JSC-09060

NASA TECHNICAL MEMORANDUM

NASA TM X-58141
June 1974

FULL-SCALE AIRCRAFT CABIN FLAMMABILITY TESTS OF IMPROVED FIRE-RESISTANT MATERIALS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM X-58141		

4. Title and Subtitle	5. Report Date
FULL-SCALE AIRCRAFT CABIN FLAMMABILITY TESTS OF IMPROVED FIRE-RESISTANT MATERIALS	June 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Robert N. Stuckey, Daniel E. Supkis, and L. James Price	JSC-09060
9. Performing Organization Name and Address	10. Work Unit No.
Lyndon B. Johnson Space Center Houston, Texas 77058	501-38-19-01-72
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, D.C. 20546	Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Full-scale aircraft cabin flammability tests to evaluate the effectiveness of new fire-resistant materials by comparing their burning characteristics with those of older aircraft materials are described. Three tests were conducted and are detailed. Test 1, using pre-1968 materials, was run to correlate the procedures and to compare the results with previous tests by other organizations. Test 2 included newer, improved fire-resistant materials. Test 3 was essentially a duplicate of test 2, but a smokeless fuel was used. Test objectives, methods, materials, and results are presented and discussed. Results indicate that the pre-1968 materials ignited easily, allowed the fire to spread, produced large amounts of smoke and toxic combustion products, and resulted in a flash fire and major fire damage. The newer fire-resistant materials did not allow the fire to spread. Furthermore, they produced less smoke, lower concentrations of toxic combustion products, and lower temperatures. The newer materials did not produce a flash fire.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
· Flame Propagation · Combustion · Flammable Gases · Burning Time · Calorimeters · Thermocouples · Gas Analysis	STAR Subject Category: 02.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	64	$3.00

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FULL-SCALE AIRCRAFT CABIN FLAMMABILITY TESTS

OF IMPROVED FIRE-RESISTANT MATERIALS

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SUMMARY

Three full-scale aircraft flammability tests were performed to evaluate the effectiveness of new fire-resistant materials by comparing their burning characteristics with those of earlier interior cabin materials. Sidewalls, windows, ceiling panels, hatracks, passenger service units, and three rows of seats were installed along one side of a Boeing 737 fuselage section. A fuel ignition source was located beneath the outboard seat of the middle row of seats and ignited electrically. The fuel used for test 1 and test 2 was JP-4; a smokeless fuel was used for test 3 because smoke produced by the fuel ignition source can mask the burning of cabin materials and increase the analysis difficulties. The test results confirmed that pre-1968 aircraft materials ignite easily, propagate flames rapidly, produce large amounts of smoke and toxic products, and could sustain a flash fire. The newer fire-resistant materials decompose rather than ignite and do not support fire propagation; therefore, they produce less smoke, lower concentrations of toxic combustion products, and lower cabin temperatures.

INTRODUCTION

Although commercial aircraft provide a remarkably safe means of transportation, when accidents do occur, they sometimes involve fires that result in loss of human life, destruction of the aircraft, or both. A 1967 review of commercial jet incidents and accidents (ref. 1) revealed that fires caused or contributed to passenger deaths in 12 of 16 impact-survivable aircraft accidents occurring from 1958 to 1966. All 12 accidents involved external fuel fires that resulted in interior cabin fires in 11 cases. Several additional accidents resulting in loss of life because of fire or toxic products have occurred since the results presented in reference 1. Fires in unattended aircraft have also resulted in gutted aircraft interiors. These accidents illustrated the need for improved fire-resistant materials for aircraft interiors.

Since the early 1960's, the manufacturers of commercial aircraft and the airlines, aided by the Federal Aviation Administration (FAA), the Aerospace Industries Association of America, Inc. (AIA), the Air Line Pilots Association, and the National Fire Protection Association have sought firesafety improvements by screening, testing, and using improved nonflammable and fire-resistant materials. The test programs included full-scale mockup flammability tests of aircraft interior configurations (refs. 1 to 5). Experience has shown that full-scale mockup tests are necessary. Individual materials that self-extinguish in laboratory tests, when used in a final configuration with other materials, may develop synergistic reactions to the ignition source, the configuration geometry, and the environmental conditions.

