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Fuel Fire Penetration Test and Destruction of a Transport Aircraft

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Final Report

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16. Abstract

A British Airtours Boeing 737 expierenced an engine failure during takeoff at the Manchester International Airport, in Manchester, England, in 1985 which resulted in 55 fire fatalities. The aircraft's reported initial fuselage burnthrough time of 15 to 20 seconds was inconsistent with previous accidents and Federal Aviation Administration (FAA) large-scale burnthrough tests. The FAA conducted a fire test using a Convair 880 test aircraft designed for investigating fuselage resistance to burnthrough when subjected to a wind driven, offset, large fuel fire which incorporated certain elements of the Manchester fire. The test showed that this condition resulted in an initial burnthrough time of 1 minute 10 seconds and ignition of the cabin furnishings about 1 minute later. This test also investigated the locations of the initial burnthroughs and the paths in which the interior fire spread to get to the cabin. It was determined that fire penetration was due to melting fuselage skin and not by access through open doors or outflow valves.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

EXECUTIVE SUMMARY

The objective of this project was to experimentally determine the burnthrough characteristics of a transport aircraft when exposed to a large pool fire located upwind of the fuselage. This project focused on the burnthrough locations, the resulting fire paths to the passenger cabin, and the characteristics of an unimpeded interior fire. Previous testing by the Federal Aviation Administration (FAA) examined burnthrough when the fuselage was over or adjacent to the fuel fire under low or no wind conditions.

The design model for this test was the British Airtours B737 ground accident that occurred on August 22, 1985, in Manchester, England, after aborting a takeoff due to an engine failure. The Boeing 737 was subjected to an upwind fuel fire that penetrated the aircraft quickly, initially reported as little as 15 seconds. The final report submitted by the Accident Investigation Board estimated the burnthough time to be 60 seconds.

This test was designed to incorporate many key elements of the Manchester accident including, but not limited to, timed door opening sequences, exterior pool fire size and location, wind speed and direction, and aircraft configuration.

The test resulted in a cabin burnthrough time of 1 minute 10 seconds, with cabin furnishings igniting at about 2 minutes 15 seconds. This was consistent with previous FAA testing conducted by Webster using a Convair 880 standing on the landing gear with a fuel fire under the aft fuselage. This earlier test produced a cabin burnthrough time of under 2 minutes. The substantial fuselage damage that occurred in both tests was similar within the time constraints of the previous test where the fire was extinguished at 6 minutes. The results of this report's test showed that the open doors and the outflow valve did not provide the fire entry points as was theorized in the Manchester accident. The cabin was penetrated by the external fuel fire directly through the fuselage skin, igniting the interior cabin materials. Main cabin temperature peaks and corresponding oxygen depletion in the first-class cabin indicated at least three flash fires occurred in the passenger cabin before the tail section separated from the aircraft.

INTRODUCTION

PURPOSE.

The objective of this project was to experimentally determine the burnthrough characteristics of a transport aircraft when exposed to a large fuel fire located upwind of the fuselage. It was determined in previous testing that a fuselage exposed to an external fuel fire located under the aft fuselage would resist flame penetration into the cabin for a period of approximately 2 minutes [1]. This project examines the effects of an offset, wind-driven fuel fire on an intact fuselage and the resultant interior fire propagation.

BACKGROUND.

The scenario for this test was provided by the accident report of the British Airtours Boeing 737-236, August 22, 1985, accident that occurred at Manchester International Airport, Manchester, England [2]. While the Boeing 737-236, registration G-BGJL, was on takeoff roll, it experienced a port engine failure, and an engine burner can burnthrough flame pierced the left wing fuel tank. The port engine trailed fire from the leaking wing fuel tank as the crew aborted the takeoff and turned right onto taxiway Delta. The plane came to a halt on the taxiway where fuel continued to spill from the ruptured wing tank which eventually discharged approximately 600 gallons of Jet-A fuel. The fuel formed an elongated burning pool located 15 feet to the left of the fuselage. The wind at 7 knots and 60° left relative to the nose of the aircraft carried the fire plume onto the aft fuselage. The fire quickly penetrated the hull, allowing smoke and heat to fill the cabin as the passengers attempted to evacuate the aircraft. Fifty-five people lost their lives in spite of the prompt airport fire service response. The investigation following the fire reported that the seats and cabin furnishings exhibited the greatest fire damage on the right (downwind) side of the cabin.

The early burnthrough, reported initially to be as little as 15 seconds, was inconsistent with previous accidents and Federal Aviation Administration (FAA) burnthrough tests which were previously conducted on a DC-8 and a Convair 880 [1] at Charlotte Aircraft Company in Maxton, North Carolina. The DC-8 aircraft was subjected to adjacent fuel fires in a wheels-up configuration. The Convair 880 was tested wheels down and the pool fires located under the fuselage. The wind conditions ranged from calm to a 7-knot crosswind. In burnthrough test four, the Convair 880 was exposed to a 600-gallon fuel fire located under the aft fuselage. The fuselage provided protection from significant sustained fire penetration in the cabin for approximately 2 minutes. Earlier penetration by the external fuel fire occurred only in those areas where the acoustic insulation was damaged or removed and in particularly vulnerable areas, such as the door seals, which allowed the passage of small, nonproductive flames and smoke into the cabin.

Several theories were advanced to explain the rapid fire penetration and the extensive damage reported on the right side of the cabin of the Boeing 737 at Manchester. One theory was that the fire penetrated the cheek area on the left side of the aircraft and traveled between the floor and the top of the cargo compartment to the right side of the cabin where it penetrated the cabin through the floor air return grills. Another theory was that the fire was drawn through the right rear door by aerodynamic forces caused by the fuselage shape, the wind direction, and the combination of open doors and hatches. A third theory was that the fire penetrated into the empennage crawlthrough area through the open pressure control, outflow valve.

The test described in this report, involving an offset fuel fire with a winddriven flame, duplicated many aspects of the Airtours accident in an attempt to resolve the early burnthrough question and to determine the probable mode of flame penetration into the cabin.

APPROACH.

This test incorporated as many key elements of the Manchester fire as possible including fire size and location, relative wind and velocity, and sequenced door and escape hatch openings. The test article was a Convair 880, a four engine transport jet. The CV-880 was complete with the exception of the engines. The interior was fitted with a first-class and coach seating configuration. The seats were not fire blocked. The aircraft was modified to resemble a Boeing 737 in several critical areas including the removal of the left wing outboard engine pylon and the aft galley, installation of an additional row of seats in place of the aft galley, modifications at the outflow valve location, and installation of insulation in the empennage crawlthrough area. This insulation was configured to be similar to the B737-200 insulation.

The test site was a graded 200-foot-diameter circle in an area where there were no vertical wind obstructions. The aircraft was positioned 15 feet downwind of a 20- by 20-ft fuel pan such that the prevailing wind would blow across the pan 60° left of the aircraft nose. This fuel pan was located inside of a larger 30- by 30-ft pan to reduce the possibility of fuel spillage contaminating the ground (figure 1).

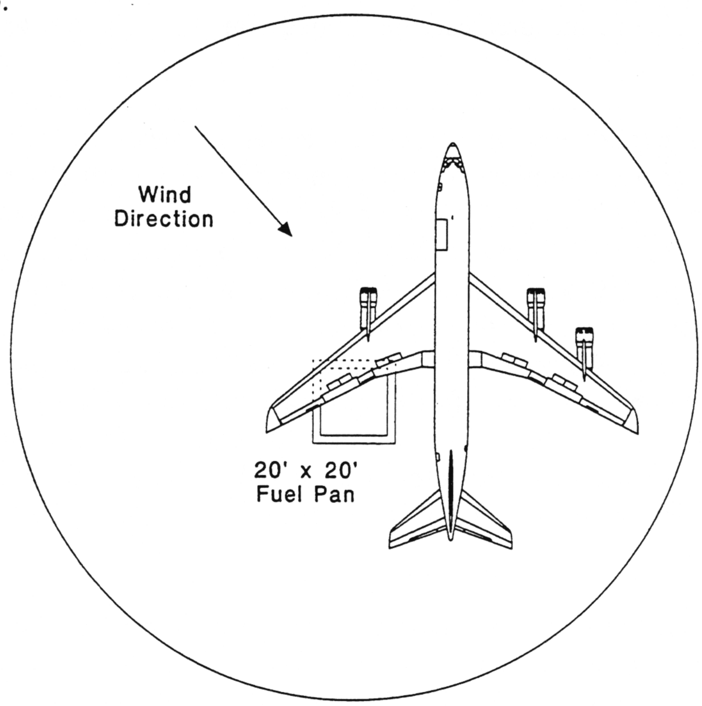

FIGURE 1. TEST CONFIGURATION

The interior of the aircraft was instrumented to determine the location and path of any fire penetrations and subsequent interior fires. The parameters measured included temperature, heat flux, combustion product gases, and smoke density. The interior was fitted with video cameras to record the fire. The exterior fire was recorded using video and motion picture equipment.

The forward doors and the right overwing escape hatch were modified to open at a preset schedule to match the reported openings of the doors on the Airtours B737. The right rear door was opened prior to the pool fire ignition.

The pool fire was ignited when wind conditions were favorable, the doors were opened at the required times, data were collected using high-speed computer data acquisition, and the fire was recorded visually using video and motion picture cameras.

TEST PROCEDURE

TEST ARTICLE PREPARATION.

The preparation of the Convair 880 was accomplished in two phases. The first phase consisted of modifying the aircraft to resemble the Boeing 737 in critical areas. The second phase included instrumentation and safety modifications.

AIRCRAFT MODIFICATIONS. The two engine B737 is 27 feet shorter than the four engine CV880 (table 1). This required moving the fuel pan aft from under the wing such that the flame impingement would be similar to the Airtours fire.

TABLE 1. PHYSICAL DIMENSIONS OF A CONVAIR 880 VERSUS A BOEING 737-200

	Convair 880	Boeing 737-200
Length	127 ft. 4 in.	100 ft. 4 in.
Wing Span	120 ft. 0 in.	93 ft. 0 in.
Tail Height	34 ft. 3 in.	37 ft. 0 in.
Gear Track Width	18 ft. 10 in.	17 ft. 2 in.
Fuselage Width (od)	11 ft. 6 in.	12 ft. 4 in.
Top of Fuselage Height	12 ft. 5 in.	13 ft. 2 in.

The outboard left engine nacelle and pylon were removed to provide an unobstructed airflow across the wing, simulating the two engine B737.

The outflow valve cutout, located in the empennage crawlthrough, was enlarged to 6 inches by 14 inches and left wide open to simulate the B737 condition on the ground of the outflow valve.

The empennage crawlthrough was insulated with 1-inch fiberglass insulation to match the insulation installed in a B737 in this area. The aft right galley was removed from the aircraft and a row of seats installed in its place, simulating the seating configuration in the Airtours B737.

The port and starboard doorways and the starboard overwing exit were opened. The openings were covered with steel panels fitted with cables. These panels were attached with breakaway fittings allowing the panel to be removed from a remote location by pulling on the cables. In this manner, the sequence of door openings that occurred at Manchester could be simulated.

SAFETY MODIFICATIONS. When the aircraft was positioned on the test site, the air was removed from the tires to eliminate the possibility of explosion. The landing gear struts were also depressurized. All hydraulic fluid accumulators were also removed to eliminate explosion hazards. The fuel in the wing tanks was completely drained and the tanks refilled with water. This lessened the possibility of explosion and provided a heat sink effect in the wings, simulating a full fuel load.

INSTRUMENTATION.

INSTRUMENTATION DESIGN. Temperature measurement devices (thermocouples), heat flux measurement devices (calorimeters), and smoke density meters were installed at several locations in the aircraft. This instrumentation was designed to track the burnthrough locations and subsequent fire paths that resulted from the external fuel fire penetrating the hull. There were four locations where optical smoke density, heat flux, and the vertical temperature distribution of the cabin air were measured: stations 498, 669, 1106, and 1280 (see appendix C). The concentrations of oxygen, carbon monoxide, and carbon dioxide were also measured at station 498. In addition, two instrumentation slices were installed at right angles to the aircraft centerline at stations 1040 and 1192. This instrumentation, consisting of thermocouples and calorimeters, was designed to measure the thermal intensity of the external fuel fire impingement on the aircraft hull and the effect of the external fire on the interior of the aircraft. To supplement the temperature and heat flux data, video cameras were installed in the aircraft to document smoke and flame incursion as well as any internal fires. Motion picture and video coverage were utilized to document the external fuel fire, providing a full 360° view of the aircraft. All sensor signal wires were protected from fire damage by wrapping them with Kaowool insulation. The interior video cameras were an inexpensive type able to withstand the environment until cabin obscuration occurred. A full listing of the instrumentation type and location is described in appendix C. A general listing of the instrumentation follows.

1. Four instrumentation trees were installed at stations 498, 669, 1106, and 1280. Cabin temperature was measured by type K thermocouples located at the floor level, 28, 57, and 76 inches above the floor (ceiling height: 78 inches). A calorimeter was located at the 48-inch level and positioned to measure the heat flux radiating from the rear of the aircraft. A smoke meter, consisting of a collimated light beam incident upon a photocell, was installed at the 48-inch level to measure the optical smoke density in the cabin.

2. Type K thermocouples were installed to measure the air temperature in each of the aft galleys.

3. A group of type K thermocouples were installed to provided a temperature profile slice vertically across the fuselage at stations 1040 and 1192. The locations of these thermocouples included

   a. below the floor to measure

      (1) the air temperature in the left cheek, the external fire temperature, and the fuselage skin temperature.

      (2) the air temperature in the cavity located between the cargo liner and the cabin floor.

      (3) the air temperature in the cavity between the cargo floor and outer skin of the fuselage.

      (4) the air temperature in the right cheek, the external fire temperature, and the fuselage skin temperature.

      (5) the cargo compartment air temperature.

   b. above the floor to measure

      (1) the temperature in the left floor air return grill.

      (2) the temperature in the cavity formed between the cabin ceiling and the fuselage skin (attic).

      (3) the temperature in the right floor air return grill.

   c. a calorimeter and thermocouples that were grouped together on the left and right sides just below the window to measure the heat flux of the exterior fire and the temperatures of the external fire, fuselage skin, and the interior panels.

4. Empennage crawlthrough instrumentation provided

   a. the external fire temperature measured with a thermocouple that extended 4 inches through the open outflow valve opening.

   b. the air temperature measured 6 inches above the outflow valve opening.

   c. the crawlthrough air temperature by a thermocouple that was located near the top of the compartment.

5. Gases were measured 48 inches above the floor at station 498. Carbon monoxide, carbon dioxide, and oxygen were continuously monitored throughout the test.

6. The wind speed and direction relative to the nose of the aircraft were recorded throughout the test.

7. Video coverage: Five video cameras were located in the interior of the aircraft and four cameras were used to record the exterior of the aircraft. The cameras were located in the following locations:

   a. Interior

      (1) Aft cargo compartment, located at the forward bulkhead facing aft.

      (2) Empennage crawlthrough, focused on the outflow valve.

      (3) First-class cabin, facing the cabin partition separating first-class and coach compartments.

      (4) Main cabin, just aft of the cabin partition facing aft.

      (5) Facing the aft service door.

   b. Exterior

      (1) The left side.

      (2) Aft of the fuselage, looking at tail section.

      (3) The right side.

      (4) Right three-quarter view.

TEST RESULTS AND ANALYSIS

PRETEST CONDITIONS.

The total fuel load in the external container pan was 600-gallons JP-4 aviation kerosene primed with 5 gallons of aviation gasoline. The fuel was floated over 6 inches of water to protect the steel containment pan. The wind speed blew between 9 and 15 knots, averaging 12 knots. The wind direction was 60° left of the nose, shifting plus or minus 5°. Prior to pool ignition the right rear door was opened and the right front door was opened 3 in. Two minutes before ignition, the data system was activated and the video cameras started. The pool was ignited at time 0 minutes 0 seconds. The pool fire was allowed to develop for 20 seconds before the test sequence was started.

PLANNED TEST SEQUENCE.

The planned sequence of events for this test were based on the British Airtours August 22, 1985, accident report produced by the Department of Transport Air Accidents Investigation Branch of the Royal Aerospace Establishment [2].

TABLE 2. PLANNED SEQUENCE OF EVENTS

Time	Event
Pretest	Right rear door opened, pool filled with 600 gallons of JP-4
0:00	Right forward door opened a few inches, pool fire fully developed
0:25	Left forward door opened
0:45	Right overwing escape hatch opened
1:10	Right forward door fully opened

ACTUAL SEQUENCE OF EVENTS.

The following event time line was compiled from analysis of computer collected data, internal and external video coverage, external high-speed motion picture photography, and the notes and observations taken during the test.

Time (minutes)	Event
-2:00	Computer, video start
0:00	Pool fire ignition, event markers flashed
0:20	Pool fire fully developed
0:45	Left forward door opened
1:10	Right overwing exit opened
1:10	Fire visible in empennage crawlthrough (not through outflow valve)
1:11	Fire penetration in the main cabin left side above the window level at approximately station 1220
1:23	Right forward door opened fully
1:35	Smoke coming out of right rear door
2:00	Heavy black smoke filling ceiling of rear main cabin at the burnthrough (vicinity of station 1220)
2:08	Smoke penetration through upper door seal in aft cargo compartment
2:25	The seats are in flames at the initial cabin burnthrough (station 1220)
2:30	Heavy black smoke coming out of right rear door
2:31	Heavy black smoke rolls forward down the aisle between the overhead storage bins to the first-class divider (station 640)
2:47	Small fireball erupts from the right rear door

Time (minutes)	Event
2:48	Main cabin video fully obscured
2:50	Black smoke billows into first-class cabin at the ceiling level between the overhead storage bins.
2:51	A flash fire or flashover occurs in the empennage crawlthrough
2:58	Smoke in first-class cabin retreats aft to first-class divider
3:28	Smoke advances forward into first-class cabin to approximately station 500
3:30	Intermittent flames out of right rear door
3:35	Smoke out of right overwing exit
3:38	Smoke in first-class cabin advances toward cockpit
3:50	First-class cabin video fully obscured
3:55	Gas and temperature data indicate that a flash fire has occurred in the main cabin.
3:58	White smoke out of right forward door
4:20	Black smoke out of right forward door
5:00	Gas and temperature data indicate that a second flash fire has occurred in the main cabin.
6:30	Gas and temperature data indicate that a third flash fire has occurred in the main cabin.
8:00	Pool fire diminishing
8:12	Tail separates from fuselage at station 1264
9:45	Light smoke out of left forward door
10:00	Internal fire burned through windows on left side at stations 973 and 1011
11:15	Pool fire out
13:00	Smoke at left forward door stops
14:16	Heavy black smoke from left forward door
19:00	Flames from left forward door
19:05	Smoke from left top of the fuselage at station 749
19:15	Top of fuselage turning brown at stations 749 and 603
20:12	Entire top of fuselage burned through from station 749 aft
21:45	Fire penetration through top of fuselage at station 508
23:20	Entire top of fuselage burned through from station 479 aft
24:50	Top of fuselage burned through from forward doors aft (station 342)
27:55	All combustibles aft of station 758 consumed, fuselage burned down to window level
29:30	Forward cabin fire dying down as remaining combustibles consumed
33:00	Remaining fire is extinguished by Airport Fire Service

THE EXTERIOR FIRE.

All times referenced are from pool fire ignition, time 0 minutes 0 seconds.

FLAME IMPINGEMENT. The pool fire became fully developed 20 seconds after ignition. The wind driven flame (60° left of the nose at an average speed of 12 knots) struck the fuselage between stations 1070 and 1300 trailing towards the rear of the aircraft and covering the top of the fuselage from station 1200 aft (figures 2, 3). A small amount of flame blew under the fuselage aft of the right rear door from station 1294 aft. A relatively large amount of flame blew over the fuselage from station 1220 aft to the vertical stabilizer. Occasionally, the flame from under the fuselage and the flame from over the fuselage combined in the vicinity of the right rear door, station 1262. The fire remained fairly constant for approximately 8 minutes then diminished as the fuel was exhausted until it was out at 11 minutes.

FIGURE 2. FLAME IMPINGEMENT ON PORT AFT FUSELAGE

Thermocouple temperatures recorded outside the fuselage at station 1192 measured just below the base of the window peaked at 1200°F 1 minute after pool ignition then subsided to an average of 400°F until the 8-minute mark when the temperature again peaked at 1400 and 1600°F at the 9-minute mark (figure B-1). The heat flux at this location peaked at 19 BTU/ft^2-sec but averaged 5 BTU/ft^2-sec (figure B-2). These measurements were 2 to 3 feet forward of the flame plume. The flame temperature at the cheek area, also at station 1192, followed the same trend as figure B-1 (figure B-3).

FIGURE 3. FLAME IMPINGEMENT ON STARBOARD AFT FUSELAGE

The thermocouples installed on the starboard side at both the cheek area and the window level were not directly impinged by the fuel fire plume. The external air temperature at both locations remained quite low until the tail separated from the aircraft at the 8-minute mark. This exposed the thermocouples to the diminishing pool fire (figures B-4 and B-5).

The fire temperature recorded outside of the outflow valve peaked at 1750°F 1 minute after pool ignition, dropped to 500°F, and then peaked again at 1600°F 6 1/2 minutes after ignition (figure B-6)

FUSELAGE RESISTANCE TO BURNTHROUGH.

There were four locations at station 1192 where a temperature profile could be determined through the fuselage hull. These were just below the window level and in the cheek area adjacent to the cargo compartment on both the port and starboard sides. Thermocouples were provided to indicate the temperature exterior to the skin, the skin temperature, and the temperature of the interior sidewall panels.

Figure B-1 shows the temperature profile on the port side just below the window. The skin temperature reached 900°F, which is the approximate incipient melt point for aluminum, in 2 minutes. The cabin sidewall, however, stayed relatively cool reaching only 150°F in this period. It should be noted that this skin location was only in the fuel fire for a very short period of time.

Figure B-3 shows the temperature profile through the hull on the port side in the cheek area. The skin in this area appears to melt 7 minutes after pool ignition. However, the air temperature in the cheek area did not rise significantly, reaching only 150°F before the tail separated.

Figure B-4 is the temperature profile through the hull on the starboard side in the cheek area. The area had no significant exposure to the pool fire. The air temperature did begin to rise at about 5 minutes, but this appears to be from internal convective heating, not external radiant heating.

Figure B-5 is the temperature profile through the hull just below the window on the starboard side. The area was not exposed to the exterior pool fire. The temperature of the interior sidewall panel began to rise at 5 minutes. This is an indication of the interior cabin fire and not burnthrough as can be seen by the lower skin temperature.

FIRE PATHS.

The fire penetrated the cabin and the empennage crawlthrough at approximately the same time, 1 minute 10 seconds after the pool fire was ignited. Video coverage was used to document each burnthrough.

EMPENNAGE CRAWLTHROUGH. The pool fire penetrated the left side of the fuselage at station 1264, 1 minute 10 seconds after pool ignition. The penetration mechanism was by direct skin melting and not the outflow valve in this case. The outer skin melted, allowing the 1-inch-thick acoustical insulation to fall away. The flames then had access to the uninsulated cabin floor above the crawlthrough which included the aft lavatories.

MAIN CABIN. Flames first appeared in the main cabin 1 minute 11 seconds after the pool fire was ignited. The fire penetrated the fuselage above the window level on the left side at station 1220. The initial burnthrough was not catastrophic or immediately threatening. A small flame burned above the window producing black smoke but not any appreciable radiant heat. The flame gradually increased in intensity igniting a seat 1 minute 15 seconds after it appeared.

THE INTERIOR FIRE.

The initial phases of the interior fire can be divided into two regions. The first concerns the area below the floor and includes the aft cargo compartment and the empennage crawlthrough. The second area includes all of the aircraft above the floor level including the main cabin, the aft lavatories, the first-class compartment, and the flight deck. The interior fire started in both locations simultaneously. The empennage crawlthrough was penetrated through the skin along the port side forward of the outflow valve. This occurred 1 minute 10 seconds after the pool fire was ignited. At the same time, flames appeared in the port side of the main cabin at station 1220 above the window level.

EMPENNAGE CRAWLTHROUGH. Initial speculation placed the outflow valve as a possible location for flame penetration. The design of the valve in the Boeing 737 insures that it is in the open position while the aircraft is on the ground. This could allow an easy path for the external fire to breach the aircraft. However, in this test, while the external temperature 2 inches outside of the valve reached as high as 1750°F, the air temperature in the empennage crawlthrough 6 inches above the valve remained relatively low (figure B-6). A video camera focused on the outflow valve did not show any flame incursions through the valve opening. The video did show flame penetration through the lower port side of the compartment 1 minute 10 seconds after the pool fire was ignited. The aluminum skin in this location is constructed of 0.050-inch 2024 T4 clad sheeting.

CARGO COMPARTMENT. The two fire paths that were considered likely, after the initial penetration, were between the cargo compartment floor and the external skin and between the cargo ceiling and the cabin floor. Figure B-7 shows the temperatures recorded by the three thermocouples that were installed in the area under the cargo compartment floor at station 1192. The port thermocouple was exposed to direct fire 4 minutes after the pool was ignited and peaked at 1700°F. The center and the starboard thermocouple registered no increase in temperature until the tail separated from the aircraft at 8 minutes 12 seconds. This indicated that there wasn't any fire propagation under the cargo compartment floor.

Figure B-8 shows three thermocouples that were installed above the cargo compartment ceiling at station 1192. All three showed a temperature rise at the two-minute mark and the port thermocouple showed a more rapid rate of increase than the center thermocouple which in turn increased faster than the starboard thermocouple. The relatively low temperatures indicated this was not a fire path; however, this may have been a path for hot gasses. The starboard floor grills did not show a corresponding temperature increase, indicating that there was little heat flow occurring under the floor (figure B-9). The port floor grill did experience a rise in temperature that corresponded with the port thermocouple below the floor (figure B-10). Again, the modest temperature increase, building to 400°F at tail separation at 8 minutes 12 seconds, indicated that at this location the path was for hot gasses only.

Figure B-11 shows the air temperature measured inside of the cargo compartment. As in previous tests [1], the temperature within the cargo compartment remained low until the compartment was physically breached. In this case, the air temperature exhibited a gradual increase to 180°F at which point the tail separated from the aircraft exposing the thermocouple to the exterior fire. The cargo compartment door seals allowed a small amount of smoke to enter the compartment as early as 2 minutes 20 seconds but with little impact on the interior temperature.

MAIN CABIN. The investigators of the Manchester accident reported that the fire damage in the main cabin appeared to be greater on the starboard side of the aircraft. This led to three theories to explain this apparent anomaly. One, that the fire penetrated the aircraft on the downwind side due to aerodynamic conditions across the hull. Two, that the fire was drawn into the open rear door due to the wind direction and the combination of open doors and escape hatches. Three, that the fire penetrated the fuselage low on the port side and traveled either over or under the cargo compartment to reach the starboard side. There was no evidence in this test of the fire traveling either over or under the cargo compartment to reach the starboard side of the aircraft (see Cargo Compartment above). The right rear door, which was open during the test, was also not a source of the interior fire. The doorway was never an intake and in fact acted as an exhaust port for smoke and hot gasses. This was determined by observation, via video, from both the interior and the exterior of the aircraft. Smoke was observed exiting the rear door as early as 1 minute 35 seconds.

The initial cabin penetration occurred on the upwind (port) side of the aircraft at station 1220. Smoke and flames became visible just above the window 1 minute 11 seconds after the pool fire was ignited. The skin in this area is constructed of 0.095-inch 2024-T4 clad aluminum sheeting. Heavy black smoke immediately began to fill the ceiling at the rear of the cabin. Just 1 minute 15 seconds after the first flames became visible (2 minutes 25 seconds after start), seat fires could be seen under the thick black smoke.

<u>SMOKE</u>. Thick black smoke filled the rear of the cabin by the 2-minute mark. The smoke stratified at the ceiling, leaving a relatively clear area extending approximately 30 inches above the floor. As the fire increased in intensity at the rear of the cabin, the smoke front moved forward and lower. Heavy black smoke rolled forward toward the first-class divider, located at station 640, at 2 minutes 31 seconds, then pulled back 8 to 10 feet, then rolled forward again. The main cabin video, located 40 inches above the floor and aft of the first-class divider, was obscured at 2 minutes 48 seconds. The first smoke into the first-class compartment appeared between the overhead storage bins at 2 minutes 50 seconds. The smoke front retreated to the first-class divider at 2 minutes 58 seconds. The smoke front again advanced to approximately station 500 in the first-class cabin at 3 minutes 28 seconds and the video camera became fully obscured at 3 minutes 50 seconds.

Figures B-12, B-13, B-14, and B-15 are percent light transmission measurements obtained 48 inches above the floor. The smoke meter for figure B-12 was located in the rear of the aircraft at station 1280. This figure shows a steep drop in light transmissibility beginning 1 1/2 minutes after the pool fire was ignited or only 19 seconds after the first flame penetration was observed in the main cabin at station 1220.

Figure B-13 shows a similar curve from a smoke meter located at station 1106, 48 inches above the floor. This figure shows a steep drop in transmission beginning 3 minutes after the pool was ignited.

Figure B-14 is from a smoke meter located at station 669, 48 inches above the floor. The figure shows a steep drop in light transmission a few seconds earlier than that recorded by the smoke meter that was located at station 1106. This indicates that the entire main cabin was obscured at virtually the same time.

Figure B-15 is from a smoke meter located in the first-class cabin at station 498, 48 inches above the floor. The figure shows a steep drop in light transmission at approximately 3 minutes 50 seconds after pool ignition. This corresponds very well with the smoke data obtained from the video coverage. In summary, the smoke front traveled from the rear of the airplane to the cockpit in approximately 1 minute 50 seconds. Percent light transmission readings at each smoke meter dropped from 90 percent to nearly 5 percent or less in a matter of 10 to 15 seconds, indicating the thickness of the smoke.

CABIN AIR TEMPERATURE. Four thermocouple trees were located in the aircraft at stations 1280, 1106, 669, and 498. Each tree measured the air temperature at four heights above the floor: 2, 28, 57, and 76 inches. The 28 and the 57 inch heights were chosen to represent a person's head level when crawling and standing. The cabin ceiling height was 78 inches.

Figure B-16 shows a vertical air temperature profile at station 1280 across from the starboard rear service door. The ceiling temperature began to rise a few seconds after the burnthrough at station 1220, approximately 1 minute 20 seconds after the pool was ignited. The ceiling temperature indication peaked at 1750°F at about 4 minutes and then dropped off to 1200°F. The temperature peaked again at 2000°F when the tail separated from the aircraft.

The thermocouple tree at station 1106 was located 10 feet forward of the initial burnthrough at station 1220 (figure B-17). The ceiling temperature began a rapid rise 2 minutes after the pool fire was ignited or just 50 seconds after the burnthrough. The ceiling temperature peaked at 1700°F at 4 minutes after pool ignition.

The thermocouple tree at station 669 measured a far less severe rise in the air temperature due to its distance from the initial burnthrough and resultant interior fire (figure B-18).

The thermocouple tree located at station 498 measured the temperature profile in the first-class cabin (figure B-19). This area was the farthest away from the initial burnthrough.

CABIN GAS MEASUREMENT. Some limited cabin air gas concentration data were collected at station 498 by continuous sampling of the cabin air at a height 48 inches above the floor level. Oxygen, carbon dioxide, and carbon monoxide data were collected using Beckman gas analyzers installed in the forward cargo compartment.

Figure B-20 shows the oxygen level recorded in the first-class cabin. The oxygen level oscillated up and down beginning at 4 minutes after pool ignition. The level dropped to 9 percent at 5 minutes, rebounded to 17 percent at 5 minutes 30 seconds, dropped to 5 percent at 6 minutes, climbed to 17 percent at 7 minutes, and then leveled off at 1 percent at 9 minutes into the test. This oscillation roughly corresponds to the advancing and retreating smoke front described earlier.

Figure B-21 shows the carbon monoxide concentration recorded in the first-class cabin. The concentration of CO exceeded the 2 percent limits of the analyzer at approximately 4 1/2 minutes after pool ignition.

Figure B-22 shows the concentration of carbon dioxide recorded in the first-class cabin. The maximum level exceeded the limit of the analyzer, which was limited to 10 percent. The CO_2 level reached significant amounts 4 minutes after pool ignition where the concentration increased above 10 percent.

FLASH FIRE. Flash fires can occur in an enclosed area when the gases given off by pyrolysis reach a flammable concentration and are ignited by the heat of the fire. The result is a rapid increase in temperature and a gas fire throughout the enclosure. This type of fire is self-limiting due to the rapid consumption of the available oxygen. If the oxygen concentration is replenished the process can repeat itself. Flash fires normally do not occur in well ventilated fires due to the loss of the pyrolysis gases and unrestricted oxygen supplies.

Analysis of the gas data collected in the first-class cabin at station 498 (figures B-20, B-21, B-22) and the temperature data collected in the main cabin at station 1106 (figure B-17) indicate that a series of three flash fires occurred in the main cabin prior to the tail separating from the fuselage. These flash fires occurred at approximately 3 minutes 55 seconds, 5 minutes, and 6 minutes 30 seconds. Figure B-17 shows rapid temperature rises near the ceiling with peaks at the times stated. The oxygen data reveals a corresponding rapid decrease in the oxygen concentration (figure B-20). The carbon monoxide and carbon dioxide data show a corresponding rapid increase in concentrations (figures B-21 and B-22). Replenishment of the oxygen through the open forward doors allowed the process to repeat twice more before the tail separated. The large opening created by the tail separating vented the pyrolysis gases and allowed an unrestricted supply of oxygen to the fire.

FUSELAGE DESTRUCTION.

The external fuel fire burned steadily for 8 minutes and did not self-extinguish from lack of fuel until 11 minutes 15 seconds had elapsed. The fire plume was blown by the 12-knot wind against and over the rear fuselage (figures 4 and 5). However, long before the pool fire was out, the interior of the aircraft supported a self-sustaining cabin fire. Two minutes twenty-five seconds after the pool ignition a visible seat fire was observed in the main cabin. Two minutes thirty seconds into the test, heavy black smoke was observed pouring from the starboard rear service door. A small fireball erupted from the starboard rear service door at 2 minutes 47 seconds.

A flash fire occurred in the empennage crawlthrough at 2 minutes 51 seconds. Intermittent fire was observed coming out of the right rear service door beginning at 3 minutes 30 seconds. Heavy black smoke began to pour from the right overwing emergency door at 3 minutes 35 seconds (figure 6). White smoke began to pour from the right forward service door at 3 minutes 58 seconds. This quickly changed to heavy black smoke at 4 minutes 20 seconds.

The main cabin experienced a series of flash fires at approximately 3 minutes 55 seconds, 5 minutes, and 6 minutes 30 seconds.

The entire tail section of the aircraft separated at approximately station 1264 and collapsed to the ground at 8 minutes 12 seconds (figure 7).

The port side windows burned through from the inside at stations 973 and 1011 at the 10-minute mark (figure 8).

Heavy black smoke began to pour from the port forward entry door at 14 minutes 16 seconds, followed by flames in the doorway at 19 minutes.

FIGURE 4. FULLY DEVELOPED FUEL FIRE, FORWARD VIEW, 20 SECONDS AFTER IGNITION

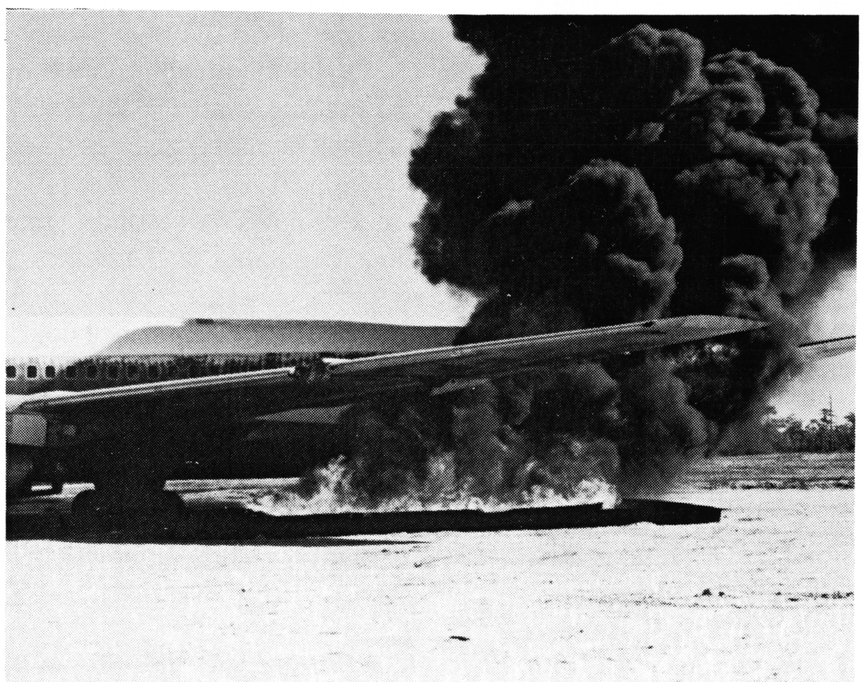

FIGURE 5. FULLY DEVELOPED FUEL FIRE, 20 SECONDS AFTER IGNITION

FIGURE 6. SMOKE POURS FROM STARBOARD OVERWING EXIT, 3 MINUTES 35 SECONDS AFTER IGNITION

FIGURE 7. TAIL SEPARATES FROM FUSELAGE, 8 MINUTES 12 SECONDS AFTER IGNITION

FIGURE 8. INTERNAL FIRE PROGRESSES FORWARD TO STATION 933, 10 MINUTES AFTER IGNITION

The top of the fuselage began to turn brown at stations 749 and 603, and by 20 minutes 12 seconds, the entire top of the fuselage from station 749 aft is burned through (figure 9). Flames penetrated the top of the fuselage at station 508 at 21 minutes 45 seconds. The entire top of the fuselage from station 479 aft was consumed by the fire at 23 minutes 20 seconds. By 24 minutes 50 seconds, this had progressed to station 342 (figure 10). At 27 minutes 55 seconds, all combustibles aft of station 758 were consumed, the fuselage was burned down to the window level, and the fire continued to burn in the first-class cabin. By 29 minutes 30 seconds, the fire in the first-class cabin and the cockpit began to die down as all remaining combustibles were consumed.

At 33 minutes, the remaining smoldering fire was extinguished by the Airport Fire Service (figure 11).

