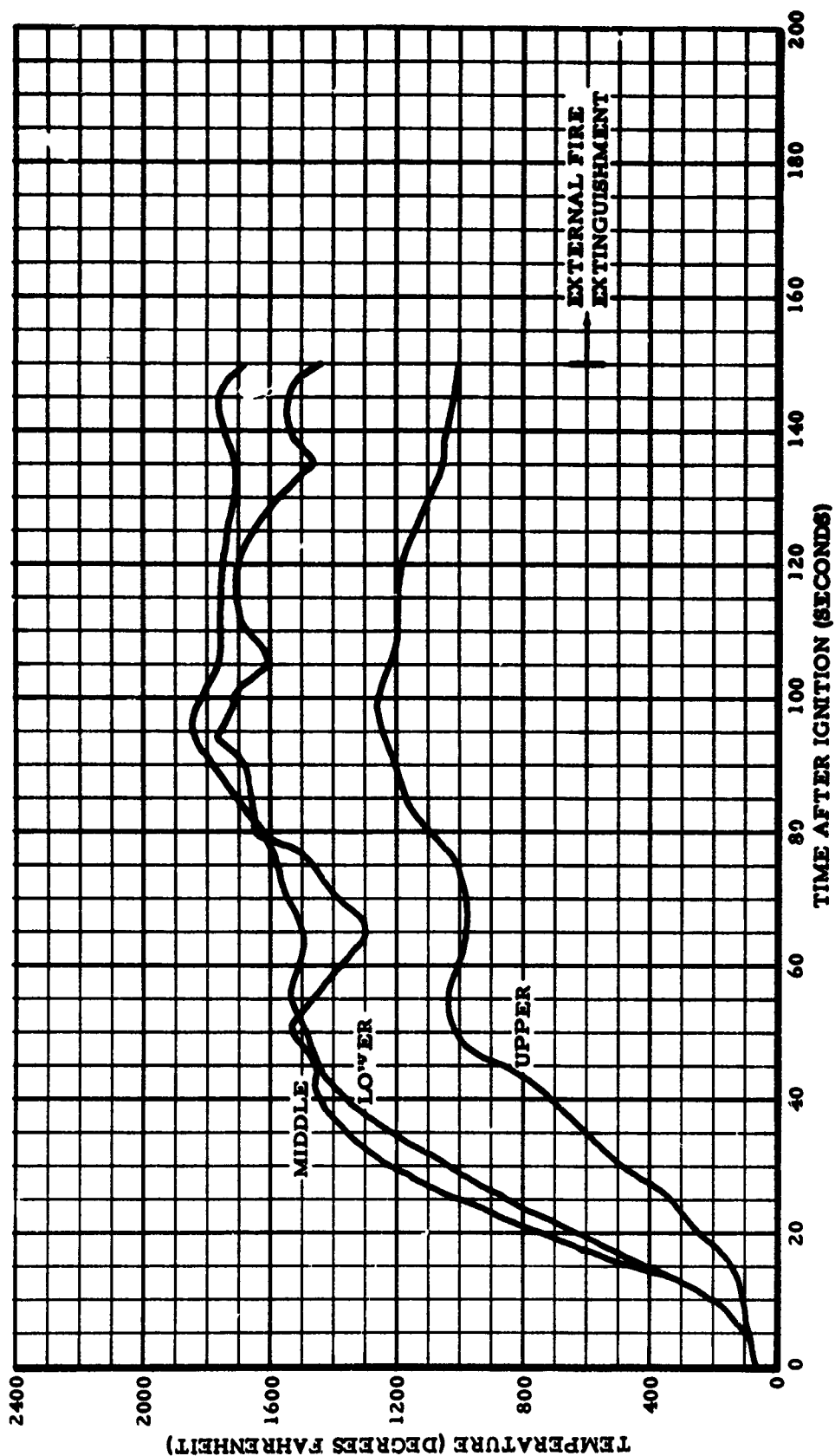


FIGURE 23 - TITANIUM FUSELAGE SKIN TEMPERATURE (CENTER SECTION) DURING AN EXTERNAL FUEL FIRE

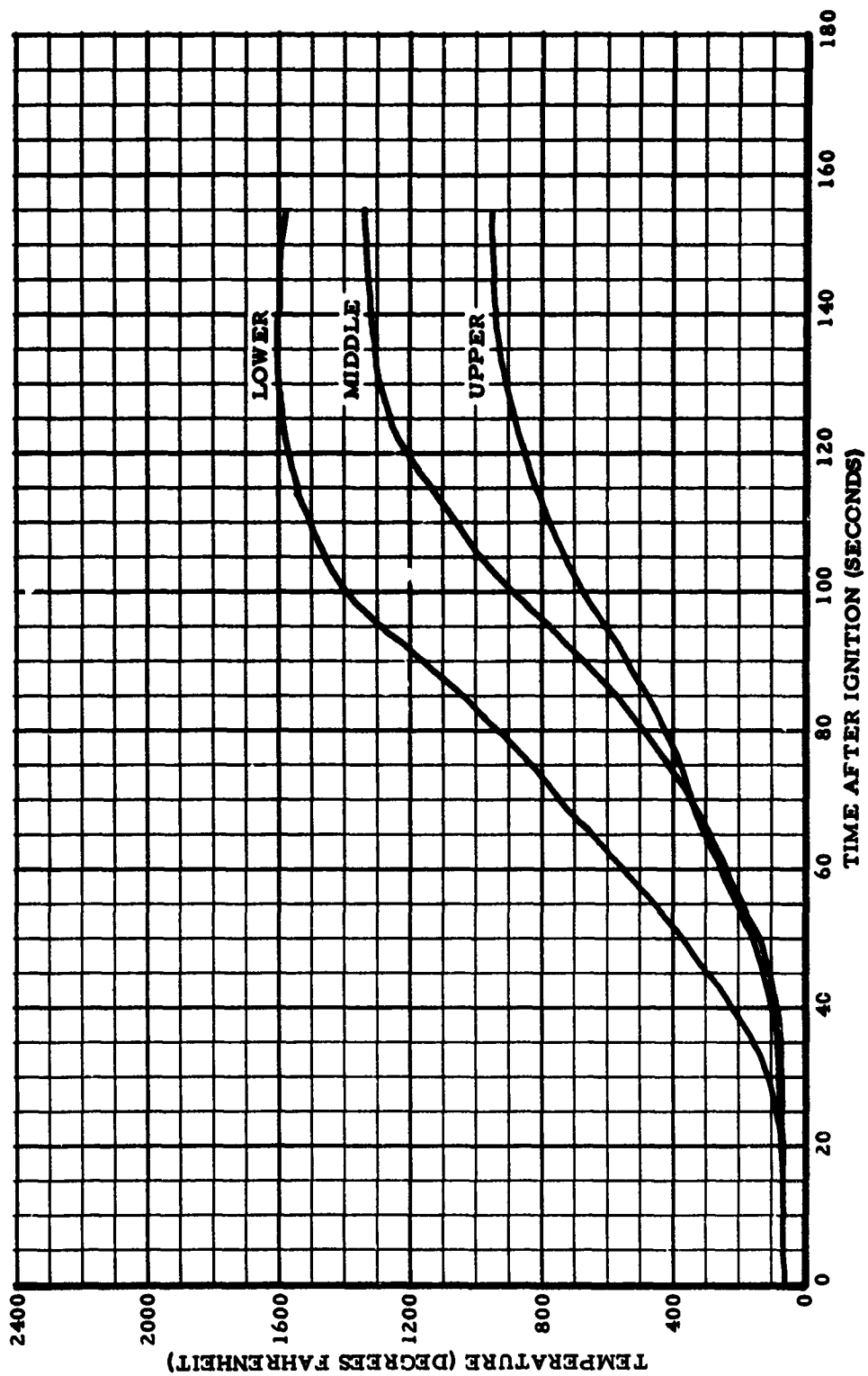


FIGURE 24 - TITANIUM FUSELAGE STRINGER TEMPERATURE (CENTER SECTION) DURING AN EXTERNAL FUEL FIRE

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

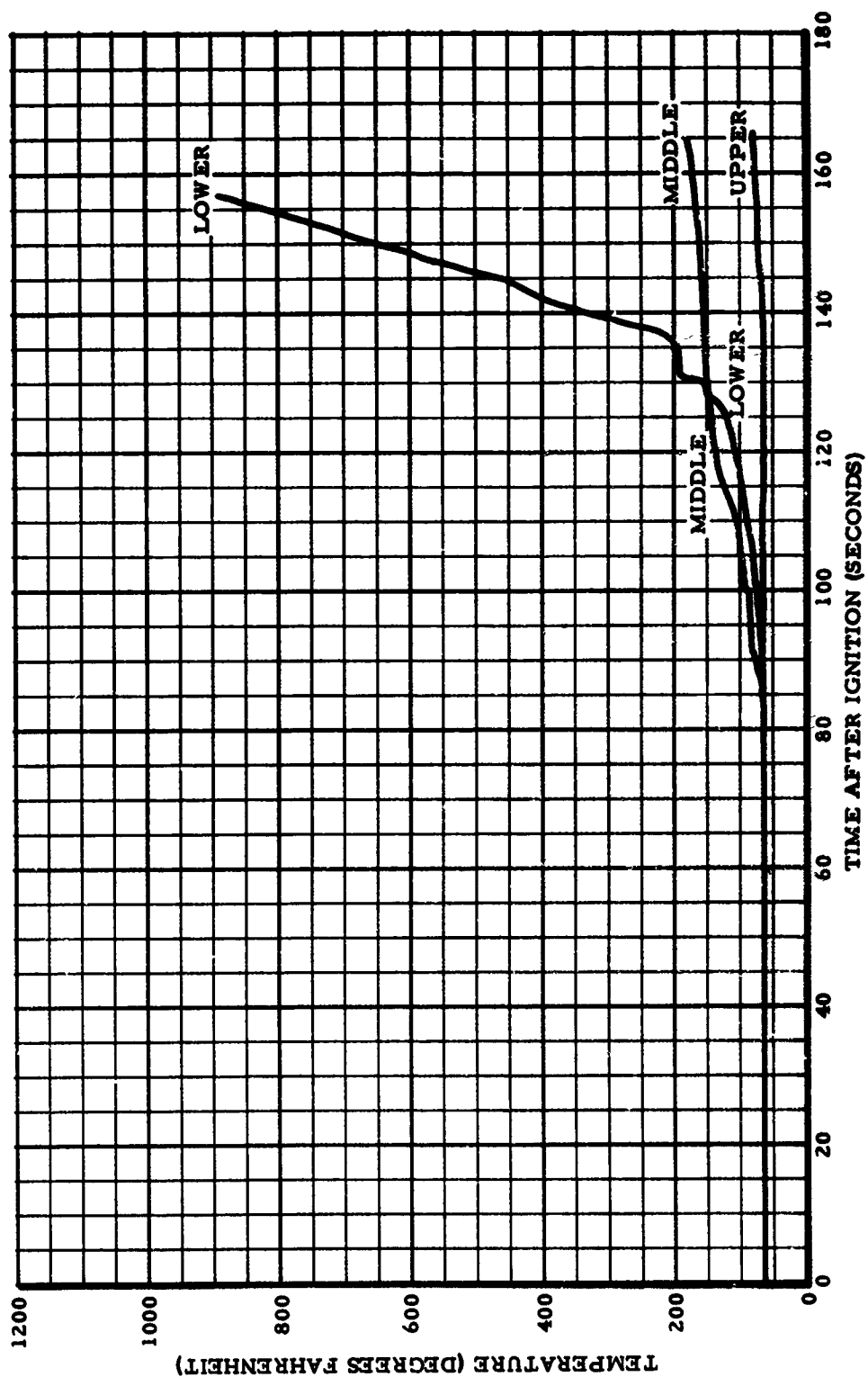


FIGURE 25 - TITANIUM FUSELAGE INSULATION TEMPERATURE (CENTER SECTION) DURING AN EXTERNAL FUEL FIRE

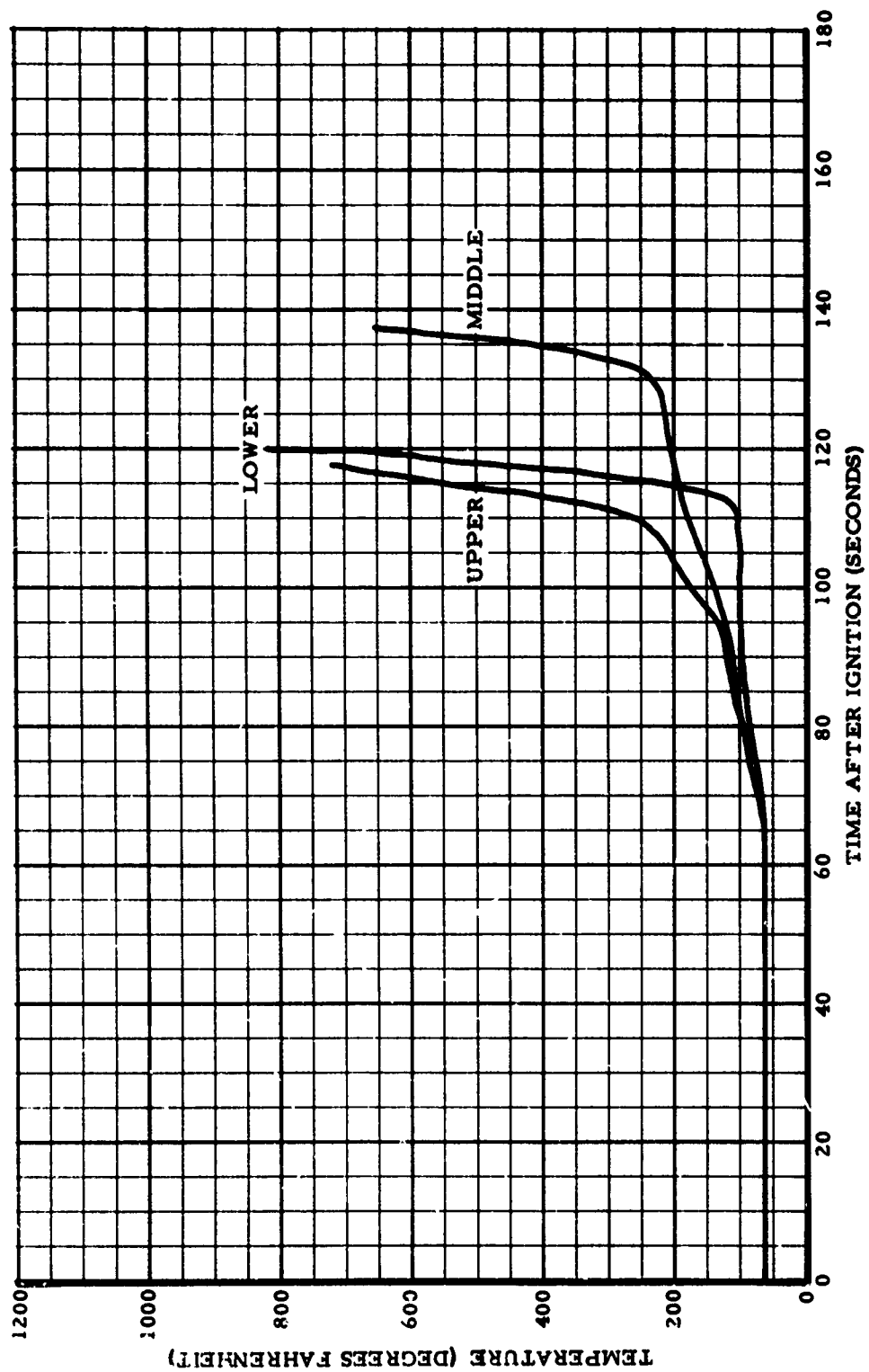


FIGURE 26 - TITANIUM FUSELAGE CABIN WALL TEMPERATURE (CENTER SECTION) DURING AN EXTERNAL FUEL FIRE

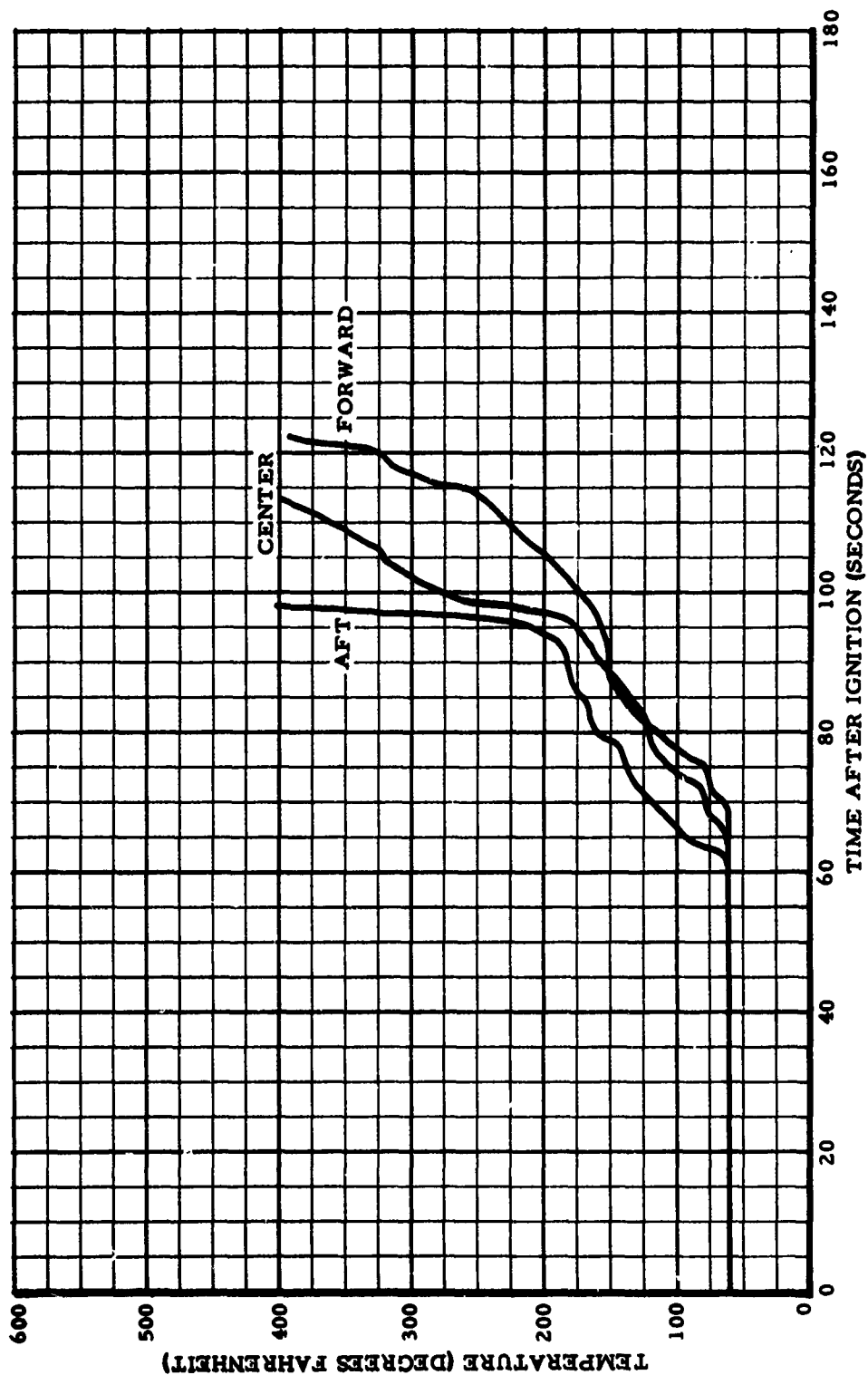


FIGURE 27 - TITANIUM FUSELAGE CABIN AIR TEMPERATURE DURING
AN EXTERNAL FUEL FIRE

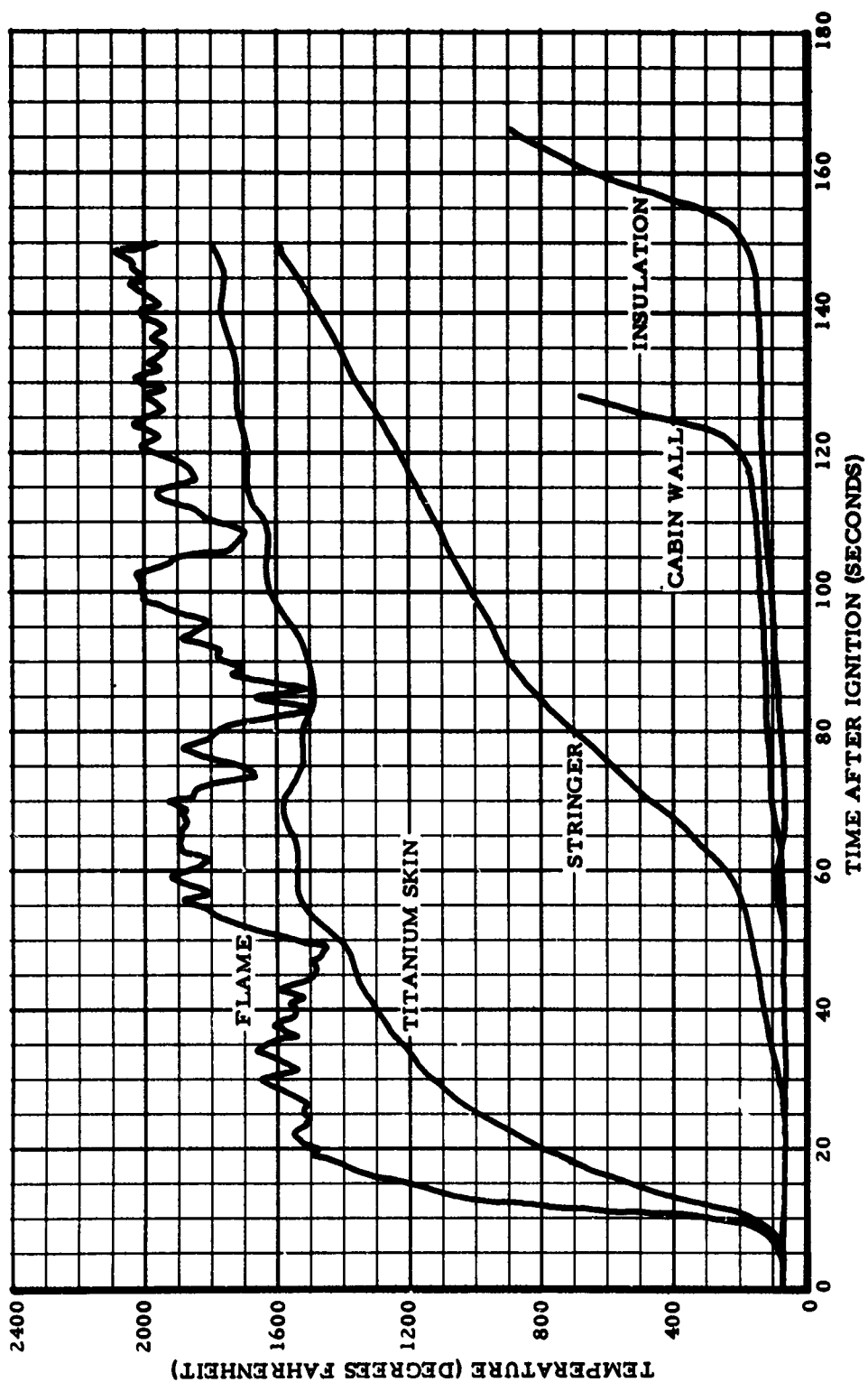


FIGURE 28 - TITANIUM FUSELAGE TEMPERATURE (AFT SECTION, MIDDLE GROUP) DURING AN EXTERNAL FUEL FIRE

skin and stringer were heated by the external fuel fire, with the skin temperature always exceeding the stringer temperature. If the direction of heat transfer was uniformly from the fire to the cabin, it is obvious that the insulation temperature should have exceeded the cabin wall temperature for the duration of the test. Since the cabin wall and insulation temperatures exhibited just the opposite behavior--except for a short time increment about 60 seconds after ignition when the insulation thermocouple was apparently detecting the combustion of RTV silicone sealant--it is clear that heat transfer from the fuel fire did not directly cause the rapid cabin heating. Of course, the fuel fire was indirectly responsible because it heated the RTV silicone sealant and silicone-bonded insulation which decomposed and burned within the cabin environment. Figure 29 shows data from the upper group of thermocouples at the aft section. At this location the heat from the fuel fire was not nearly