One of the most comprehensive full-scale aircraft test programs was conducted by the AIA (ref. 1). These flammability tests included 2.4-meter (8 foot), 4.6-meter (15 foot), and 12.2-meter (40 foot) long mockups of typically furnished fuselage sections. Materials in use at that time (1967 to 1968) as well as newer fire-resistant materials were tested by exposing the cabin interior to a fuel-fed fire. Temperatures, propagation paths, smoke density, and noxious gases were measured and evaluated to determine the benefits gained from use of fire-resistant materials. This approach - the evaluation of cabin interior materials when exposed to fuel-fed fires by performing full-scale mockup tests - was selected for the tests covered by this report.

As a result of the Apollo command module fire in 1967 and of the ensuing investigations related to the Apollo Program, the Skylab Program, and so on, new materials having excellent fire-resistant qualities in an oxygen-enriched environment have been developed. The oxygen enrichment creates more stringent conditions than those encountered on present commercial aircraft. Some of these new materials are promising possibilities for aircraft application and were selected as candidates for this test program.

The flammability tests were performed in a section of a Boeing 737 fuselage. In test 1, conducted to provide a baseline for subsequent tests and a correlation with the AIA tests, materials installed in aircraft before the 1968 issuance of more stringent Federal Air Regulations on flammability of aircraft cabin materials were used. Tests 2 and 3 were performed to determine the benefits derived from materials having improved fire-resistant characteristics.

As an aid to the reader, where necessary, the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

EXPERIMENTAL PROGRAM

Test Objectives

The overall objective of this test series was to evaluate the effectiveness of new fire-resistant cabin materials as compared with older materials that remain in use in some aircraft. In this series, three separate tests were performed. For test 1, in which pre-1968 materials typical of those in use on Boeing 737, 727, and 707 aircraft were used, the primary objectives were to compare results with data obtained from a similar test conducted by the AIA in 1967 and to provide a baseline for subsequent tests in the Boeing 737 fuselage using newer, improved fire-resistant materials. The objectives of test 2 were to evaluate newer fire-resistant materials in a full-scale configuration and to compare the results with those of test 1, in which the older aircraft cabin materials were used. For test 3, the primary objective was to allow a better determination of the amount of smoke produced by the newer fire-resistant materials by using a smokeless fuel ignition source. A secondary objective of test 3 was to provide another set of data on the newer materials. For each test, sufficient data were required to accomplish the following objectives.

1. To define the degree of propagation and the magnitude of fires resulting from a fuel ignition source within the cabin

2. To identify the gaseous products of combustion occurring as a result of such ignition

3. To determine the degradation of visibility within the cabin because of smoke

Test Setup

A 4.6-meter (15 foot) long section of a Boeing 737 fuselage (fig. 1) was furnished to simulate the passenger cabin of a commercial jet transport. Sidewalls, windows, ceiling panels, hatracks, passenger service units, and three rows of triple seats were installed along one side of this fuselage section. In addition, to protect the outer aluminum skin of the fuselage, the entire section was lined with a high-temperature ceramic insulation of an alumina-silica composition. A typically furnished interior is shown in figure 2 and a schematic of the test setup in figure 3.

The ignition source for tests 1 and 2 consisted of 0.95 liter (1 quart) of JP-4 aircraft fuel contained in a 30.5- by 30.5-centimeter (1 by 1 foot) pan and having a burning time of approximately 5 minutes. The pan was placed under the outboard seat of the middle row of seats (fig. 3) and ignited electrically. For test 3, the JP-4 fuel was replaced by 1.18 liters (1.25 quarts) of a smokeless fuel (composed of 50 percent acetone and 50 percent methanol) to avoid masking the smoke produced by the burning materials. The additional fuel was used to compensate for the lower energy per unit mass content of the smokeless fuel. For all three tests, an airflow rate of 5.7 m^3/min (200 ft^3/min) was provided through the 4.6-meter (15 foot) test section as shown in figure 3. Two carbon dioxide fire extinguisher systems were installed in the fuselage for terminating the tests. One system was installed in the 4.6-meter (15 foot) test section for local extinguishment, and a larger capacity system was installed throughout the fuselage to provide protection if the fire spread beyond the test section. This test setup basically duplicated the 4.6-meter (15 foot) mockup test conducted by the AIA in 1967 to 1968 (ref. 1).