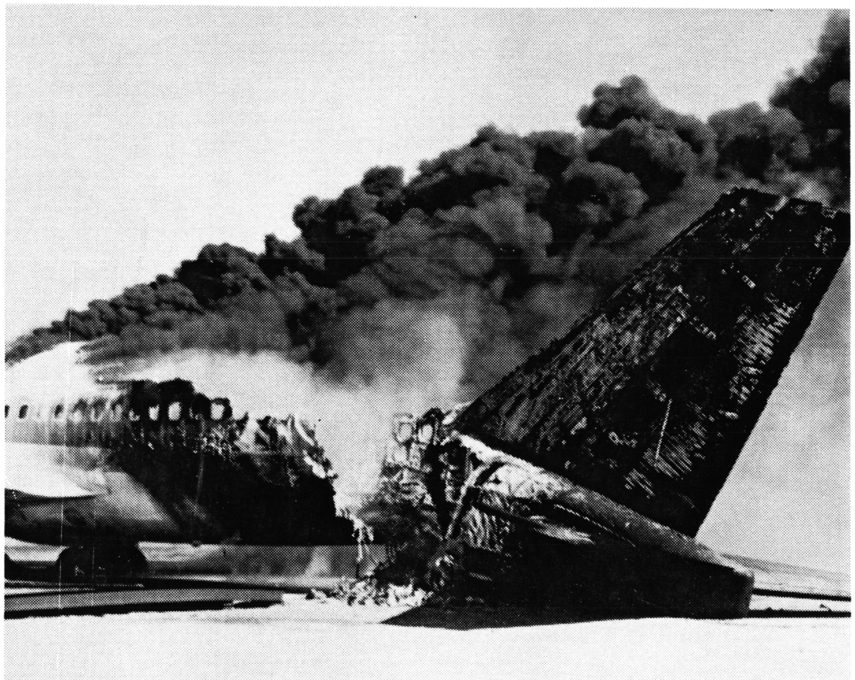

FIGURE 9. THE TOP OF THE FUSELAGE IS BURNED THROUGH FROM STATION 749 AFT, 20 MINUTES 12 SECONDS AFTER IGNITION

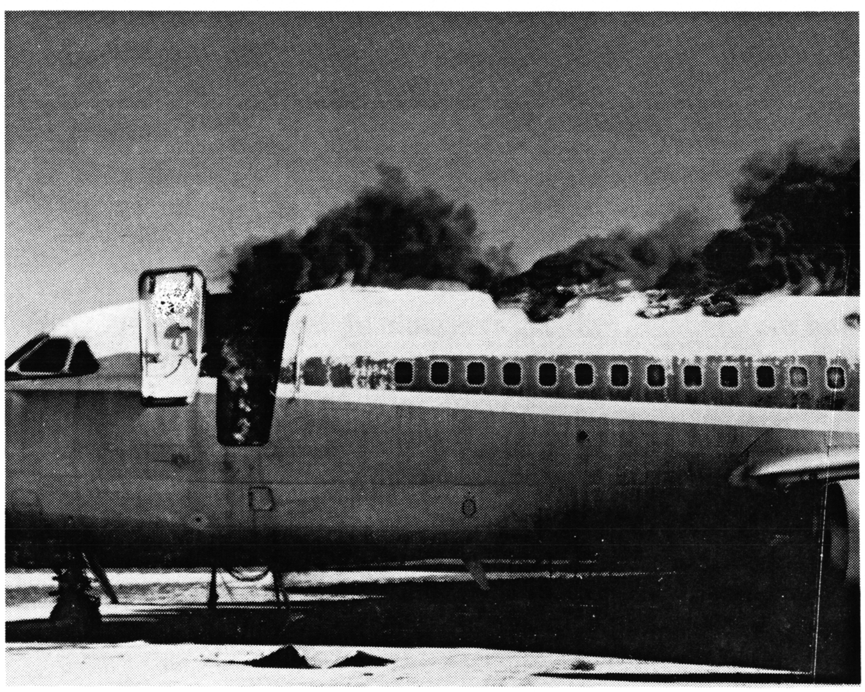

FIGURE 10. FIRST-CLASS CABIN IS COMPLETELY ENGULFED IN FLAMES, 24 MINUTES 50 SECONDS AFTER IGNITION

FIGURE 11. REMAINING FIRE IS EXTINGUISHED BY AIRPORT FIRE SERVICE, 33 MINUTES AFTER IGNITION

FUSELAGE DAMAGE. The fuselage was intentionally allowed to burn completely. One objective of this portion of the test was to examine the unimpeded fire propagation in an "unrescued" fuselage. This allowed observation of the time and manner for the interior fire to destroy the top of the fuselage. The Airport Fire Service was instructed to standby until the interior fire had run its course.

The entire interior of the aircraft was completely gutted. There were no recognizable interior furnishings. All of the windows, with the exception of those on the flight deck, were consumed. The top of the fuselage was burned down to just above the windows (figures 12 and 13). The entire empennage assembly was separated from the fuselage at station 1264 (figure 14). The cabin floor was consumed aft of the main wing spar. Forward of the main wing spar, the floor was intact as well as the forward cargo compartment. The remaining floor support beams were weakened, twisted, and sagging.

The forward cargo compartment ceiling liners were pulled away and charred (figure 15). The forward cargo compartment door was operational.

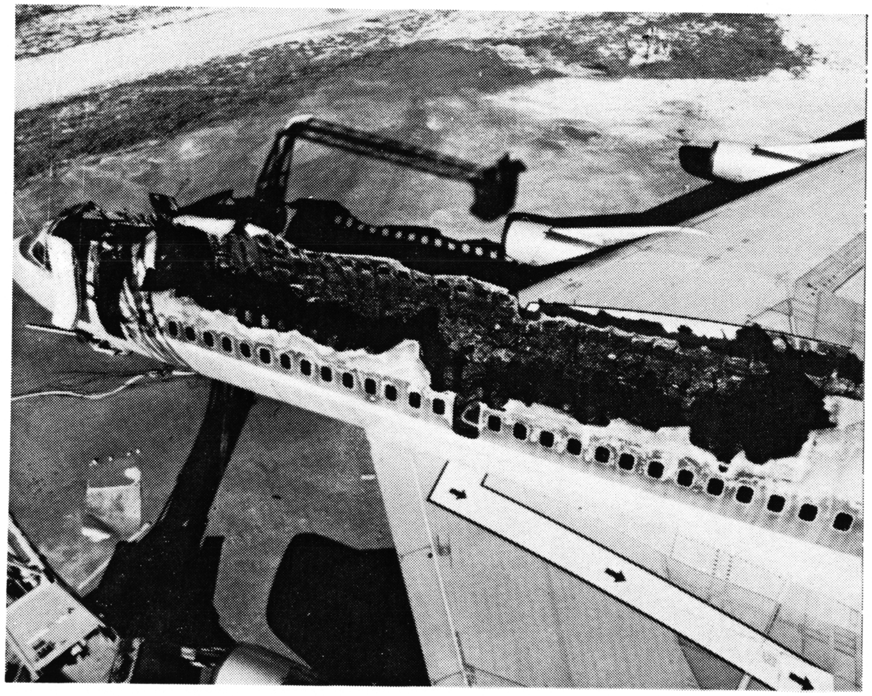

FIGURE 12. AERIAL VIEW OF CABIN FORWARD AFTER FIRE

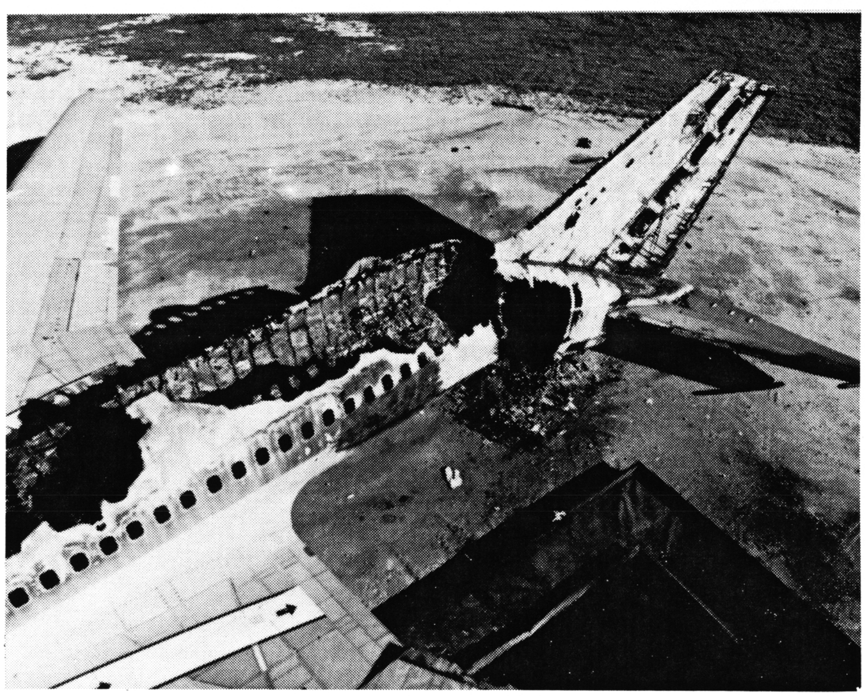

FIGURE 13. AERIAL VIEW OF CABIN AFT AFTER FIRE

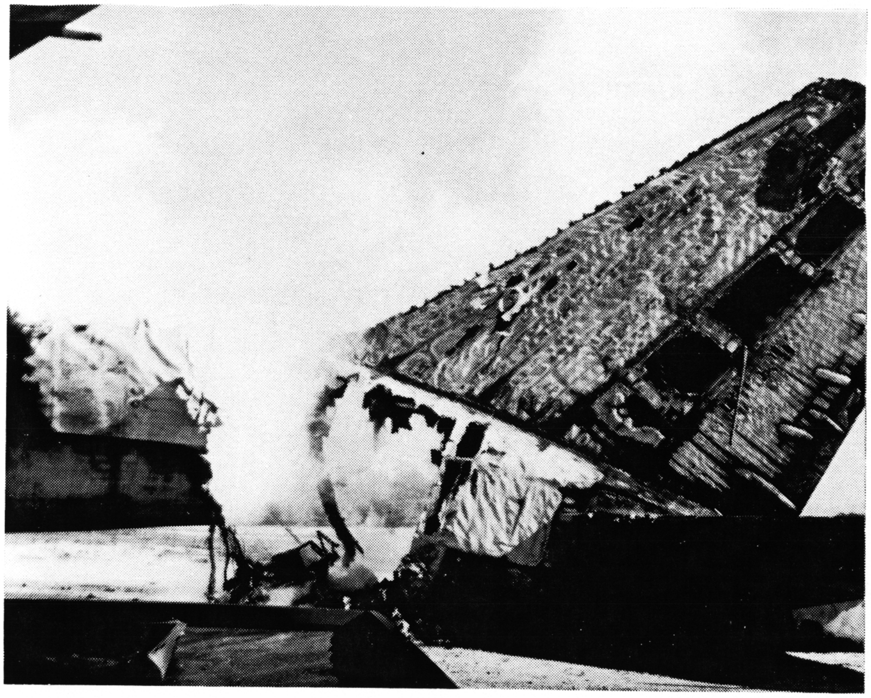

FIGURE 14. THE EMPENNAGE SEPARATED FROM THE FUSELAGE AT STATION 1264

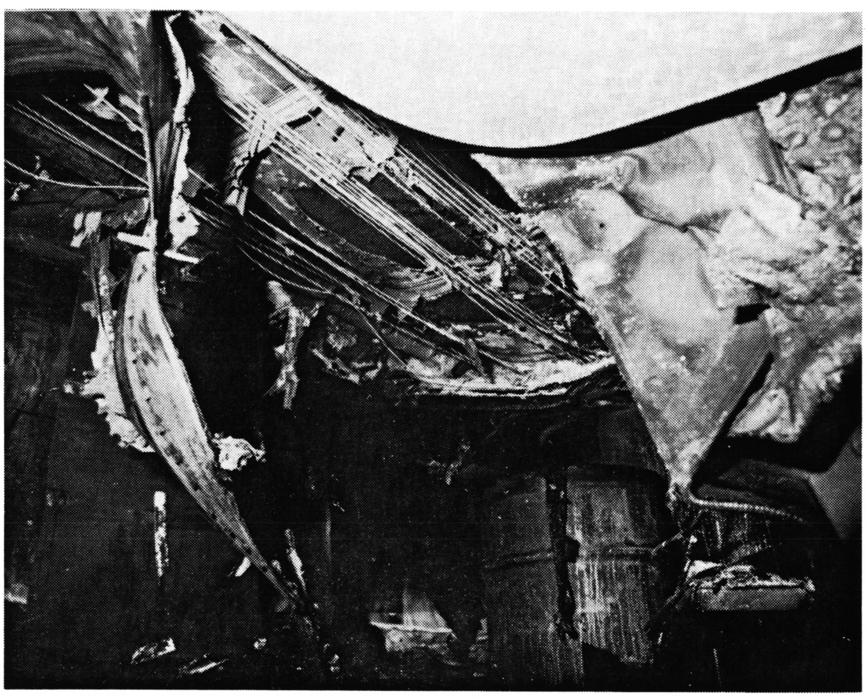

FIGURE 15. FORWARD CARGO COMPARTMENT CEILING LINERS ARE PULLED AWAY AND CHARRED

The skin on both sides of the leading edge of the vertical stabilizer and the port horizontal stabilizer was perforated. The starboard side of the vertical stabilizer was heavily coated with soot (figure 16). The starboard horizontal stabilizer was soot coated but relatively undamaged. The tail cone was lightly soot coated but undamaged to the naked eye.

The port wing had a light soot coating on the underside and the skin on the trailing edge was melted. The upper surface of the wing was clean and undamaged. The starboard wing was clean and undamaged. The landing gear and tires were not damaged by the fire.

FIGURE 16. STARBOARD SIDE OF VERTICAL STABILIZER HEAVILY COATED WITH SOOT

DISCUSSION.

The investigators of the accident at Manchester determined that the external fuel fire penetrated the Boeing 737 left cheek area in approximately 5 to 20 seconds. This provided the fire with two paths. The first was to allow fire and smoke to travel up into the passenger cabin through the floor level air conditioning grills. The second path available to the fire was to travel across the aircraft through the cavity formed by the cargo compartment ceiling and the cabin floor. Both of these paths were "powered" by differential pressure gradients caused by the exterior wind blowing across the fuselage and the combination of aircraft door openings.

In addition to this method of fire entry, it was also determined that the external fire entered the cabin by direct penetration just above the floor level within 1 minute after the aircraft stopped.

They found no evidence of a fully developed flashover or flash fire but did, however, allow for a number of localized gaseous ignitions.

The investigators also stressed the significance of the crosswind to the fire development and the entry paths.

The results of this test did confirm some of the Manchester findings although penetration into the aircraft occurred at a slower pace. The first indication of penetration occurred at 1 minute 10 seconds in both the empennage crawlthrough and the main cabin. In each case, the method was direct penetration by melting fuselage skin. The penetration in the crawlthrough was more severe with little to impede the fire after the skin failed. The penetration into the main cabin was quite small and did not result in igniting any cabin furnishings for close to 1 minute 15 seconds. There was no evidence of a mechanism that would have drawn the fire under the floor nor was there any thermocouple data to indicate that the fire traveled into the main cabin through the floor grills.

The offset, wind-driven fire was proven to be similar in severity to a fire located directly under the fuselage. The skin melt and penetration times were consistent with those found in previous testing. However, the differential pressure effects caused by the wind and the open doorways were unconfirmed. The open doorways did contribute to the recurrent flash fires by allowing additional oxygen in.

The data collected indicate that three flash fires occurred in the main cabin prior to the tail separating at 8 minutes 12 seconds.

The fuselage did not exhibit the same degree of downwind (starboard) side fuselage damage that was described in the Manchester report. The combination of fuel fire location and wind speed and direction caused most of the flames from the offset fuel fire to strike the fuselage and go over the top of the aircraft. This leeward damage was very pronounced in the previous testing performed with the fuel fire located under the fuselage and a light crosswind. It is possible that a shift of the fuel fire to a location closer to the aircraft might result in more of the fire plume blowing under the fuselage and correspondingly more leeward side fire damage.

CONCLUSIONS

1. A wind-driven flame from an offset fire source is similar to a fire located directly under the fuselage in terms of burnthrough and fuselage damage. The fuel fire produced a burnthrough time of 1 minute 10 seconds after pool ignition.

2. The mode of fire penetration into the cabin was direct melting of the fuselage skin and burning of the insulation and interior panels.

3. There was no evidence of fire spreading across the aircraft beneath the cabin floor, either over or under the aft cargo compartment.

4. The open rear service door was not a factor in starting the interior fire.

5. The open outflow valve was not a factor in starting the interior fire.

6. The separation of the tail assembly allowed direct flame impingement to the interior of the rear of the aircraft.

7. A series of three flash fires occurred in the main cabin prior to the tail separating.

8. The divider between coach and first class impeded the flow of smoke and radiant heat from the rear of the aircraft to the front.

9. The configuration of open doors and external wind conditions produced some airflow from the front of the aircraft to the rear as evidenced by the slow smoke propagation forward.

10. The interior cabin materials, once ignited, easily supported a self-sustaining fire until all flammable materials were consumed.

REFERENCES

1. Webster, H. et al., Full-Scale Air Transport Category Fuselage Burnthrough Tests, DOT/FAA/CT-TN89/65, February 1990.

2. King, D. F., Aircraft Accident Report No. 8/88, Air Accidents Investigation Branch, Royal Aerospace Establishment, Farnborough, England, December 15, 1988.

APPENDIX A—CONVAIR 880 STATION DIAGRAM

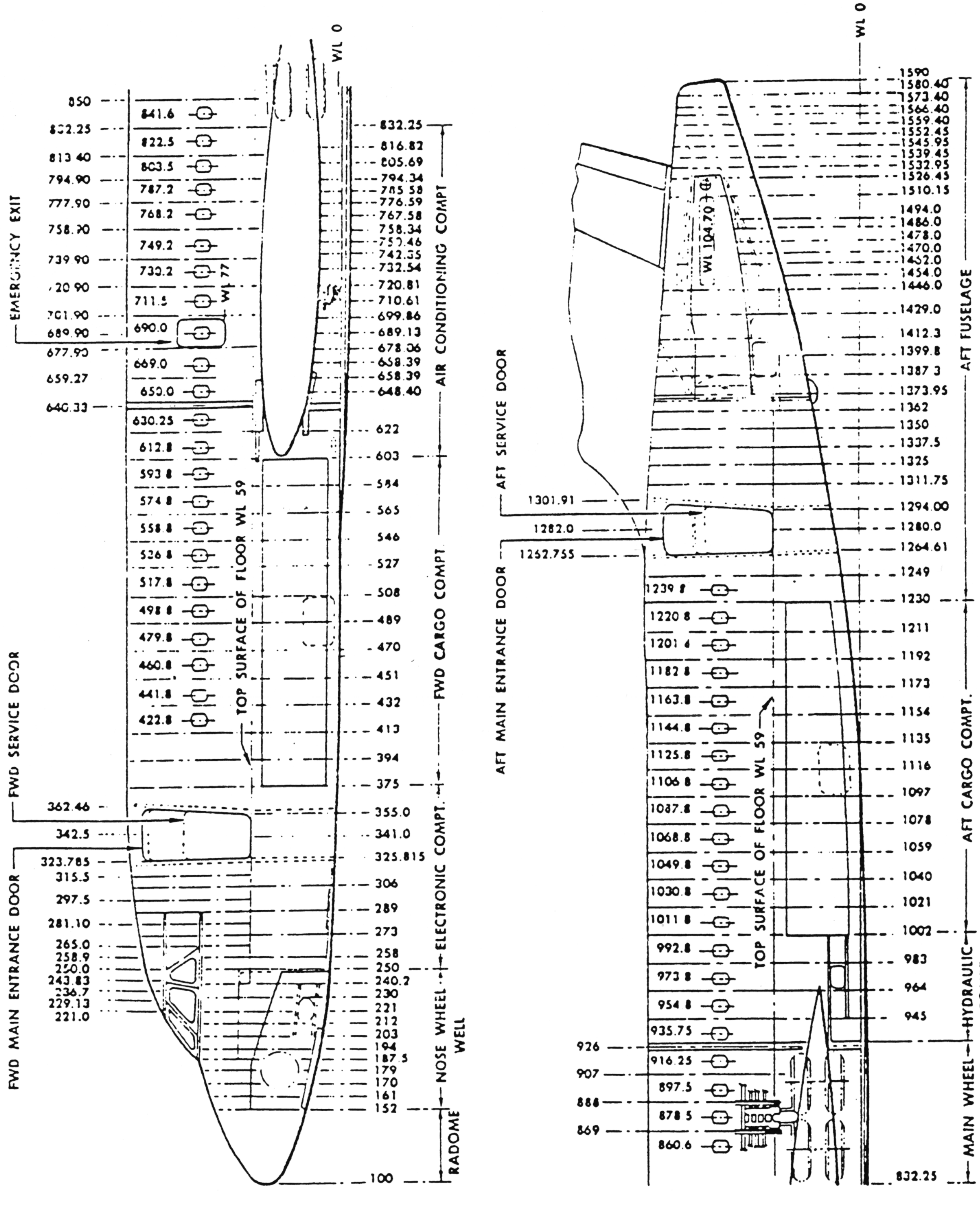

FIGURE A-1. FUSELAGE STATION DIAGRAM

APPENDIX B—SELECTED SENSOR DATA PROFILES USED IN TEXT ANALYSIS

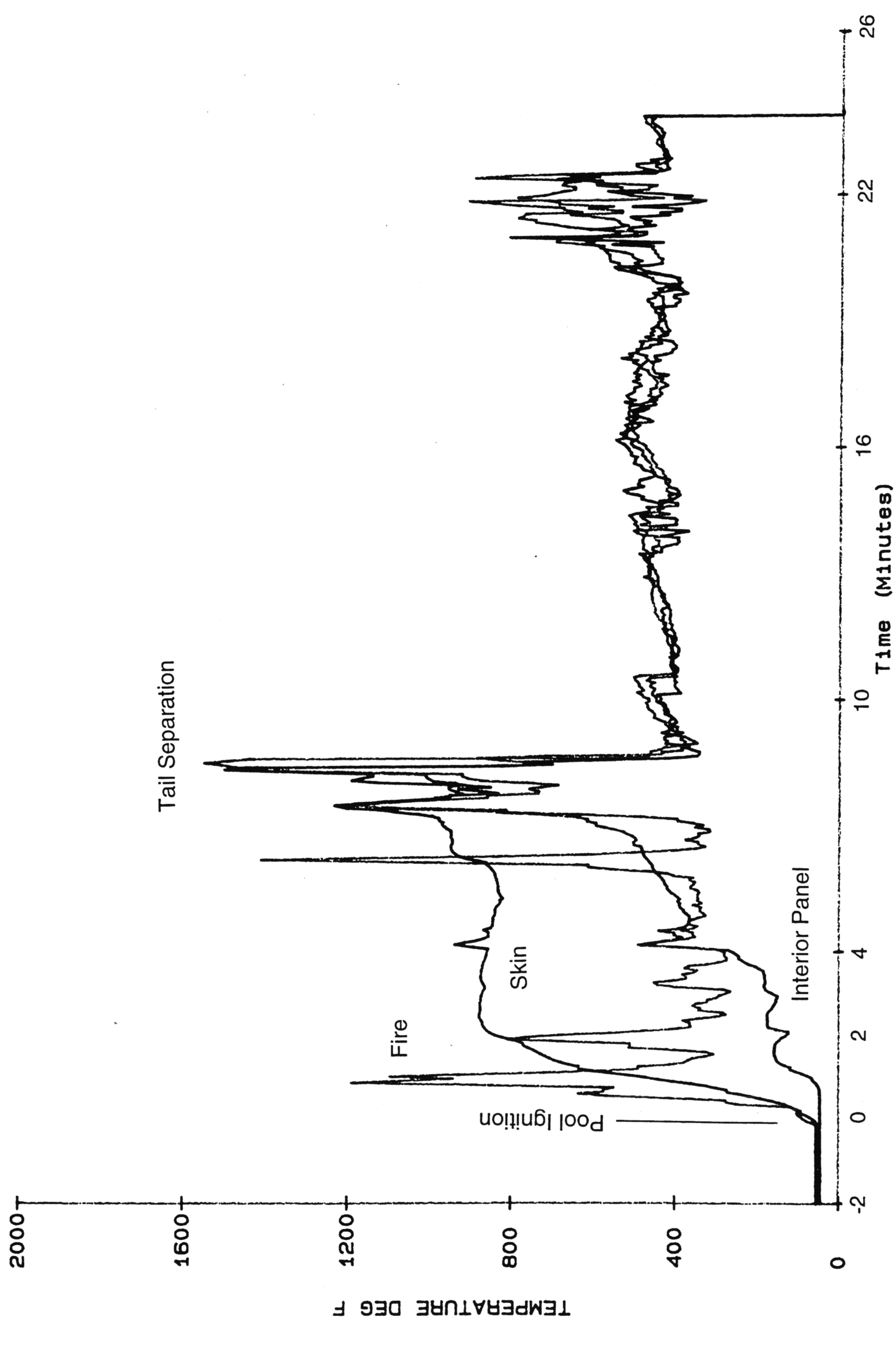

FIGURE B-1. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, BELOW THE WINDOW, PORT SIDE

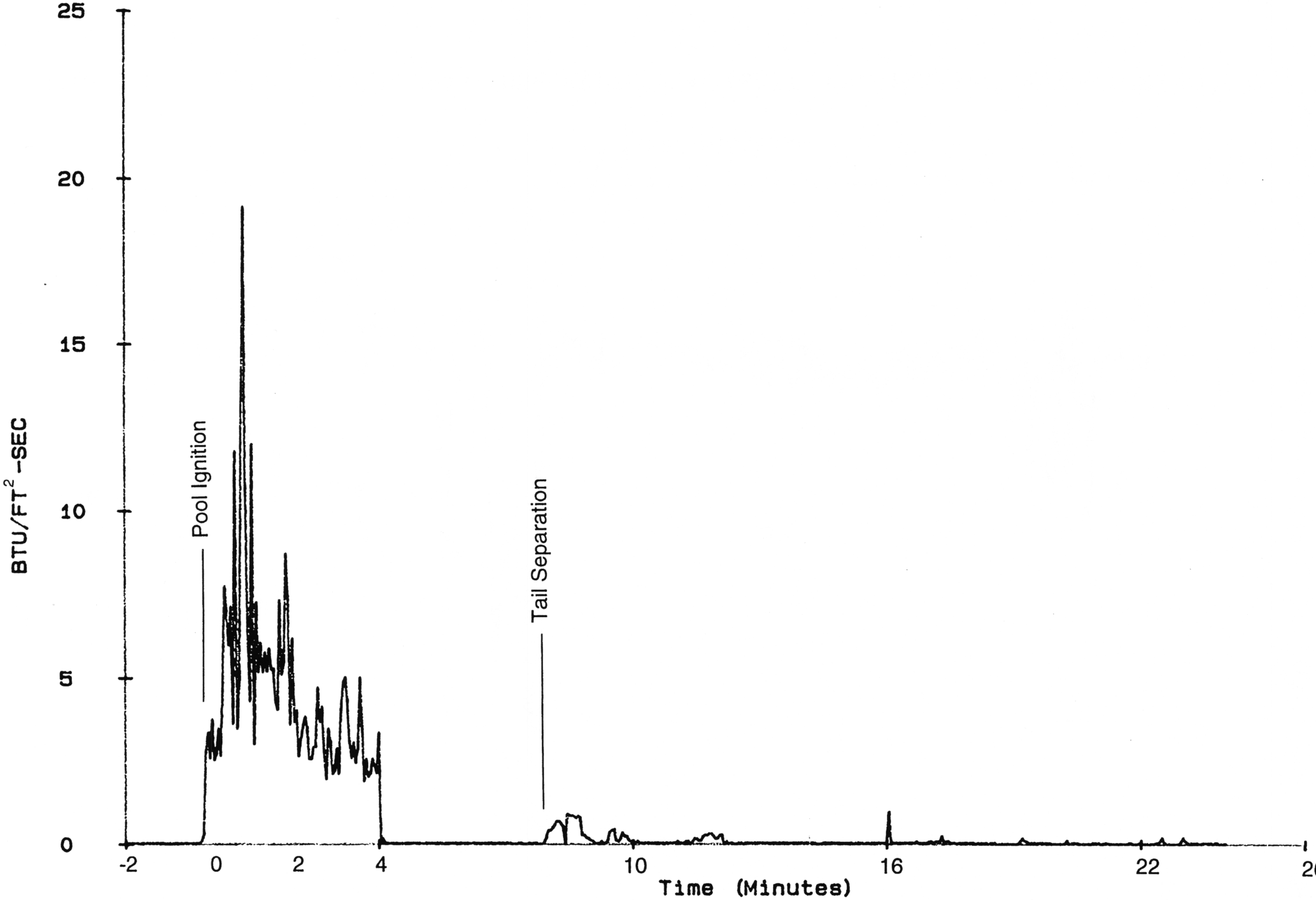

FIGURE B-2. EXTERNAL HEAT FLUX AT STATION 1192, PORT SIDE

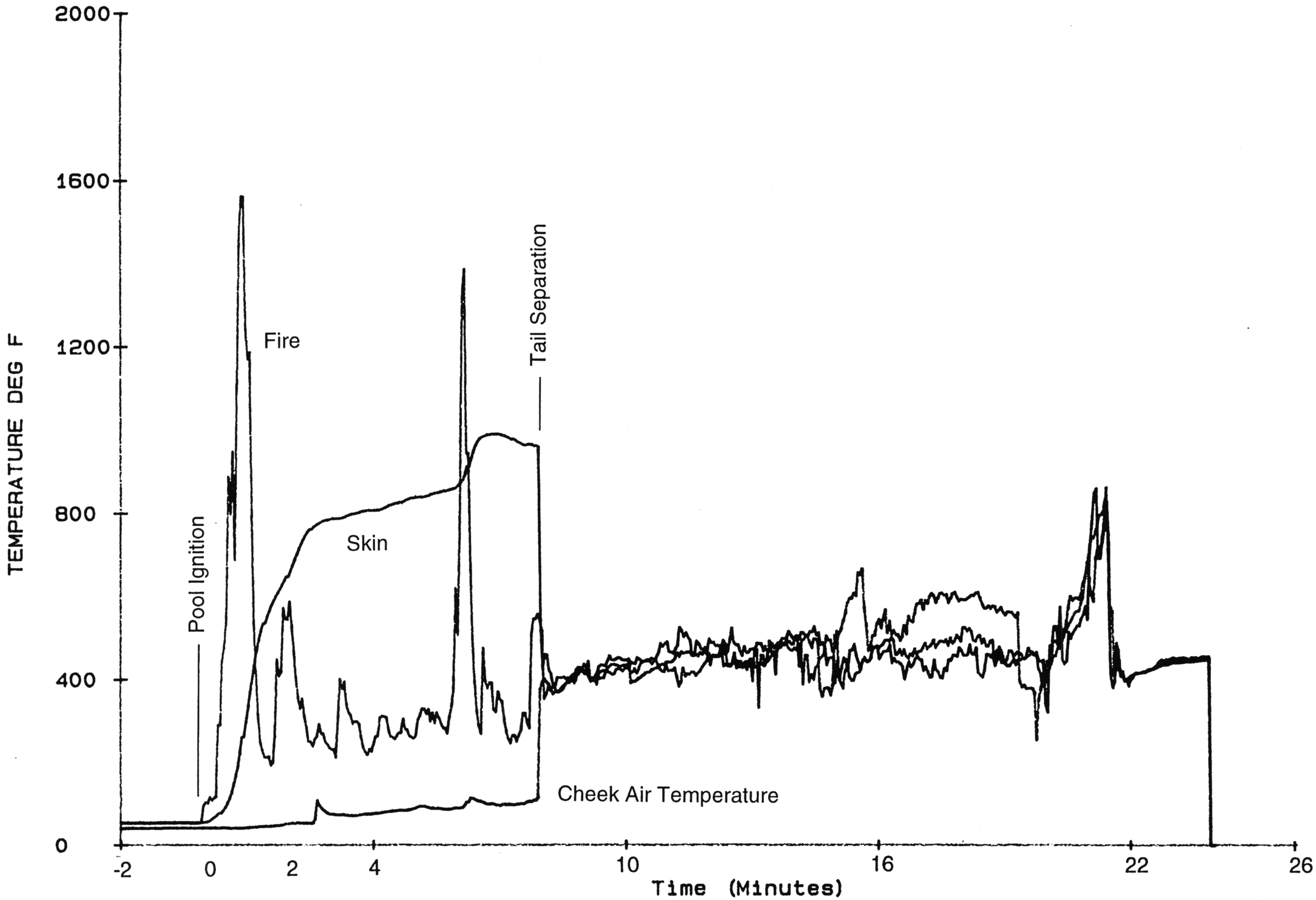

FIGURE B-3. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, CHEEK AREA, PORT SIDE

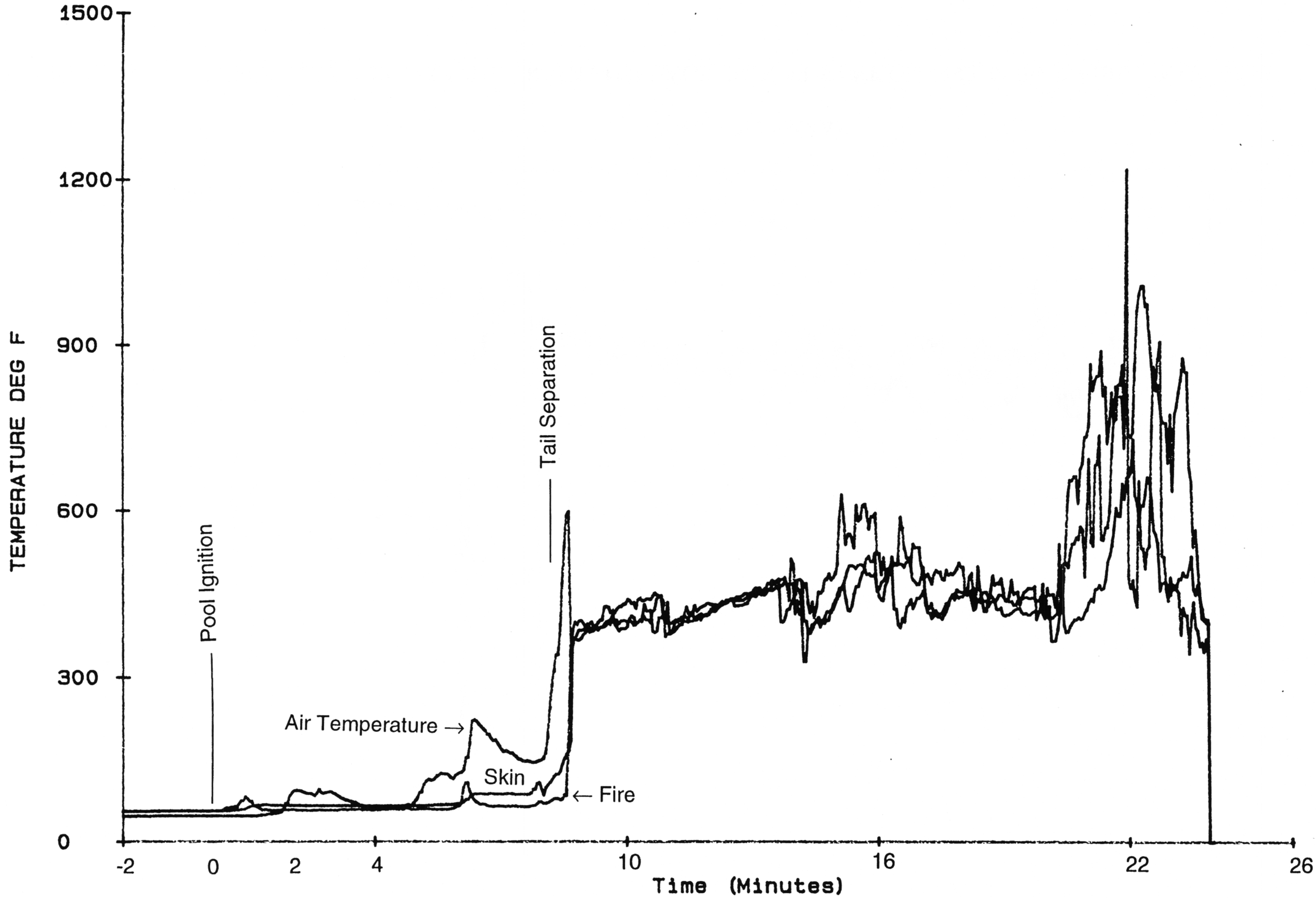

FIGURE B-4. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, CHEEK AREA, STARBOARD SIDE

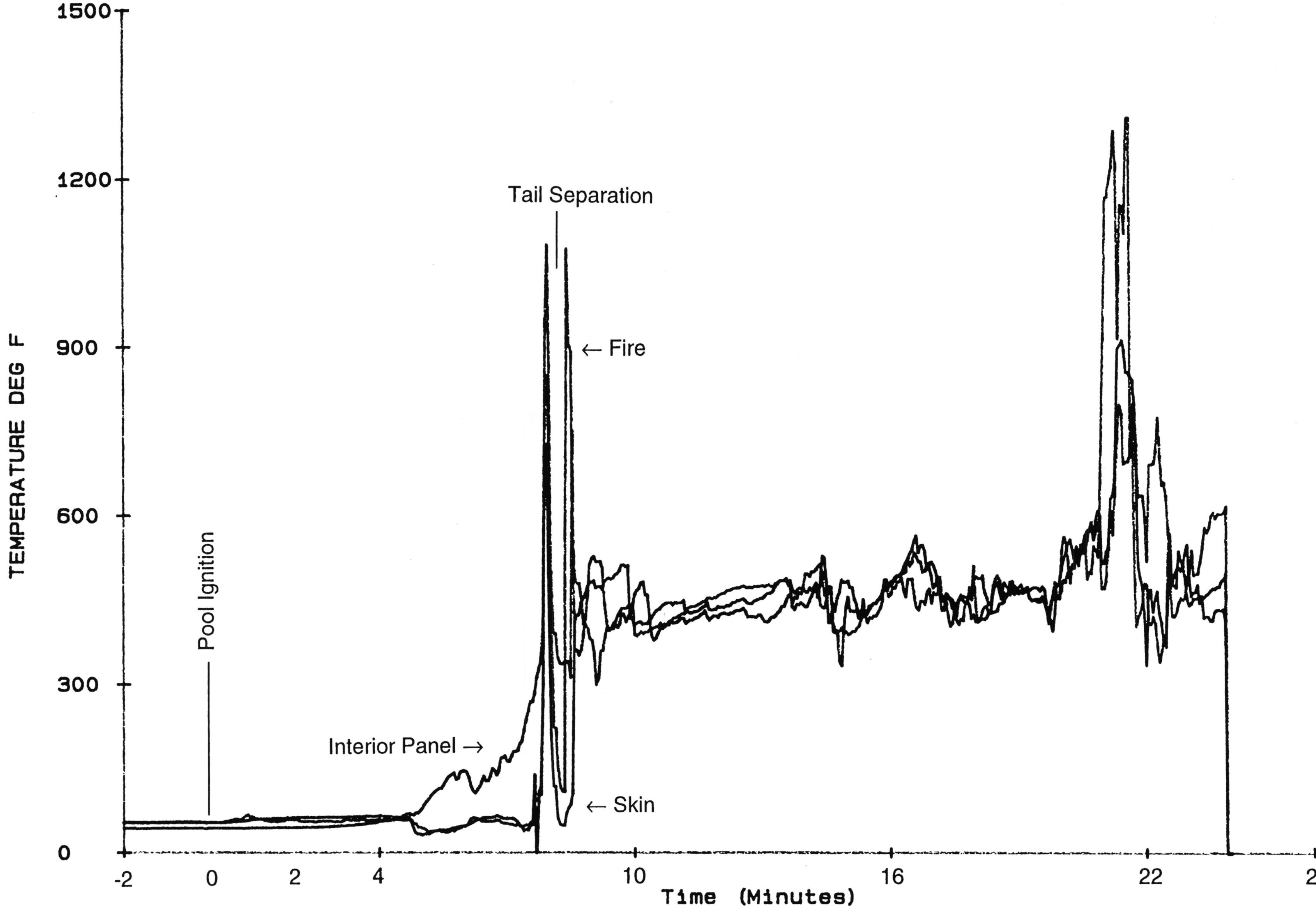

FIGURE B-5. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, BELOW WINDOW, STARBOARD SIDE