as severe as that experienced by the middle group of thermocouples. Note that the cabin air and wall temperatures eventually rose above the stringer temperature. Again the important relationship is that, throughout the test, the cabin air temperature exceeded the cabin wall temperature, which exceeded the insulation temperature, thus providing evidence for the deduced mechanism of early cabin heating.

Before this test, considerable speculation was being expressed about the protection that could be provided to the passengers within a titanium fuselage during an external fuel fire. One estimate was that "the cabin will stay room-temperature comfortable for 30 minutes in a roaring fire" (Reference 12). However, this test demonstrated that the cabin pressure sealant and insulation, located adjacent to the titanium skin, were potential sources for the generation of smoke and volatile gases which would produce fatal conditions within the cabin in a matter of a few minutes. Actually, if the sealant and insulation were inert, the degree of protection could be considerable, as is explained below. Figure 30 compares the theoretical titanium skin and insulation temperatures (Appendix A) with the experimental data at the center section, middle group. The predicted skin temperature exceeded the data near the beginning of the test, since it was assumed that the radiative heat flux was at its steady-state value right at ignition; i.e., the fire buildup was not accounted for in the theoretical calculations. The steady-state skin temperature, which was a boundary condition for the calculation of the insulation heating, agreed reasonably well with the data. Therefore, any agreement between theory and data for the insulation temperature could be interpreted as signifying the validity of the calculation procedure. This agreement is amazingly evident in Figure 30, but