Instrumentation

Instrumentation was provided to measure temperatures, cabin pressure, smoke density, and heat flux. In addition, two separate systems were used to take gas samples every 30 seconds during the tests. Toxic product percentages were determined by subsequent analysis of these samples. (See the appendix.) Color and infrared movies were taken during the tests, and still photographs were taken before and after each test. Black and white and infrared television (TV) cameras were also used to monitor the tests. (In addition, six persons observed the tests through windows on the side of the fuselage opposite the test region.) Besides duplicating the AIA instrumentation, additional instrumentation was provided to allow a more detailed measurement and evaluation of test results. The instrumentation locations are shown in figure 3, and a brief description of each type of instrumentation is presented in the appendix.

Tests

Three full-scale tests were performed in the Boeing 737 fuselage. Materials for test 1 were supplied by United Airlines and included pre-1968 Boeing 737, 727, and 707 material configurations. Materials used in tests 2 and 3 were newer fire-resistant materials, also representative of interior materials installed in two NASA Gulfstream aircraft for in-use evaluation. Details of the test interiors are given in tables I and II. The interior configurations before testing are shown in figures 4 to 7. A smokeless fuel was used in test 3; otherwise, the setup was the same as that of test 2.

RESULTS AND DISCUSSION

Because the test methods used in this program were selected to allow correlation and comparison with the AIA test results (ref. 1), the results of the NASA Lyndon B. Johnson Space Center (JSC) tests are compared to the AIA results, as well as to each other. In addition, results of fire tests conducted by the FAA on aircraft passenger seats (ref. 2) are discussed and compared to the JSC test results. Flammability testing cannot be considered an exact science, and results of separate test programs can be compared in general terms only. Any numerical values should be interpreted as approximations, not as exact numbers. Gas analysis results, in particular, are acutely affected by variations in test parameters and sampling techniques.

Pre-1968 Materials Test (Test 1)

Test results.- Smoke was observed immediately after ignition of the JP-4 fuel source in test 1. This initial smoke appeared to come mainly from the JP-4 ignition source; however, some smoke was observed coming from the outboard seat cushion as it was ignited by the JP-4 fire. The fire increased in size as the outboard seat and the adjacent sidewall began to burn. Visibility of the fire was lost to observers, TV monitors, and motion picture cameras at approximately 60 seconds elapsed time as black smoke filled the cabin. Temperatures in the test section increased slowly until 60 seconds; then, the temperatures increased more rapidly as the fire spread and more materials were ignited. Apparently, a flash fire, which is a rapid burning of accumulated hot combustible gases, began at approximately 95 seconds because of an accumulation of such gases along the ceiling of the cabin interior. Indicative of the flash fire phenomenon was a rapid increase of cabin temperatures (fig. 8) followed by oxygen depletion to a concentration of less than 5 percent (fig. 9). In addition, the concentration of nonhydrolyzable products of combustion - carbon dioxide, carbon monoxide, methane, and ethylene - increased rapidly as the oxygen was depleted (figs. 10 to 13). Data for hydrolyzable products of combustion - chlorides, fluorides, and cyanides - are not available for test 1 because of an error in analyzing the gas samples. Thermocouple (TC) data indicate that the flash fire originated beneath the hatrack, spread to the ceiling and to the seats, and propagated beneath the hatrack for the full length of the test section. The propagation path along the forward end of the test section cabin walls was downward from the hatrack, as illustrated by a post-test photograph (fig. 14). The damage to the seats other than the one directly above the ignition source was more severe at the top of the seats. This damage indicated heating and burning from above and is further evidence of a flash fire. The damage is shown in figures 15 and 16.