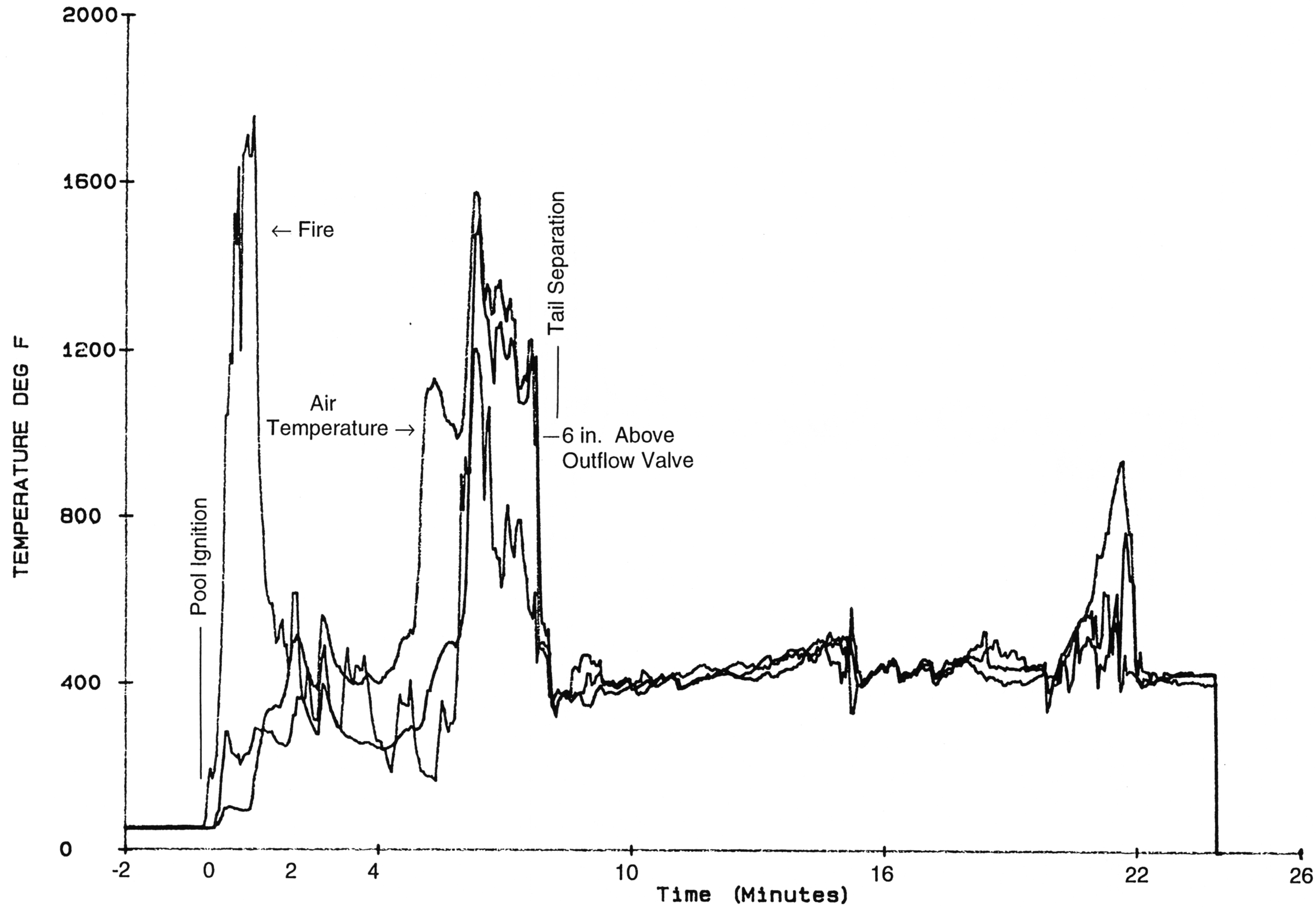

FIGURE B-6. AIR TEMPERATURE IN THE CRAWLTHROUGH AND ABOVE THE OUTFLOW VALVE AT STATION 1300

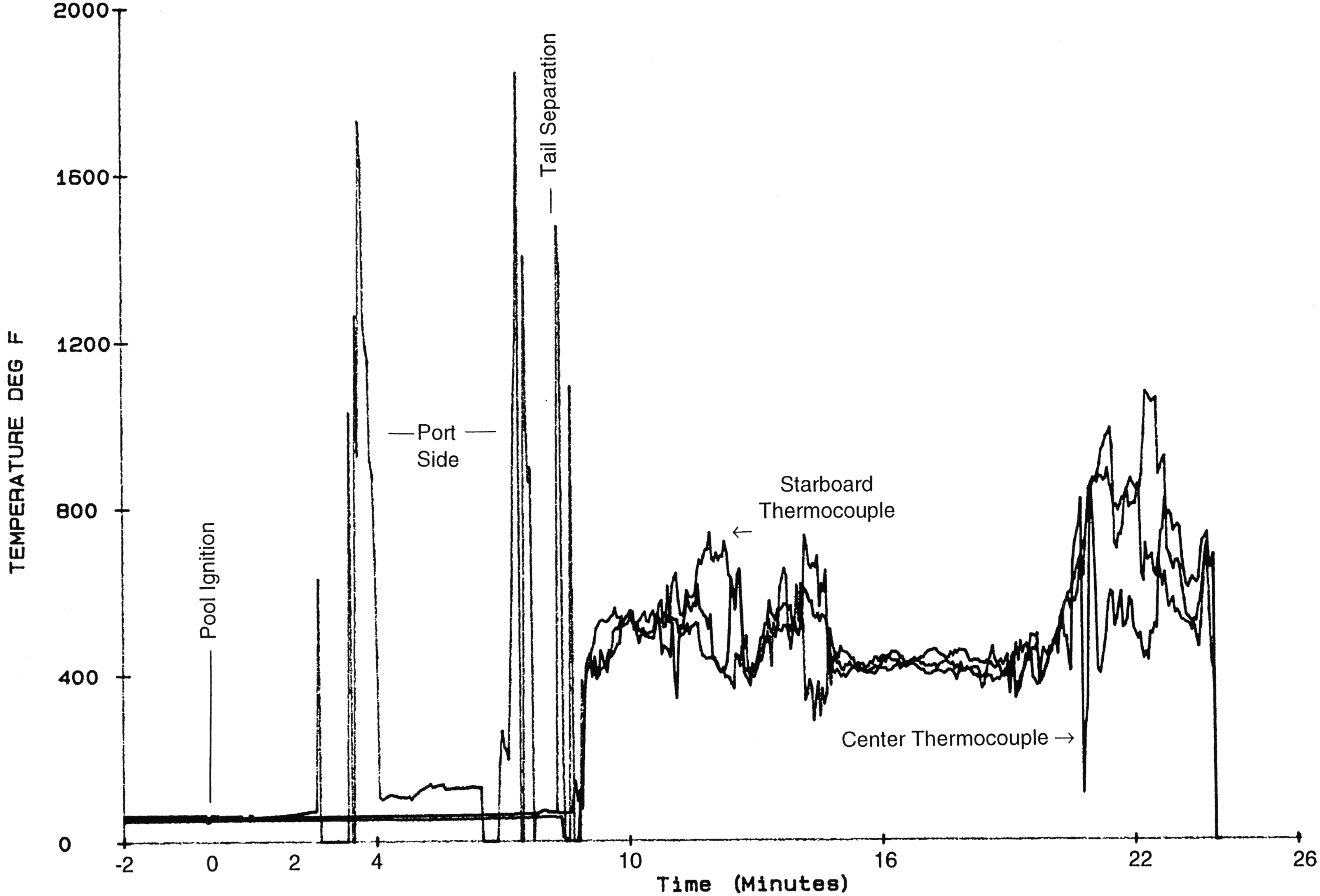

FIGURE B-7. AIR TEMPERATURE UNDER THE CARGO COMPARTMENT FLOOR AT STATION 1192

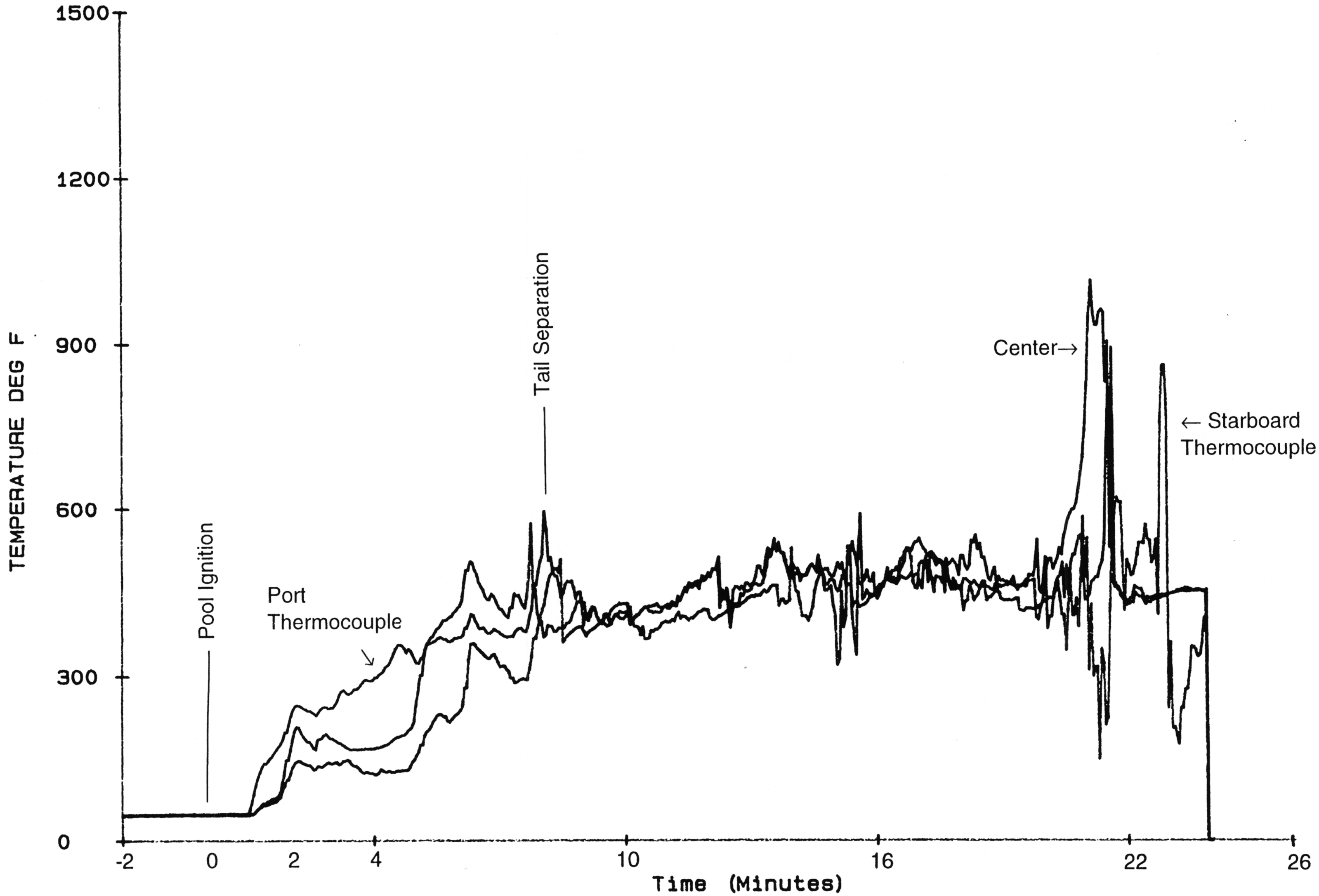

FIGURE B-8. AIR TEMPERATURE ABOVE THE CARGO COMPARTMENT FLOOR AT STATION 1192

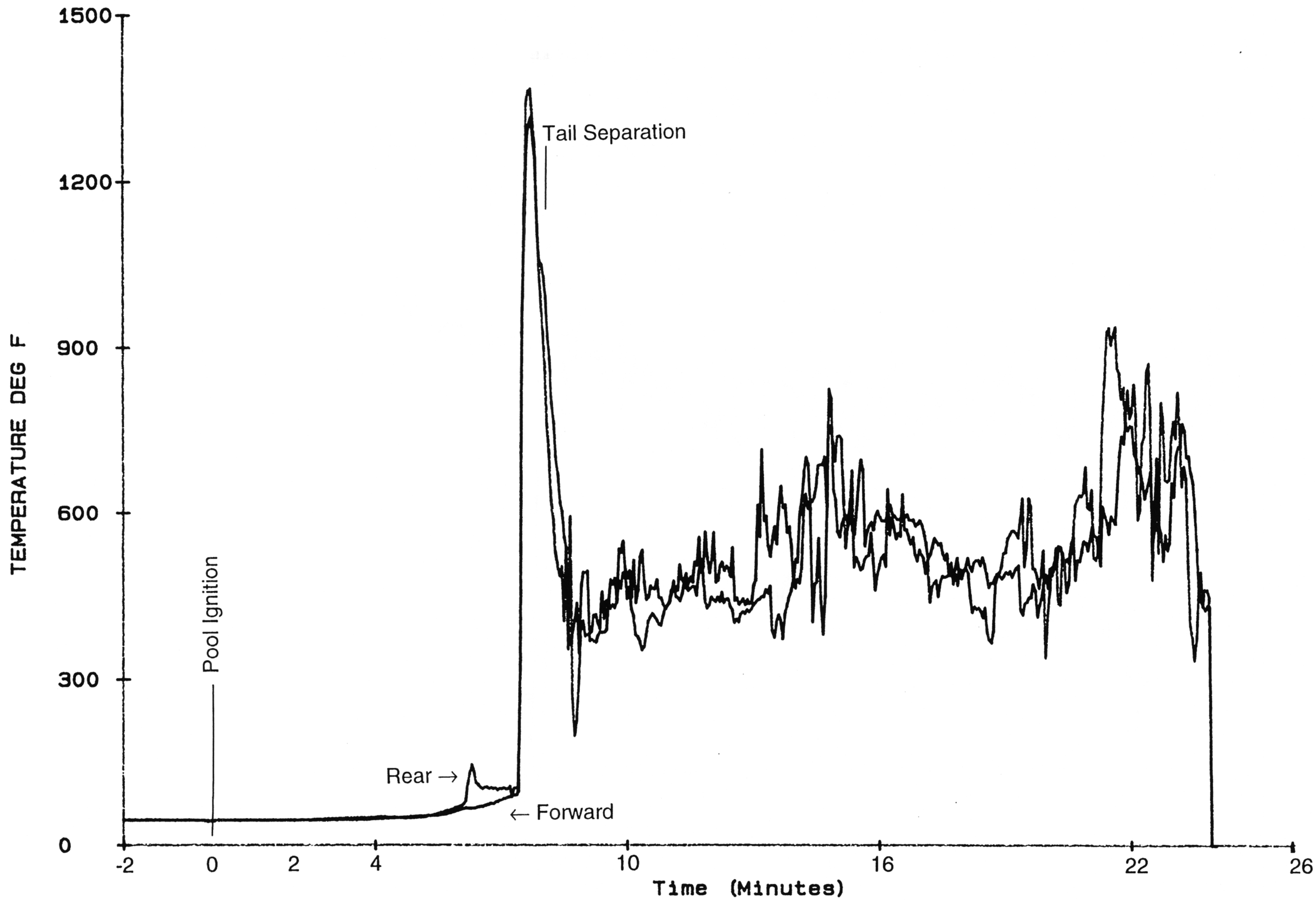

FIGURE B-9. AIR TEMPERATURE AT THE FLOOR GRILLS AT STATIONS 1192 AND 1040, STARBOARD SIDE

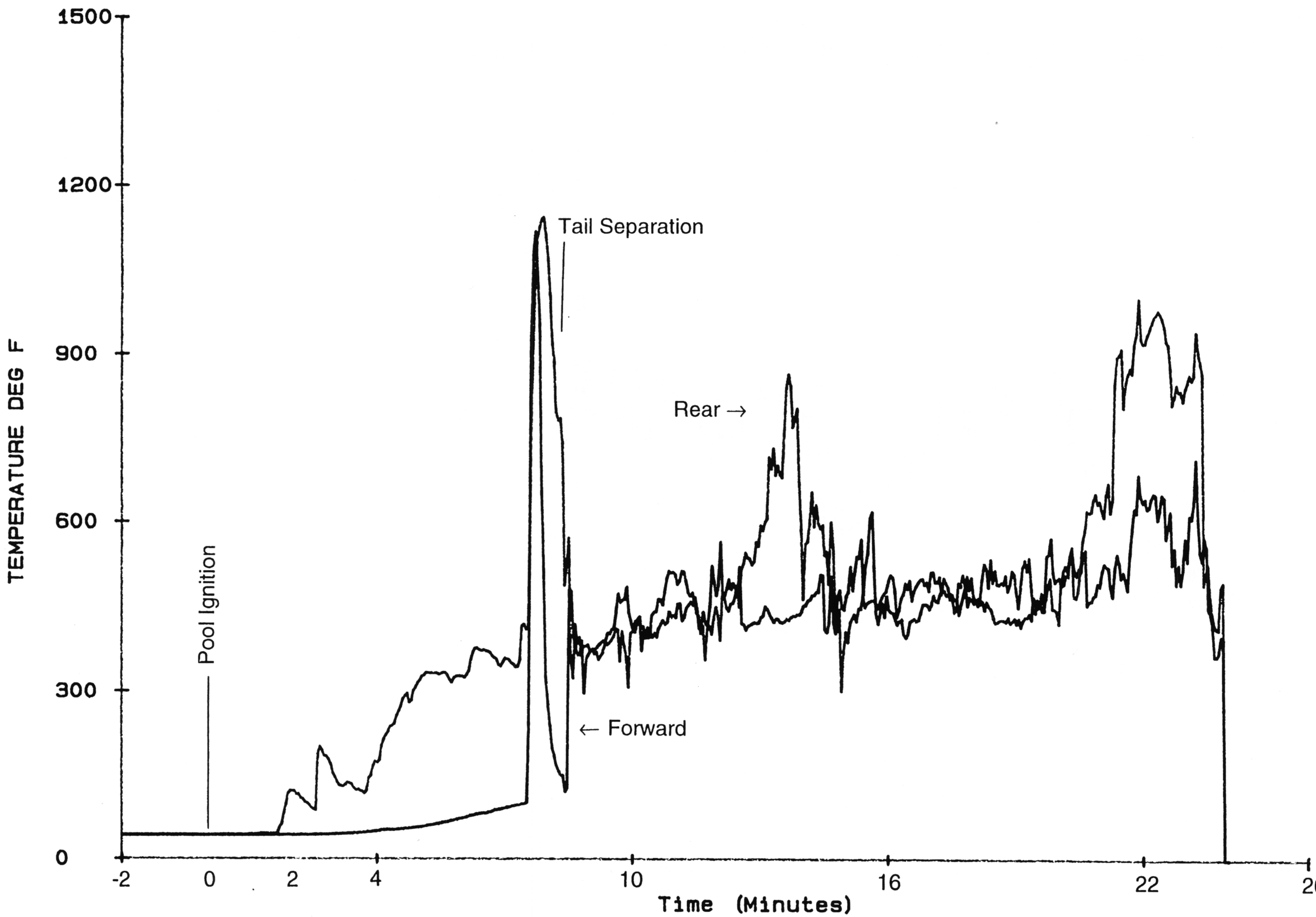

FIGURE B-10. AIR TEMPERATURE AT THE FLOOR GRILLS AT STATIONS 1192 AND 1040, PORT SIDE

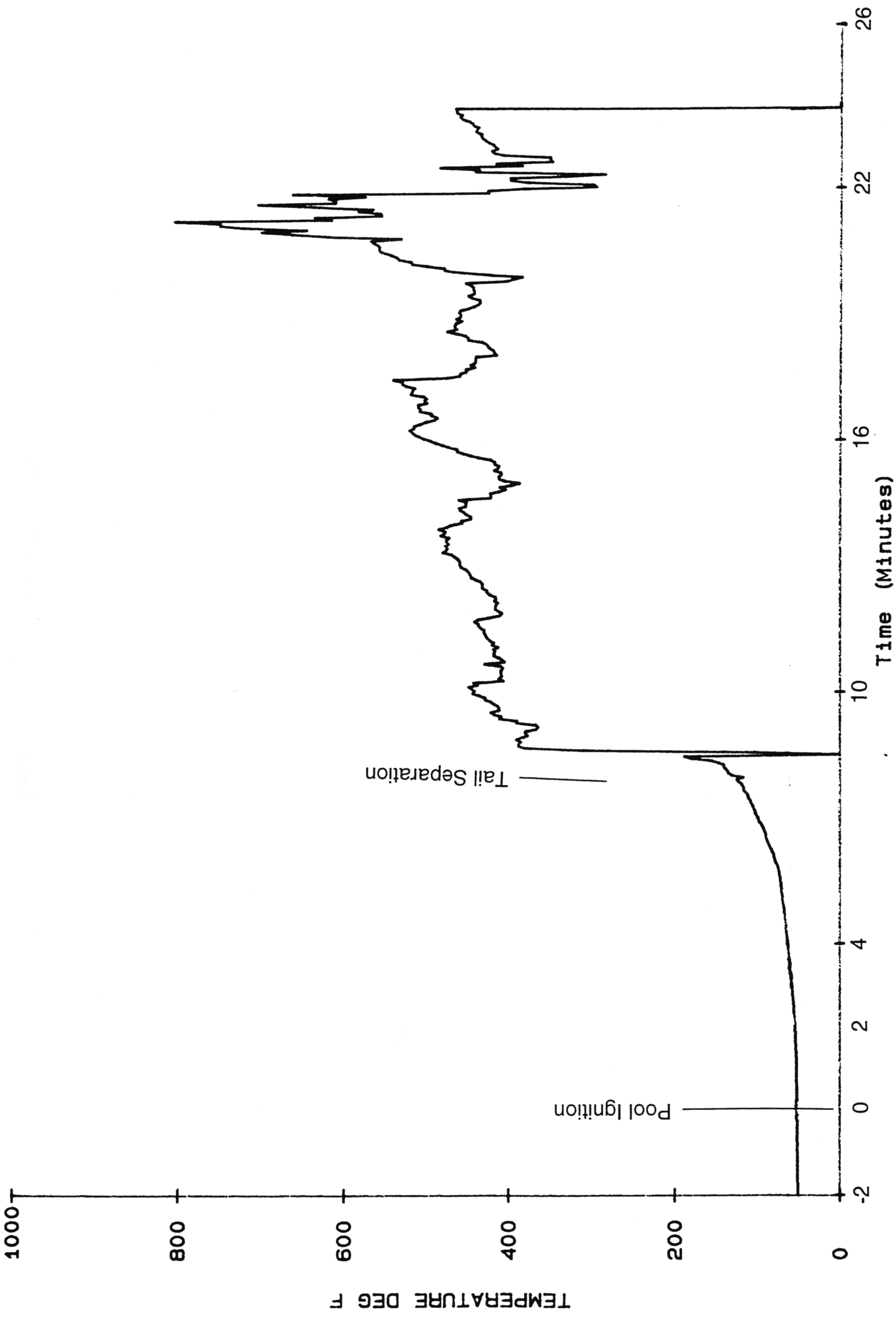

FIGURE B-11. CARGO COMPARTMENT AIR TEMPERATURE AT STATIONS 1040 AND 1192

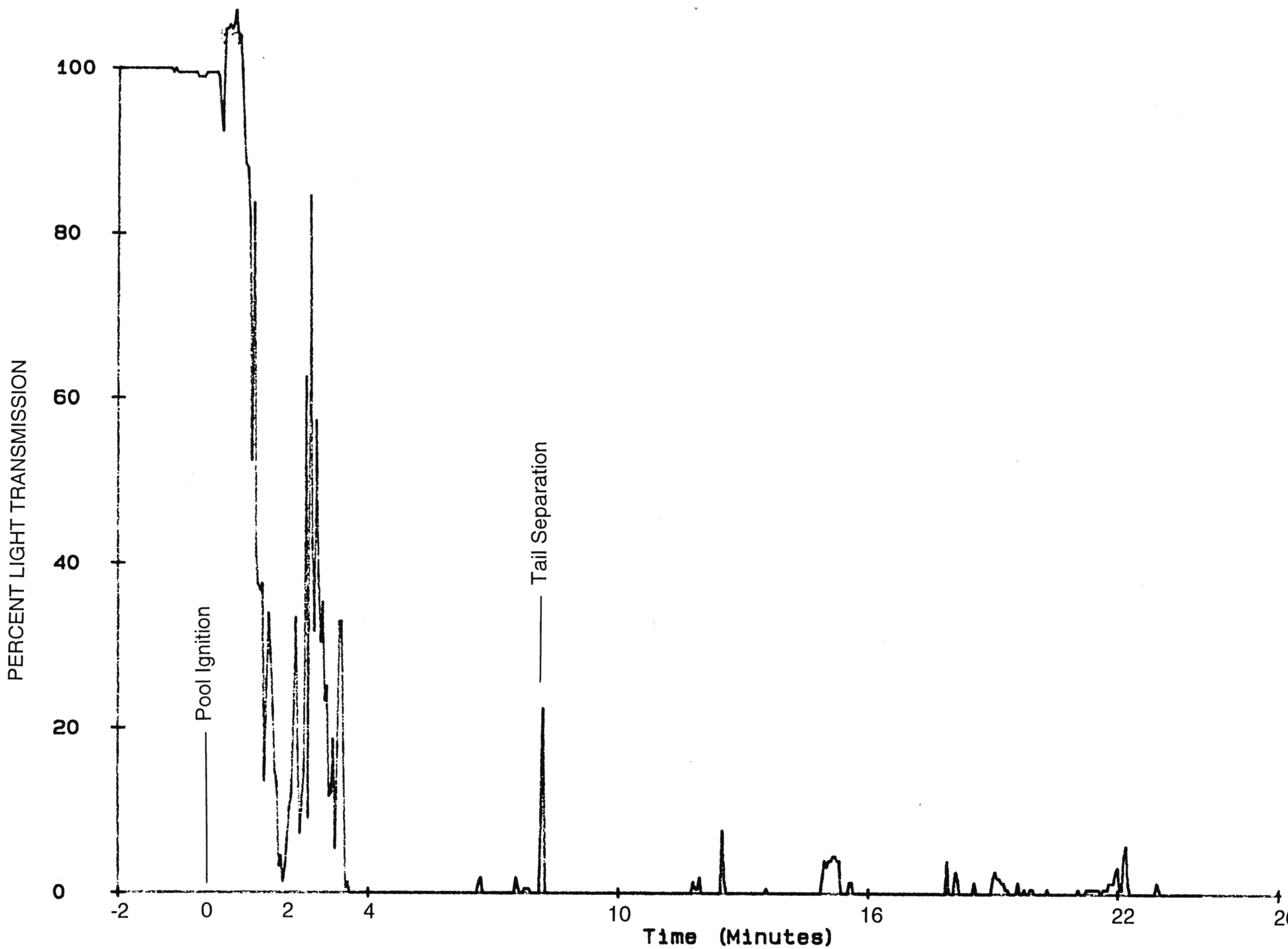

FIGURE B-12. SMOKE DENSITY AT STATION 1280

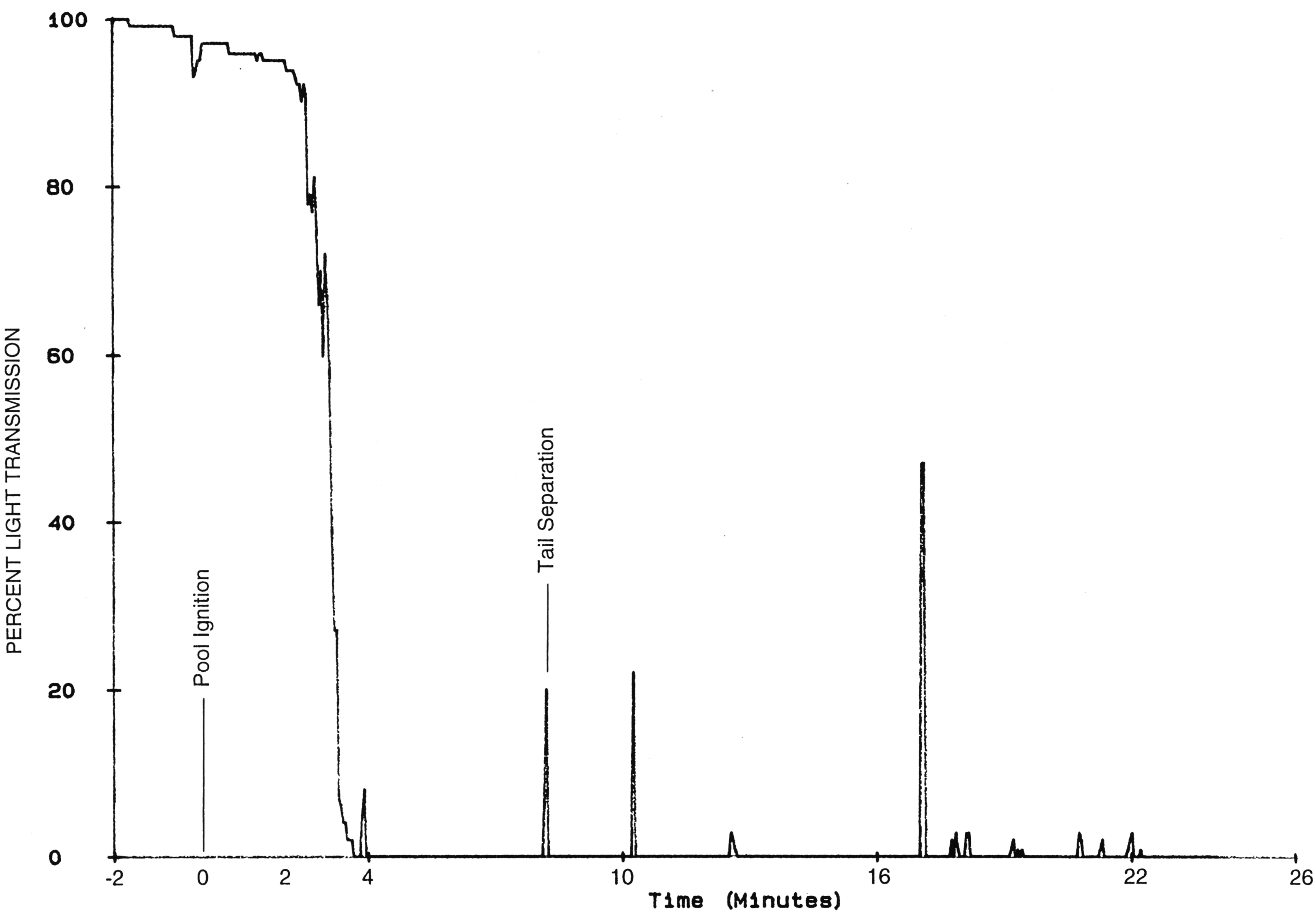

FIGURE B-13. SMOKE DENSITY AT STATION 1106

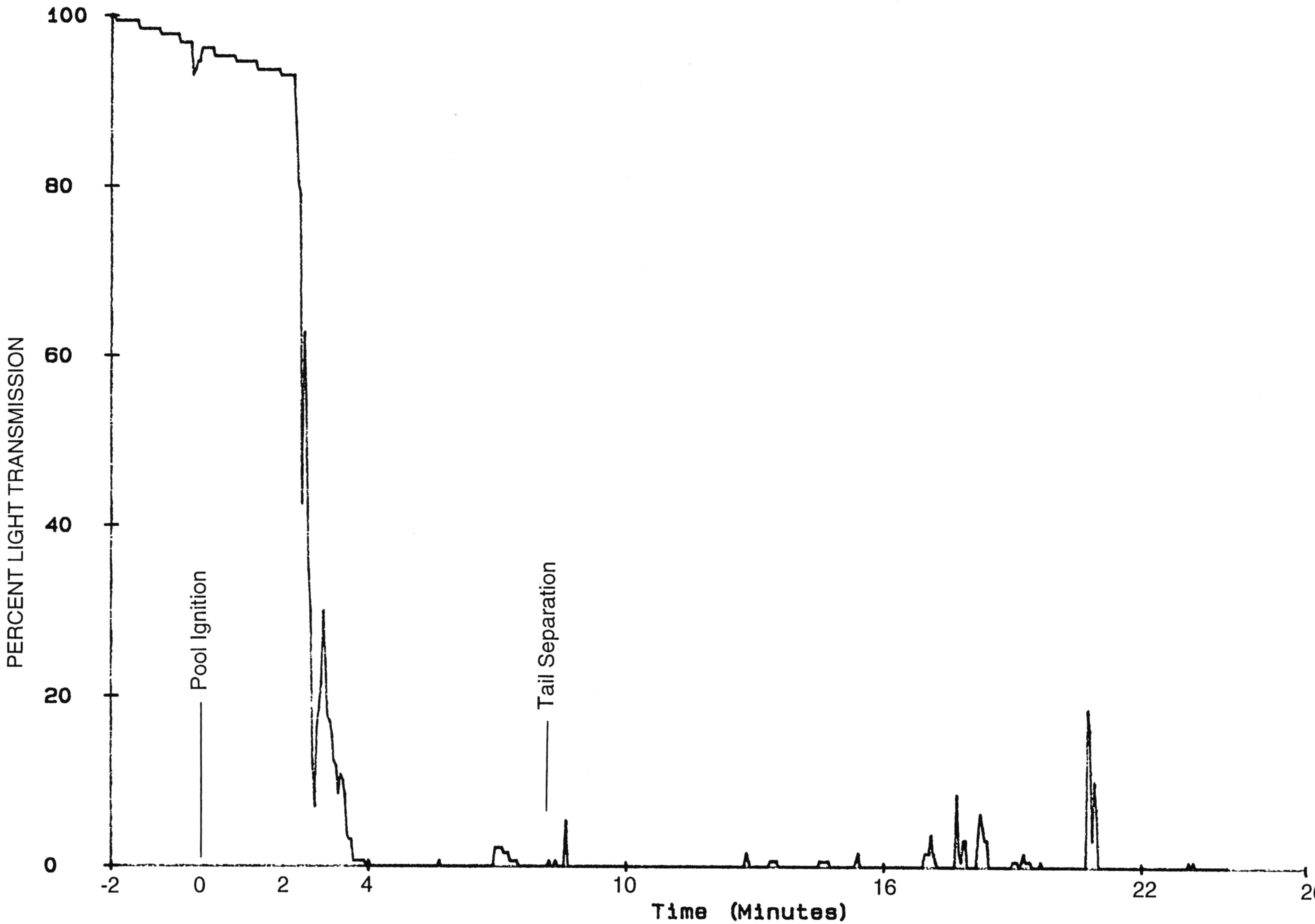

FIGURE B-14. SMOKE DENSITY AT STATION 669

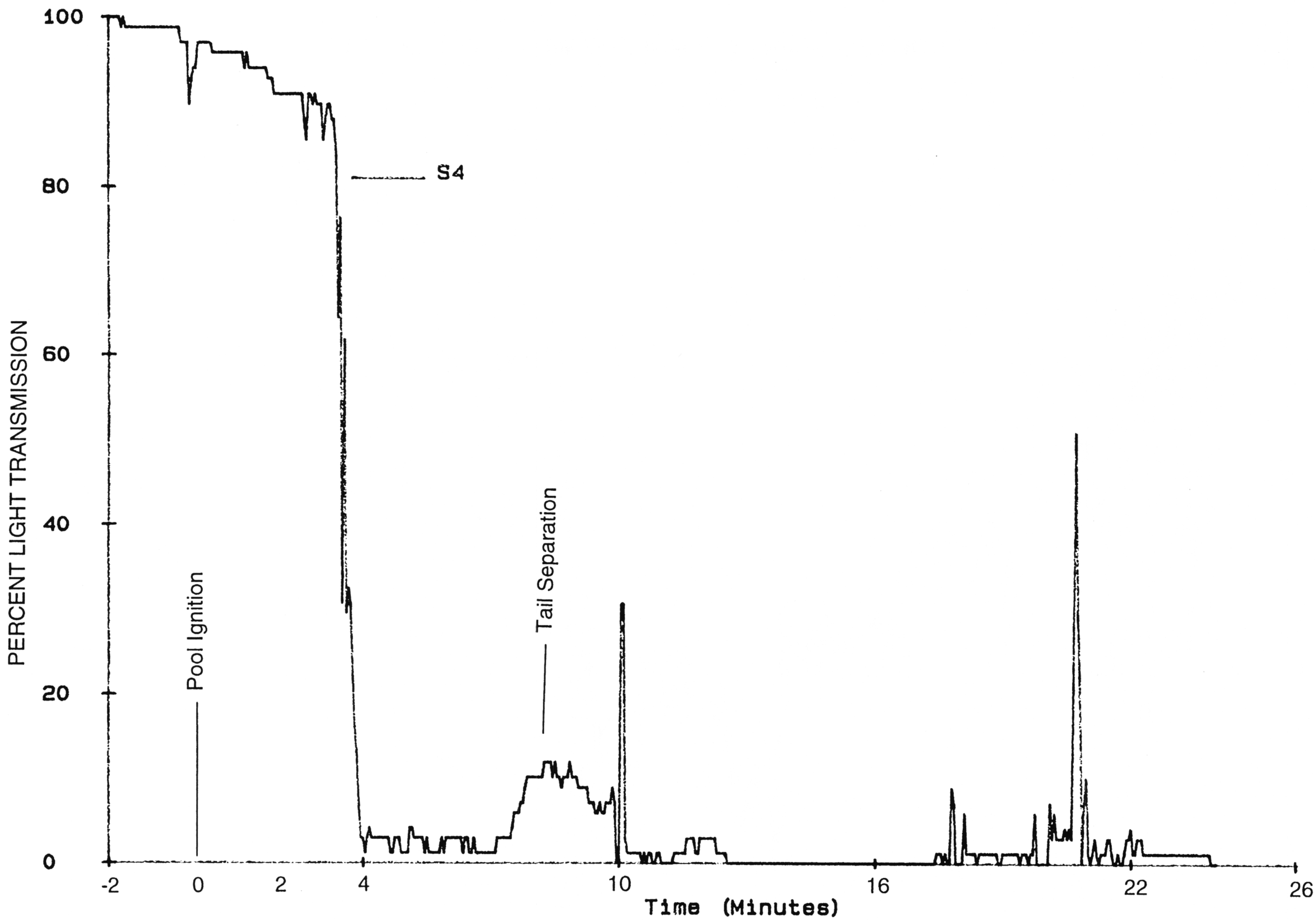

FIGURE B-15. SMOKE DENSITY AT STATION 498

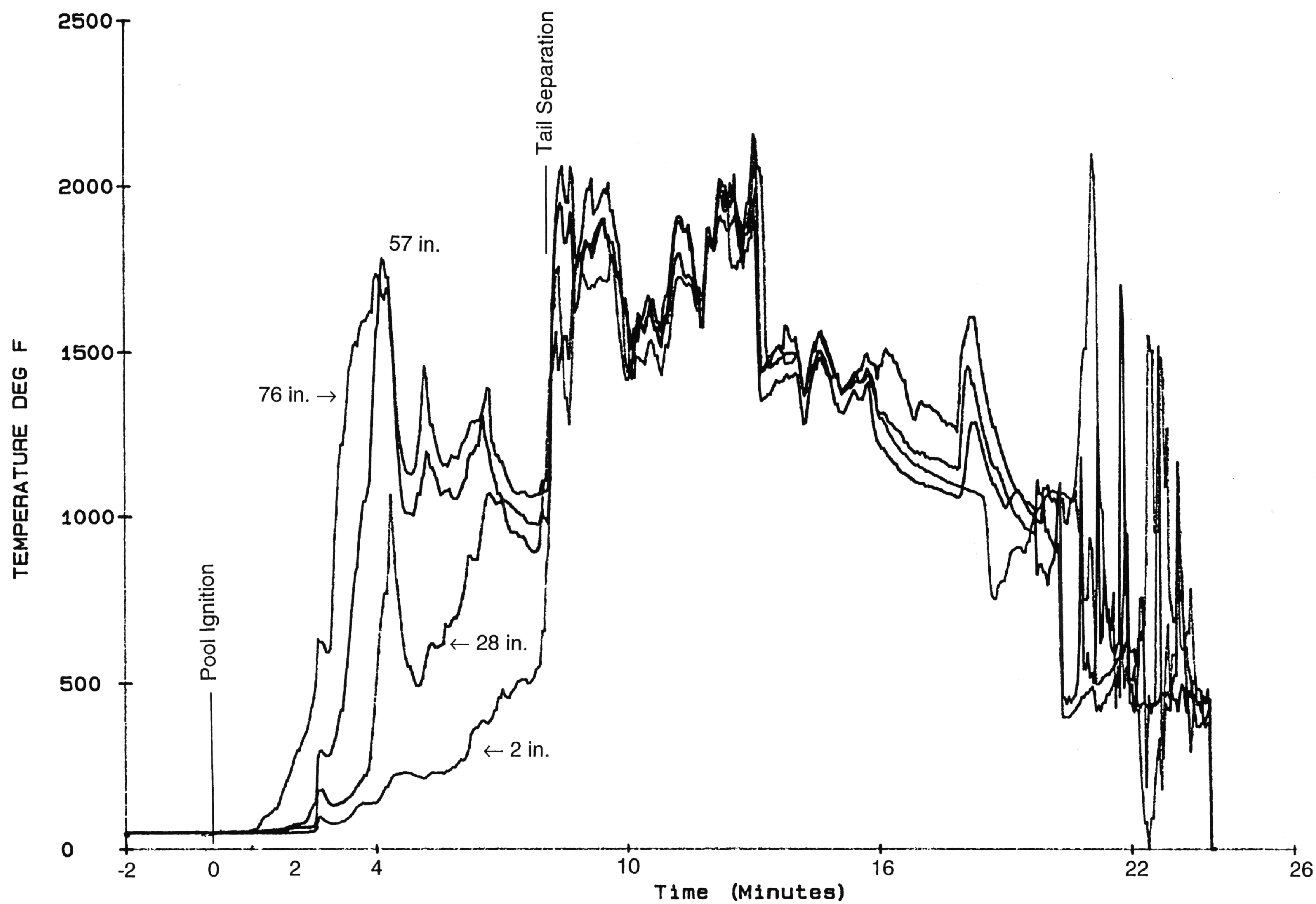

FIGURE B-16. THERMOCOUPLE TREE 1 AT STATION 1280

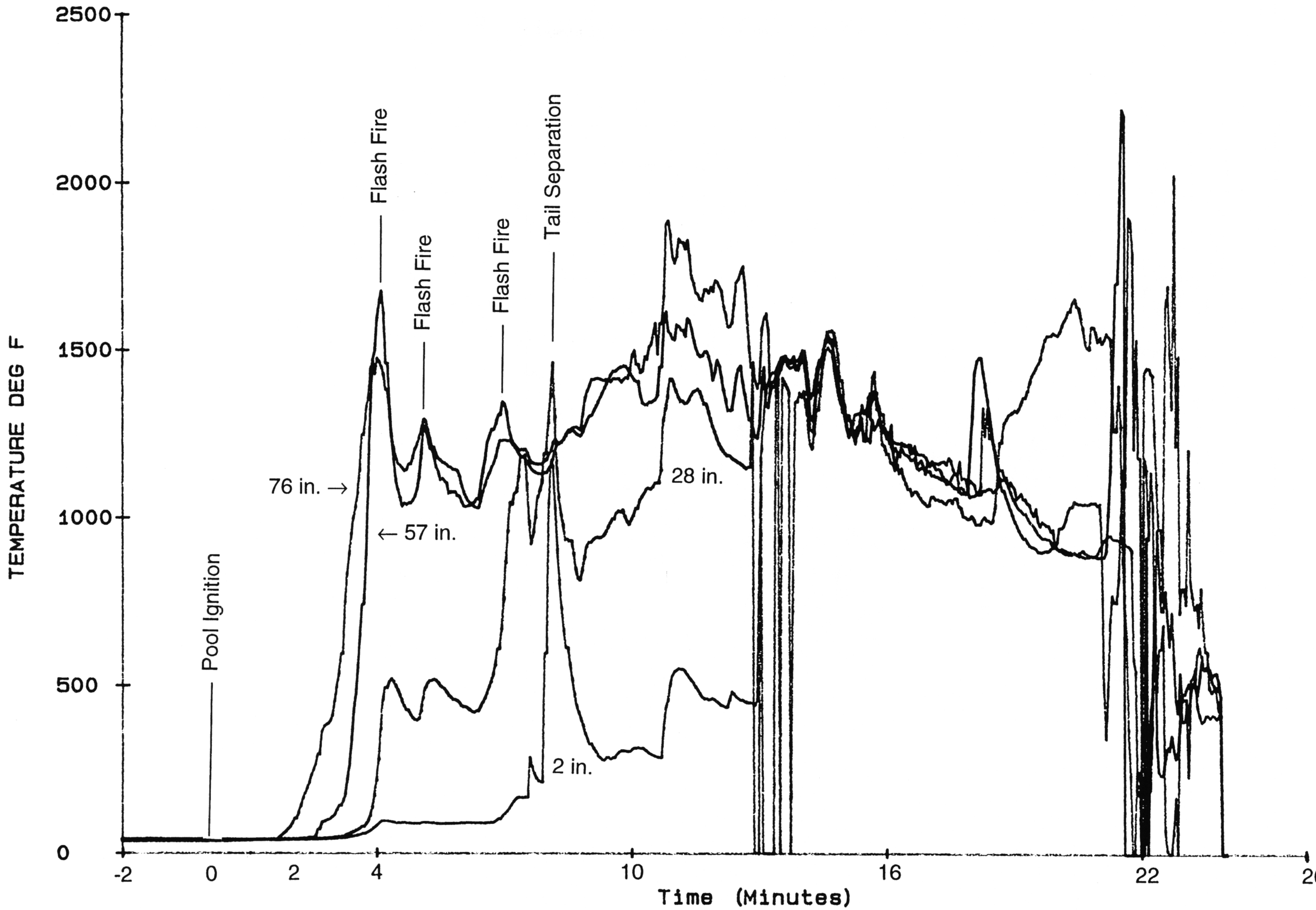

FIGURE B-17. THERMOCOUPLE TREE 2 AT STATION 1106

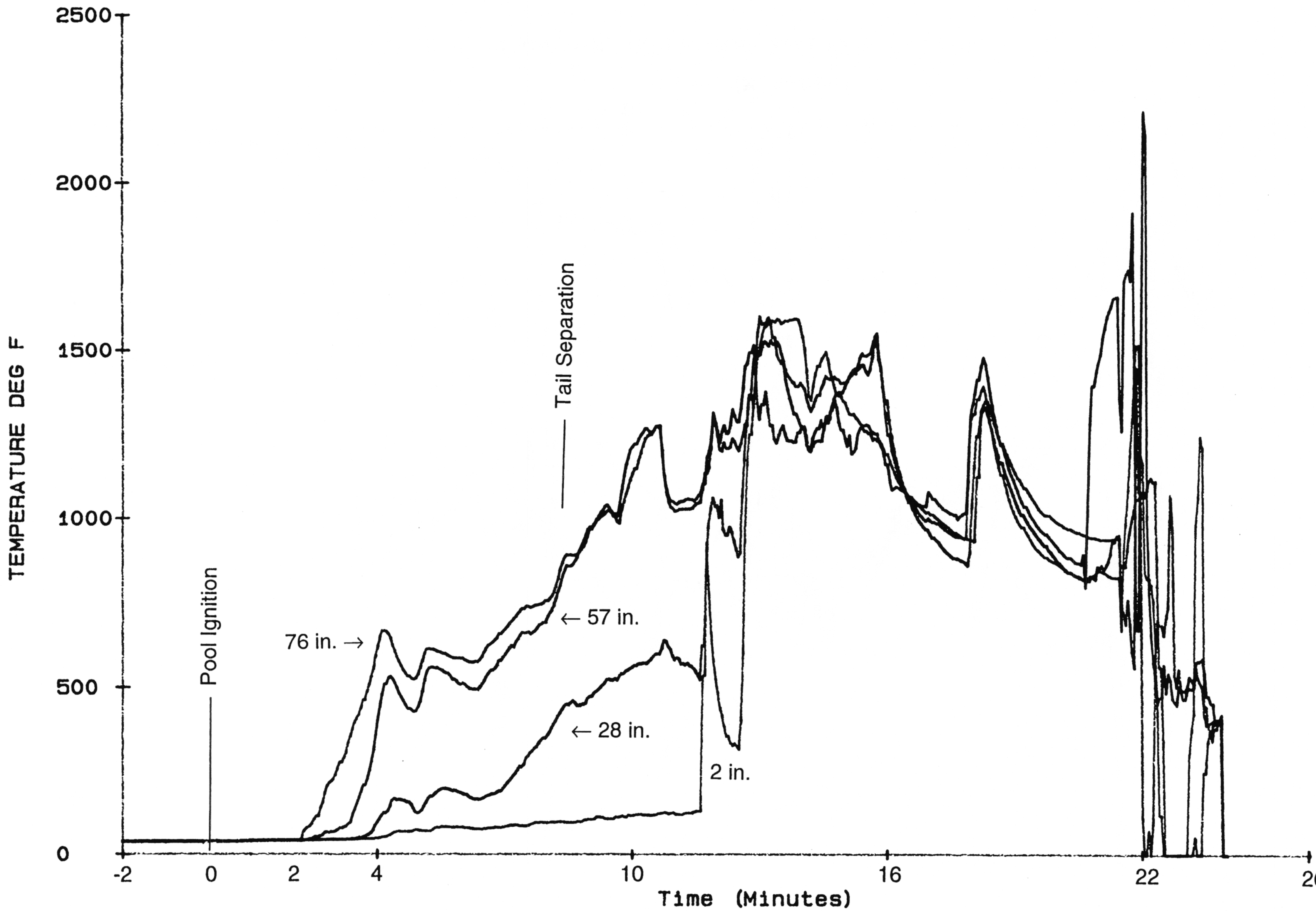

FIGURE B-18. THERMOCOUPLE TREE 3 AT STATION 669

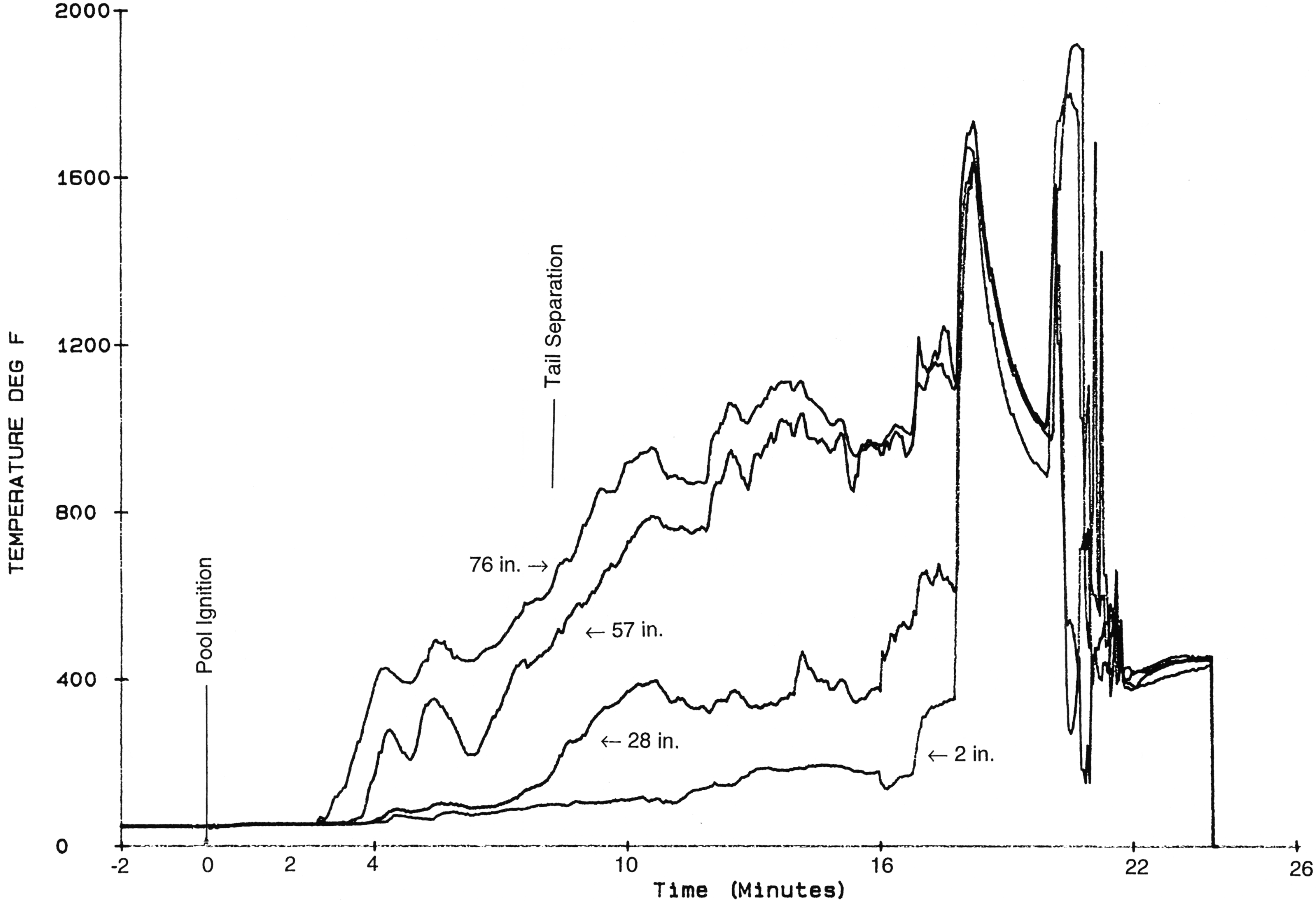

FIGURE B-19. THERMOCOUPLE TREE 4 AT STATION 498

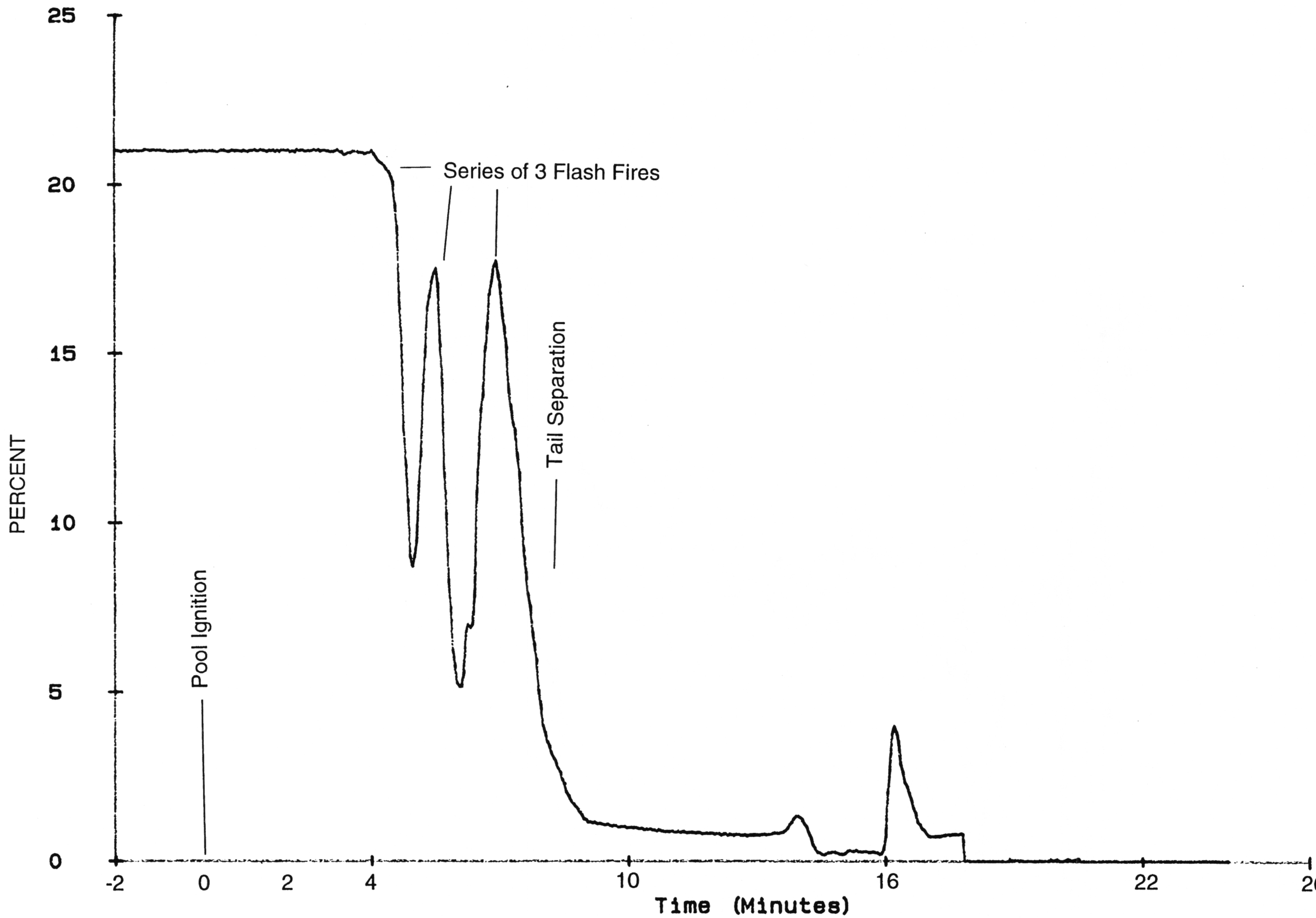

FIGURE B-20. OXYGEN CONCENTRATION AT STATION 498

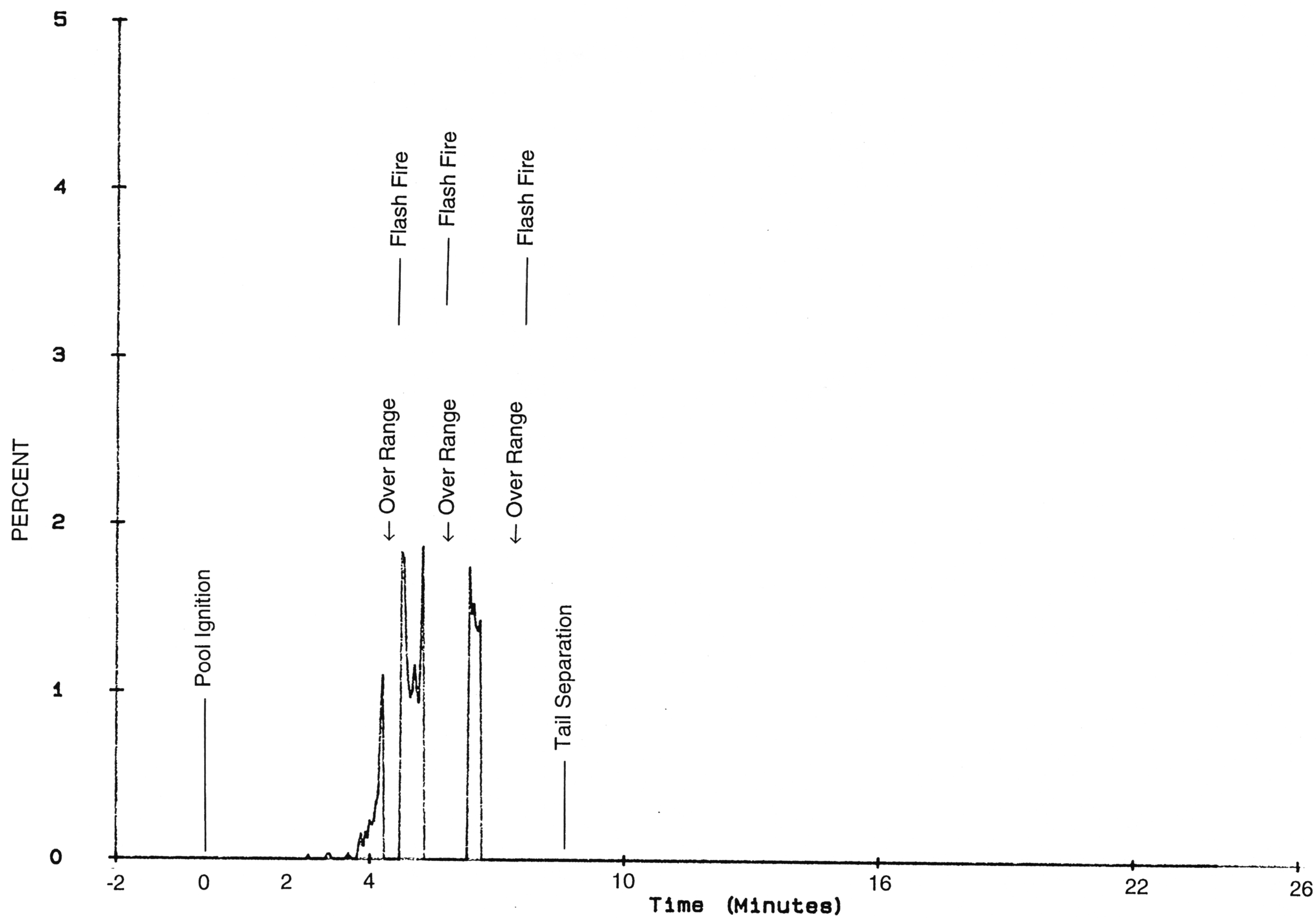

FIGURE B-21. CARBON MONOXIDE CONCENTRATION AT STATION 498

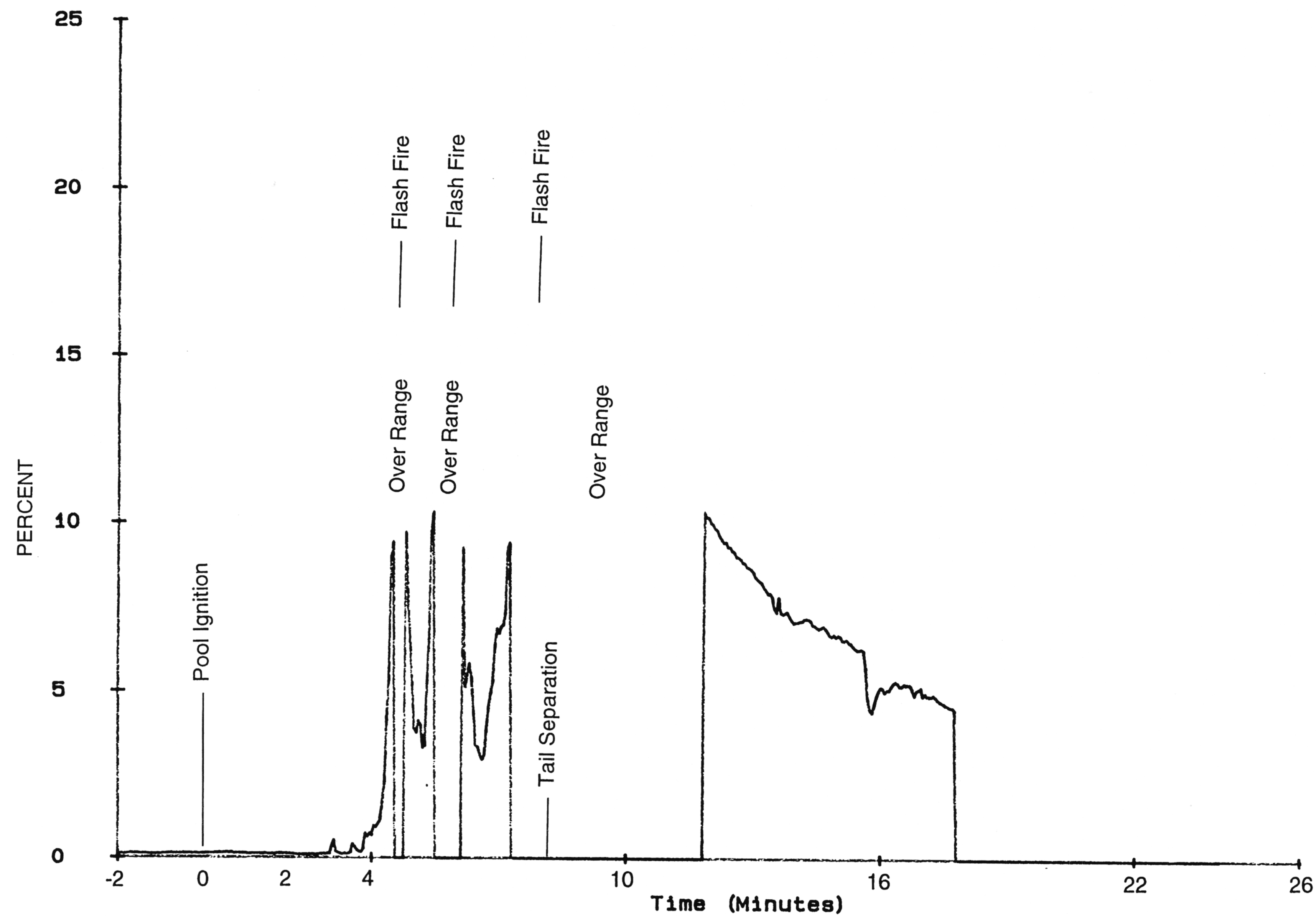

FIGURE B-22. CARBON DIOXIDE CONCENTRATION AT STATION 498

APPENDIX C—INSTRUMENTATION AND SENSOR LOCATIONS

A. Instrumentation

1. Temperature measuring devices:

   Type K Chromal/Alumel thermocouples, stainless steel sheathed, grounded, manufactured by Thermo Electric, Part Number K116U-304-0-24-OX.

2. Heat Flux measuring devices:

   Circular Foil Heat Flux Gage Calorimeters, Model 1000-1, range 0-20 Btu/Ft^2 sec, manufactured by Thermogage.

3. Smoke meter:

   Constructed by FAA, consisted of a collimated light beam incident upon a photocell.
   Exposed beam length: 4 in.
   Photocel: Hugen Weston Photoronic Cell, Model 856-9901011-YR
   Light source: Magna-light pen

4. Gas analyzers:

   Oxygen: Beckman model OM-11 EA oxygen analyzer
   Carbon Monoxide: Beckman model 864 Infrared gas analyzer
   Carbon Dioxide: Beckman model 864 Infrared gas analyzer

5. Data acquisition system:

   Compaq 386-33 IBM compatible computer
   Omega Data Acquisition, 96 channels, 3-second scan rate

B. Sensor Location

Figure C-1 shows the locations of the sensor groupings by station number. The sensors at stations 498, 669, 1106, and 1280 measure the cabin environmental conditions. The sensors at stations 1040 and 1192 were designed to detect the burnthrough locations and fire paths.

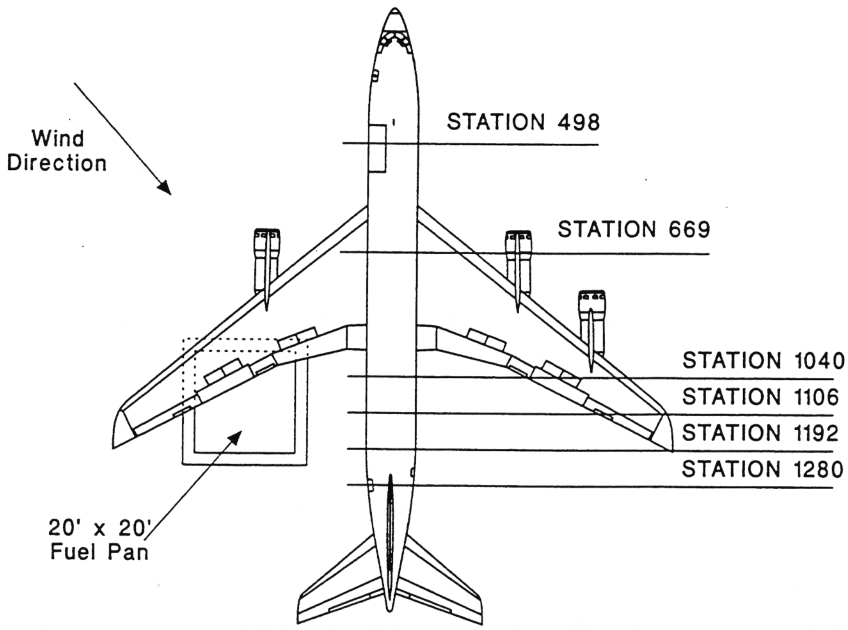

FIGURE C-1. SENSOR LOCATIONS BY STATION NUMBER DIAGRAM

Station 100

Designator	Type	Location	Purpose
W89	anemometer	6 feet above radome	wind speed
W90	anemometer	6 feet above radome	wind direction

Station 498

Designator	Type	Location	Purpose
T16	thermocouple	2 in. above the floor	air temperature
T15	thermocouple	28 in. above the floor	air temperature
T14	thermocouple	57 in. above the floor	air temperature
T13	thermocouple	76 in. above the floor	air temperature
S87	smoke meter	48 in. above the floor	smoke density
C80	calorimeter	48 in. above the floor looking aft	heat flux
CO	gas analyzer	48 in. above the floor	carbon monoxide
CO_2	gas analyzer	48 in. above the floor	carbon dioxide
O_2	gas analyzer	48 in. above the floor	oxygen

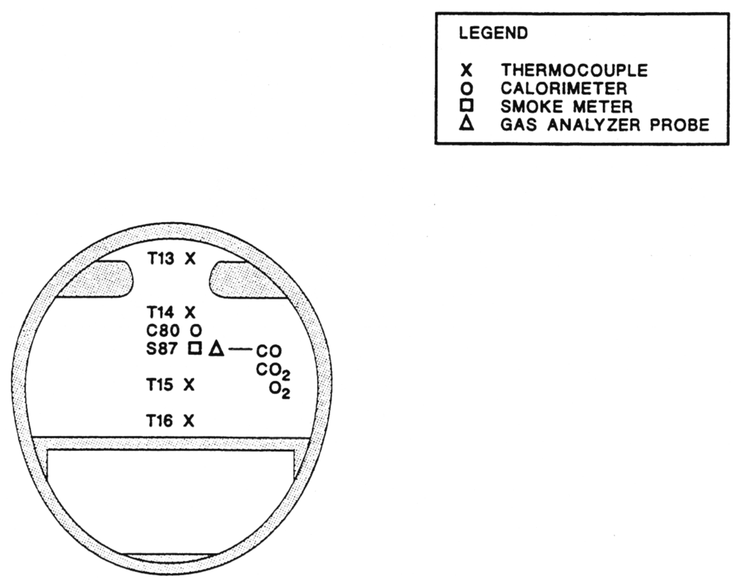

FIGURE C-2. INSTRUMENTATION LOCATIONS AT STATION 498

Station 669

Designator	Type	Location	Purpose
T12	thermocouple	2 in. above the floor	air temperature
T11	thermocouple	28 in. above the floor	air temperature
T10	thermocouple	57 in. above the floor	air temperature
T9	thermocouple	76 in. above the floor	air temperature