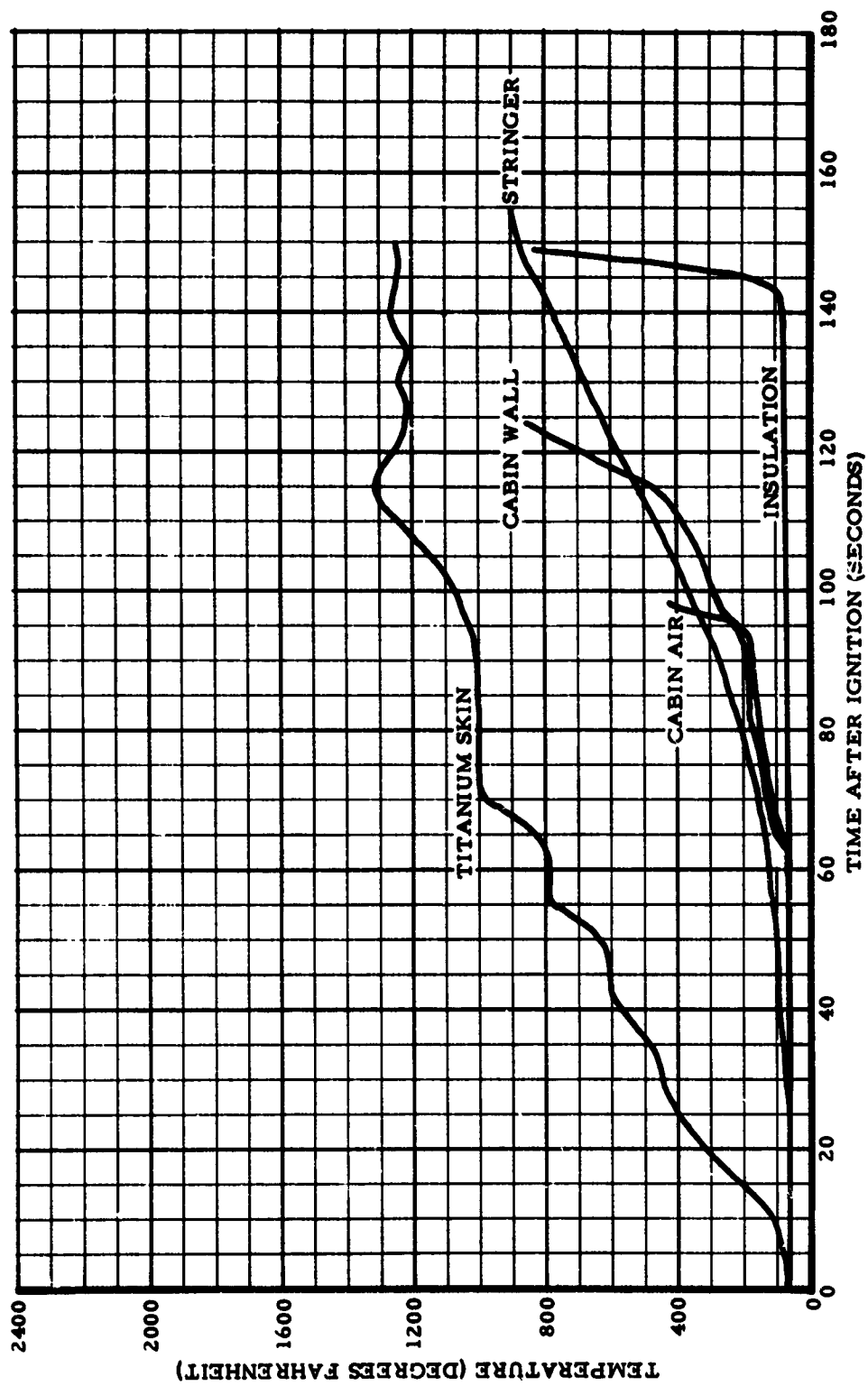


FIGURE 29 - TITANIUM FUSELAGE TEMPERATURE (AFT SECTION, UPPER GROUP) DURING AN EXTERNAL FUEL FIRE

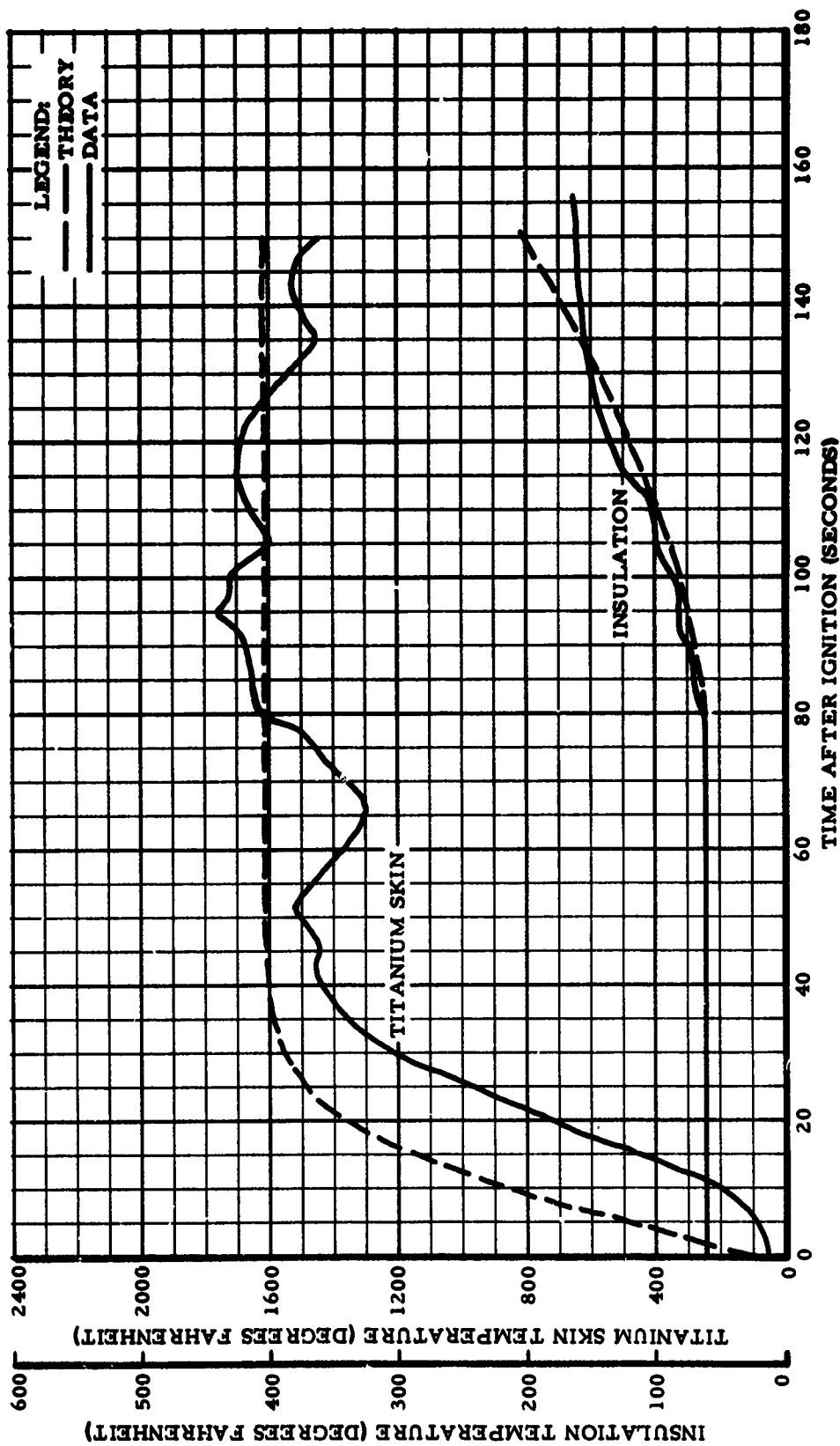


FIGURE 30 - TITANIUM FUSELAGE SKIN AND INSULATION TEMPERATURE DURING AN EXTERNAL FUEL FIRE COMPARED WITH THEORY

is misleading for several reasons. First of all, the insulation thermocouple, as was previously explained, was partially measuring heat from silicone combustion. Secondly, the predicted insulation temperature is conservative (high) since the theoretical model did not consider the heat sink capacity of the structural members, nor the heat transfer from the titanium skin to the reflective polyimide film which encapsulated the insulation. Therefore, the insulation temperature for a titanium fuselage constructed with inert insulation and sealant would be somewhere below either the theoretical or experimental curve shown in Figure 30. The cabin air temperature, assuming the prediction method to be valid, will thus be less than the prediction curve shown in Figure 1-6. It is apparent that a titanium fuselage without windows exposed to a roaring fire could provide a safe cabin environment for a significant time if the sealant and insulation are inert. The exact time can only be established by experiment, but is, at the very least, 5 minutes.

The environmental conditions at the two gas-sampling locations are shown in Figures 31 and 32. Both smoke near the window and carbon dioxide below the ceiling were detected before the cabin air showed any measurable increase in temperature. The density of smoke, as measured by the obscuration of light across a distance of 1 foot, showed the most drastic change, especially below the ceiling. Both smoke meters indicated total obscuration by shortly after 2 minutes. Generally, carbon monoxide and carbon dioxide increased significantly at both sampling locations shortly after 1 minute from ignition, and were accompanied by a decrease in oxygen. From a safety viewpoint, the presence of smoke offered the first obstacle against survivability. It would have been initially manifested by a decrease in visibility accompanied by an undeterminable amount of panic. Severe exposure to smoke also causes physiological effects which, similar to the psychological effects, have yet to be qualitatively or quantitatively defined. After the effects of smoke, a passenger would have next been hampered by the high cabin air temperatures. As indicated by the cabin wall temperature shown in Figure 26, the cabin air surpassed at least 800°F, and, judging by the slope of this curve, probably reached a considerably higher temperature. Tests at NAFEC showed cabin air temperatures reaching 1600°-1700°F during a flash fire (Reference 13). Exposure to temperatures of this level would cause unbearable pain and death in a matter of seconds (Reference 13). The concentrations of carbon monoxide, carbon dioxide and oxygen, each taken individually, would have only produced minor toxic effects (Reference 14) up to the fatality time governed by air temperature (approximately 2 minutes).