At 140 seconds, as the flash fire progressed, the maximum radiant heat flux measured at standing head level in the center aisle (fig. 17) was between 5.7×10^4 and 6.8×10^4 W/m^2 (5 and 6 Btu/ft^2 sec). Reduction of cabin visibility, as illustrated in figure 18, occurred rapidly with loss of visibility of the fire at 60 seconds and 83 percent smoke density measured at the ceiling smoke detector. Because of the high temperatures generated by the flash fire, the test was terminated after 240 seconds and the fire was extinguished with carbon dioxide.

Specific fire damage.- In the following paragraphs, the extent of fire damage to materials used in test 1 is summarized. The term "materials" refers to nonmetallic materials unless metallic materials are mentioned specifically.

1. Seats: The seat above the fire ignition source was almost completely consumed. Some of the aluminum structure had melted. The adjacent seat was also severely damaged; approximately 70 percent of the materials were consumed, and a small percentage of the metal seat structure had melted. The remaining seats were scorched; some of the cushion fabric (nylon-wool-rayon combination) and the seat-back covering (supported vinyl) was burned. The damage was most severe at the top of the seat backs. All of the nylon seatbelts were scorched and partly burned.

2. Sidewall: The sidewall material and the aluminum structure adjacent to the fuel pan had completely melted away from the floor level to the hatrack (fig. 15). The

remaining vinyl covering of the sidewall was charred or burned away.

3. Hatrack: Except for a small amount of foam on the hatrack bullnose, all the vinyl and foam padding had burned away from the honeycomb panels. The paper-core, fiberglass-covered honeycomb above the fuel pan location also burned; only the brittle remains of the fiberglass cloth were left.

4. Ceiling panels: All the vinyl covering and the paper core of the honeycomb ceiling panels had burned away. Only the brittle fiberglass cloth, which fell onto the hatrack and TC trees, remained.

5. Passenger service units: All three passenger service units burned, melted, and fell to the seats and floor below them. All of the metal structure of the center unit (above the fuel pan location), 80 percent of the back unit, and 50 percent of the front unit were melted and destroyed.

<u>Comparison with other tests</u>.- In general, the JSC test 1 and the AIA Present In-Service Materials Test were similar in configuration and materials, and they produced similar results in temperatures and smoke densities. During the AIA Present In-Service Materials Test of pre-1968 materials, a similar flash fire occurred; however, it occurred much later than that in JSC test 1 and produced slightly lower temperatures. Oxygen depletion and toxic gas production for the two tests had the same trend but were different in concentration. This difference possibly was due to variations in cabin volume and in sampling technique. The FAA seat tests on similar materials also resulted in a flash fire with comparable temperatures and products of combustion (ref. 2). The smoke density levels measured during JSC test 1 followed the same pattern as the levels recorded for the FAA seat tests of similar materials (ref. 2). The levels were characterized by a rapid reduction of visibility. Smoke production was not continuously measured during the AIA tests; therefore, no smoke density comparisons for JSC test 1 and the AIA test can be made. Because of the similarity of the results of these tests, the improved-materials test results also can be compared generally with the results of the earlier AIA and FAA tests.

New Materials Test (Test 2)

<u>Test results</u>.- Test 2 also began with an immediate indication of smoke coming mainly from the JP-4 ignition fuel and the outboard seat cushion above the fuel fire. The fire slowly increased in size until, at approximately

45 seconds elapsed time, it intensified as the fire-resistant materials decomposed and released flammable gases. Unlike the materials used for test 1, however, the fire-resistant materials burned or decomposed only where exposed to the JP-4 fuel fire and did not allow the fire to propagate; therefore, the amount of combustible gases liberated during test 2 was apparently insufficient to produce a flash fire.

After ignition, the smoke density increased, and visibility of the fire was lost at approximately 150 seconds as smoke filled the cabin. In addition, cabin temperatures slowly increased, peaked at approximately 150 seconds, and then began to decrease (fig. 19). Temperatures measured at the sidewall and seat armrest above the fuel pan reached 950 K (1250° F); however, motion pictures revealed that the TC's at these locations were partly subjected to direct flame impingement from the ignition source, both during this test and during tests 1 and 3. The gradual decrease in oxygen (fig. 9) and the gradual increase in carbon monoxide and hydrocarbons (figs. 11 to 13) indicate a typical open fire and absence of a rapid-burning flash fire. A typical open fire would gradually cease as the oxygen content of the air reached approximately 15 percent (ref. 2). Examination of figures 9 and 19 shows that the temperatures began decreasing as the oxygen content approached the 15-percent level. Maximum heat flux measured during test 2 (fig. 17) was less than 0.57×10^4 W/m^2 (0.5 Btu/ft^2 sec) at 140 seconds after fuel ignition.