S86	smoke meter	48 in. above the floor	smoke density
C79	calorimeter	48 in. above the floor looking aft	heat flux

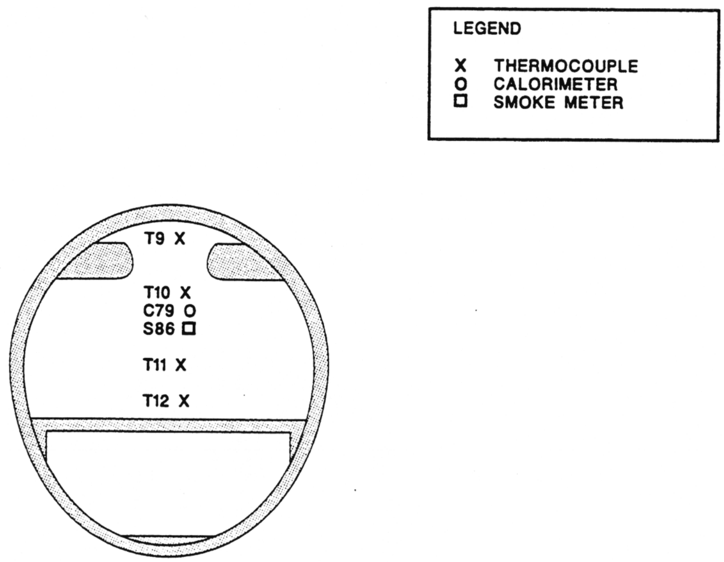

FIGURE C-3. INSTRUMENTATION LOCATIONS AT STATION 669

Station 1040

Designator	Type	Location	Purpose
T52	thermocouple	attic, port side	attic air temperature
T53	thermocouple	attic, center	attic air temperature
T54	thermocouple	attic, starboard	attic air temperature
T49	thermocouple	2 in. outboard of skin	exterior flame temp.
T50	thermocouple	on skin, interior	skin temperature
T51	thermocouple	between insulation and interior panel	heat transfer to cabin
C76	calorimeter	through skin, facing exterior fire	exterior heat flux
T55	thermocouple	2 in. outboard of skin	exterior flame temp.
T56	thermocouple	on skin, interior	skin temperature
T57	thermocouple	between insulation and interior panel	heat transfer to cabin
C77	calorimeter	through skin, facing outward	exterior heat flux
T69	thermocouple	floor grill, port	potential flame path to cabin
T68	thermocouple	floor grill, starboard	potential flame path to cabin
T33	thermocouple	under floor, port	air temperature
T34	thermocouple	under floor, center	air temperature
T35	thermocouple	under floor, starboard	air temperature
T32	thermocouple	cheek area, port	cheek air temperature
T31	thermocouple	on skin interior	skin temperature
T30	thermocouple	2 in. outboard of skin	exterior flame temp.
T36	thermocouple	2 in. outboard of skin	exterior flame temp.
T37	thermocouple	on skin interior	skin temperature
T38	thermocouple	cheek area, port	cheek air temperature
T39	thermocouple	cargo compartment, 6 in. below ceiling	air temperature
T61	thermocouple	below cargo floor, port	air temperature
T62	thermocouple	below cargo floor, center	air temperature
T63	thermocouple	below cargo floor, starboard	air temperature

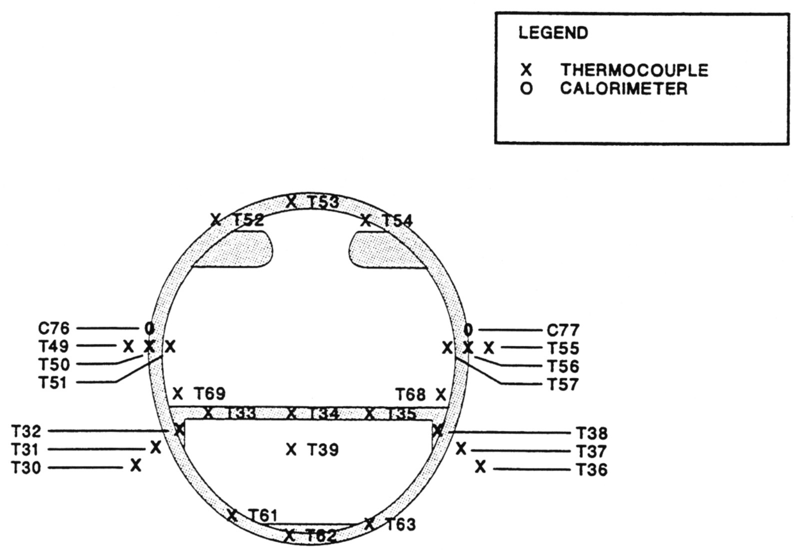

FIGURE C-4. INSTRUMENTATION LOCATIONS AT STATION 1040 (LOOKING FORWARD)

Station 1106

Designator	Type	Location	Purpose
T8	thermocouple	2 in. above the cabin floor	air temperature
T7	thermocouple	28 in. above the cabin floor	air temperature
T6	thermocouple	57 in. above the cabin floor	air temperature
T5	thermocouple	76 in. above the cabin floor	air temperature
S85	smoke meter	48 in. above the cabin floor	smoke density
C78	calorimeter	48 in. above the floor cabin looking aft	heat flux

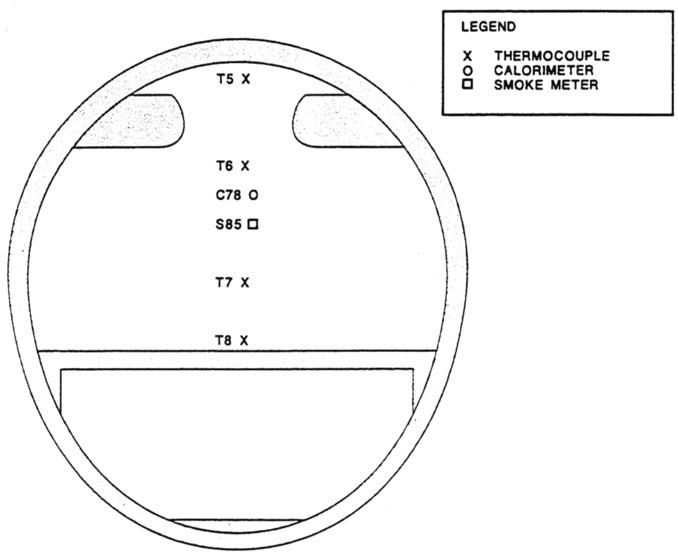

FIGURE C-5. INSTRUMENTATION LOCATIONS AT STATION 1106

Station 1192

Designator	Type	Location	Purpose
T43	thermocouple	attic, port side	attic air temperature
T44	thermocouple	attic, center	attic air temperature
T45	thermocouple	attic, starboard	attic air temperature
T40	thermocouple	2 in. outboard of skin	exterior flame temp.
T41	thermocouple	on skin, interior	skin temperature
T42	thermocouple	between insulation and interior panel	heat transfer to cabin
C74	calorimeter	through skin, looking outward	exterior heat flux
T46	thermocouple	2 in. outboard of skin	exterior flame temp.
T47	thermocouple	on skin, interior	skin temperature
T48	thermocouple	between insulation and interior panel	heat transfer to cabin
C75	calorimeter	through skin, looking outward	exterior heat flux
T67	thermocouple	floor grill, port	potential flame path to cabin
T66	thermocouple	floor grill, starboard	potential flame path to cabin
T23	thermocouple	under the cabin floor, port	air temperature
T24	thermocouple	under the cabin floor, center	air temperature
T25	thermocouple	under the cabin floor, starboard	air temperature
T20	thermocouple	2 in. outboard of skin	exterior flame temp.
T21	thermocouple	on skin interior	skin temperature
T22	thermocouple	cheek area, port	cheek air temperature
T26	thermocouple	2 in. outboard of skin	exterior flame temp.
T27	thermocouple	on skin interior	skin temperature
T28	thermocouple	cheek area, starboard	cheek air temperature
T29	thermocouple	cargo compartment, 6 in. below ceiling	air temperature
T58	thermocouple	below cargo floor, port	air temperature
T58	thermocouple	below cargo floor, center	air temperature
T60	thermocouple	below cargo floor, starboard	air temperature