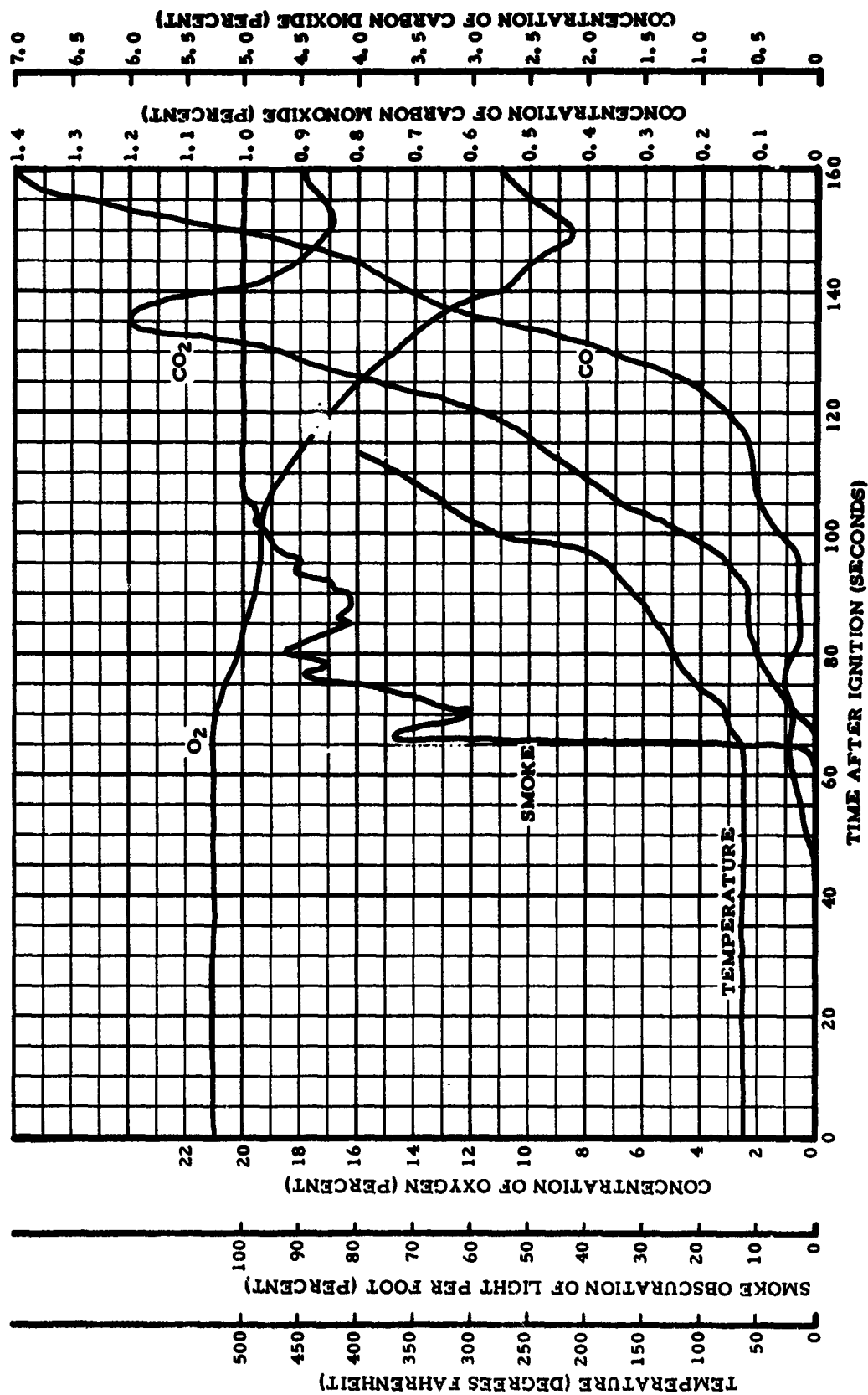


FIGURE 31 - TITANIUM FUSELAGE ENVIRONMENTAL CONDITIONS SIX INCHES BELOW CEILING DURING AN EXTERNAL FUEL FIRE

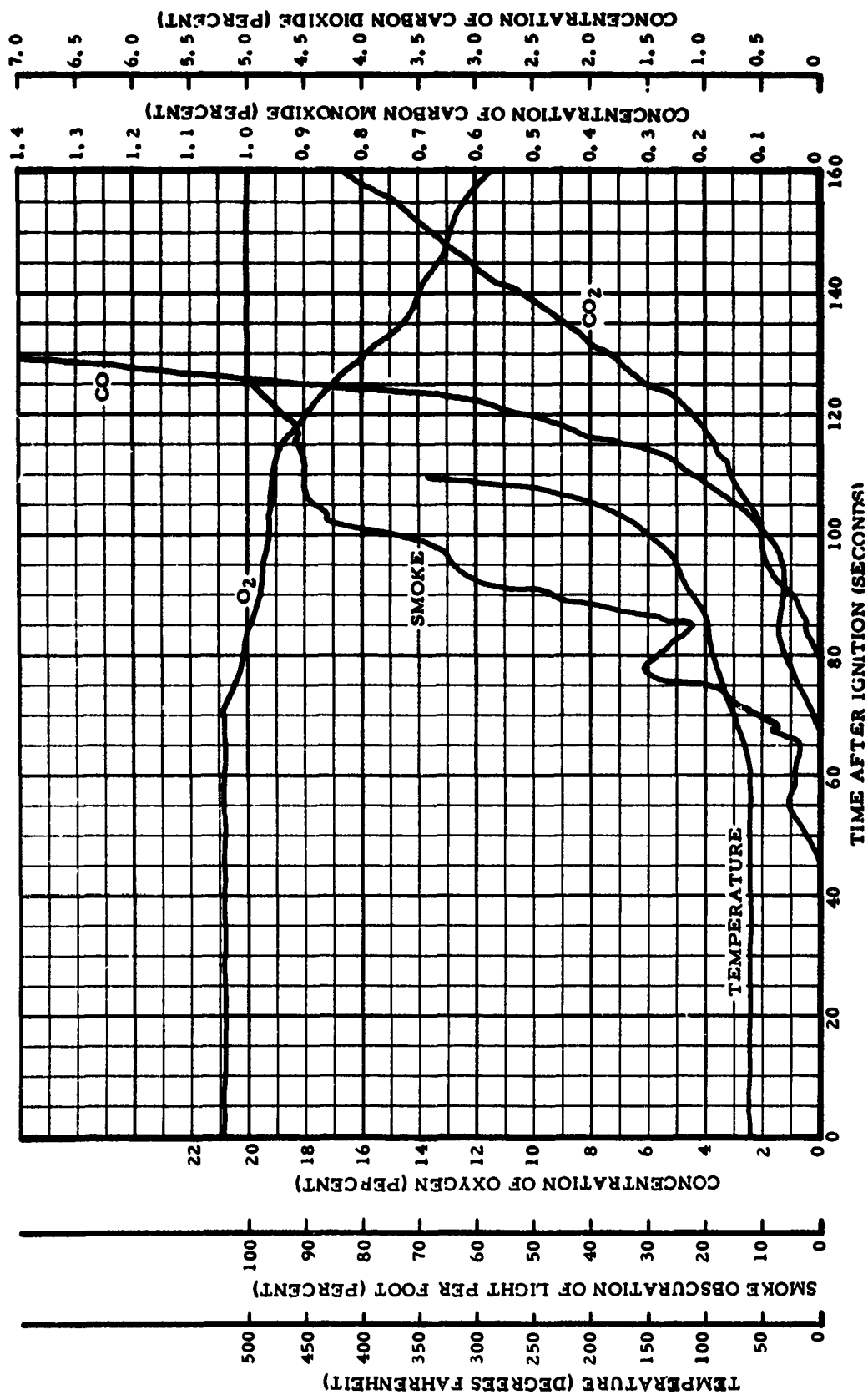


FIGURE 32 - TITANIUM FUSELAGE ENVIRONMENTAL CONDITIONS NEAR WINDOW DURING AN EXTERNAL FUEL FIRE

The gas-sampling bottles were filled at about 5 minutes after ignition. The sample was analyzed mass spectrometrically by the National Bureau of Standards, and the major components present along with approximate mole percentages is shown in the table below.

<u>Component</u>	<u>Mole Percent</u>
H ₂	0.6
H ₂ O	1.0
N ₂	79.8
O ₂	12.9
Ar	1.0
CO ₂	4.6

The concentration of oxygen and carbon dioxide both showed reasonably good agreement with the gas analyzer data. The difficulty in detecting carbon monoxide was due to the large concentrations of nitrogen, and it is conceivable that the measured nitrogen concentration actually consisted of 2-3 percent carbon monoxide. Methane was also detected, but its concentration was less than 0.5 percent and was not measured. Analysis of the gas phase decomposition products of the RTV silicone sealant, when heated in air using gas chromatography, indicated hydrogen, methane and carbon monoxide. Vacuum pyrolysis of silicone resin at 800°C produced more than 90 percent concentration of hydrogen in the gaseous products (Reference 15). The presence of hydrogen, carbon monoxide and methane within the fuselage was further evidence pointing to the RTV silicone sealant and the silicone binder within the insulation as being the primary causes for the early cabin heating and eventual flash fire.

SUMMARY OF RESULTS

1. The titanium skin and structure prevented the flames of a severe external fuel fire from entering directly into the cabin environment for 2 1/2 minutes; i.e., until extinguishment of the fuel fire.

2. Conditions within the cabin remained virtually unchanged until about 1 minute after ignition at which time there occurred significant increases in smoke, temperature, carbon monoxide, carbon dioxide and decreases in oxygen.

3. At about 1 minute 55 seconds after ignition an apparent flash fire occurred, as evidenced by a sudden increase in cabin pressure.

4. A firewhirl formed and persisted near the aft end of the fuselage. The total heat flux from the firewhirl at an aft fuselage location above the fire pit was as much as a factor of 10 greater than the heat flux at a forward location equidistant from the center of the fire pit.

5. A fire broke out from beneath the floor at 27 minutes after ignition and was caused by burning insulation.

6. Damage to the cabin from the flash fire was most severe along the ceiling and hatrack near the aft end (adjacent to the firewhirl). Evidence of localized flaming was observed at interior panel interfaces and above a duct stuffed with insulation.

7. Pressure buildup between the titanium skin and aluminum "isothermal" wall eventually ruptured the aluminum at a location above the hatrack near the aft end of the fuselage.

8. The most severe material decomposition occurred to materials immediately adjacent to the titanium skin; viz, the RTV silicone sealant and the fiberglass insulation. Of these two materials, the sealant was more extensively decomposed.

CONCLUSIONS

Based upon the results of this fire test, theoretical heat transfer calculations and additional experimental studies, it is concluded that:

1. A titanium fuselage will act as a fire barrier and prevent the flames of a severe external fuel fire from entering directly into the cabin environment.

2. During a severe external fuel fire, the cabin pressure sealant and the insulation--because of their proximity to the titanium skin--are potential sources of smoke, toxic gases and combustible gases.