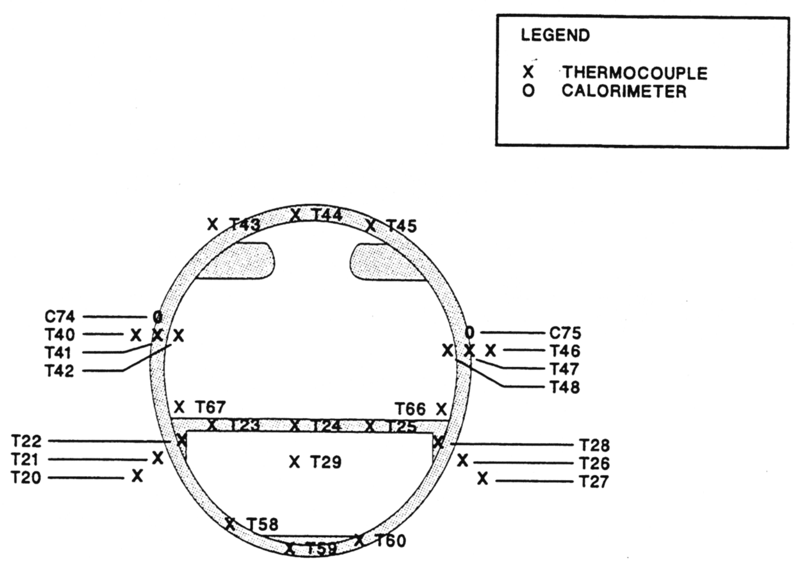

FIGURE C-6. INSTRUMENTATION LOCATIONS AT STATION 1192 (LOOKING FORWARD)

Stations 1280

Designator	Type	Location	Purpose
T4	thermocouple	2 in. above the cabin floor	air temperature
T3	thermocouple	28 in. above the cabin floor	air temperature
T2	thermocouple	57 in. above the cabin floor	air temperature
T1	thermocouple	76 in. above the cabin floor	air temperature
S84	smoke meter	48 in. above the cabin floor	smoke density
C73	calorimeter	48 in. above the cabin floor, facing starboard door	heat flux through open doorway

Stations 1300

Designator	Type	Location	Purpose
T17	thermocouple	4 in. outboard of outflow valve	exterior flame temp.
T18	thermocouple	6 in. above outflow valve	entry point
T19	thermocouple	crawlthrough	air temperature

Stations 1311

Designator	Type	Location	Purpose
T65	thermocouple	lavatory, port	air temperature
T64	thermocouple	lavatory, starboard	air temperature

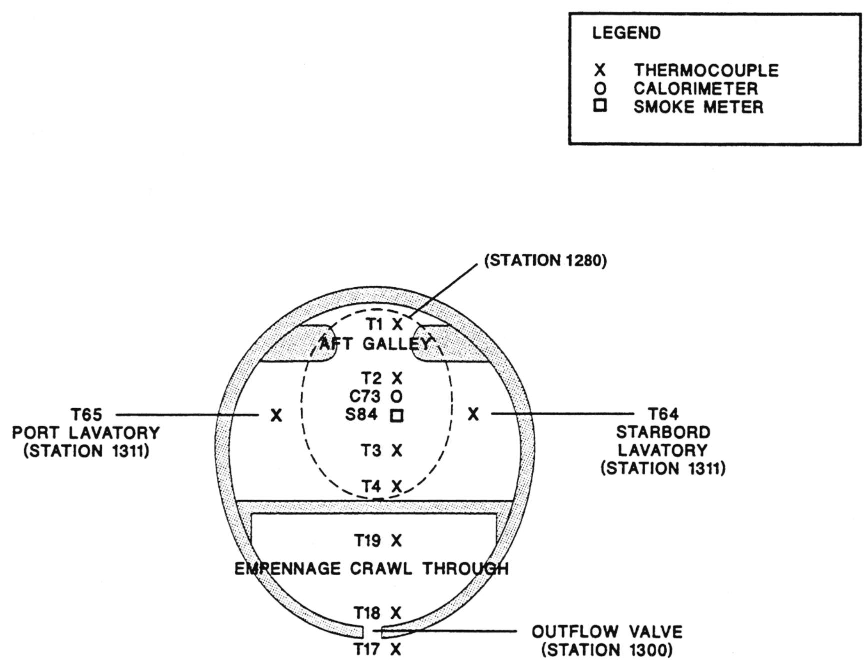

FIGURE C-7. INSTRUMENTATION LOCATIONS AT STATIONS 1280, 1300, AND 1311

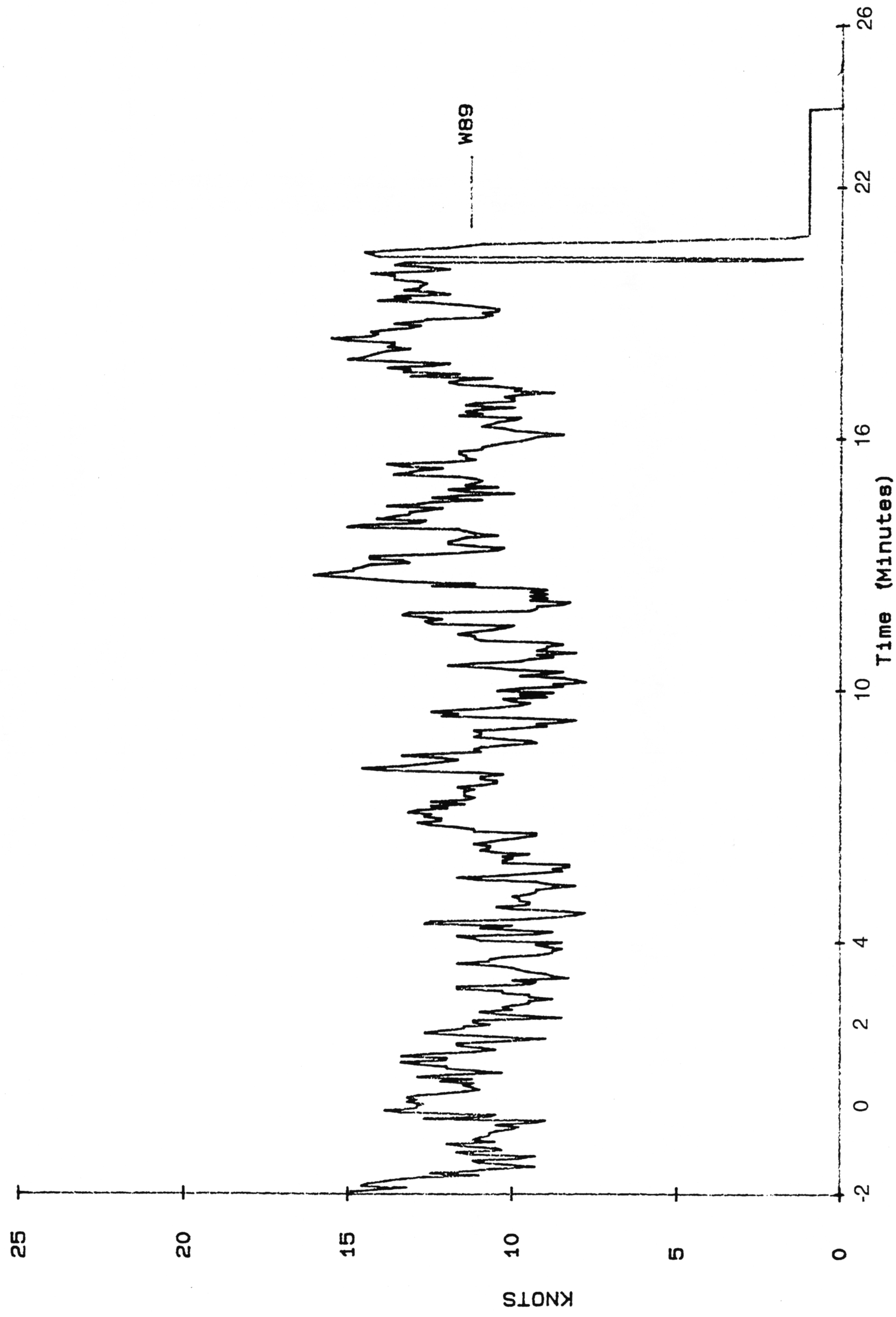

FIGURE D-1. WIND SPEED AT STATION 100

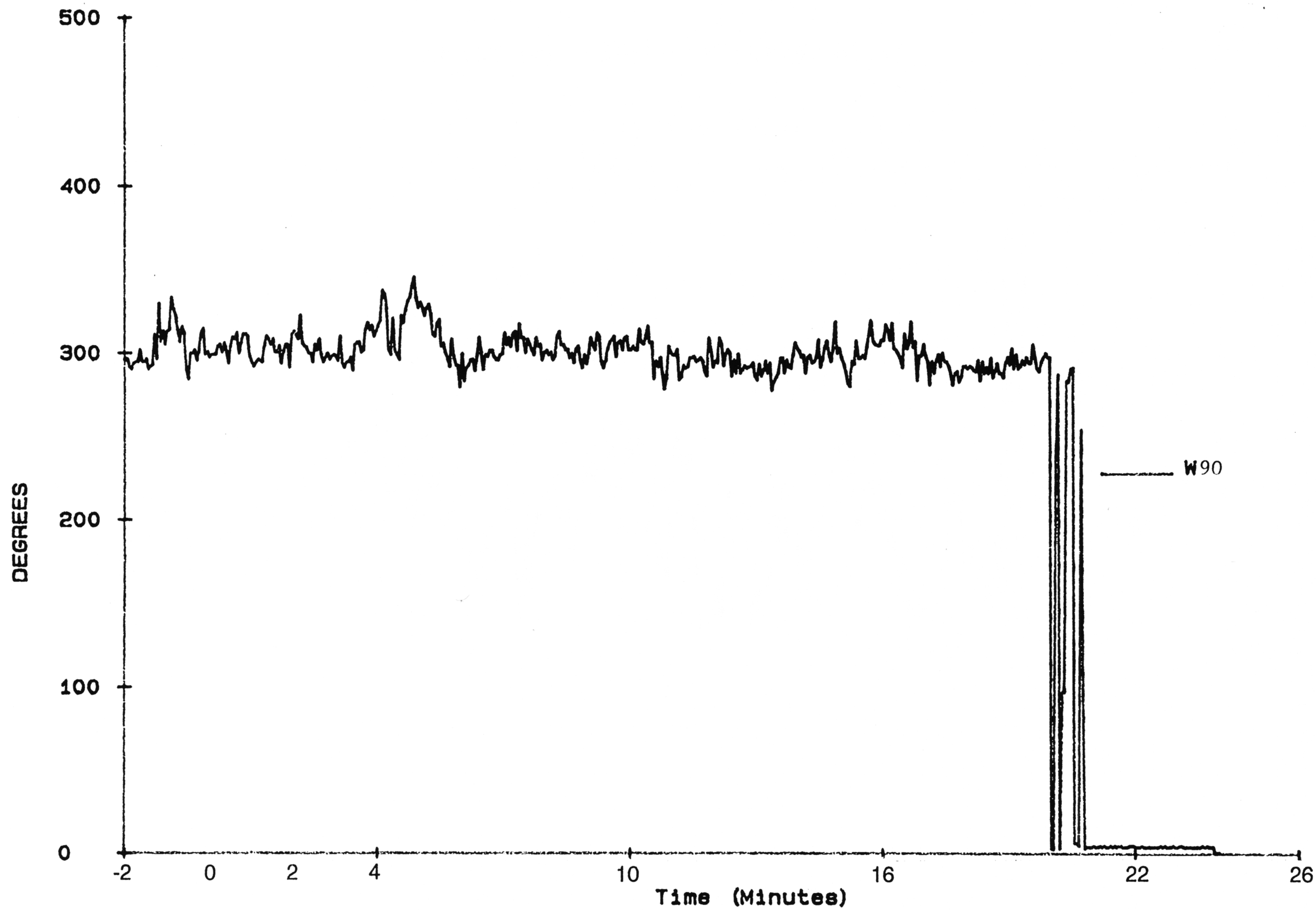

FIGURE D-2. WIND DIRECTION AT STATION 100

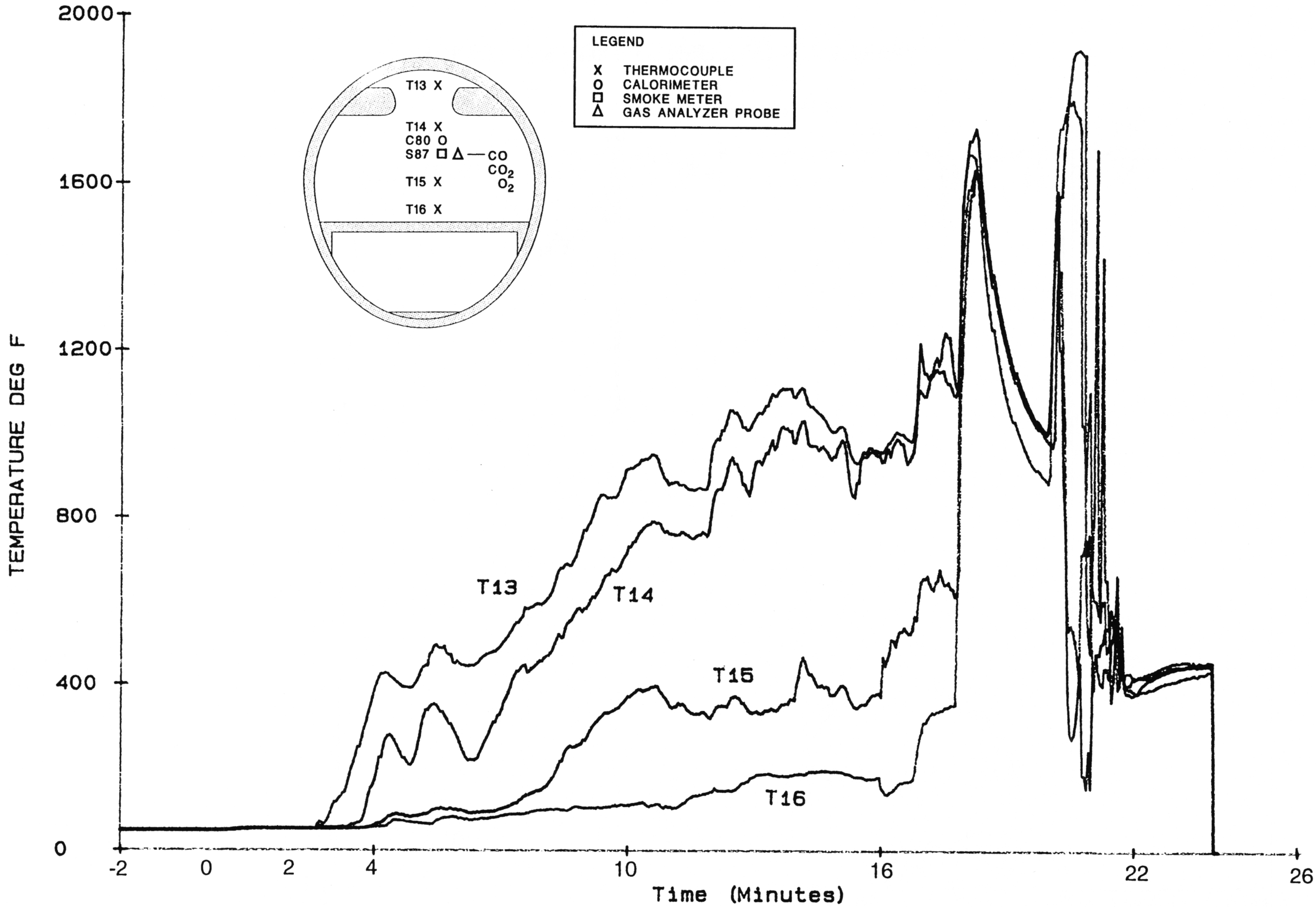

FIGURE D-3. THERMOCOUPLE TREE 4 AT STATION 498

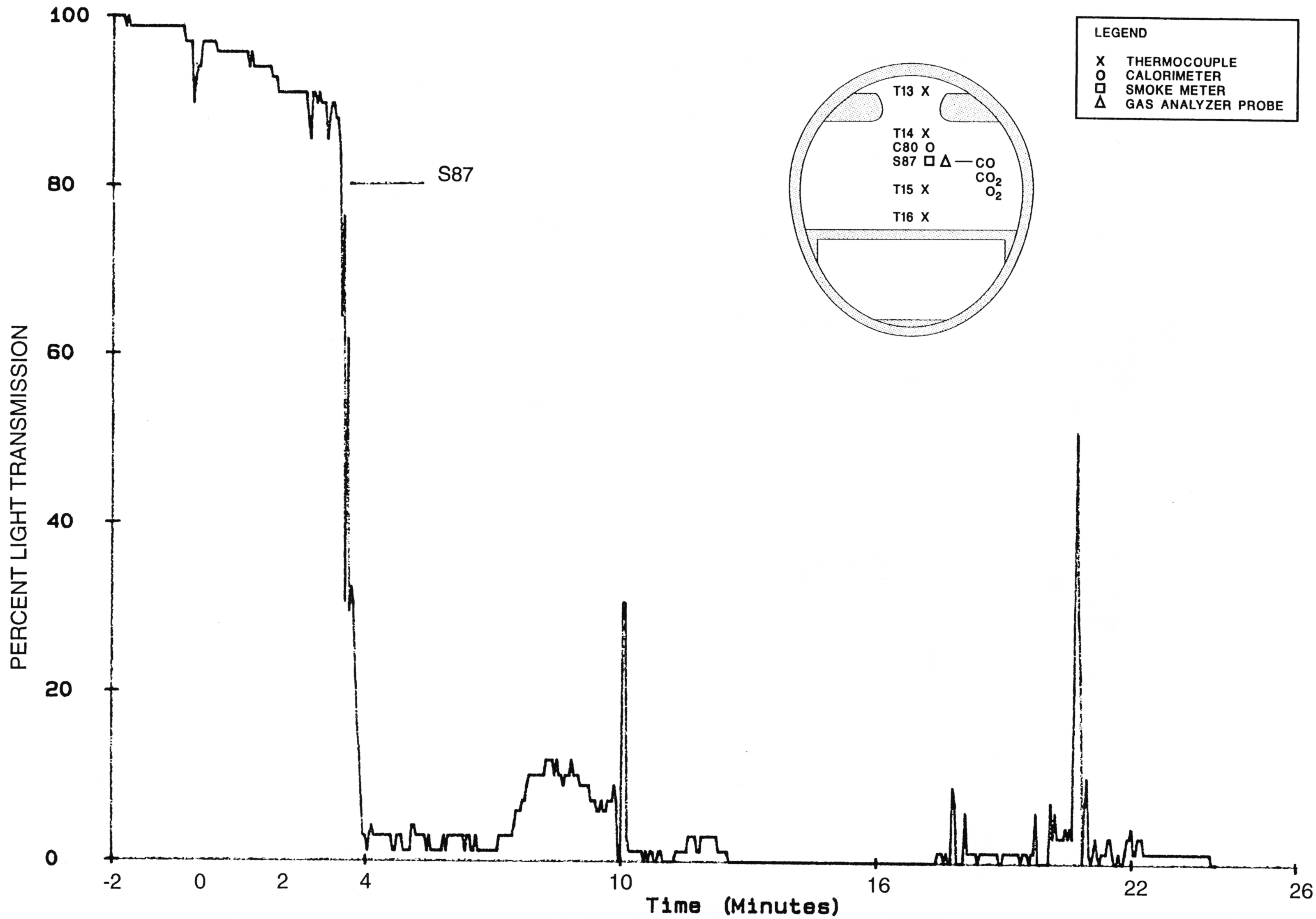

FIGURE D-4. SMOKE DENSITY AT STATION 498

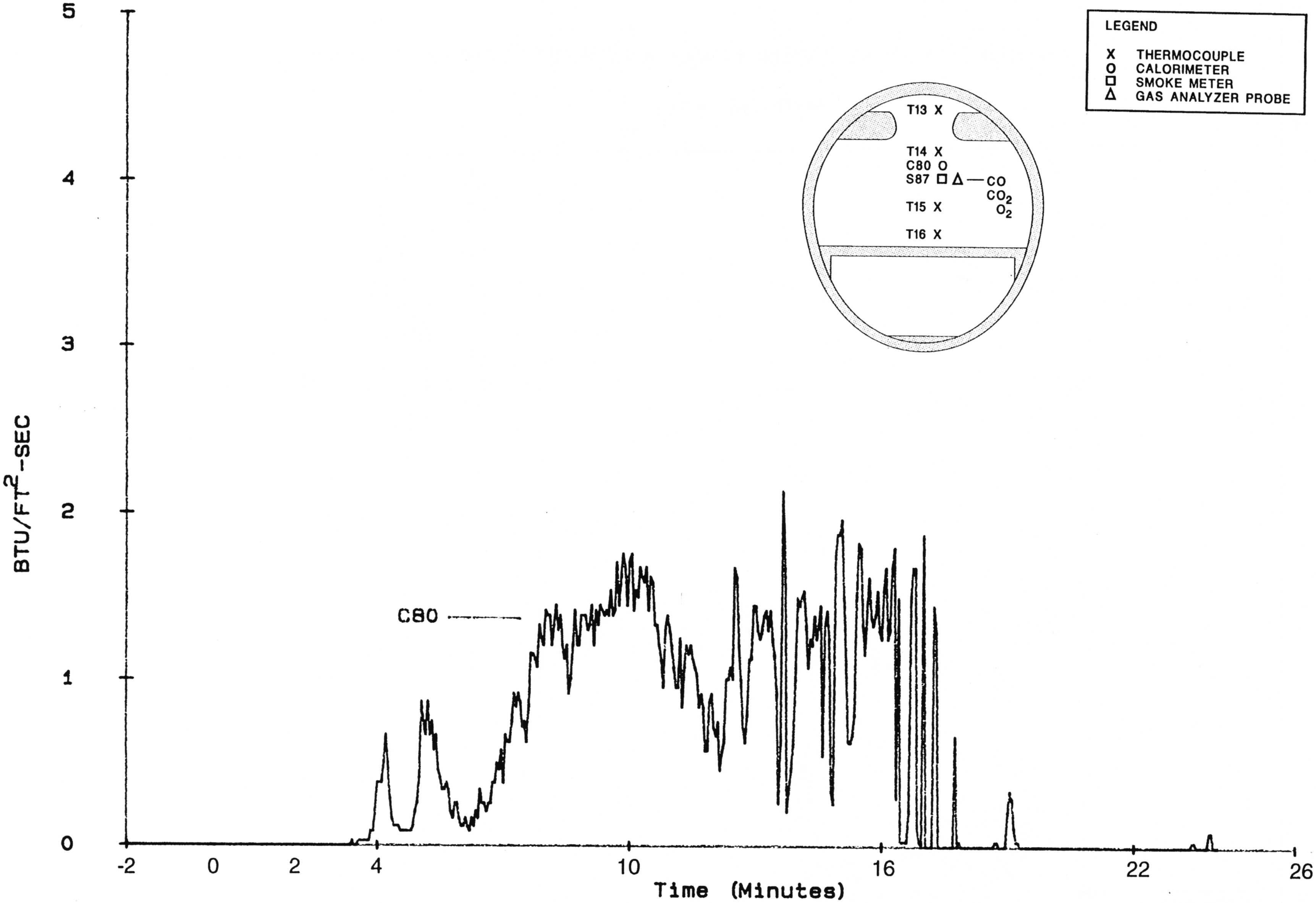

FIGURE D-5. INTERNAL HEAT FLUX AT STATION 498

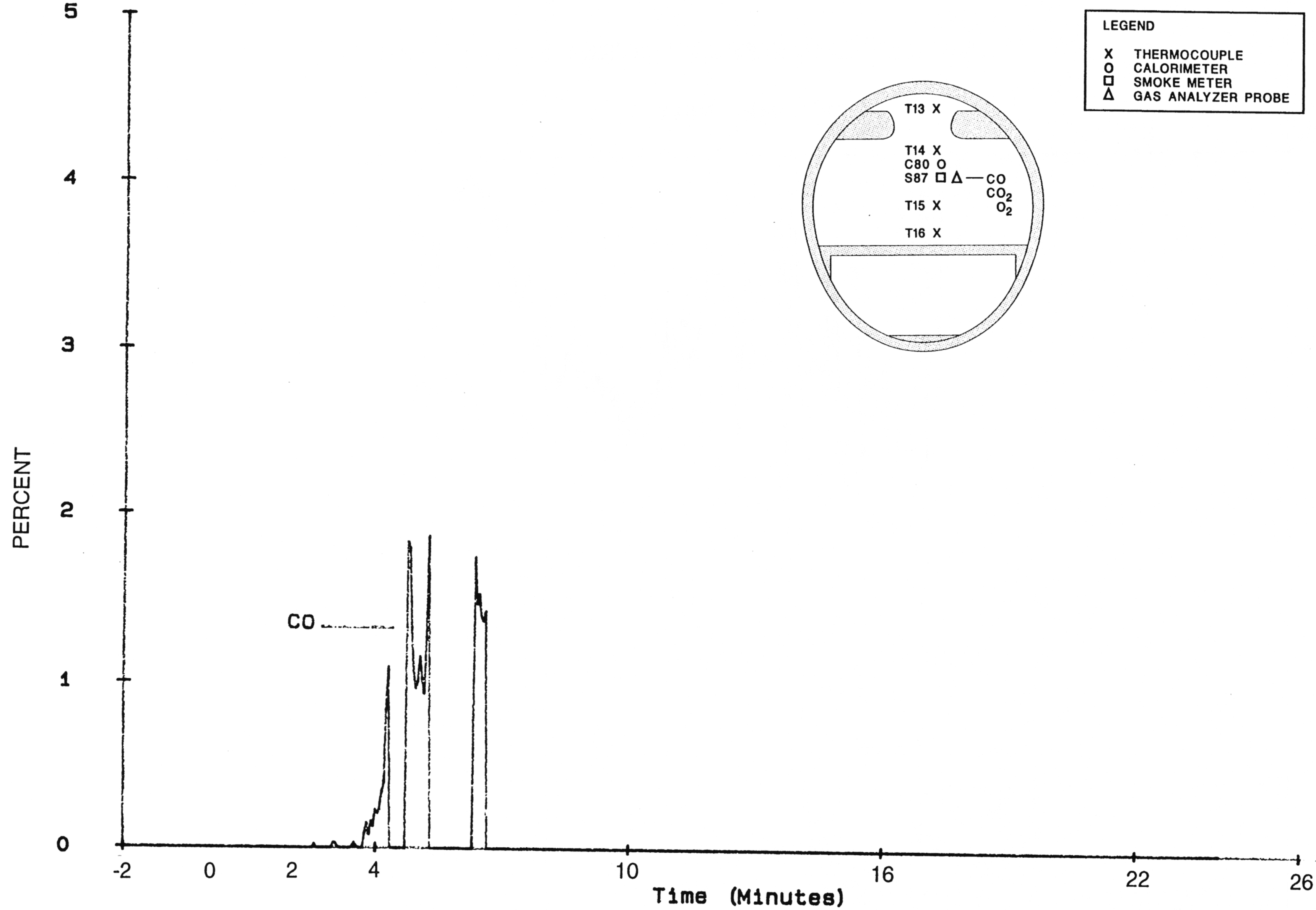

FIGURE D-6. CARBON MONOXIDE CONCENTRATION AT STATION 498

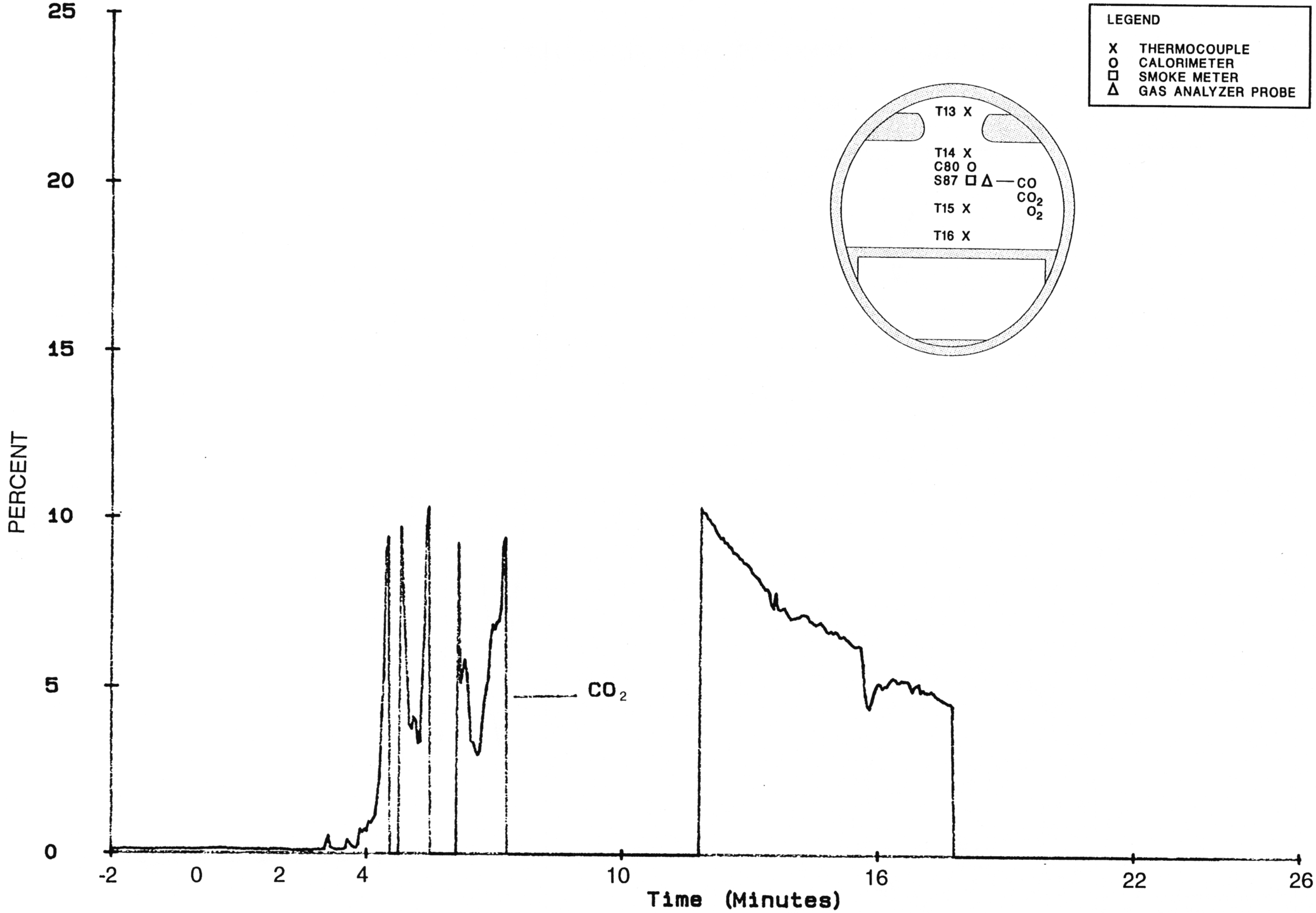

FIGURE D-7. CARBON DIOXIDE CONCENTRATION AT STATION 498

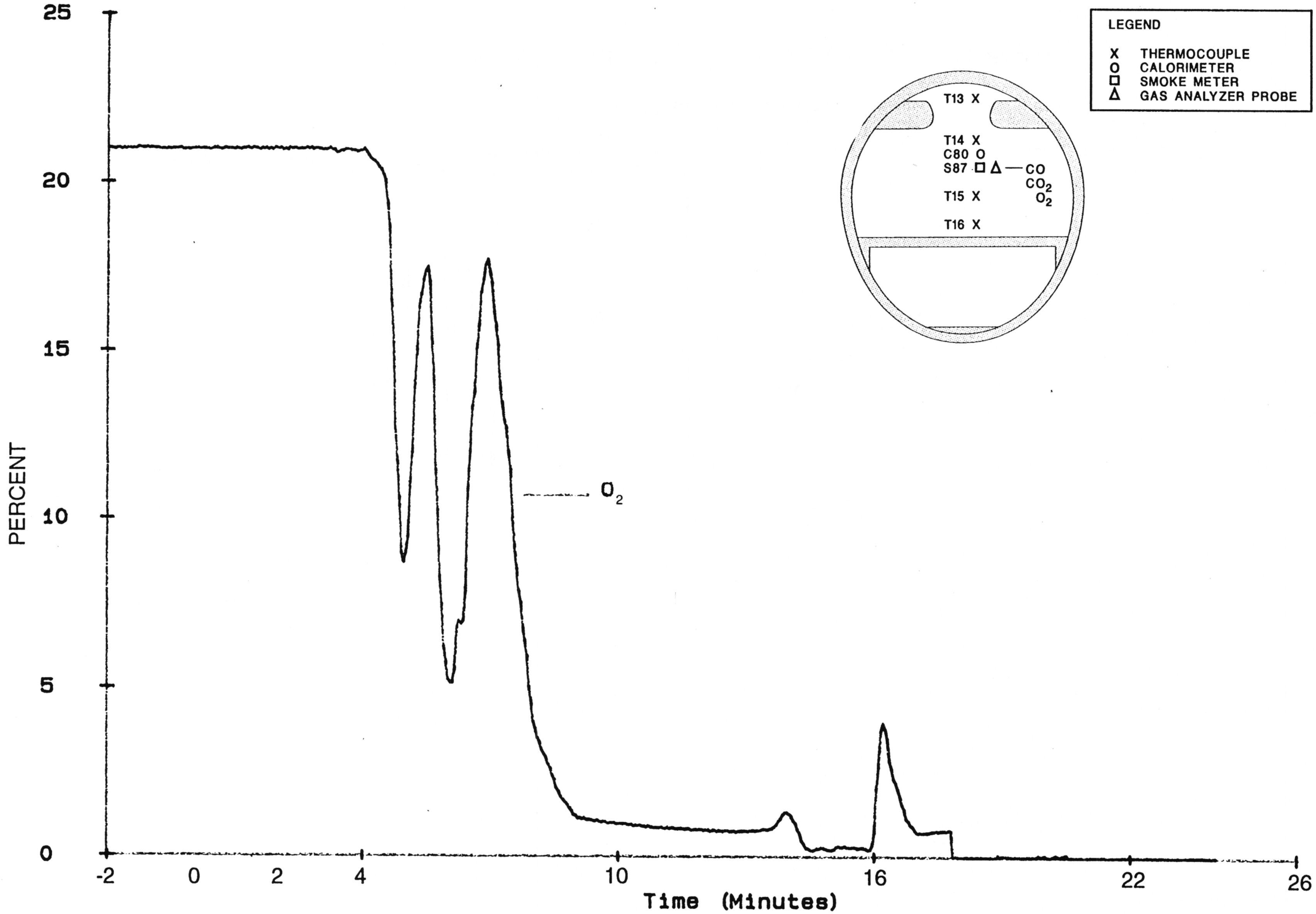

FIGURE D-8. OXYGEN CONCENTRATION AT STATION 498

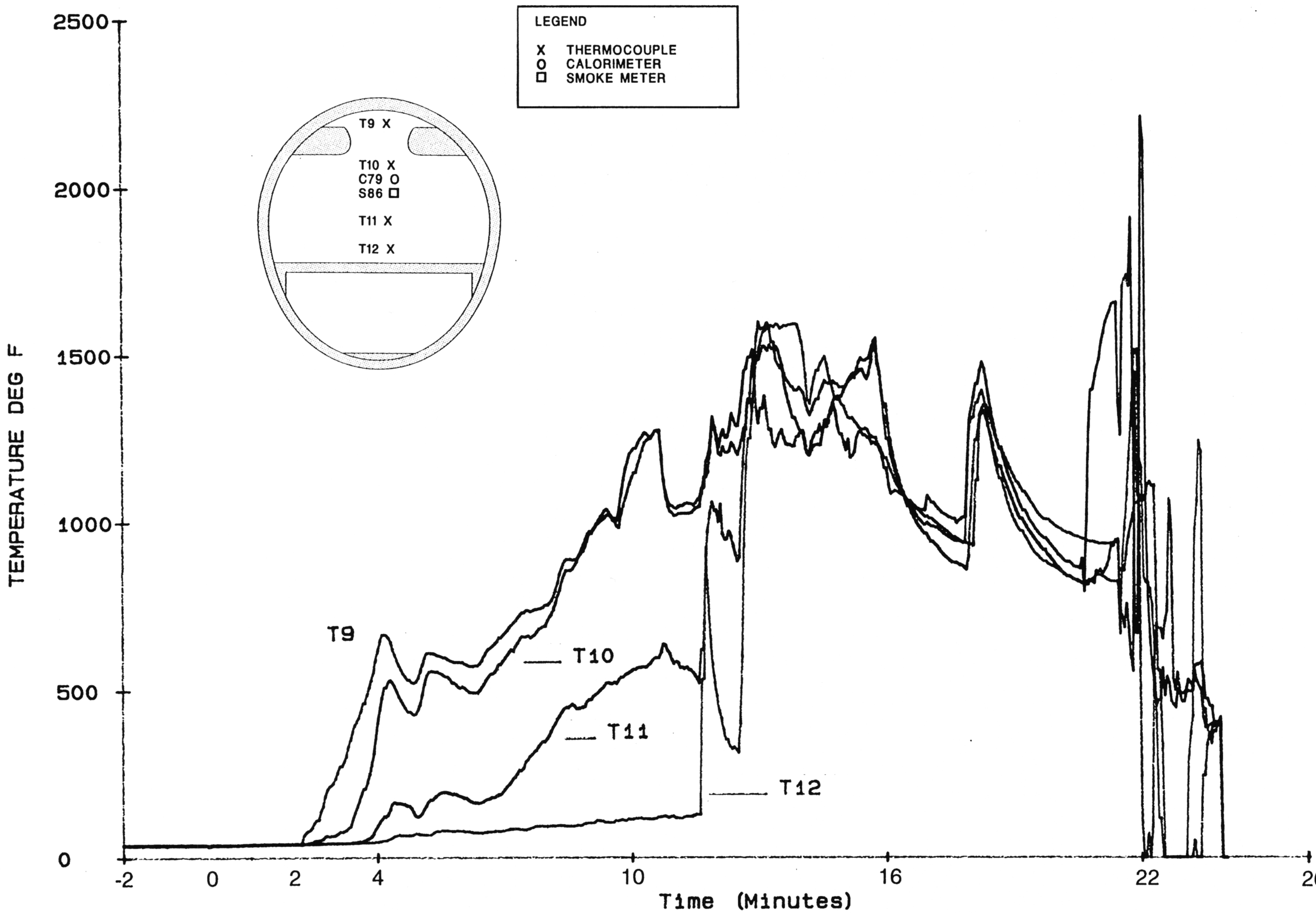

FIGURE D-9. THERMOCOUPLE TREE 3 AT STATION 669

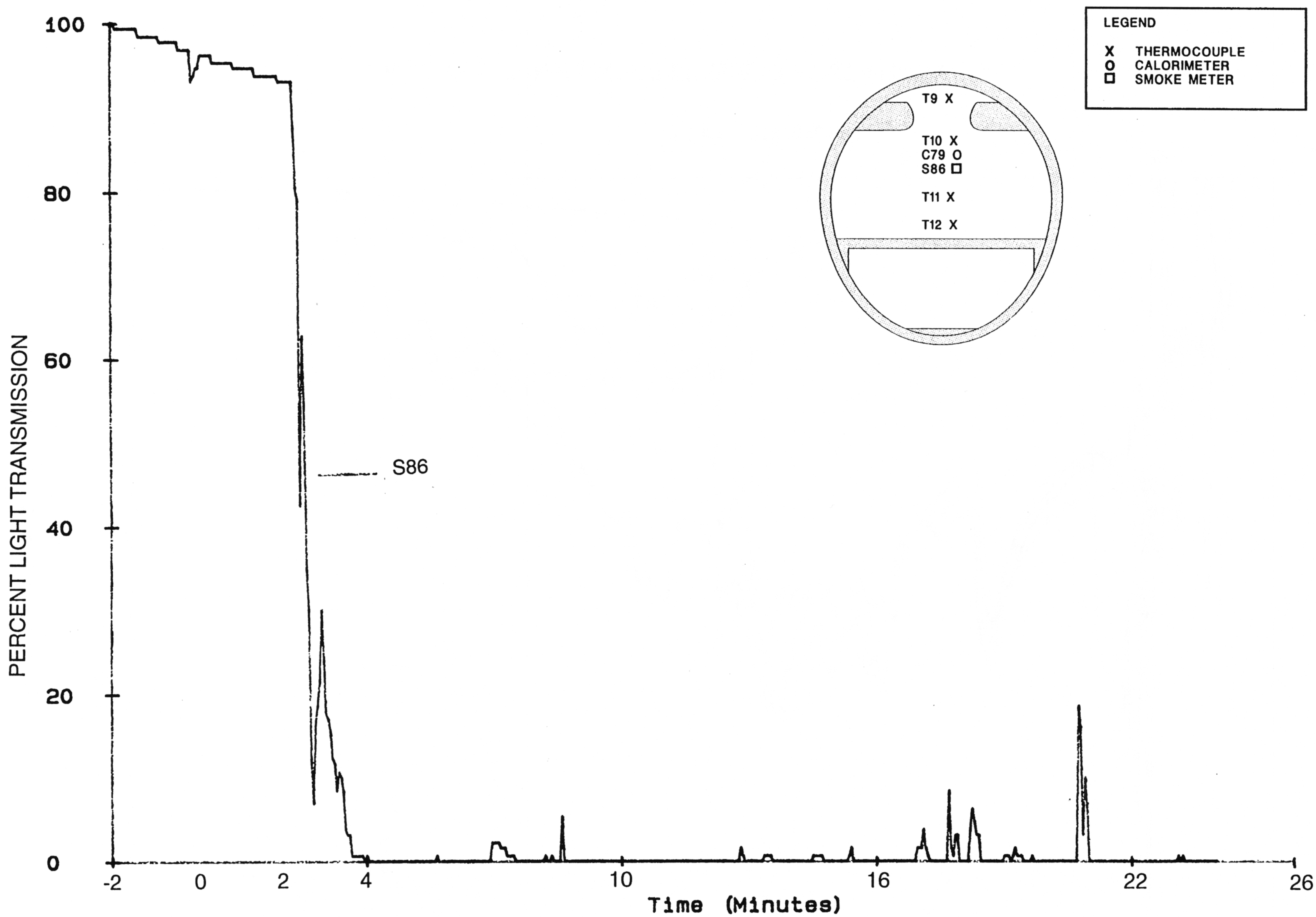

FIGURE D-10. SMOKE DENSITY AT STATION 669

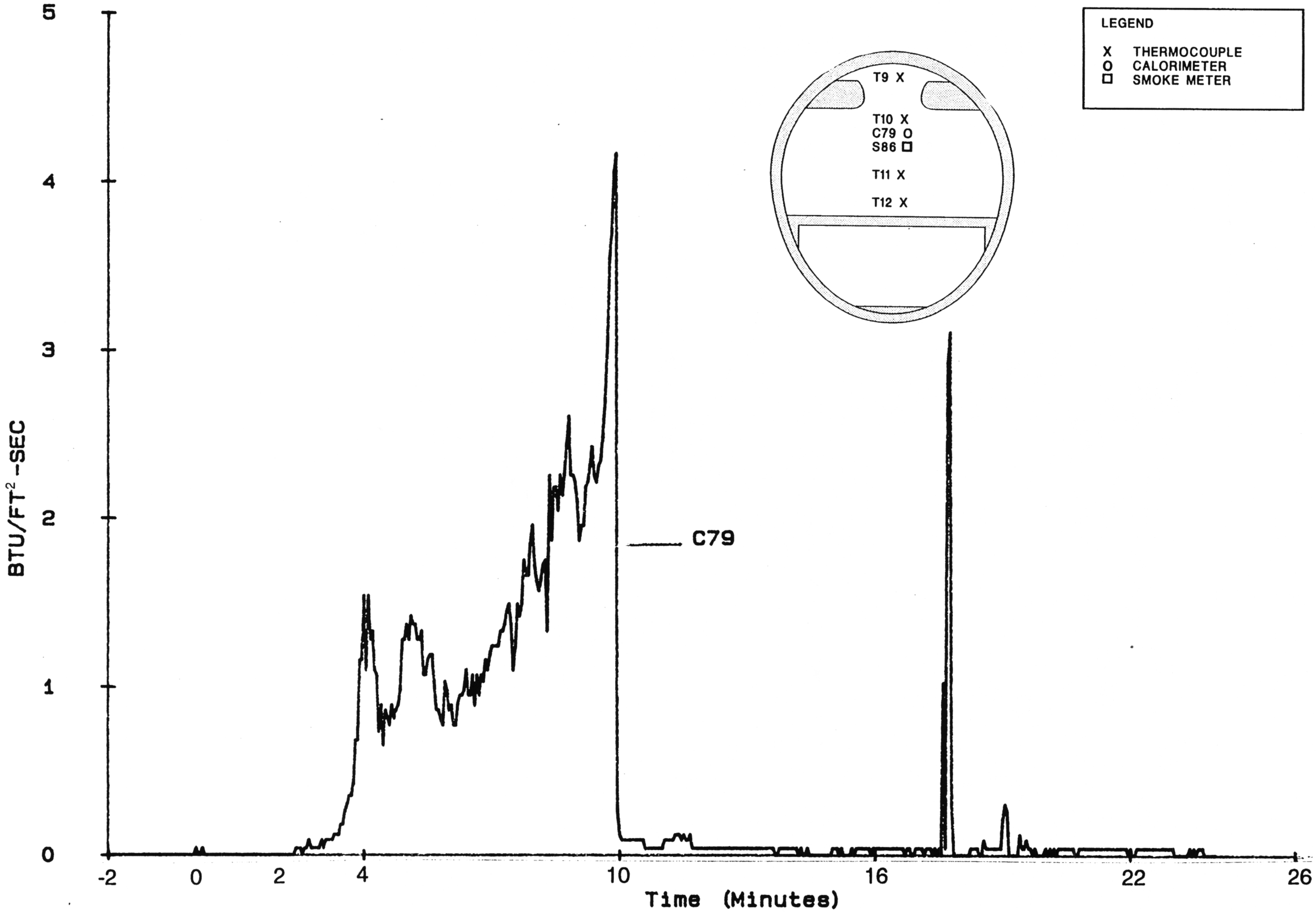

FIGURE D-11. INTERNAL HEAT FLUX AT STATION 669

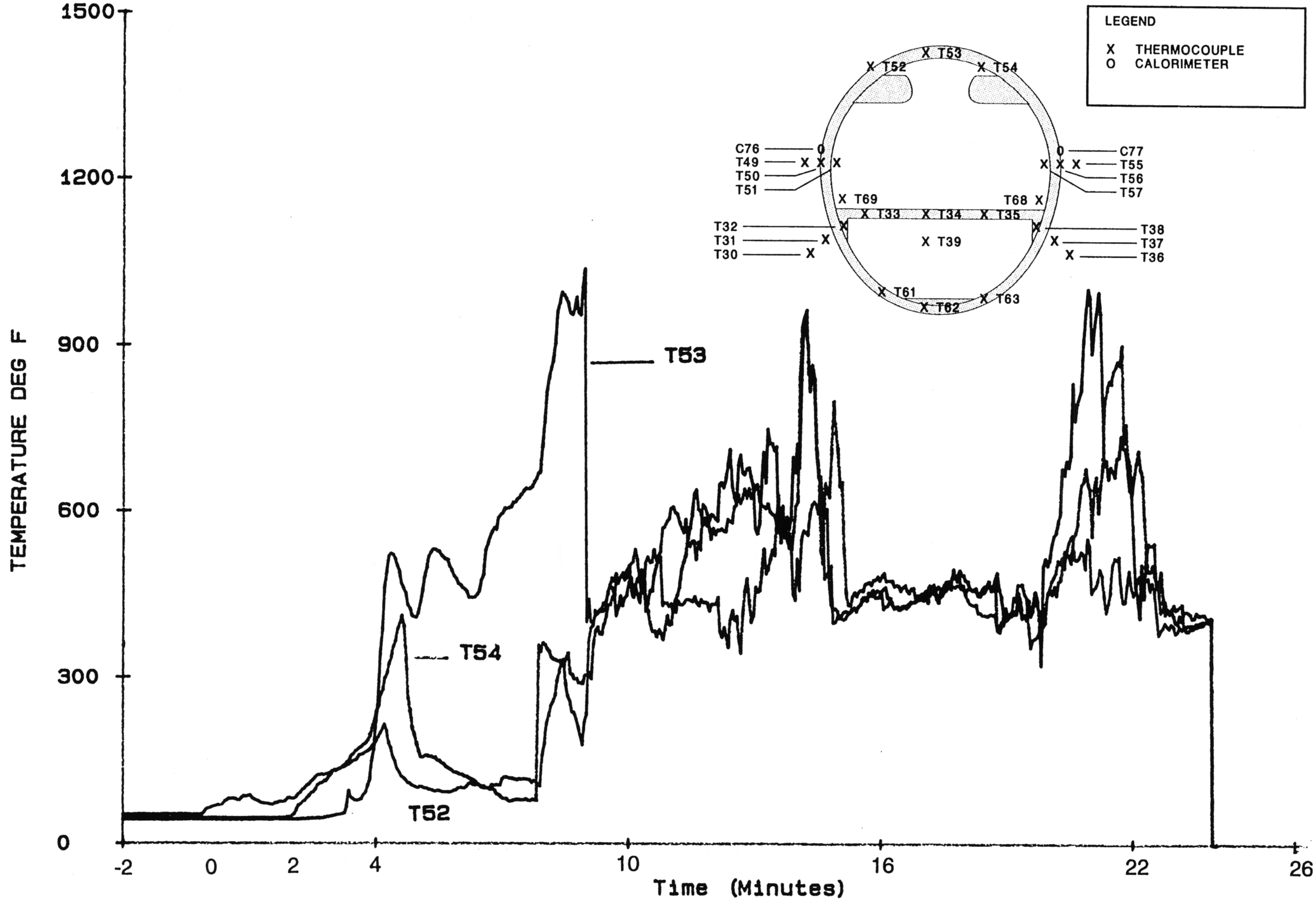

FIGURE D-12. AIR TEMPERATURES ABOVE CEILING AT STATION 1040

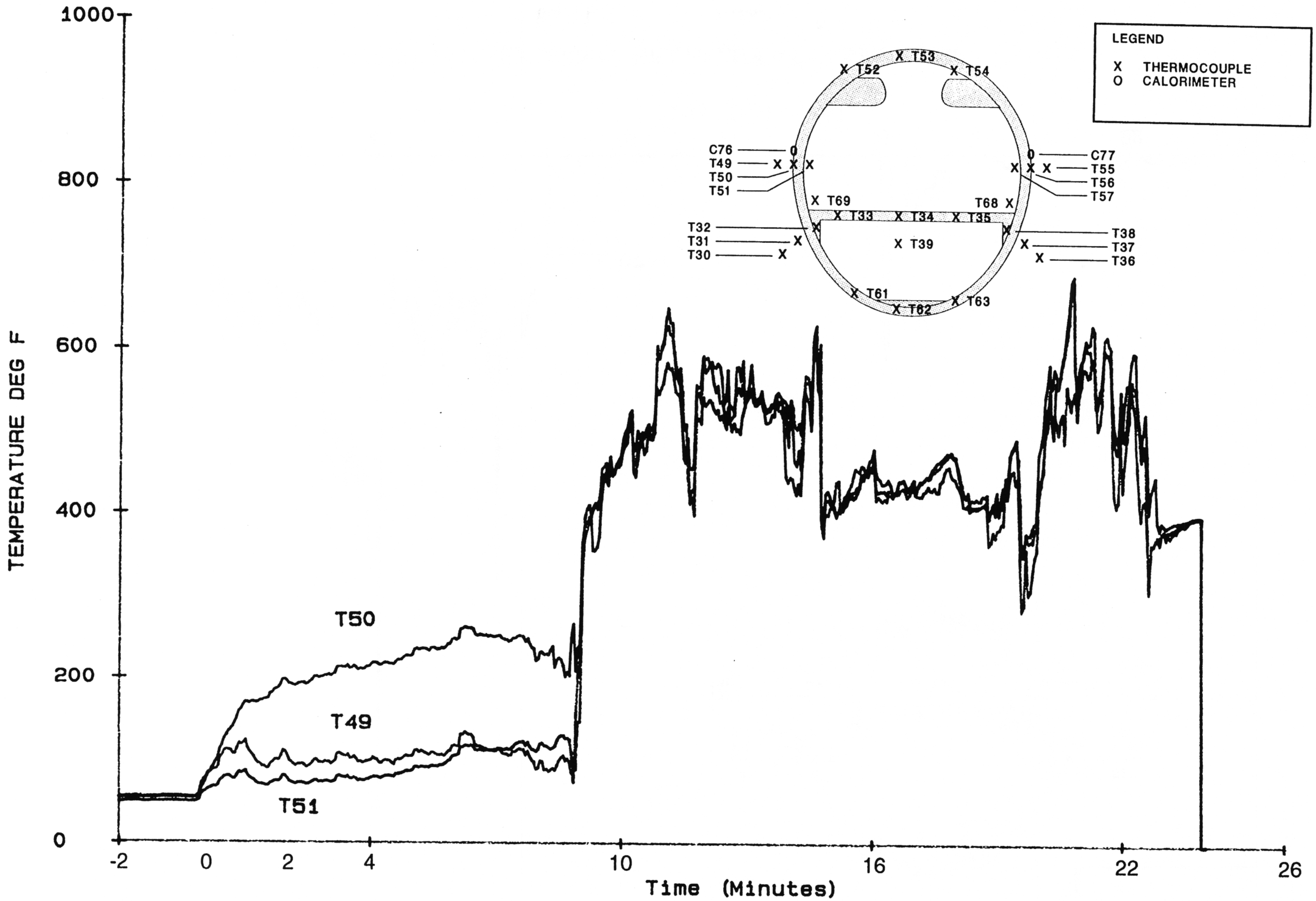

FIGURE D-13. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1040, BELOW WINDOW, PORT SIDE

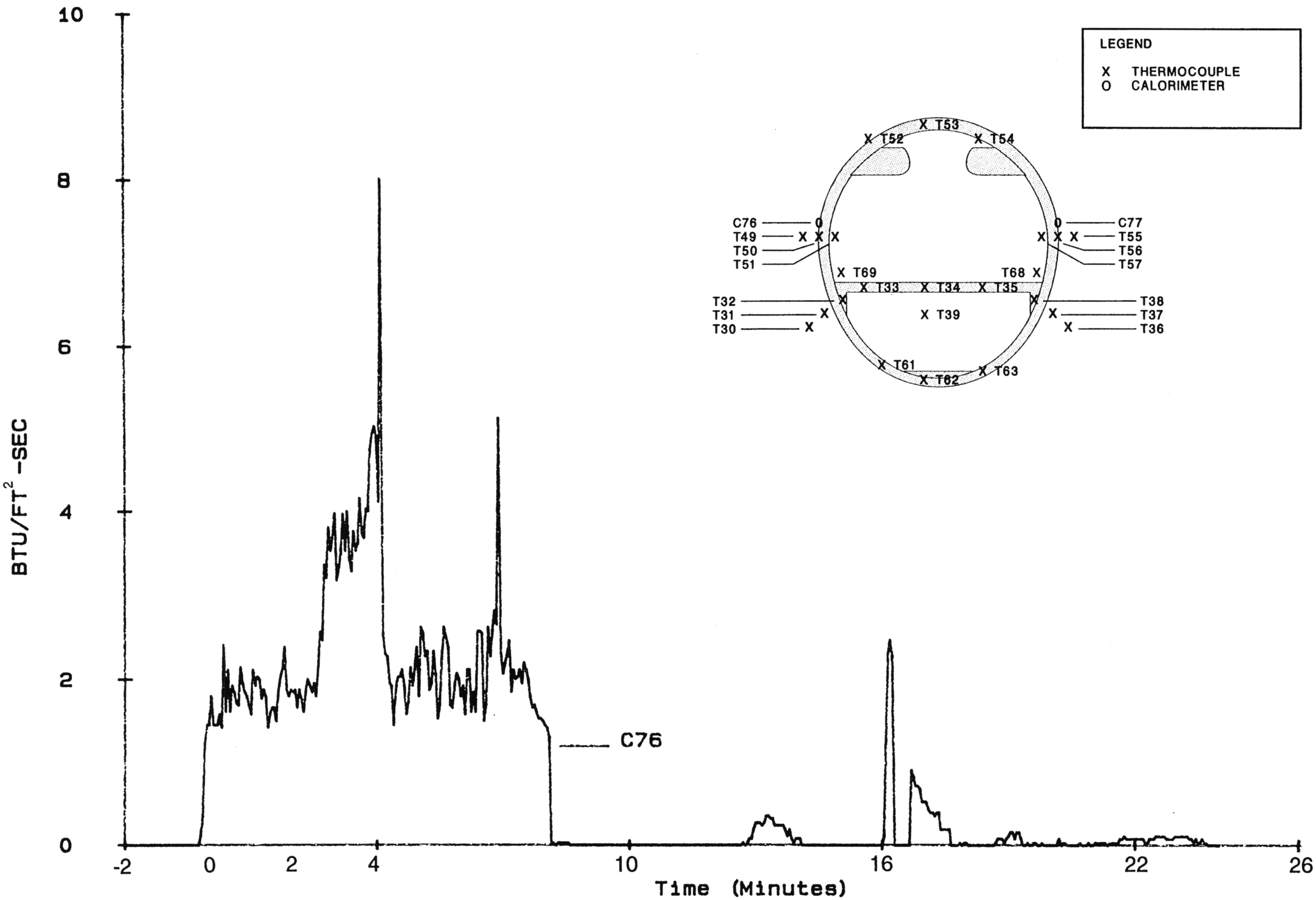

FIGURE D-14. EXTERNAL HEAT FLUX AT STATION 1040

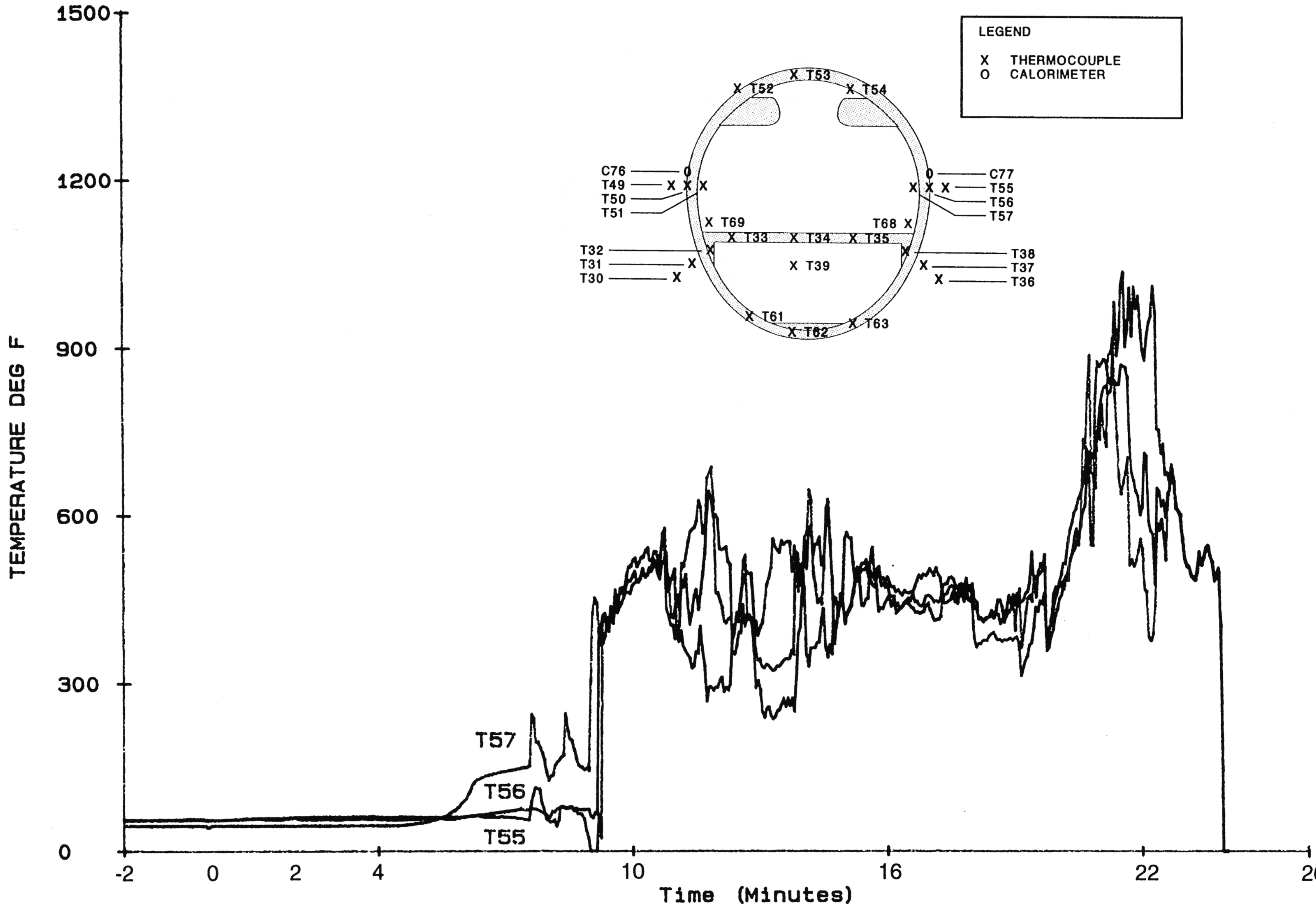

FIGURE D-15. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1040 BELOW WINDOW, STARBOARD SIDE

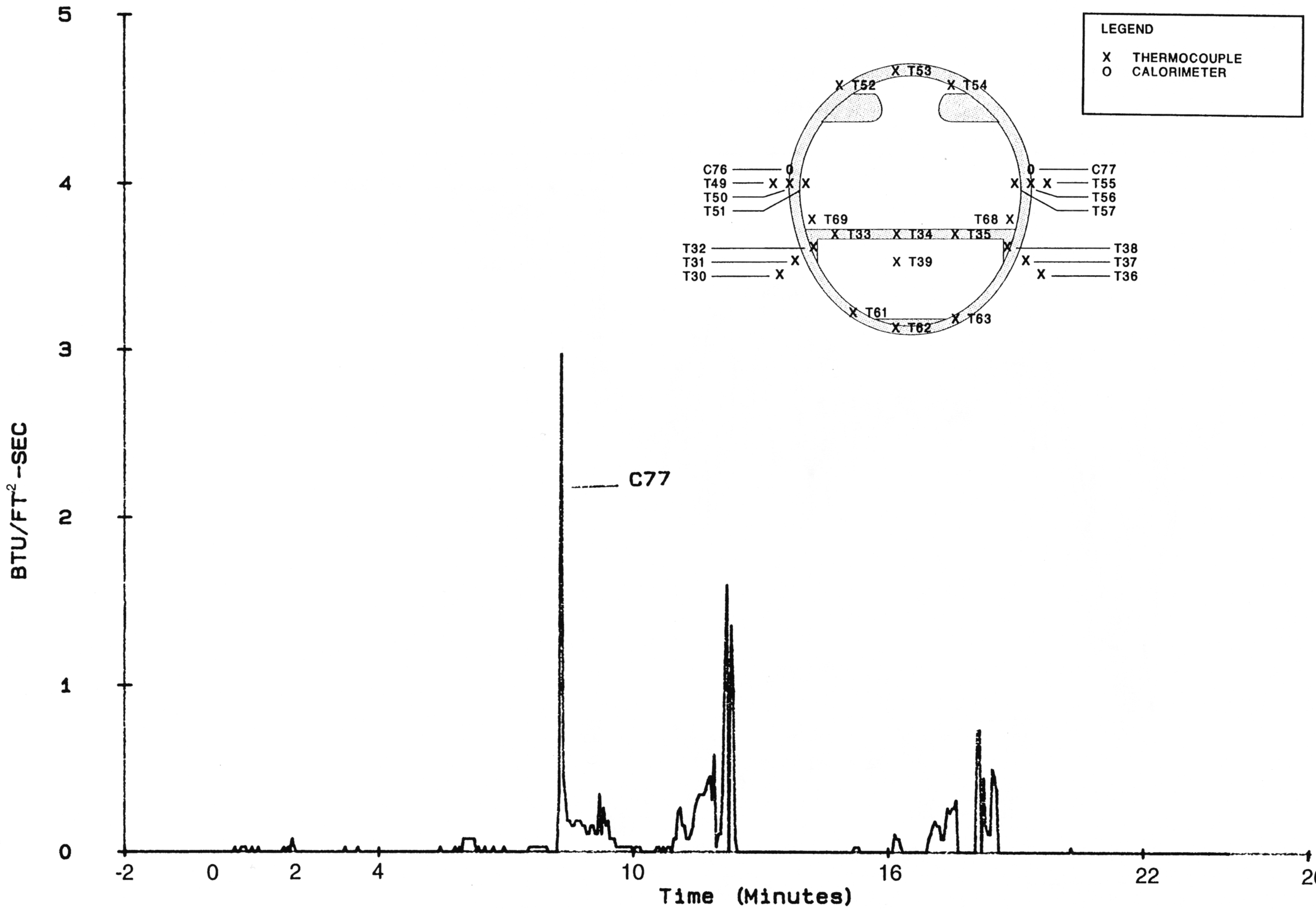

FIGURE D-16. EXTERNAL HEAT FLUX AT STATION 1040, STARBOARD SIDE

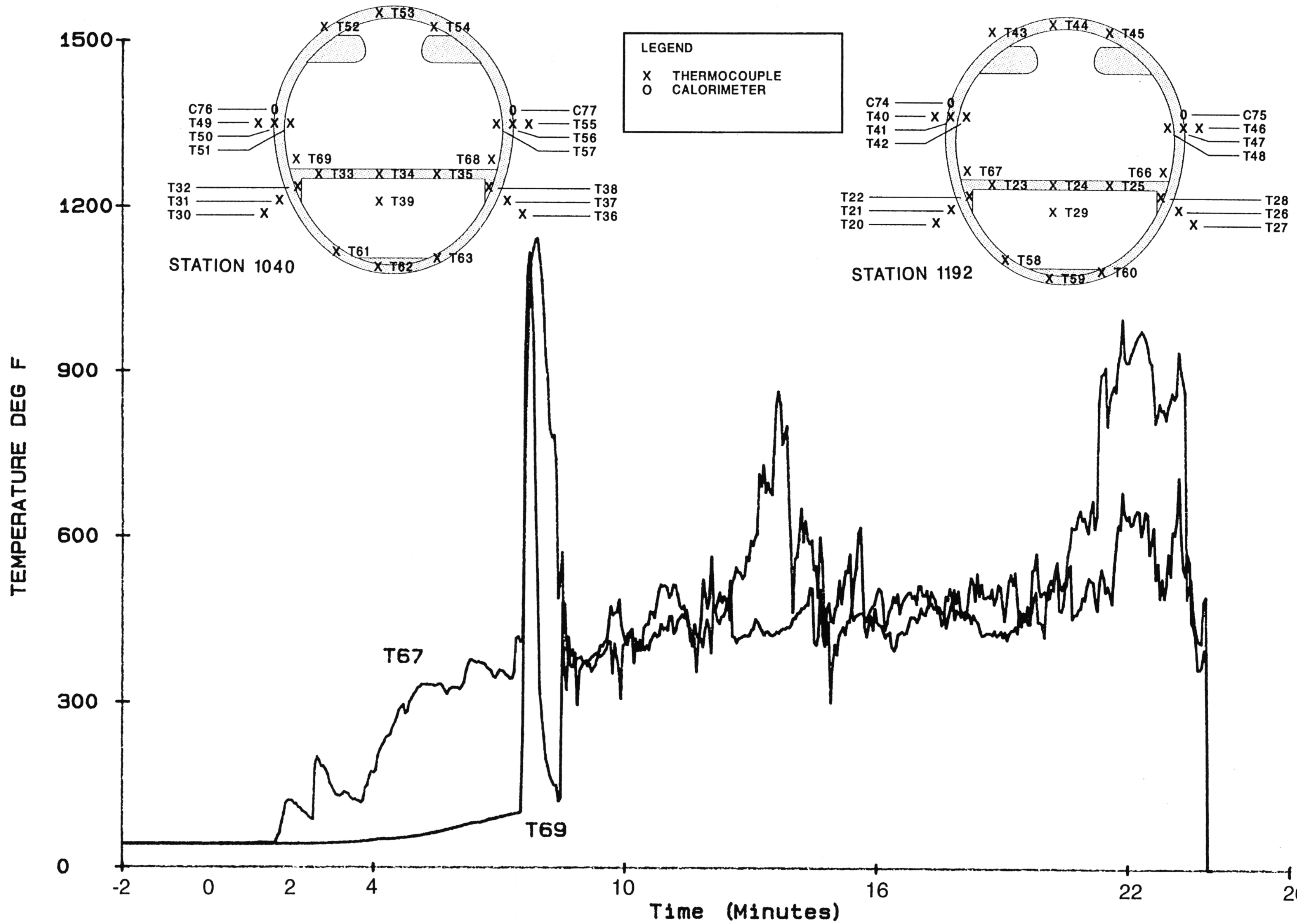

FIGURE D-17. AIR TEMPERATURE AT FLOOR GRILLS, STATIONS 1040 AND 1192, PORT SIDE

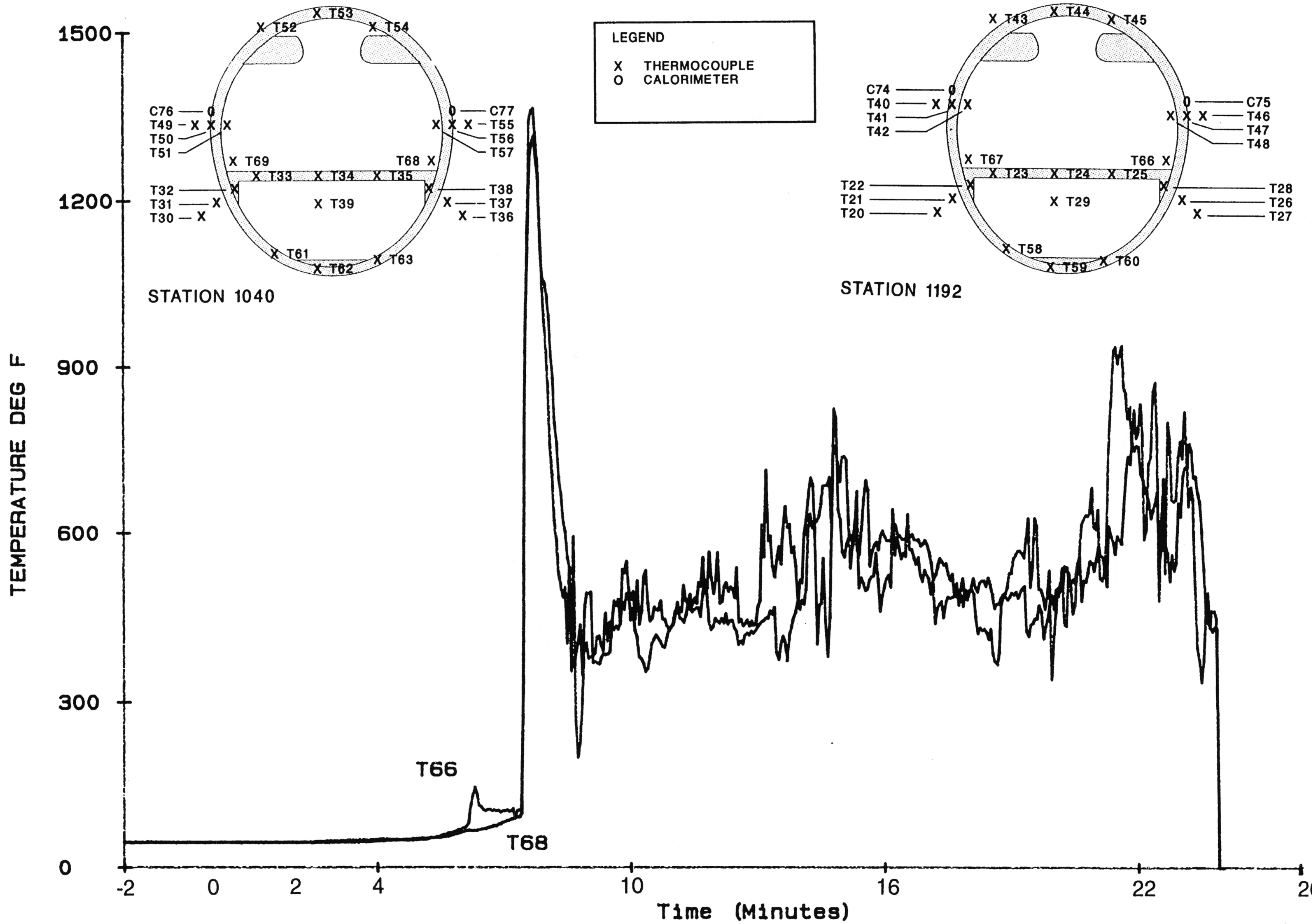

FIGURE D-18. AIR TEMPERATURE AT FLOOR GRILLS, STATIONS 1040 AND 1192, STARBOARD SIDE

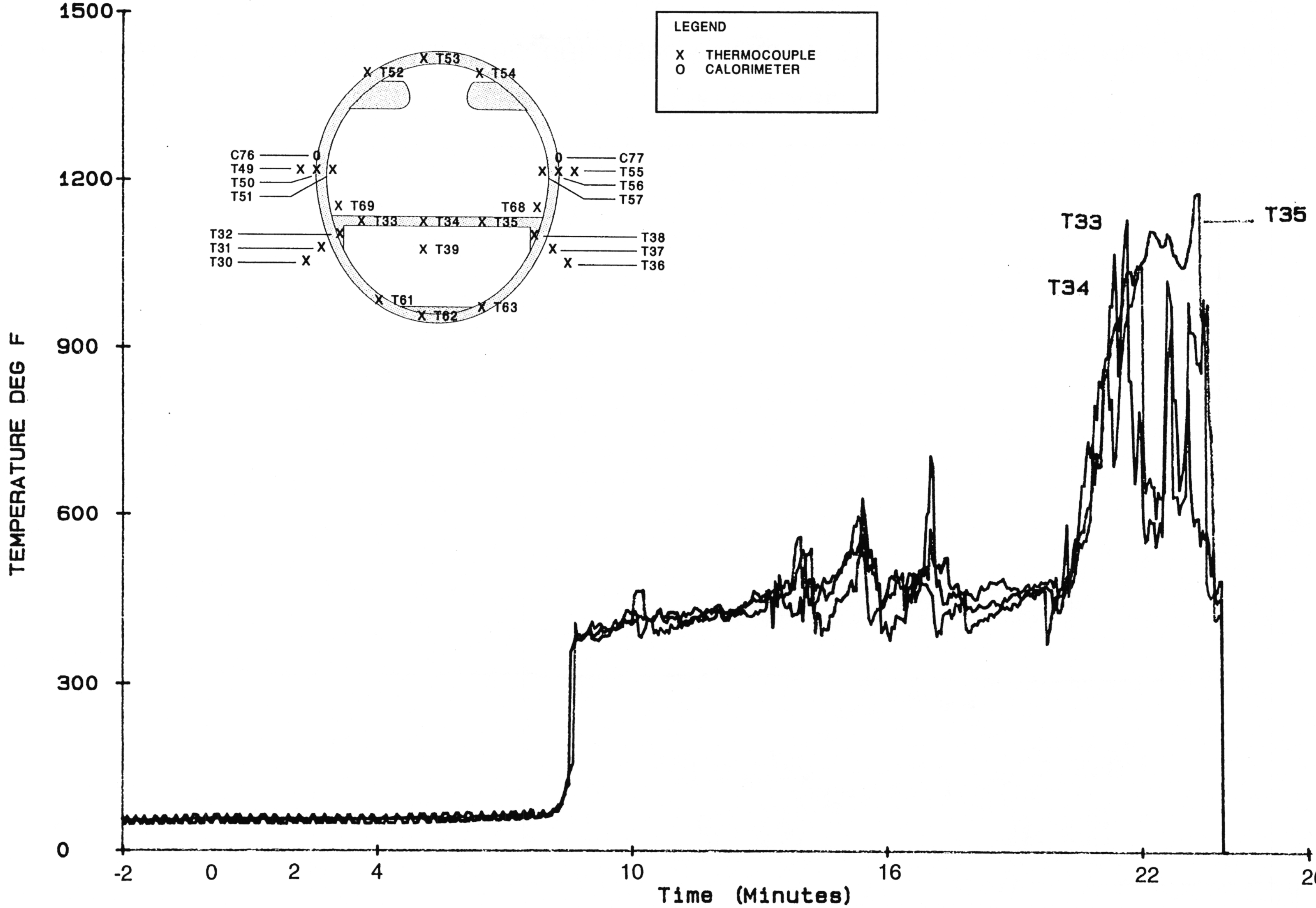

FIGURE D-19. AIR TEMPERATURE ABOVE CARGO LINER AT STATION 1040

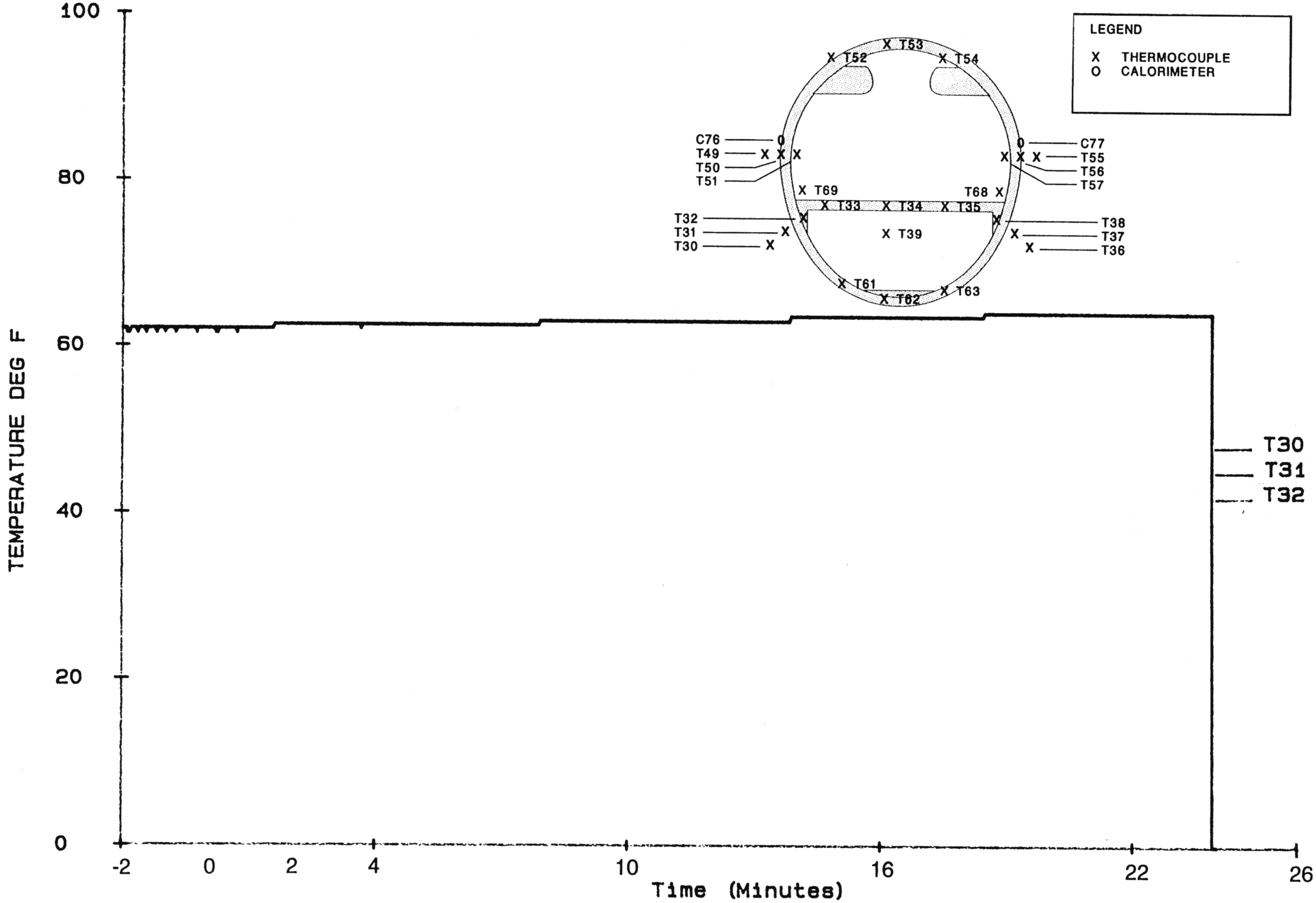

FIGURE D-20. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1040, CHEEK AREA, PORT SIDE