3. A titanium fuselage with room temperature vulcanizing silicone sealant and silicone-bonded fiberglass insulation will provide a safe cabin environment from a severe external fuel fire for approximately 1 minute. Conditions will then become increasingly more hostile and reach fatal levels by 2 minutes at the latest.

4. A titanium fuselage with an inert sealant and insulation will provide a predicted safe cabin environment from a severe external fuel fire for at least 5 minutes (assuming that the entire fuselage, including the windows, continues to prevent flame penetration into the cabin).

APPENDIX A

THEORETICAL CALCULATIONS

The process of heat transfer to the titanium fuselage is complicated by many factors. The behavior of the turbulent, diffusive, fuel fire is the most difficult to understand or predict. Consequently, no mathematical model exists for exactly describing the flame temperature (Reference 16). Moreover, the flame geometry, intermittently covering portions of the fuselage, is also beyond mathematical description. This is true for the case of an object adjacent to the fire. The effect of wind on the geometry of fuel fires has been empirically formulated in Reference 17.

Heat is transferred from the fire to the fuselage by radiation and convection, with radiation typically accounting for 90 percent of the total for the condition of negligible wind velocity (Reference 18). As the temperature of the titanium skin rises, heat is transferred through the insulation by all three modes: conduction, convection, and radiation (Reference 10). The temperature rise of the skin itself is affected by the heat capacity of the stringers and formers. Eventually, the interior cabin wall adjacent to the fire will begin to get hot, but will initially not affect the cabin air temperature. However, significant natural convective heating of the cabin air will eventually occur and may result in a fairly uniform cabin temperature if the heating is gradual. The entire heat transfer problem is further complicated by the variation of material thermal properties with temperature.

Every segment of the composite extending from the titanium skin to the cabin wall is coupled to the segment on either side of it. A mathematical solution to this heat transfer problem thus requires solving coupled, non-linear, partial differential equations: an effort beyond the scope of this project. Instead, the problem has been reduced to solving, independently, the heating of three segments: the titanium skin, insulation, and interior cabin air.

The heating of the titanium skin was calculated with the analysis reported by Geyer (Reference 2). In this model, the heat gain was assumed to be by radiation and convection, and the heat loss by radiation, convection, and conduction (Figure 1-1). Assuming a uniform skin temperature, the following equation may be written (see Table 1-1 for definition of symbols):

$$\rho c x \frac{dT}{dt} = \alpha q_r + h(T_f - T) - \epsilon \sigma T^4 - \frac{k}{z} (T - T_o) \quad (1)$$

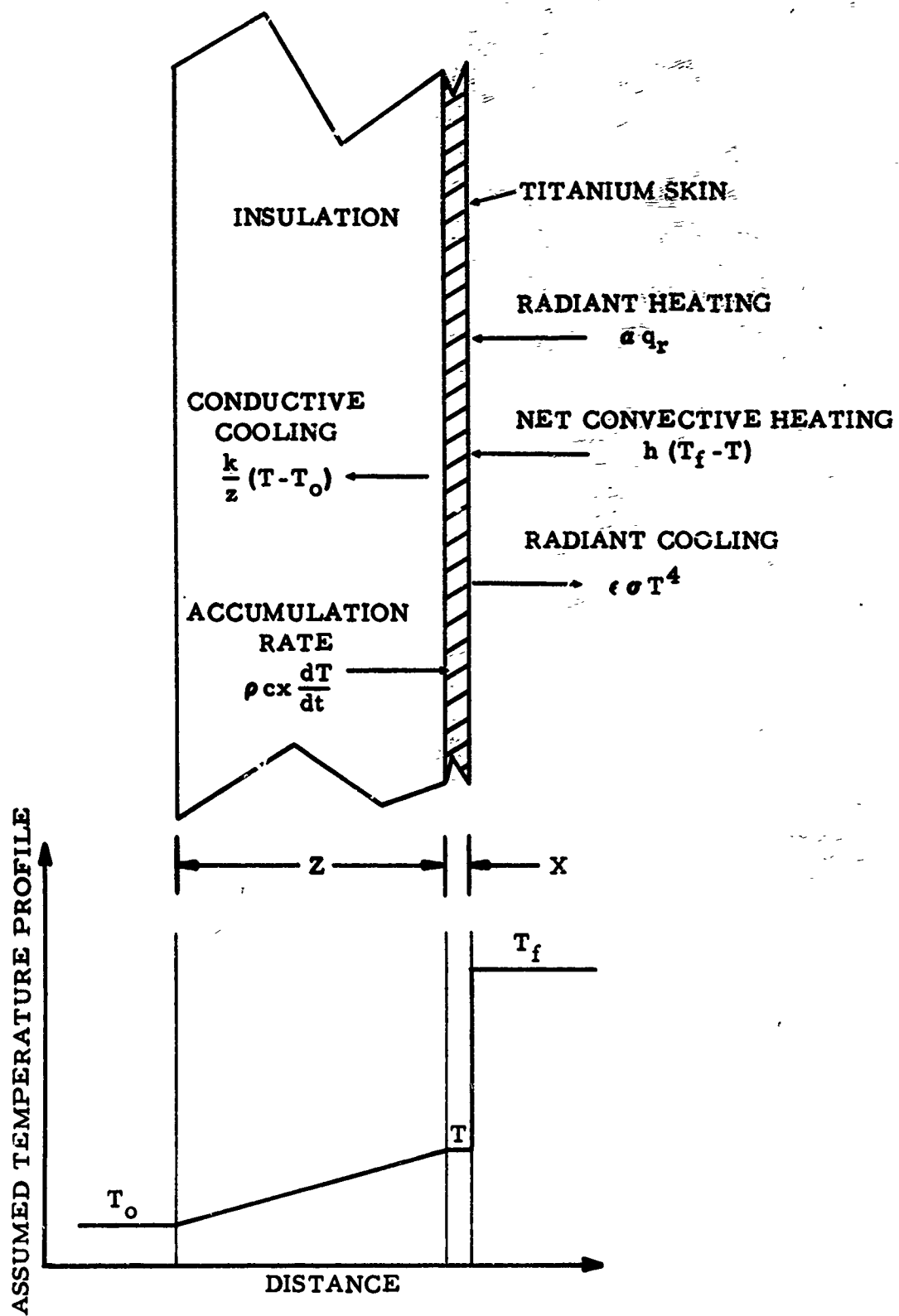


FIGURE 1-1 - SIMPLIFIED MODEL OF TITANIUM SKIN HEATING

TABLE 1-1. - DEFINITIONS AND VALUES OF SYMBOLS USED IN TITANIUM
SKIN HEATING CALCULATIONS

SYMBOL	DEFINITION	VALUE	REF
ρ	Density of titanium	278 lb/cu ft	7
c	Specific heat of titanium	0.17 Btu/lb-°F @ 1000°F	7
x	Thickness of titanium	0.032 inch	-
T	Titanium temperature	Variable	-
t	Time	Variable	-
α	Absorptivity of titanium	1.0	2
q_r	Radiant heat output of fire	31,000 Btu/sq ft-hr	2
h	Heat transfer coefficient	5.0 Btu/sq ft-hr-°F	2
T_f	Flame temperature	2000°F	2
ϵ	Emissivity of titanium	1.0	2
σ	Stefan-Boltzmann constant	0.1712×10^{-8} Btu/hr-sq ft-°R ⁴	-
k	Thermal conductivity of insulation	2.0 Btu-in/sq ft-hr-°F @ 1000°F	11
z	Thickness of insulation	4.0 inches	-
T_o	Ambient temperature	70°F (assumed)	-