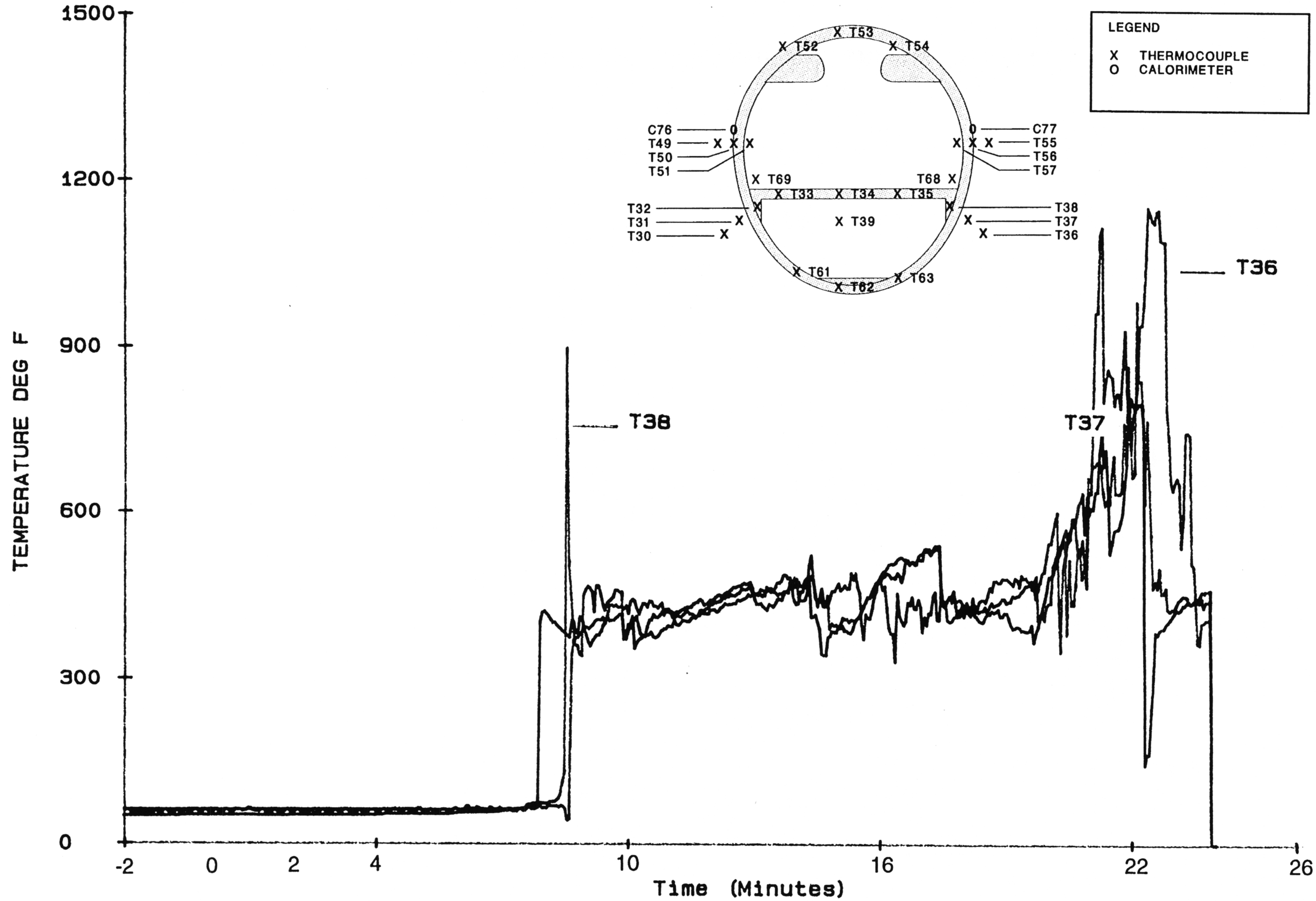

FIGURE D-21. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1040, CHEEK AREA, STARBOARD SIDE

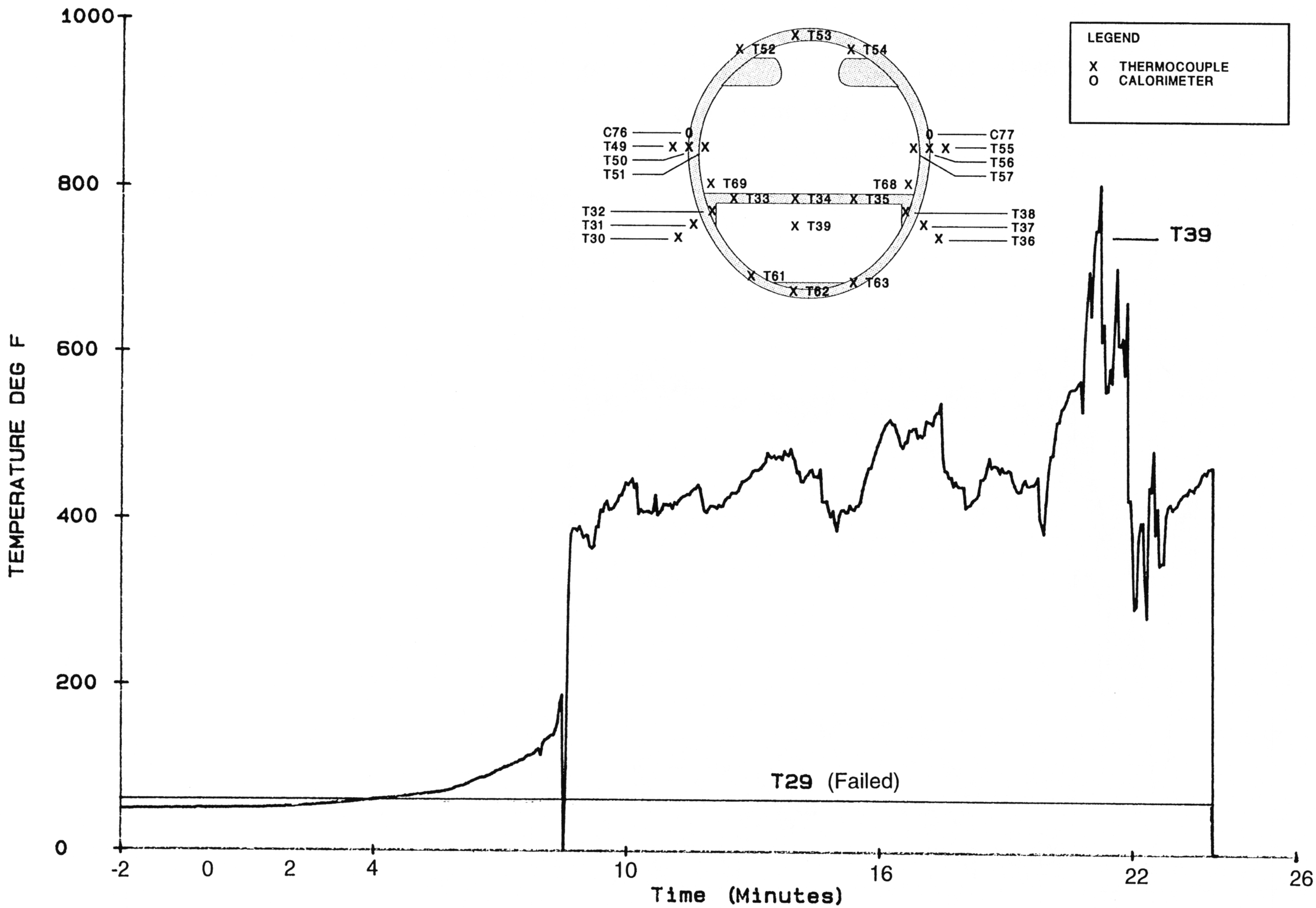

FIGURE D-22. CARGO COMPARTMENT AIR TEMPERATURE AT STATION 1040

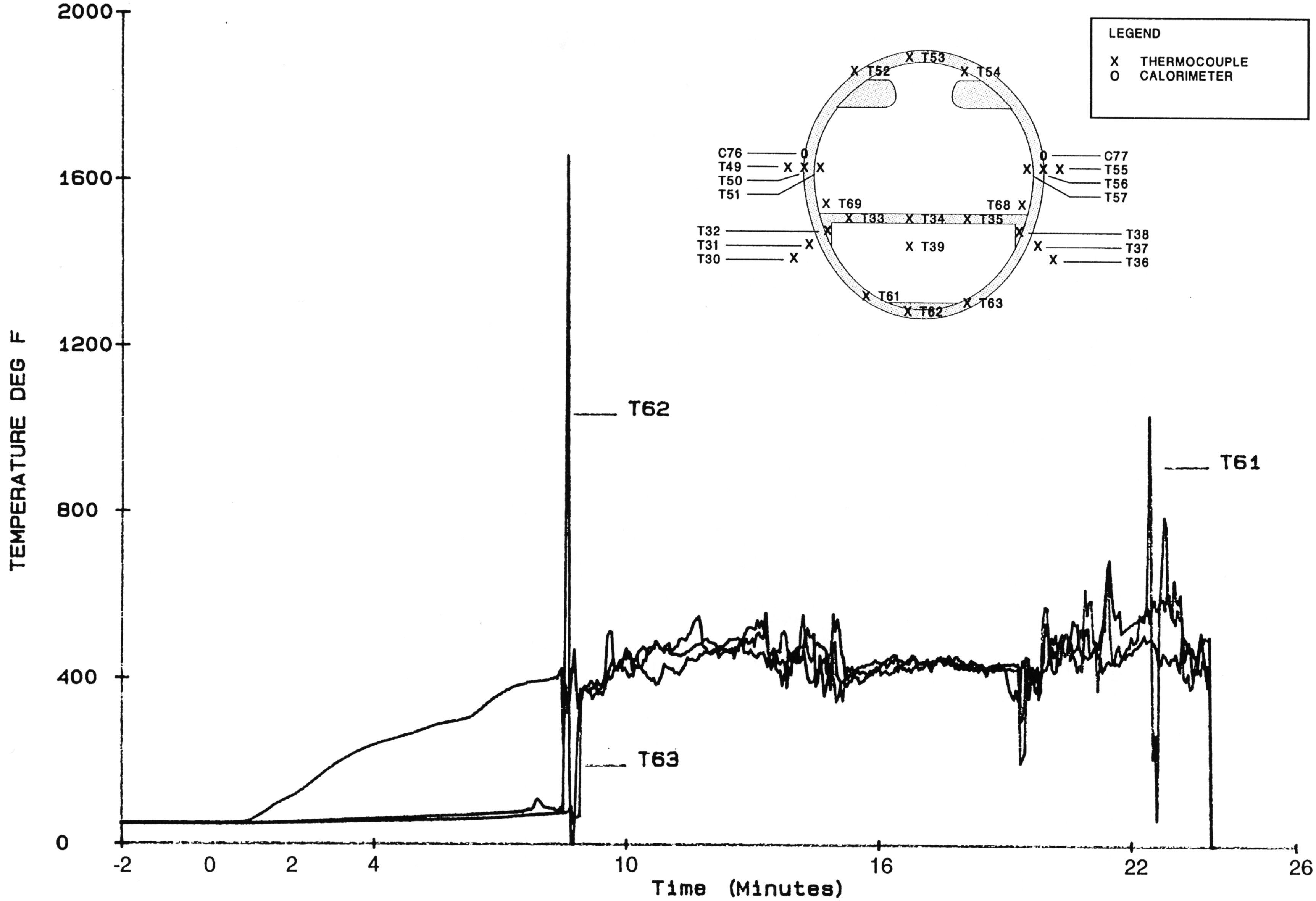

FIGURE D-23. AIR TEMPERATURE UNDER THE CARGO FLOOR AT STATION 1040

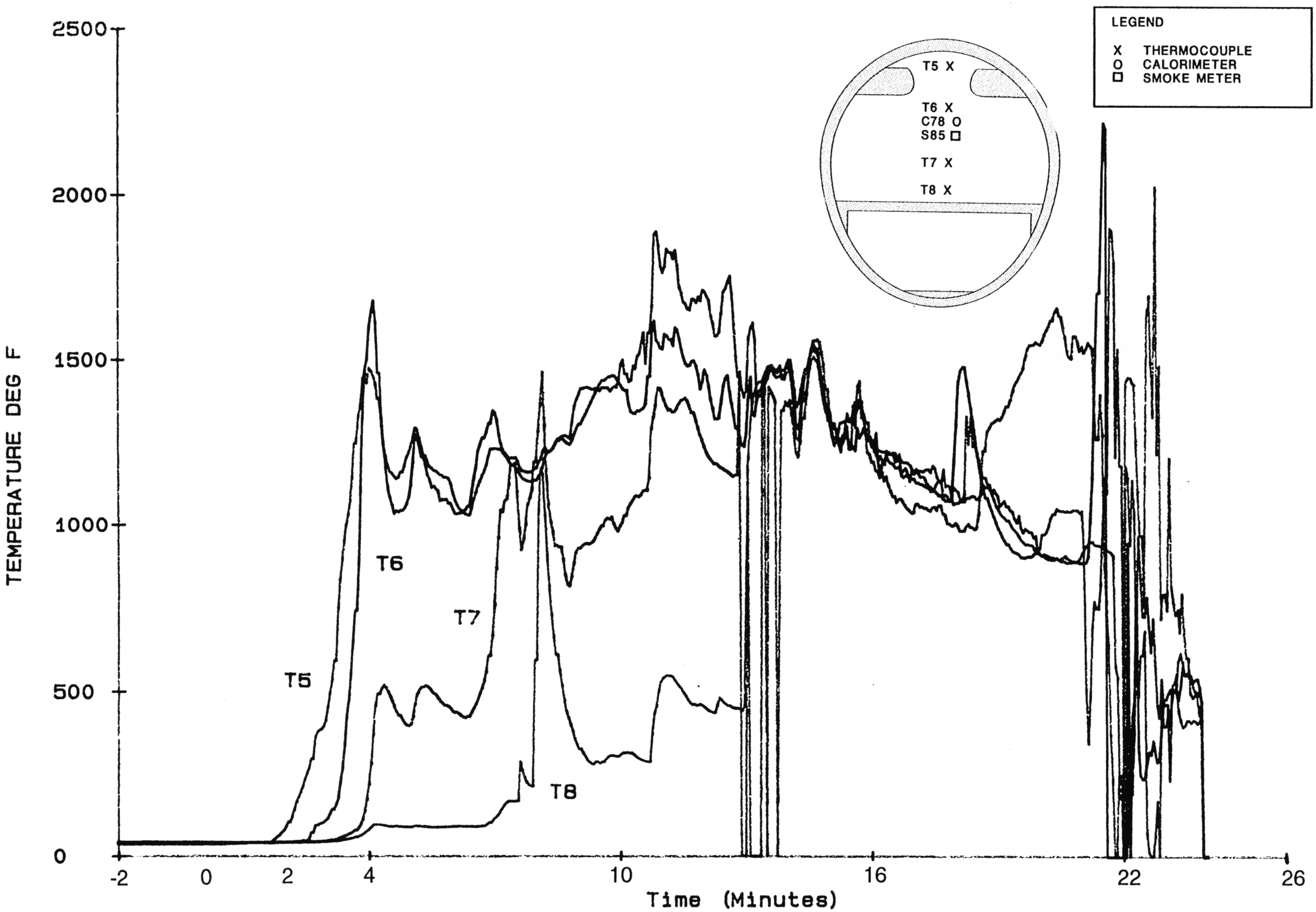

FIGURE D-24. THERMOCOUPLE TREE 2 AT STATION 1106

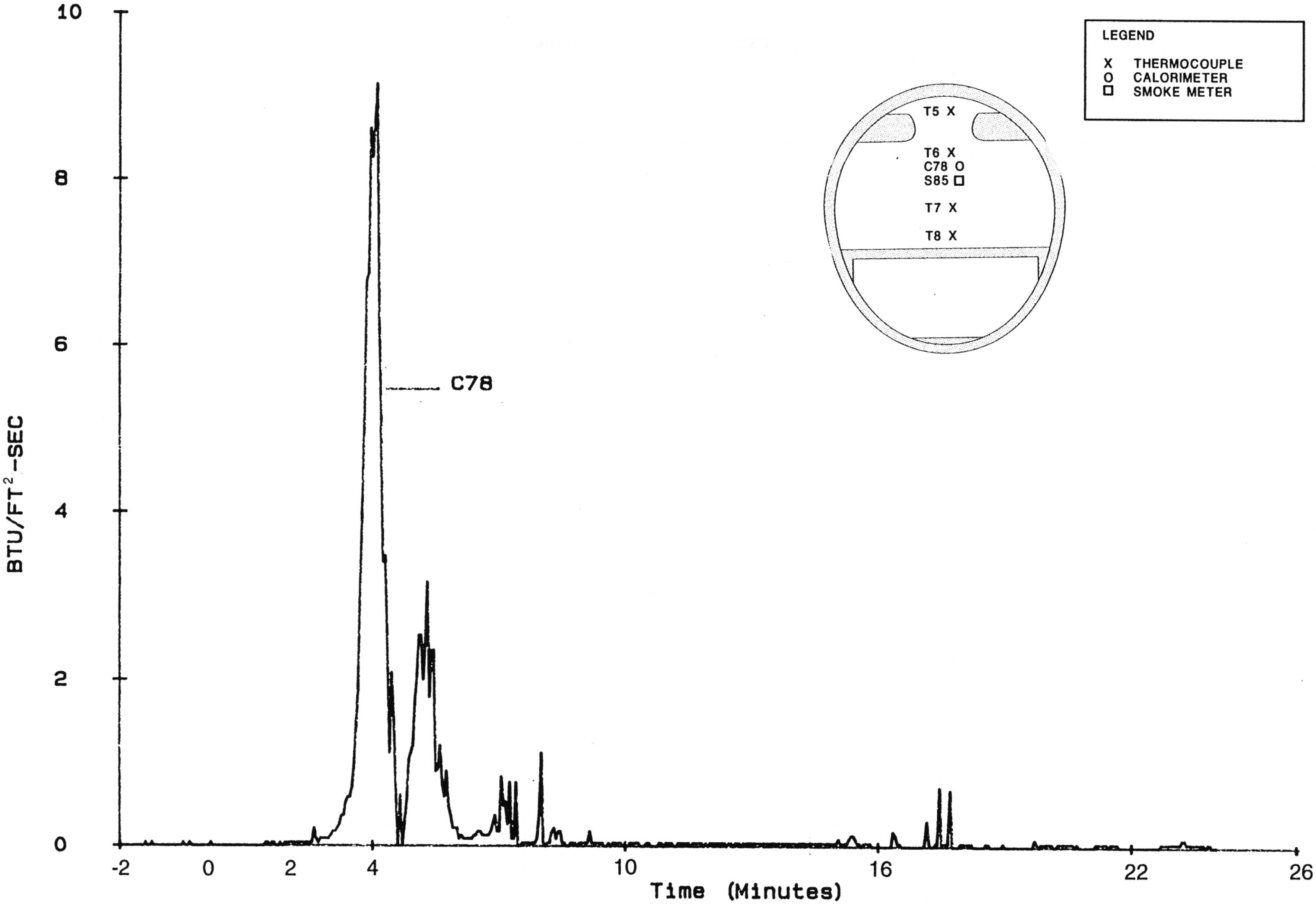

FIGURE D-25. INTERNAL HEAT FLUX AT STATION 1106

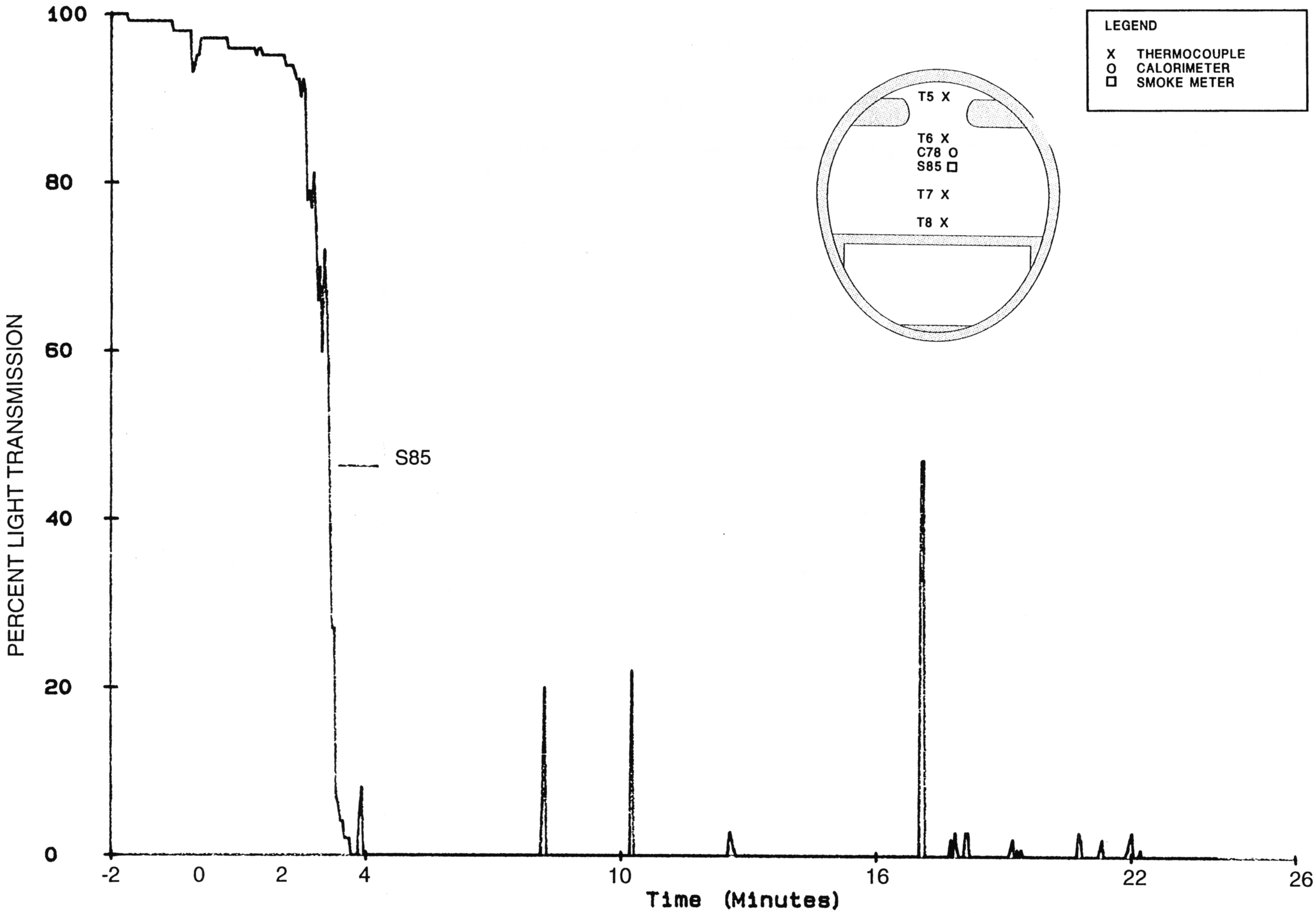

FIGURE D-26. SMOKE DENSITY AT STATION 1106

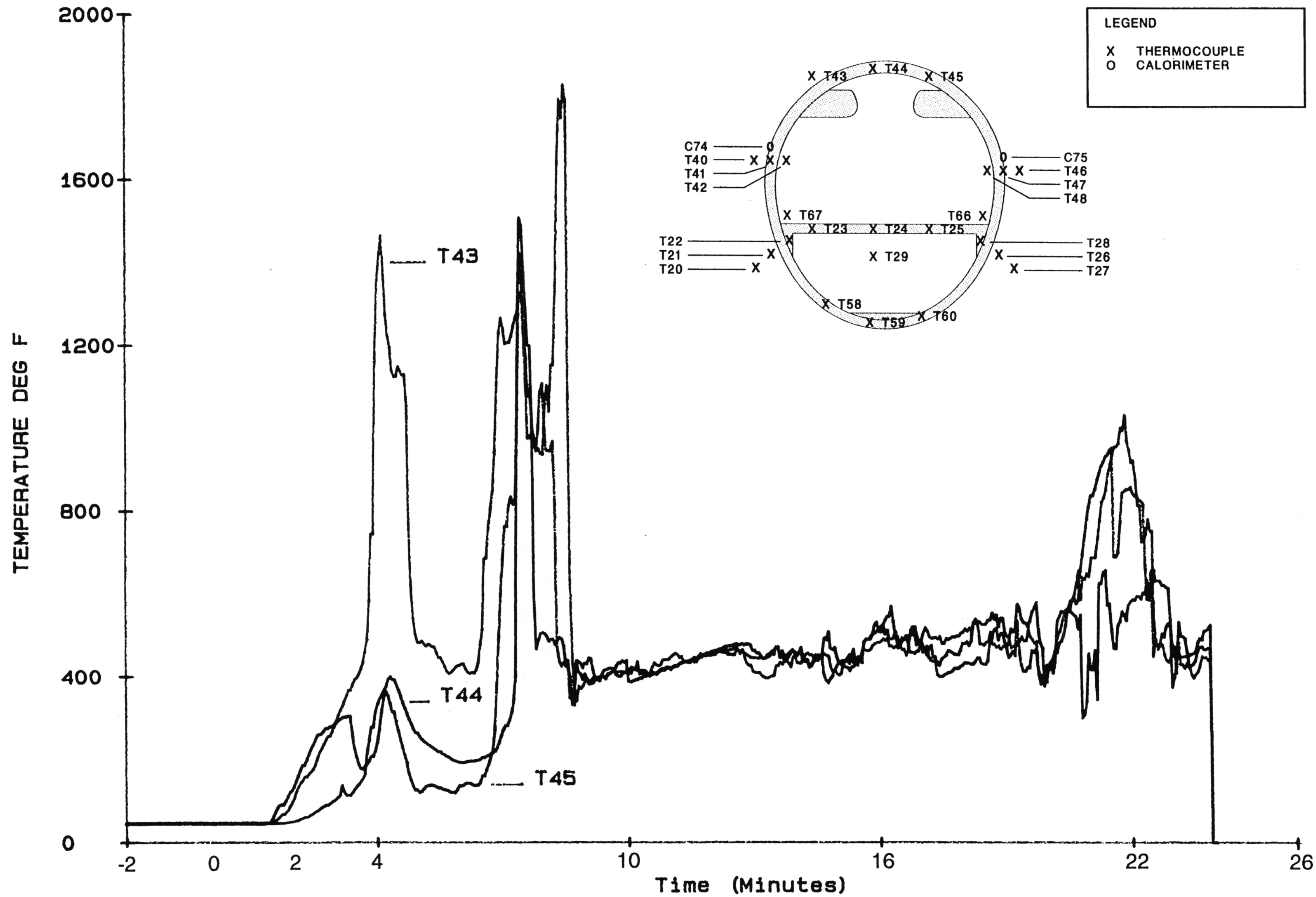

FIGURE D-27. AIR TEMPERATURES ABOVE THE CEILING AT STATION 1192

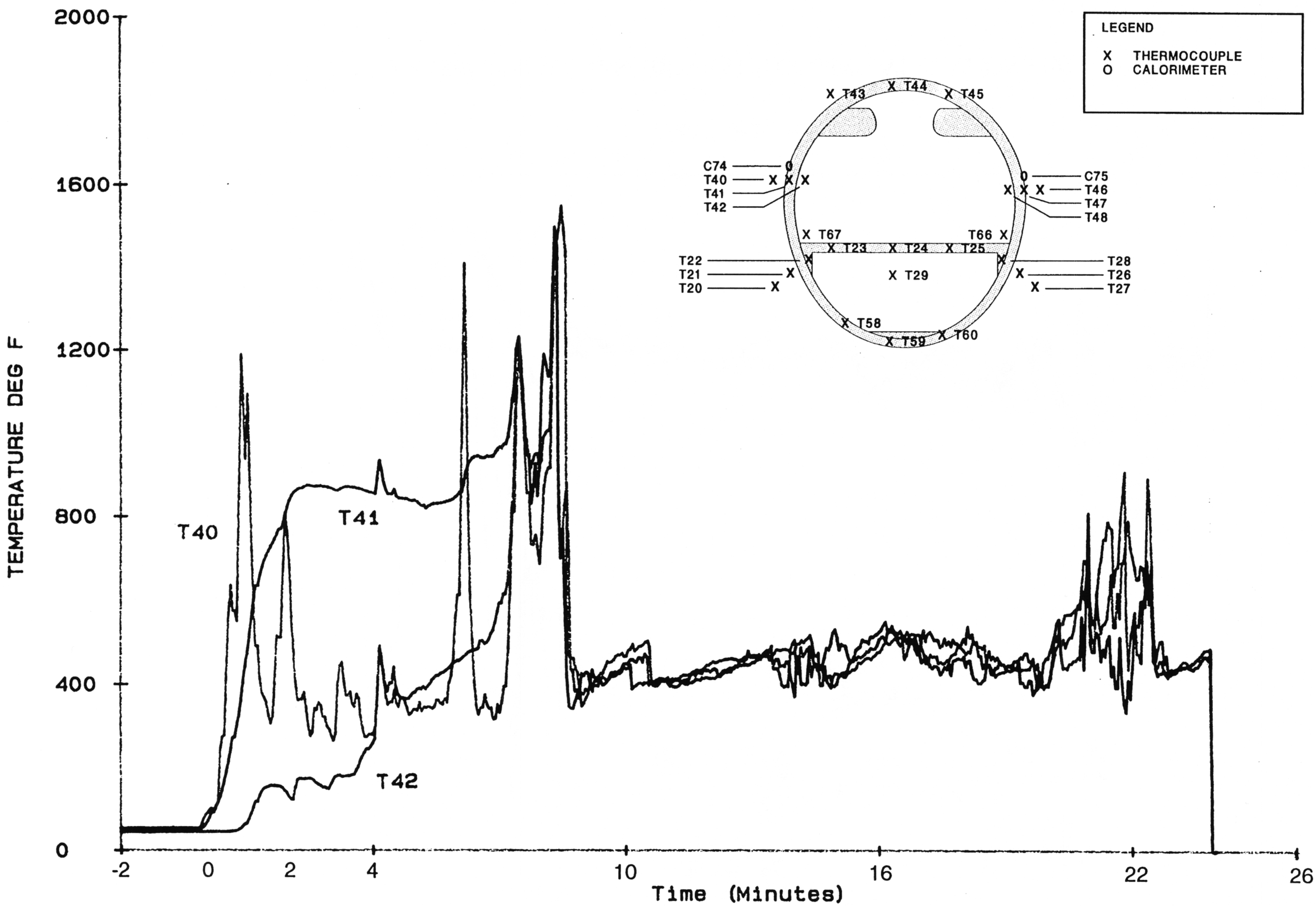

FIGURE D-28. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, BELOW WINDOW, PORT SIDE

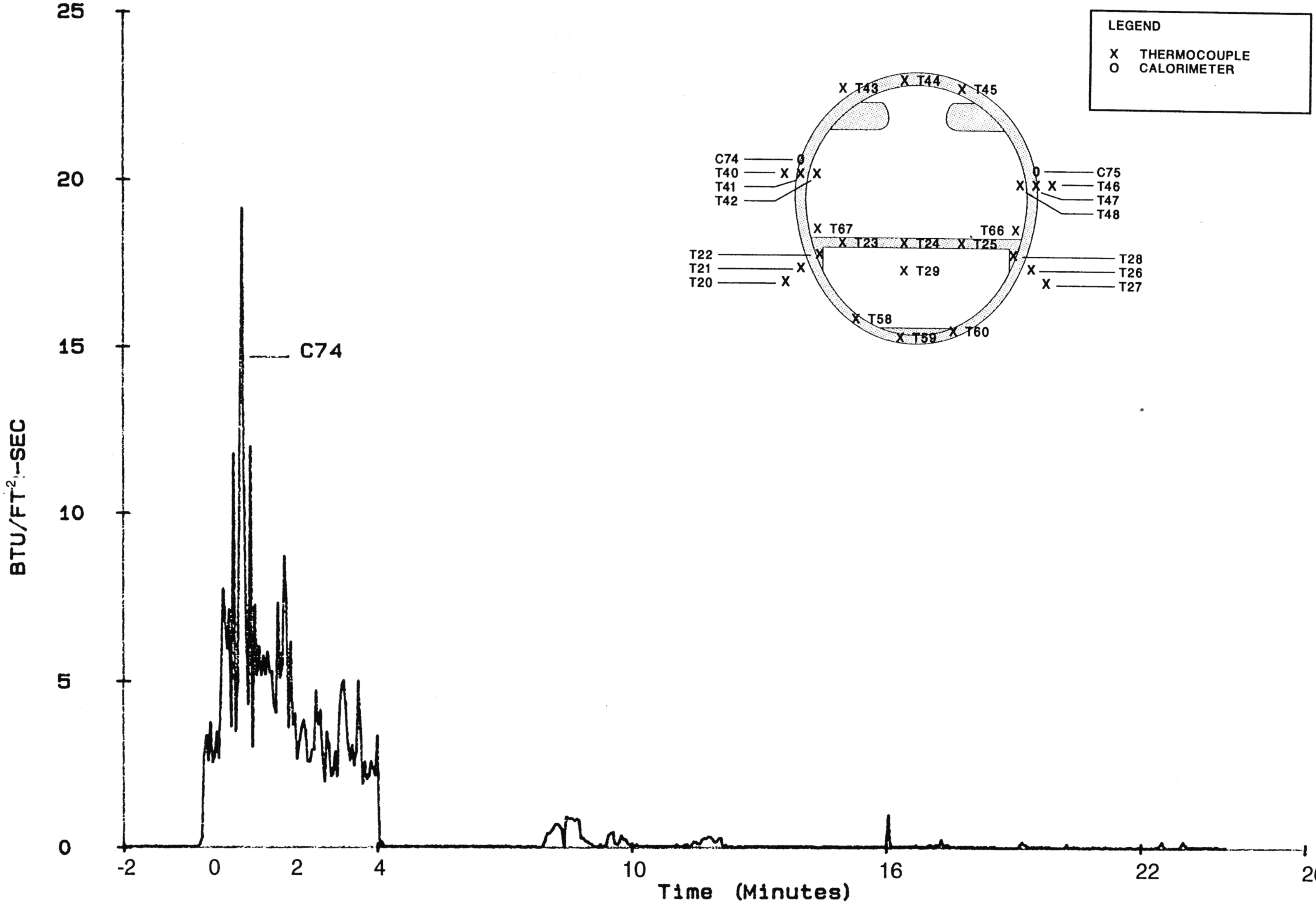

FIGURE D-29. EXTERNAL HEAT FLUX AT STATION 1192, PORT SIDE

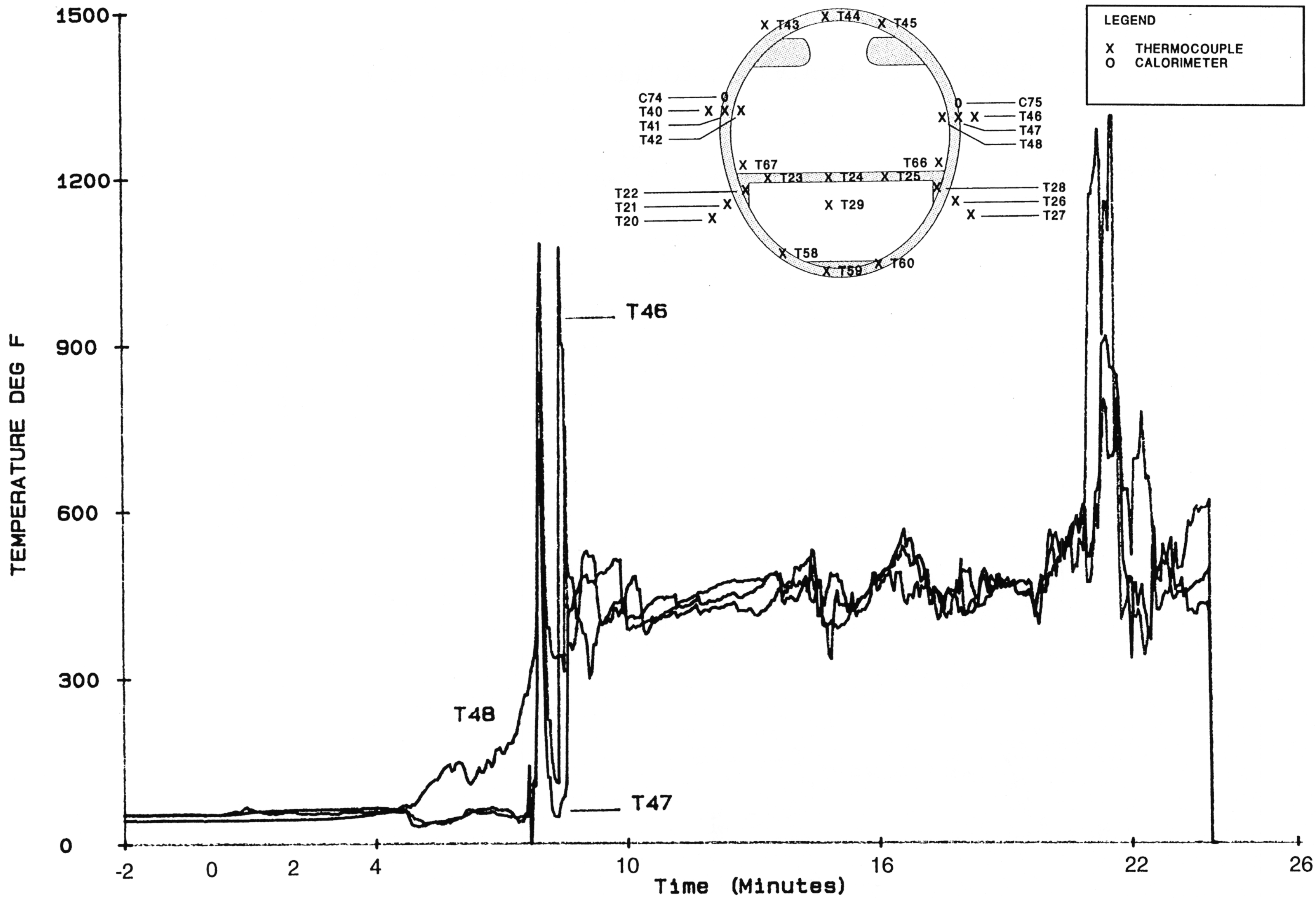

FIGURE D-30. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, BELOW THE WINDOW, STARBOARD SIDE