Equation 1 relates the rate of temperature buildup to the net heat gained by the titanium skin. Since the variables are separable this equation may be integrated to give

$$\int_{T_0}^T \frac{dT}{A+BT+CT^4} = \int_0^t dt = t \quad (2)$$

where

$$A = \frac{\alpha q_r + hT_f + \frac{k}{z} T_0}{\rho c x} \quad B = - \left[\frac{h + \frac{k}{z}}{\rho c x} \right] \quad C = - \frac{\epsilon \sigma}{\rho c x}$$

Equation 2 was integrated graphically using the data listed in Table 1-1. Notice that the flame properties are assumed to be constant even though fluctuations occur because of flame turbulence and wind. The steady-state (maximum) temperature was calculated from Equation 1 with $\frac{dT}{dt} = 0$.

The results of these calculations for predicting the titanium skin temperature as a function of time are shown in Figure 1-2. The temperature is seen to rise very rapidly and reach 99 percent of the steady-state value of 1620°F in about 40 seconds. This temperature behavior lies slightly above Welker's prediction for a stainless steel skin of similar thickness (see below).

Since the conduction heat loss term in Equation 1 is negligible compared with the other terms, the temperature history will vary directly with the flame properties, surface emissivity and absorptivity, and inversely with $\rho c x$. Thus, two materials of equal thickness and surface emissivity and absorptivity will have a temperature history that only varies inversely as $\rho c x$ at a given point in time. For these conditions aluminum will become heated faster than titanium which will become heated faster than stainless steel. However, the steady-state temperature will be equal for these materials (and the above conditions) since it is independent of ρc .

The unsteady heat conduction equation was applied to predict the heating of the insulation. The solution to this equation was obtained by applying the Schmidt-Binder numerical

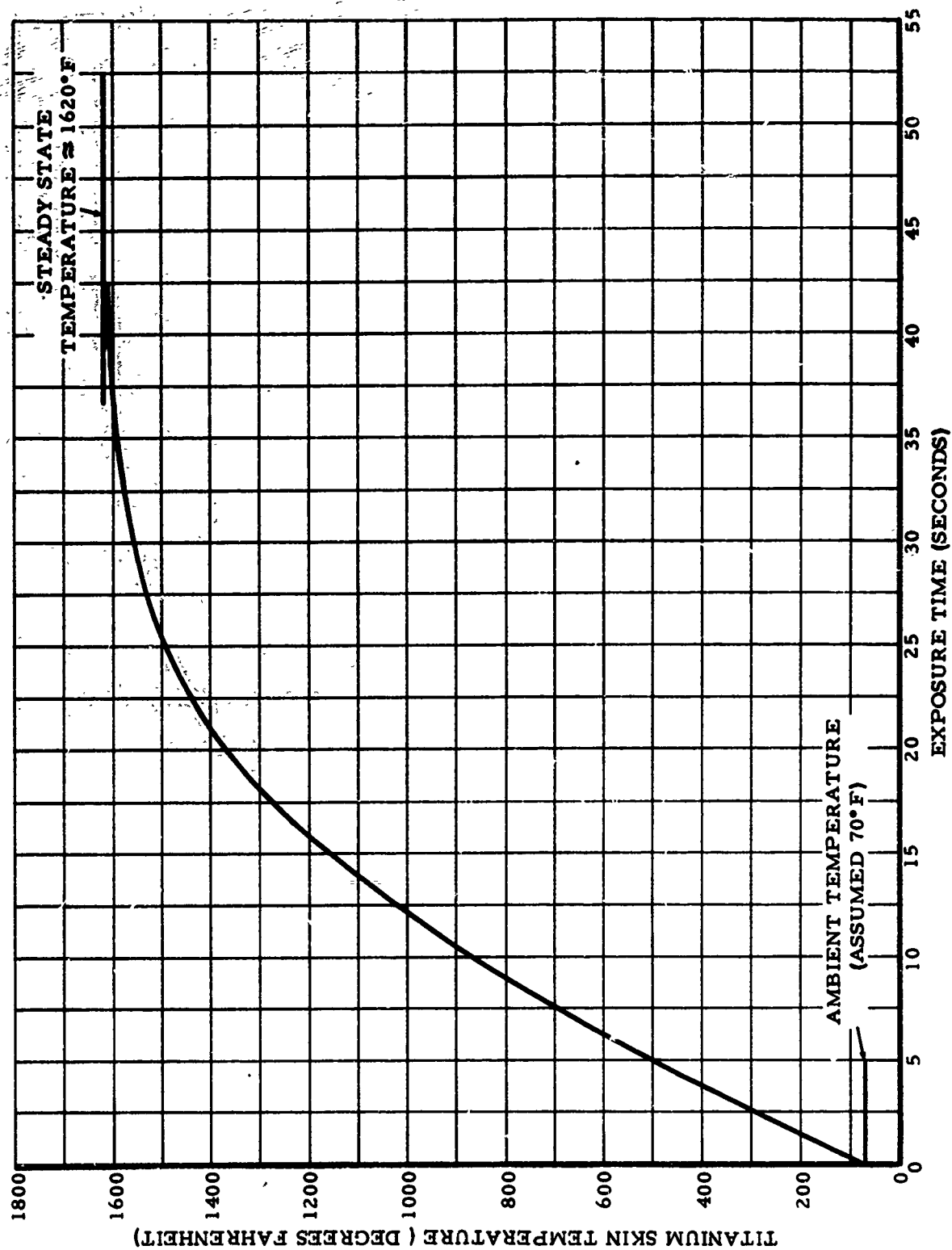


FIGURE 1-2 - PREDICTED TITANIUM SKIN TEMPERATURE DURING A
SEVERE EXTERNAL FUEL FIRE ADJACENT TO
A TITANIUM FUSELAGE

method, which is explained in standard books, for example, Gebhart (Reference 19). A length increment Δx of one-half inch was selected (Figure 1-3). The time increment was calculated from

$$\Delta t = \frac{\Delta x^2}{2} \frac{\rho c}{k} \quad (3)$$

and the temperature was calculated from

$$T_{N,t+\Delta t} = \frac{T_{N-1,t} + T_{N+1,t}}{2} \quad (4)$$

This simple calculation procedure for predicting the temperature amounts to the statement that the temperature at a location is the average of the temperatures at the adjacent points at the preceding time increment. The boundary conditions are the variable titanium skin temperature (Figure 1-2) and an assumed adiabatic condition at the cabin wall interface.

Initially, the temperature history was calculated using a constant thermal conductivity (at 800°F), specific heat and density since the Schmidt-Binder method is only applicable for a material with a constant thermal diffusivity. Both the specific heat and density remain relatively constant across the temperature range of interest; however, the thermal conductivity varies significantly (Reference 10). In order to give some account of this effect, the average thermal conductivity of the eight calculation points was used for determining each succeeding time increment (Equation 3). This calculation procedure predicted a cabin wall interface temperature which was 150°F lower (after 6 minutes) than the constant thermal conductivity results. It is believed that the variable thermal conductivity calculations are most representative of the physical behavior of the insulation.

Figure 1-4 shows the predicted insulation temperature at two locations which were instrumented with thermocouples: the cabin wall and 2.5 inches from the titanium skin. The cabin wall temperature is not predicted to rise above the ambient value until shortly after 2 minutes of fire exposure; after this, the temperature begins increasing gradually. At about 3 minutes the increase in temperature at this location becomes linear with time and reaches 685°F after 6 minutes. The temperatures at both locations appear to be converging at this point in time.

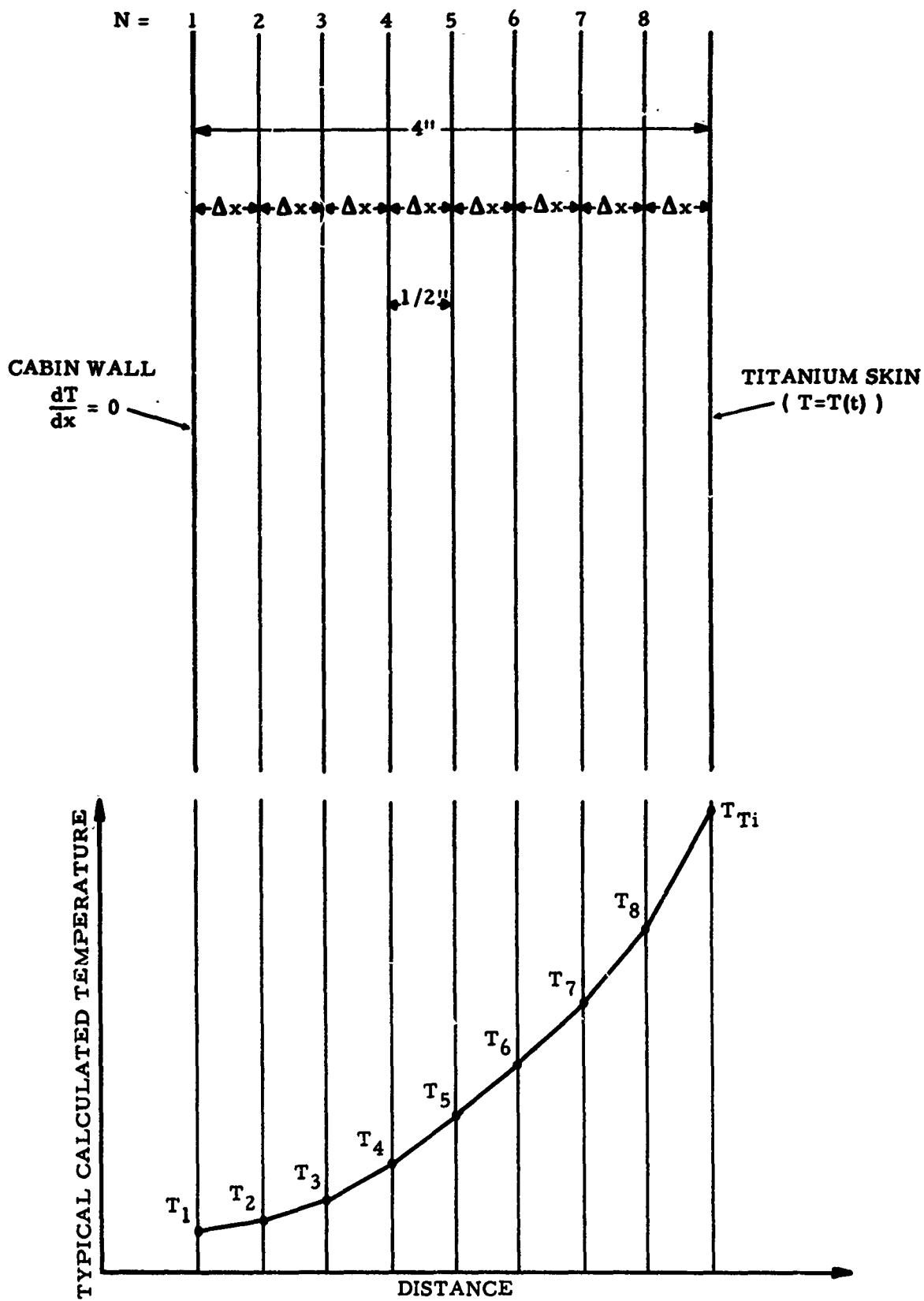


FIGURE 1-3 - NUMERICAL NETWORK AND TYPICAL TEMPERATURE PROFILE
FOR INSULATION HEATING CALCULATIONS

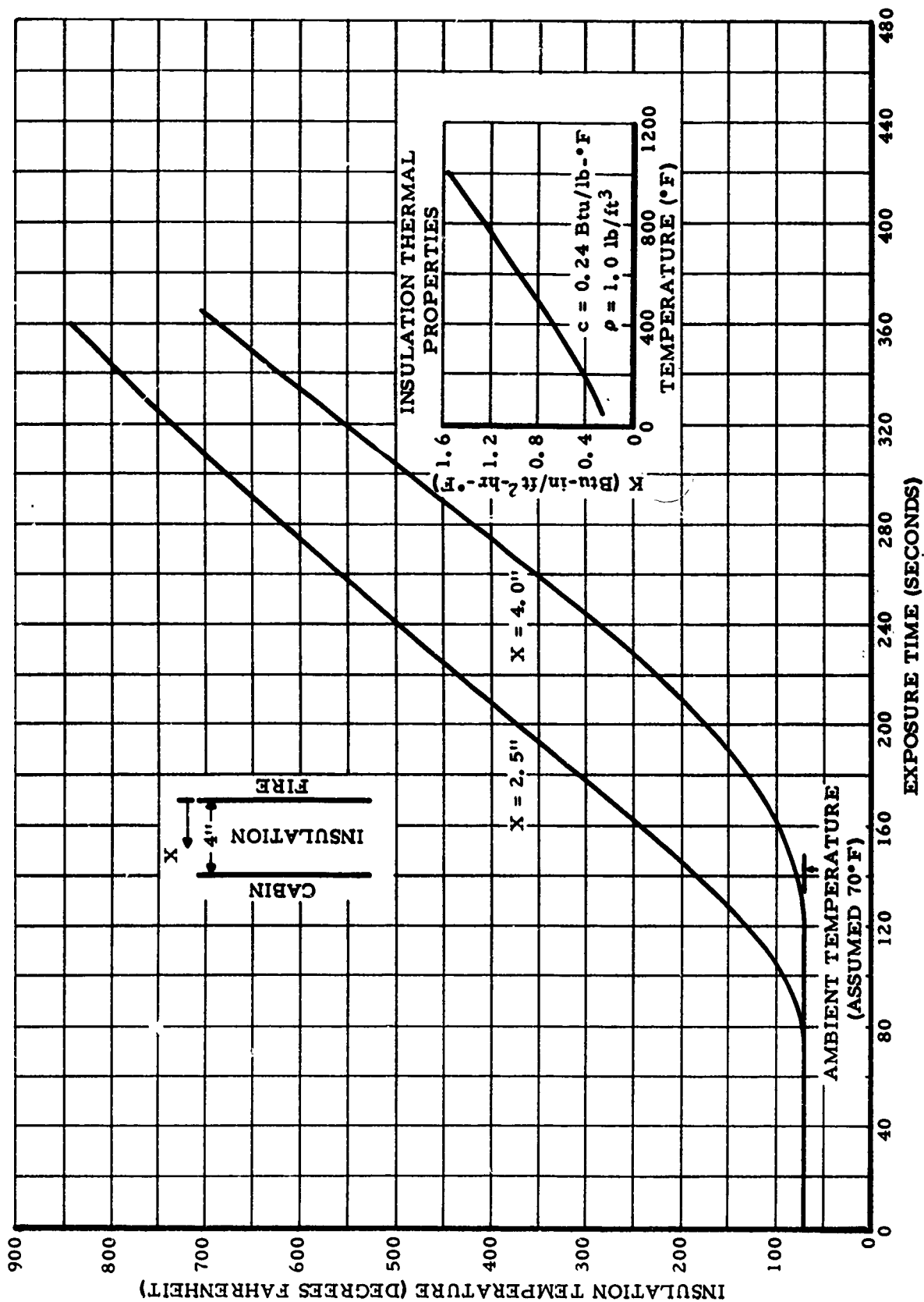


FIGURE 1-4 - PREDICTED INSULATION TEMPERATURE DURING A SEVERE EXTERNAL FUEL FIRE ADJACENT TO A TITANIUM FUSELAGE

The interior cabin air is heated by natural convection currents generated by the hot cabin wall. The average convective heat flux may be calculated from

$$\dot{q} = h (T_w - T) \quad (5)$$

where h is the average film coefficient (which is related to the Nusselt number), and T_w and T are the cabin wall and cabin air temperatures respectively. An empirical correlation recommended by Eckert and Jackson for a vertical flat plate with turbulent flow, and explained in Hsu (Reference 20), was used for calculating the Nusselt number

$$N_{Nu} = 0.021 (N_{Gr} N_{Pr})^{2/5} \quad (6)$$

where N_{Gr} and N_{Pr} are the Grashof and Prandtl numbers respectively. The Prandtl number may be considered constant and the Grashof number is calculated from its definition

$$N_{Gr} = \frac{gL^3(T_w - T)}{\nu_w^2} \quad (7)$$

where g is the acceleration of gravity, L is the height of the plate (taken as the circumferential length extending from the floor to the vertical symmetry plane as shown in Figure 15), and ν_w is the kinematic viscosity of air at the wall temperature. The average film coefficient (and the average heat transfer using Equation 5) can then be calculated from the definition of the Nusselt number

$$N_{Nu} = \frac{hL}{k_w} \quad (8)$$

where k_w is the thermal conductivity of air at the wall temperature. All the convective heat transfer is assumed to be occupied in raising the cabin air temperature; i.e.,

$$\rho C_p \frac{dT}{dt} V = \dot{q}A \quad (9)$$

where V is the volume of the fuselage and A is the area exposed to the fire. This area was assumed to comprise the surface of the fuselage extending from the floor level to the vertical symmetry plane for the length of the fire pit (Figure 1-5).

Using the previously determined cabin wall temperature history (Figure 1-4), the following finite difference procedure was used in order to calculate the cabin air temperature as a function of time:

At an initial time t when the wall temperature begins to exceed the ambient value, calculate

- (1) NG_r from Equation 7
- (2) N_{Nu} from Equation 6 with $N_{Pr}=0.72$
- (3) h from Equation 8
- (4) $\dot{q}$ from Equation 5
- (5) $\frac{dT}{dt}$ from Equation 9
- (6) $T_t + \Delta t = T_t + \frac{dT}{dt} \Delta t$

The properties of air at atmospheric pressure used in these calculations were taken from Gebhart (Reference 19).

Figure 1-6 shows the predicted cabin air temperature as a function of time. The first departure above ambient temperature occurs at about 3 minutes (as compared to 2 minutes for the cabin wall). At about 6 minutes the temperature is about 170°F with the rate of temperature rise still increasing. This is clearly shown in Figure 1-7 which shows the rate of temperature increase as a function of time; a linear rate is observed above 270 seconds. By 6 minutes the rate of temperature increase is about 1.25°F/sec.

The predicted titanium skin, cabin wall and cabin air temperatures are compared in Figure 1-8. Plotting these curves with the same scales emphasizes their different behaviors, especially that of the titanium skin compared with both the cabin wall and cabin air temperatures. The skin temperature rises abruptly to a steady-state value, while both the cabin wall and air temperatures increase more gradually.