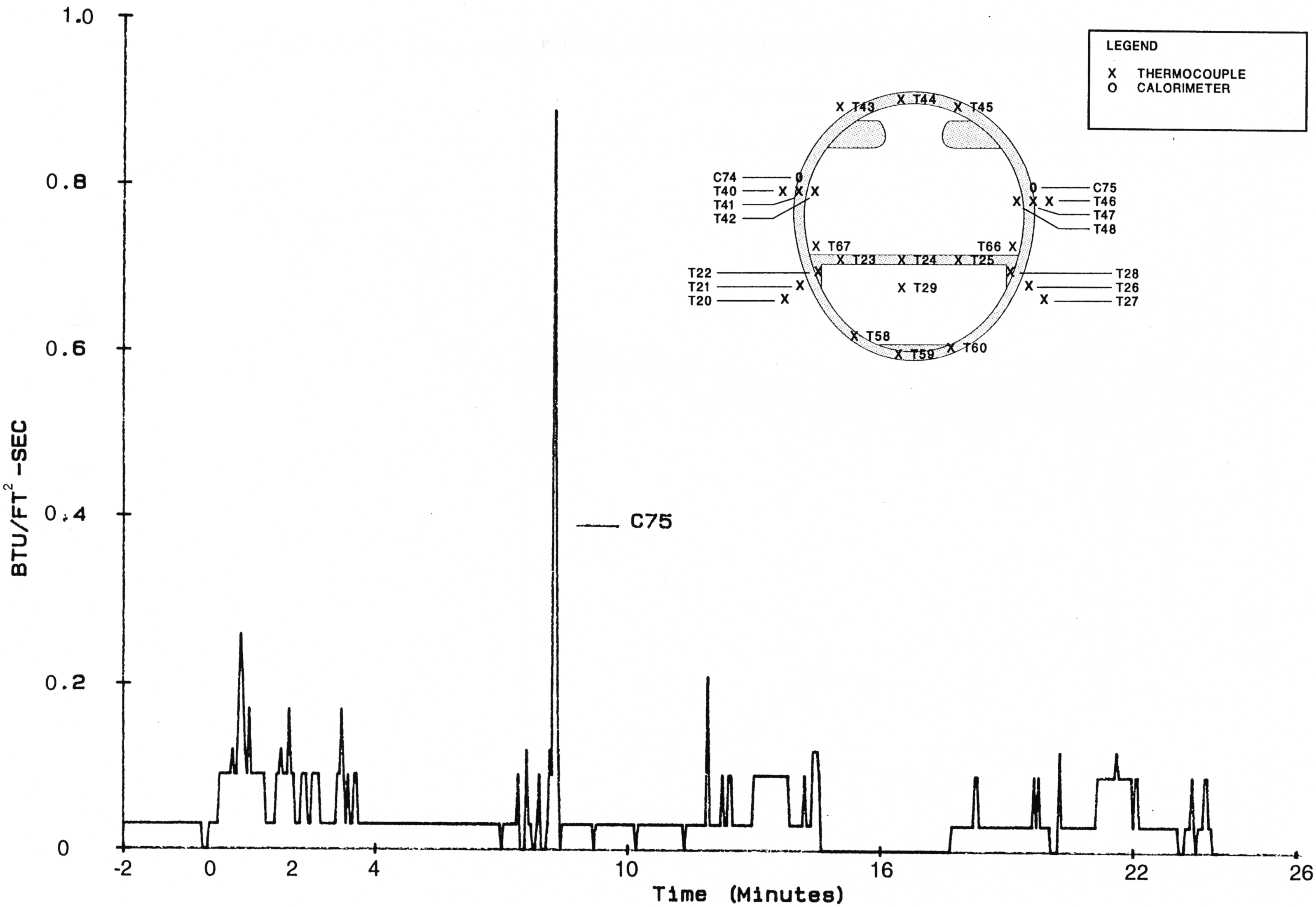

FIGURE D-31. EXTERNAL HEAT FLUX AT STATION 1192, STARBOARD SIDE

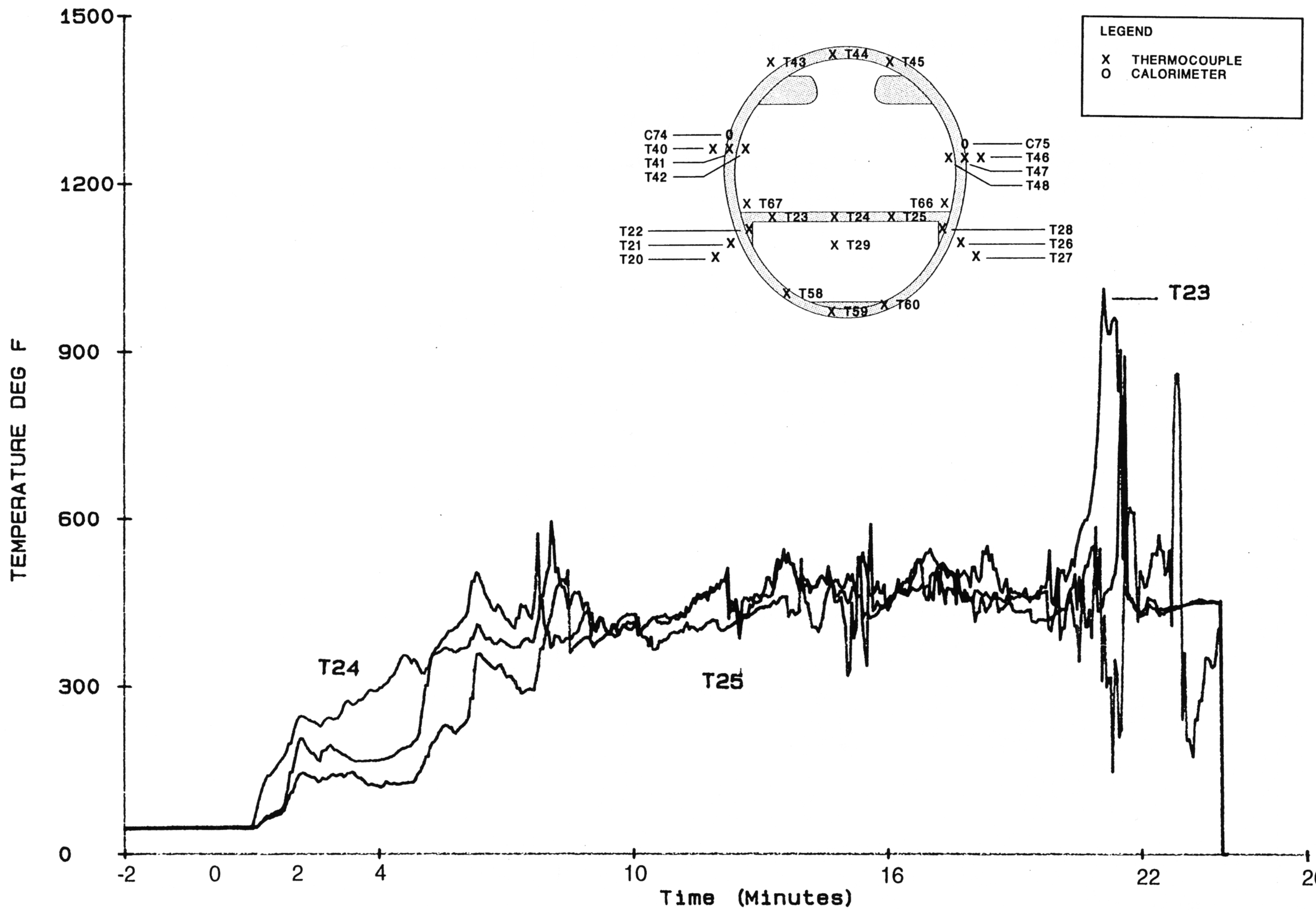

FIGURE D-32. AIR TEMPERATURE ABOVE CARGO LINER AT STATION 1192

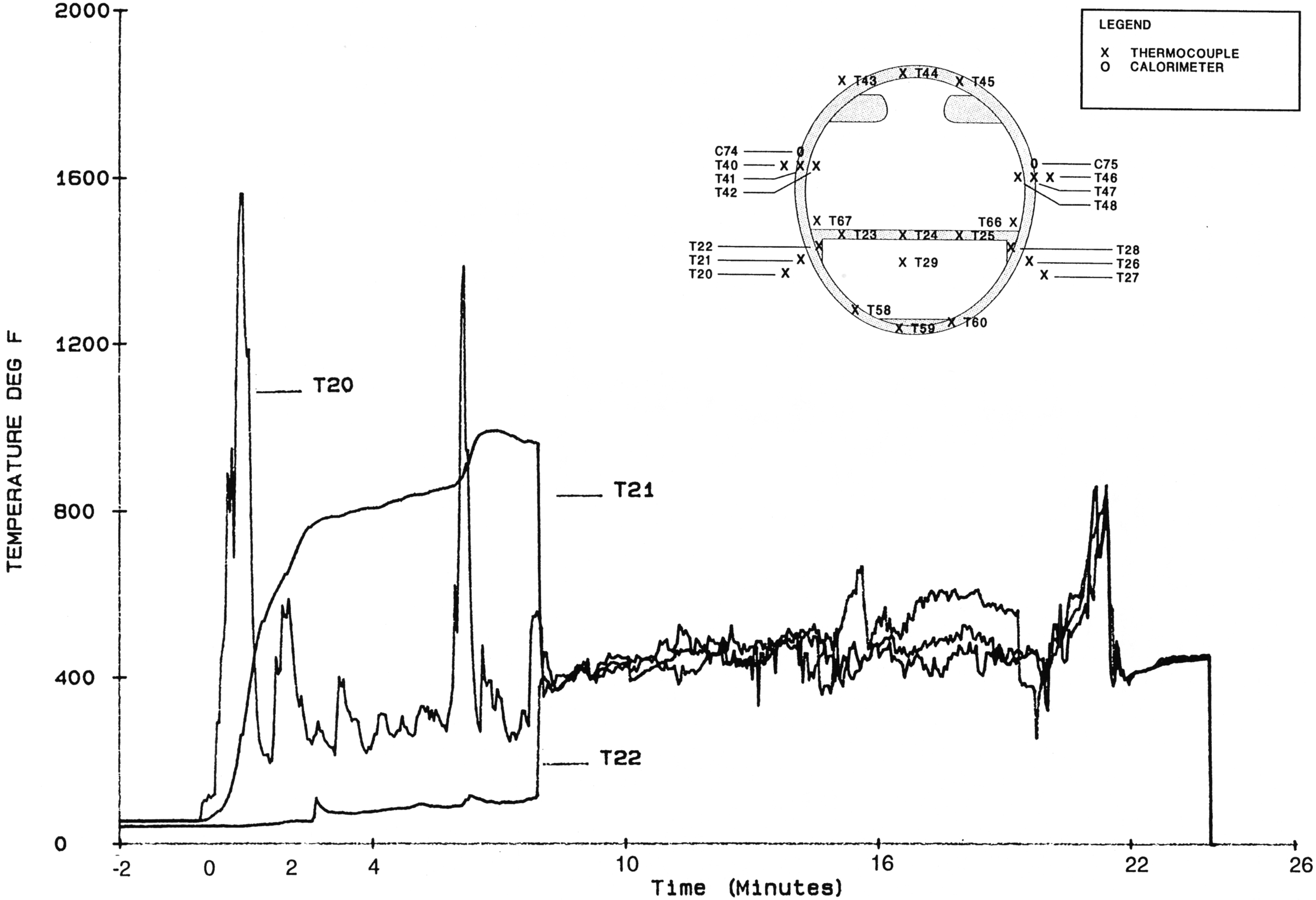

FIGURE D-33. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, CHEEK AREA, PORT SIDE

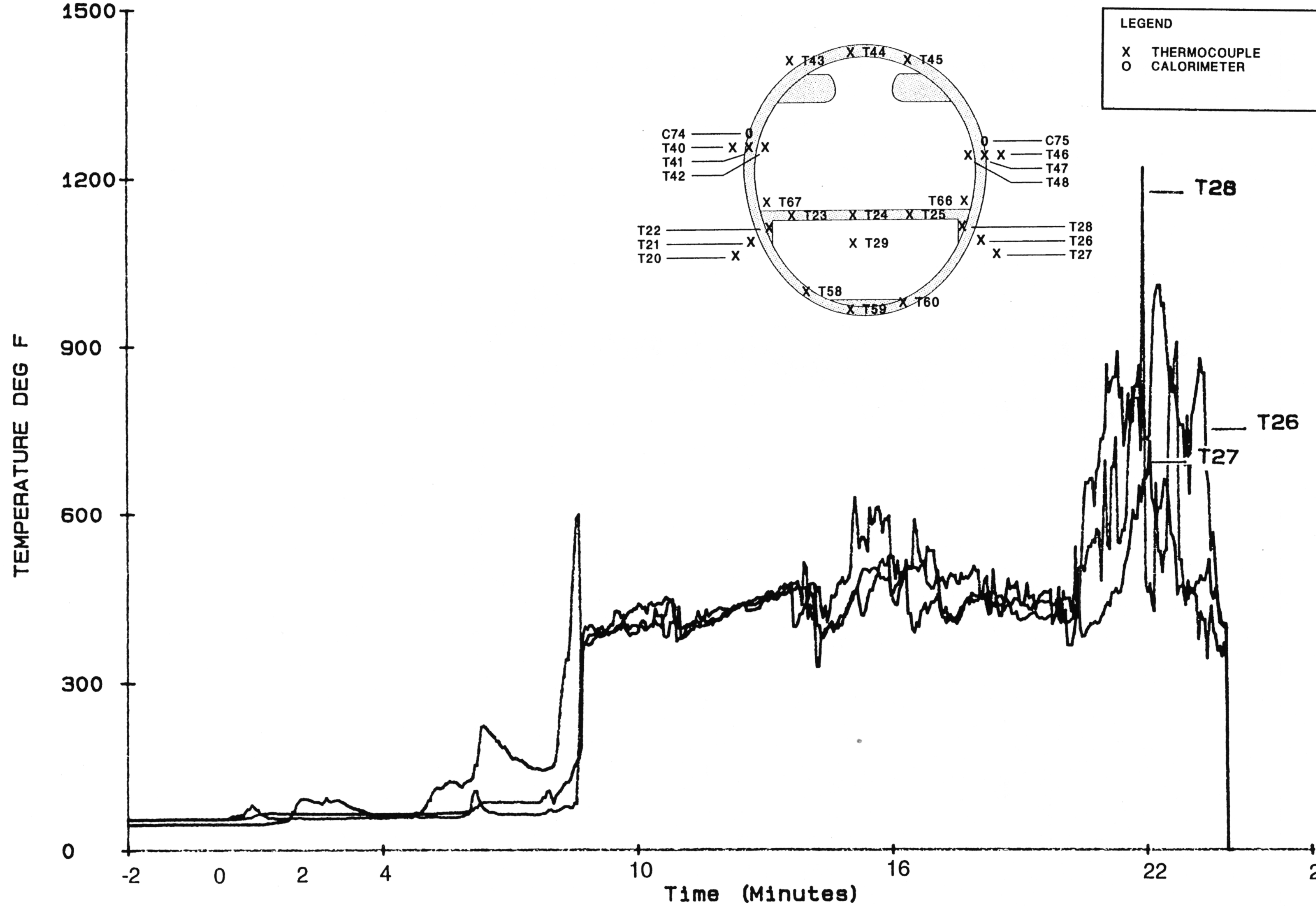

FIGURE D-34. TEMPERATURE PROFILE THROUGH FUSELAGE SKIN AT STATION 1192, CHEEK AREA, STARBOARD SIDE

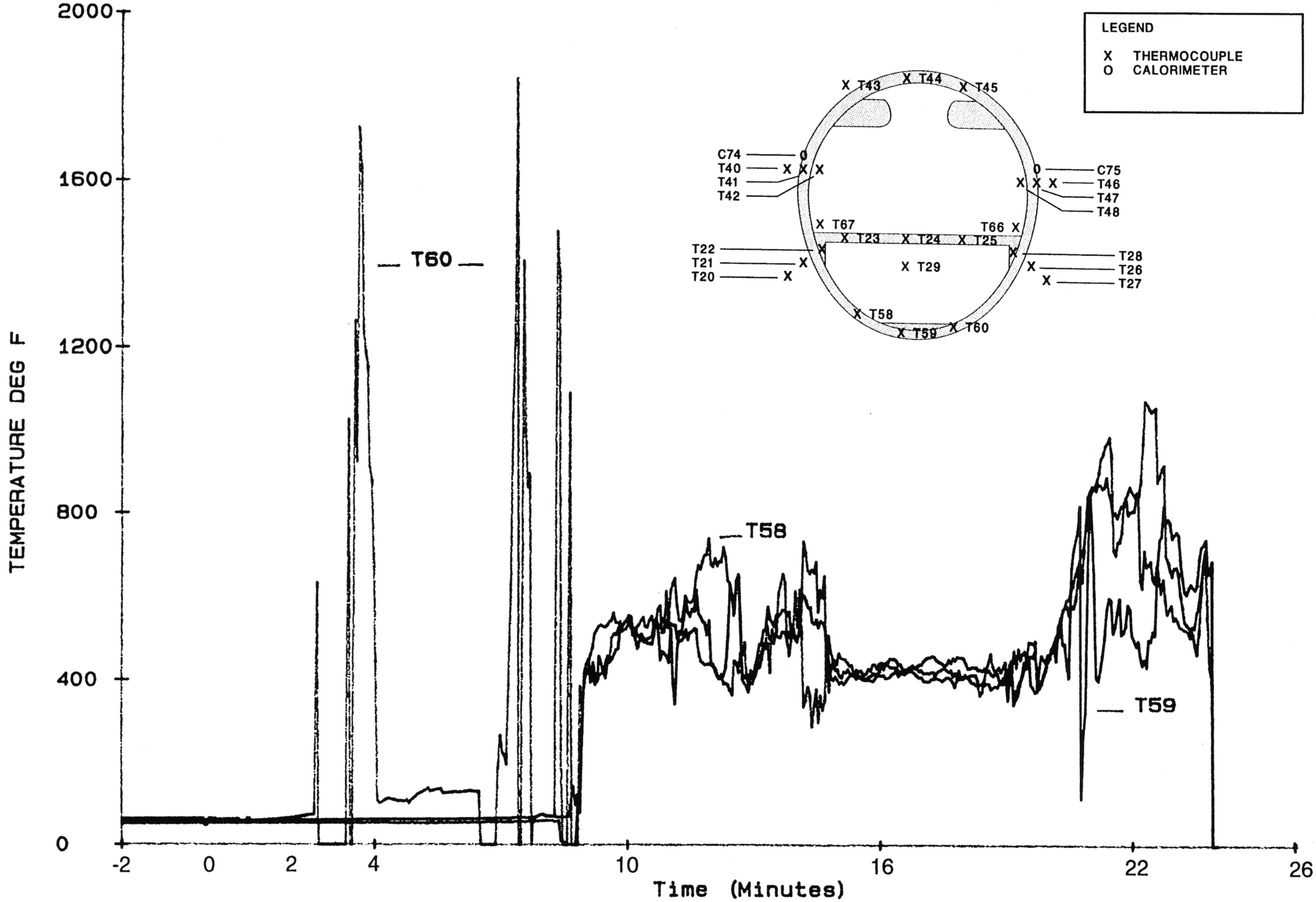

FIGURE D-35. AIR TEMPERATURE UNDER CARGO COMPARTMENT FLOOR AT STATION 1192

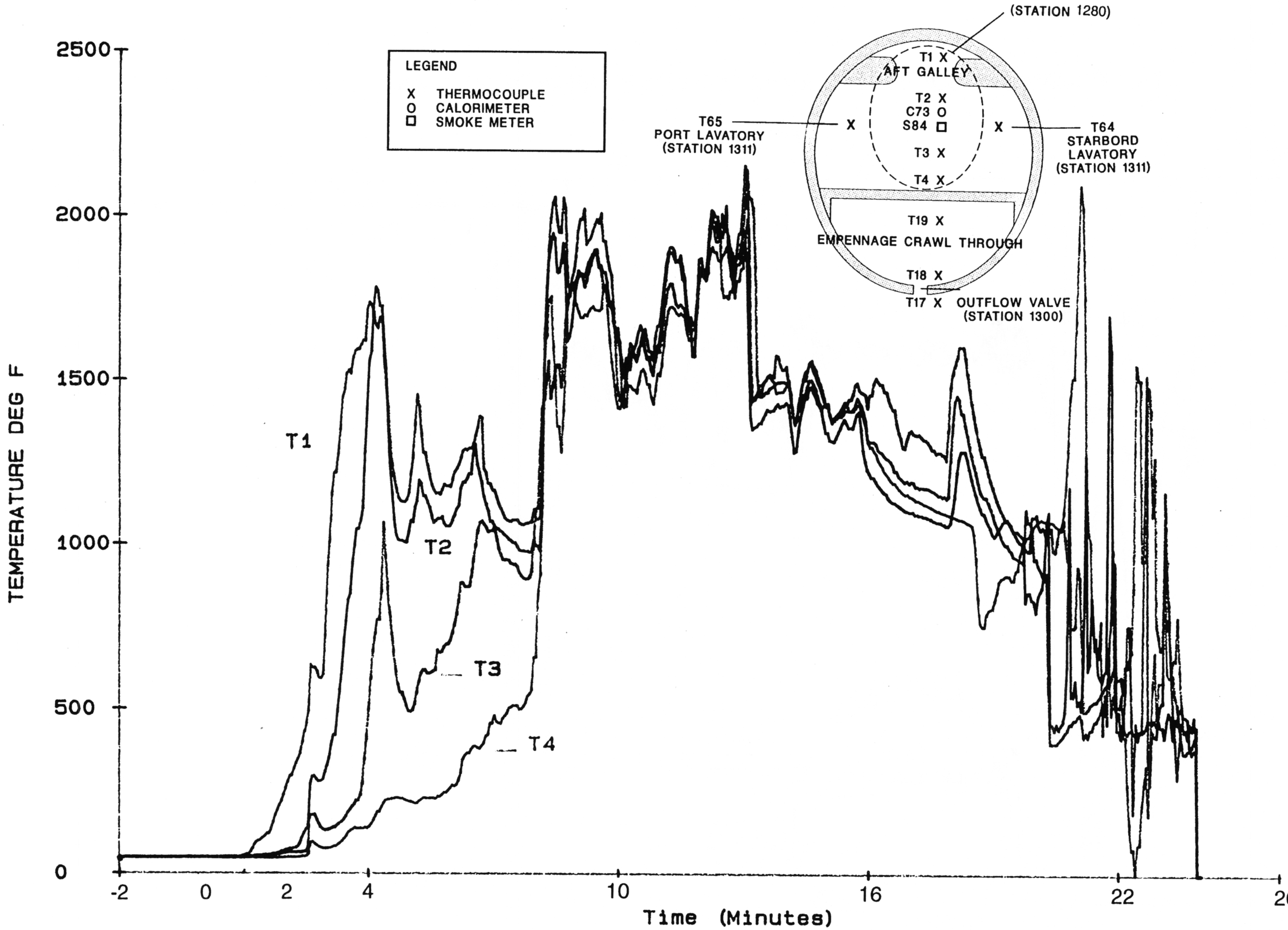

FIGURE D-36. THERMOCOUPLE TREE 1 AT STATION 1280

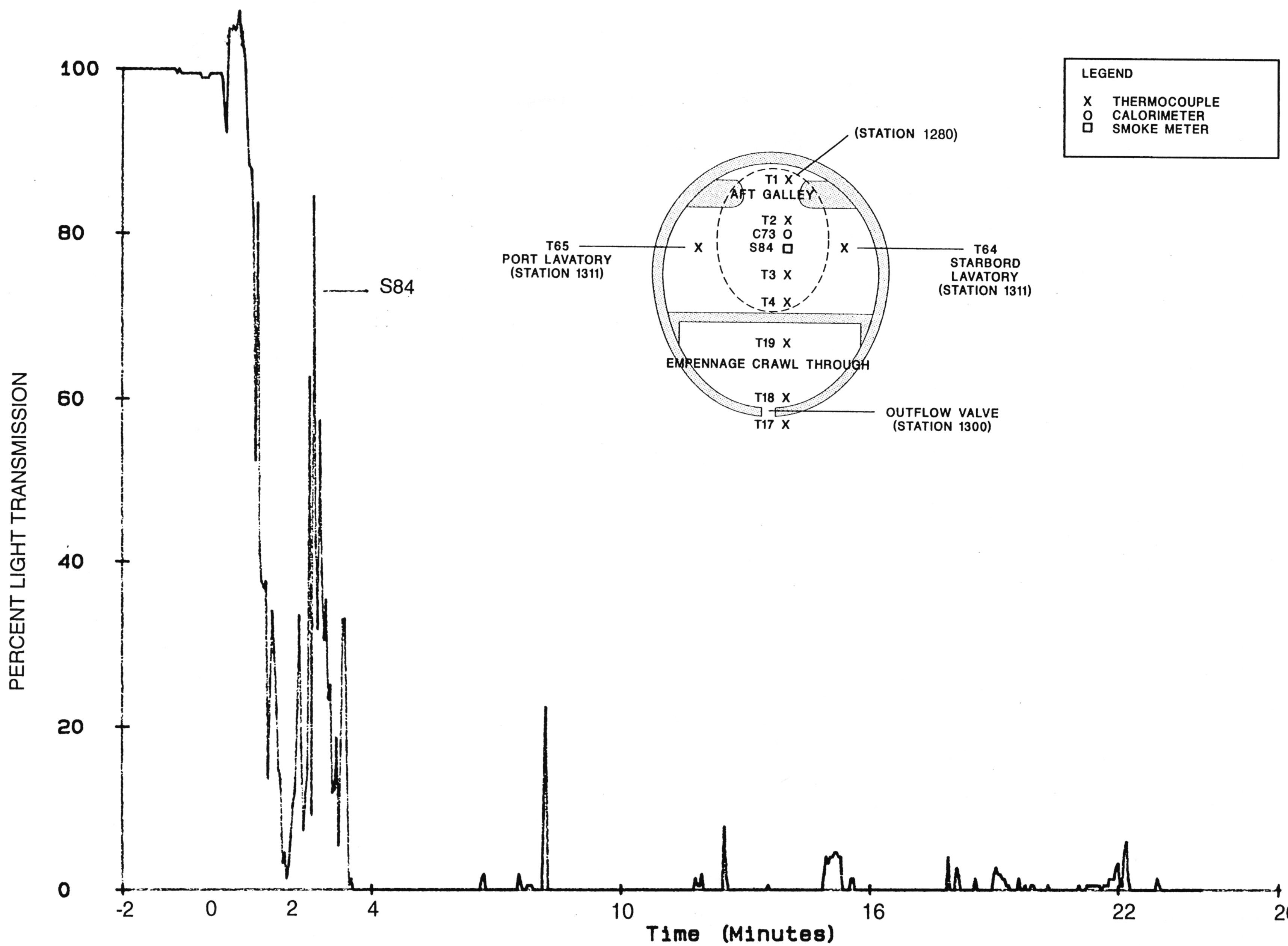

FIGURE D-37. SMOKE DENSITY AT STATION 1280

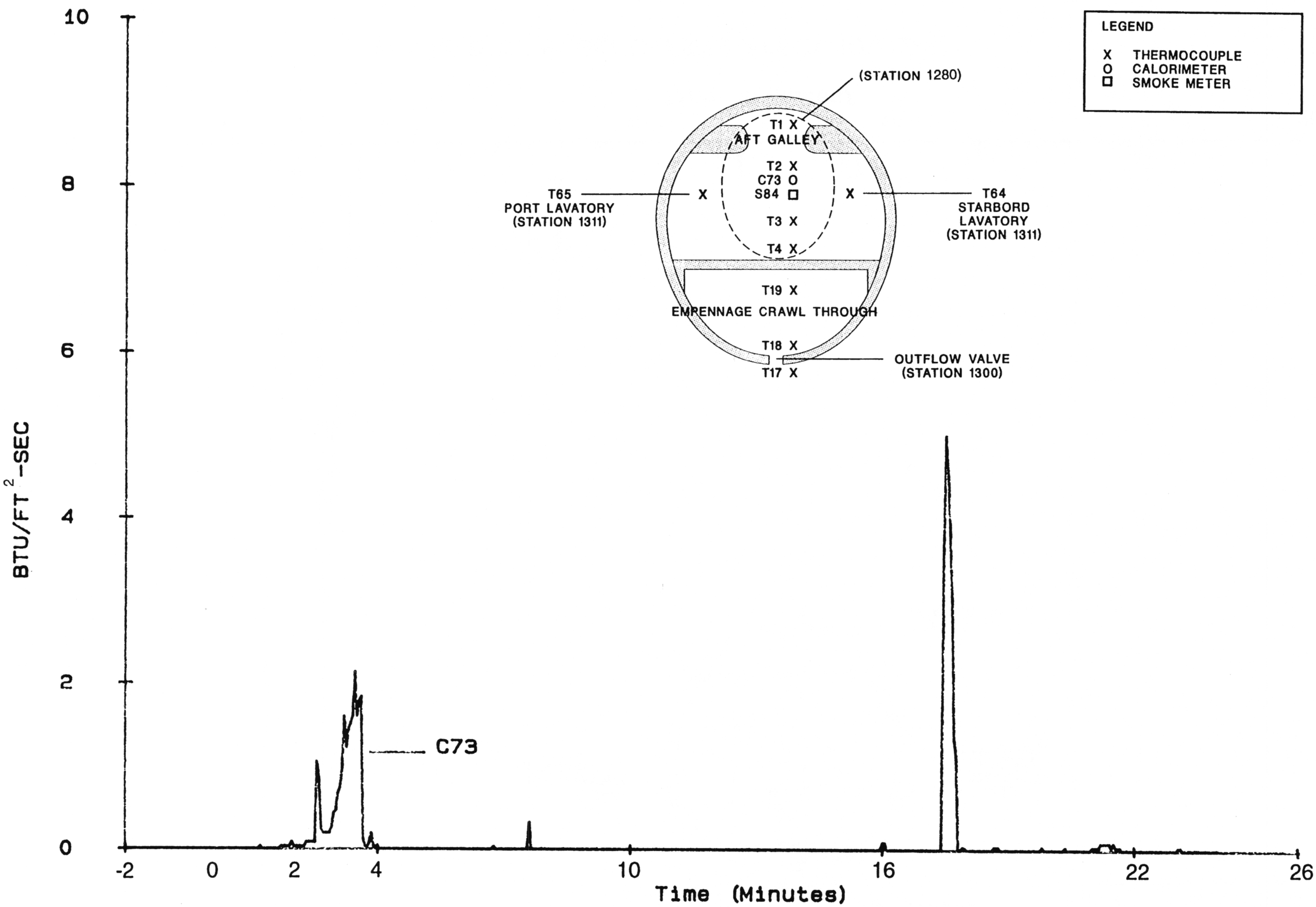

FIGURE D-38. INTERNAL HEAT FLUX AT STATION 1280

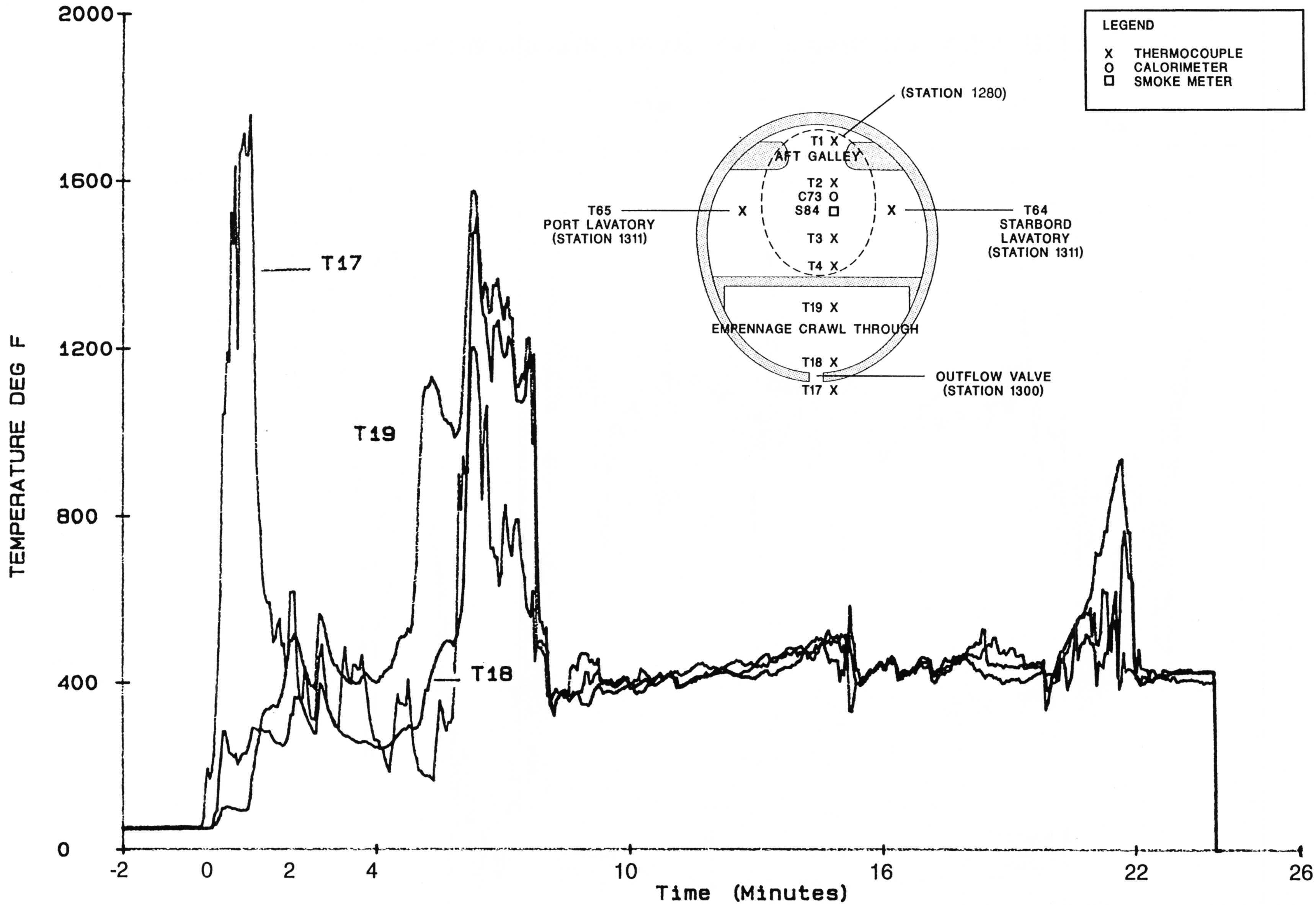

FIGURE D-39. AIR TEMPERATURE IN THE CRAWLTHROUGH AND ABOVE THE OUTFLOW VALVE AT STATION 1300

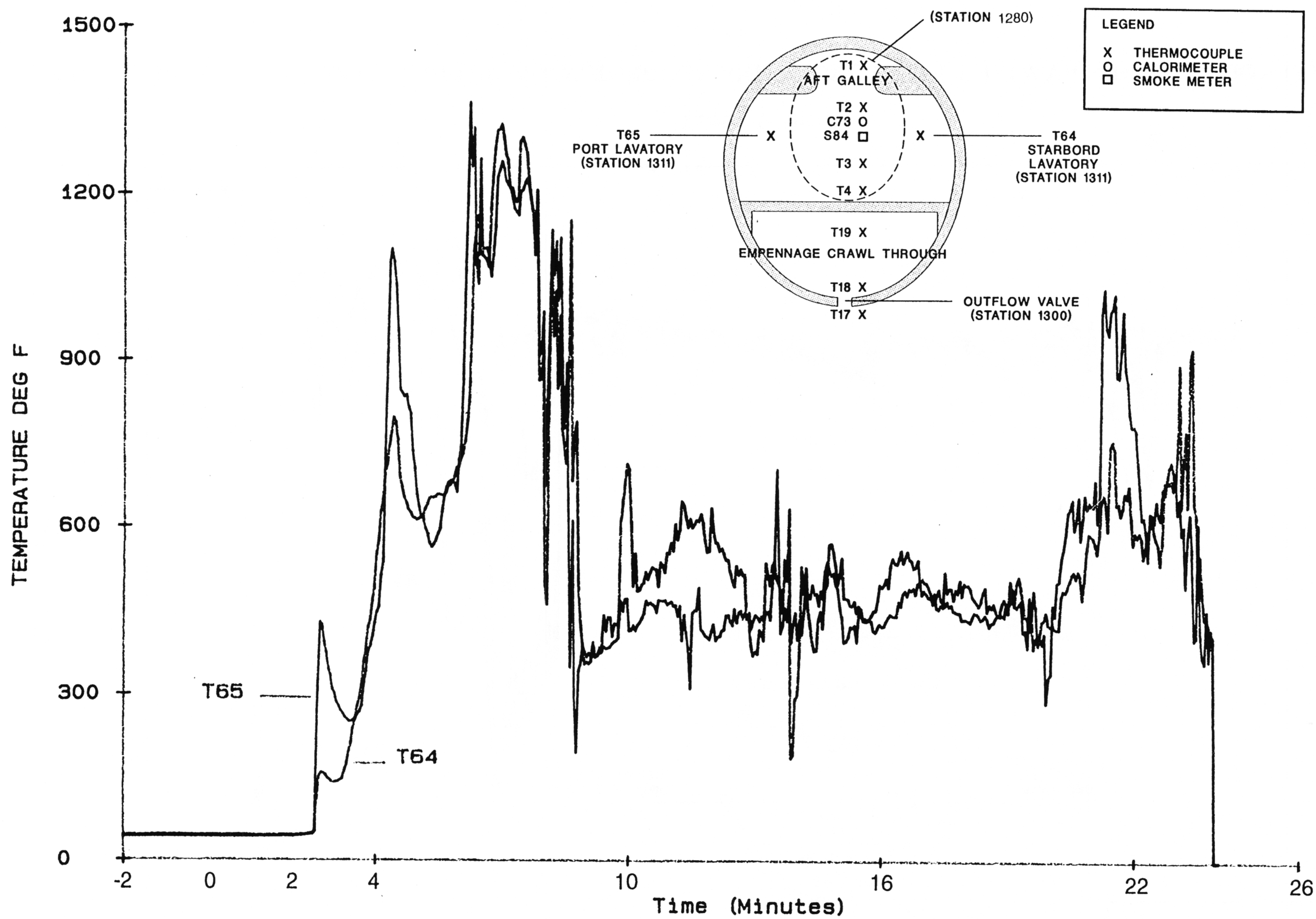

FIGURE D-40. AIR TEMPERATURE IN THE LAVATORIES AT STATION 1311