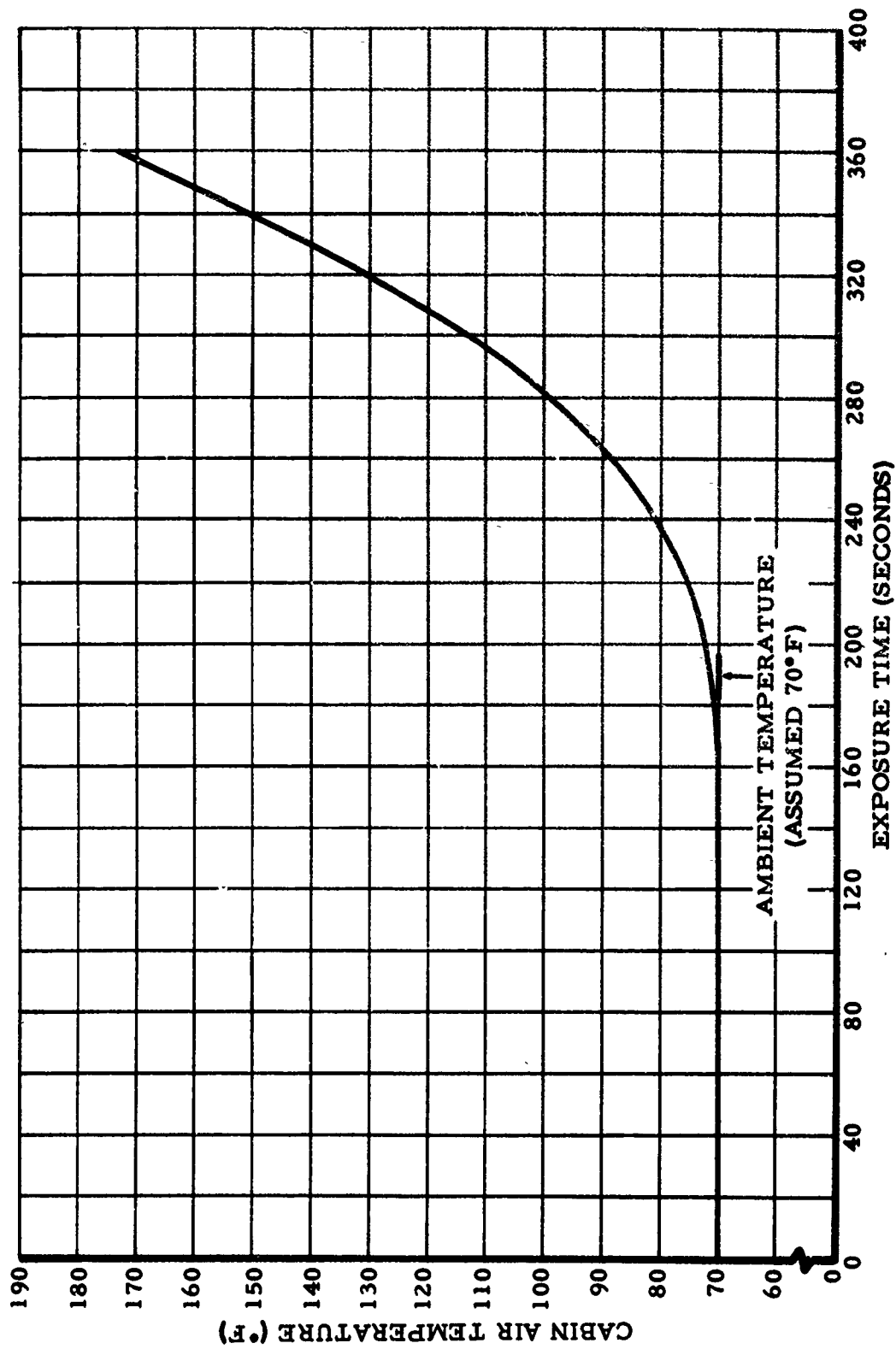


FIGURE 1-6 - PREDICTED CABIN AIR TEMPERATURE DURING A SEVERE
EXTERNAL FUEL FIRE ADJACENT TO A TITANIUM
FUSELAGE

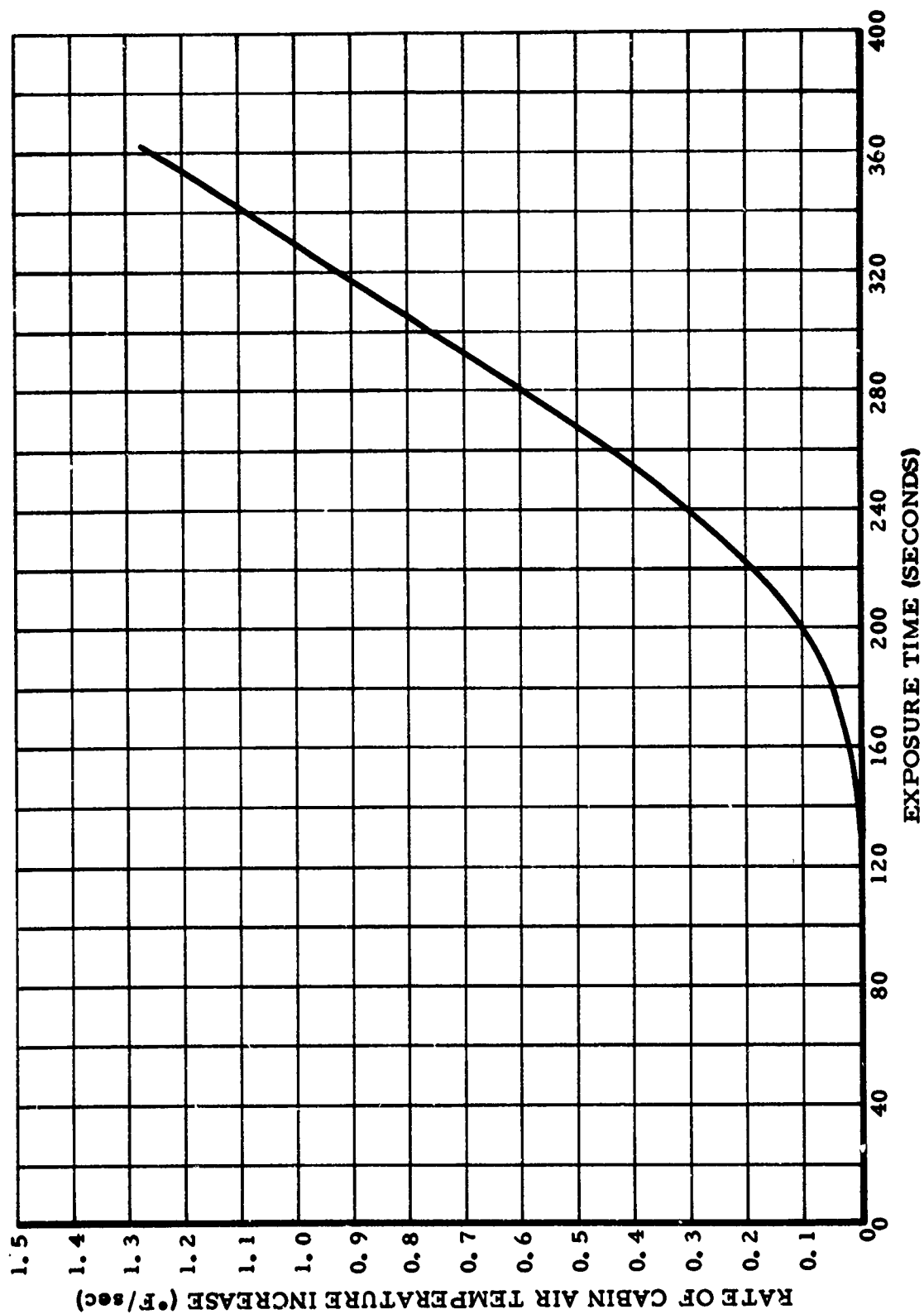


FIGURE 1-7 - PREDICTED RATE OF CABIN AIR TEMPERATURE INCREASE
DURING A SEVERE EXTERNAL FIRE ADJACENT TO
A TITANIUM FUSELAGE

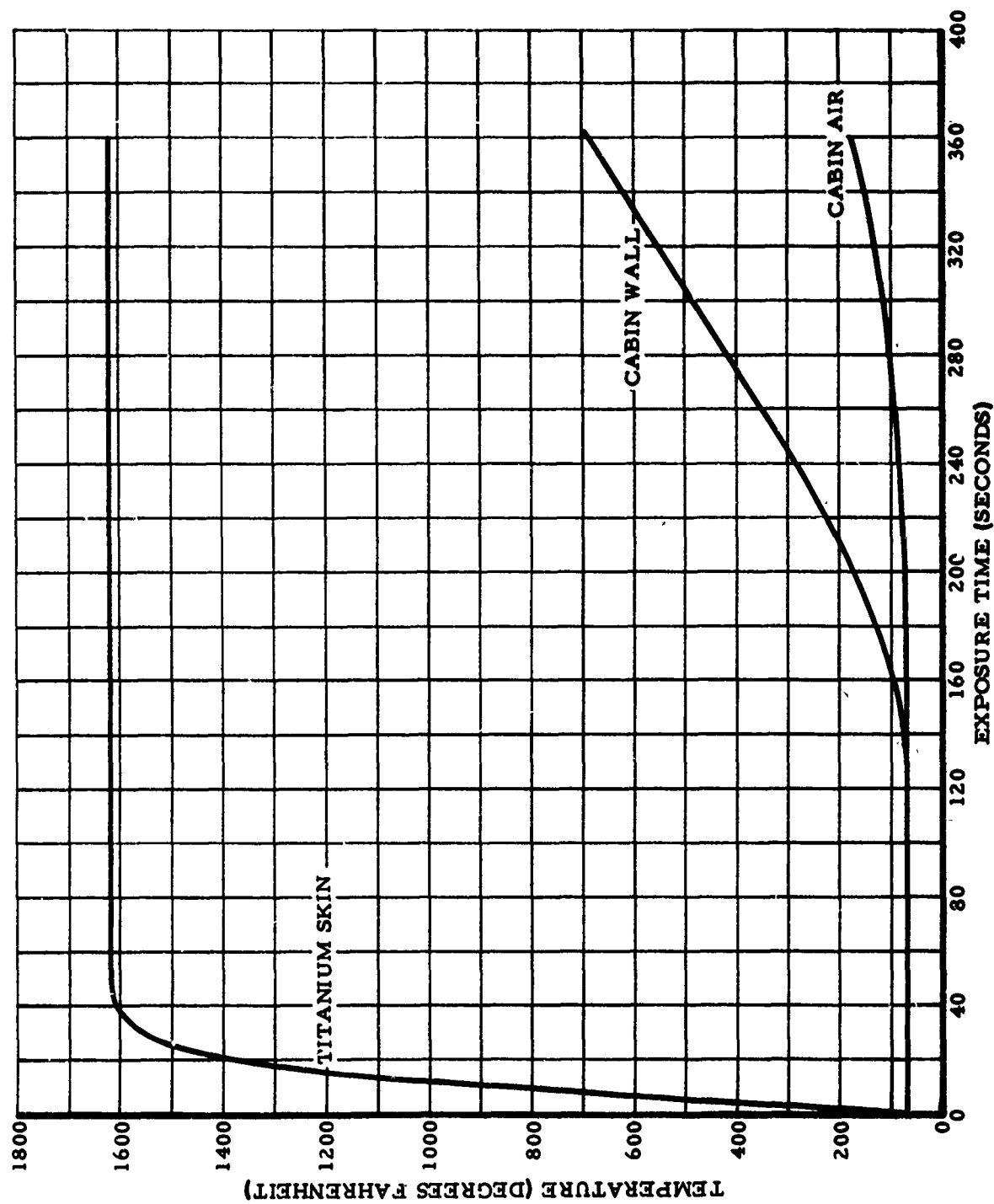


FIGURE 1-8 - PREDICTED TEMPERATURE HISTORY OF A TITANIUM FUSELAGE ADJACENT TO A SEVERE EXTERNAL FUEL FIRE

APPENDIX B

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