Figures 20 to 24 show clearly that flames did not propagate, and damage was confined to the seat above the fire and the adjacent sidewall. The ceiling was severely damaged (fig. 21), but, because of inadequate insulation behind panels adjacent to the ignition source, flames melted through the sidewall and spread between the sidewall and insulation to the unprotected back side of the ceiling panels, which had a flammable paper honeycomb core. The flames then melted through the aluminum skin above the ceiling panels, and the test was terminated after 280 seconds to prevent destruction of the fuselage. The paper honeycomb ceiling panels were not intended for involvement in the fire since they were known to be flammable and are to be evaluated in subsequent tests using fire-resistant materials.

Specific damage.- The extent of damage to the newer fire-resistant materials used in test 2 is summarized in the following paragraphs.

1. Seats: The seat above the fire was partly consumed by the fire, and some of the metal structure had melted away

(figs. 22 to 24). Approximately 95 percent of the bottom seat cushion upholstery was charred, and approximately 50 percent of the fire-retardant foam padding was consumed. The front of the seat-back upholstery was 70 percent charred, the back side was 25 percent charred and 30 percent scorched, and the foam padding was damaged only slightly. The Nomex seatbelt was almost completely charred. The other seats were not damaged except for slight scorching of the seat adjacent to the damaged seat. Fire-resistant, disposable headrest napkins had also been included for evaluation; however, most of the napkins were blown from the seats when the carbon dioxide extinguisher was activated. The napkins that remained in place were not damaged.

2. Sidewall: A 61-centimeter (2 foot) wide section of the sidewall covering (Kel-F and Fluorel on Durette) adjacent to the fuel pan was charred from the floor to the hatrack, and the aluminum panels were partly melted. The sidewall extending outward from each side of the charred area was scorched and blistered (fig. 20).

3. Hatrack: The only damage to the hatrack was on the bottom side, which was scorched and blackened.

4. Ceiling panels: The ceiling panels were heavily charred where they joined at the middle of the test section (fig. 21). Close examination revealed that the panels had burned from the back side, which had not been covered with the fiberglass cloth overcoated with Kel-F and Fluorel. (The same type of ceiling panel used in test 1 was covered on one side only with the Kel-F/Fluorel/fiberglass-cloth composite for use in test 2.) The back side had been ignited by flames that melted the sidewall and spread between the sidewall and insulation up to the back side of the ceiling panels. The remaining interior side of the ceiling was slightly scorched.

5. Passenger service units: The passenger service unit above the middle row of seats was scorched and blackened, but otherwise undamaged. The other passenger service unit was blackened on one side only (only two units were included for testing).

6. Carpet: Except for localized charring around the fuel pan caused by burning fuel droplets expelled from the pan as the fuel boiled, the wool carpet was not damaged.

Comparison with other tests.- Far less material damage occurred in test 2 than in test 1, and propagation of the fire was limited (figs. 15 and 20). A comparison of ceiling temperatures (fig. 25) indicated a maximum temperature of 505 K (450° F) for test 2, whereas, during test 1, the temperature at the same location was more than 1033 K (1400° F). Temperatures at other locations were also significantly lower in test 2 as compared to those measured in test 1. Maximum heat flux levels in test 2 were only one-fifteenth as high as those in test 1 (fig. 17). The levels of carbon monoxide and carbon dioxide were significantly lower in test 2 than in test 1 (figs. 10 and 11). Also, the loss of visibility because of smoke density occurred significantly later in test 2 than in test 1, as shown in figure 18.

The concentrations of nonhydrolyzable products of combustion produced during JSC test 2 were much lower than the concentrations found in JSC test 1 and those reported for the AIA test. The results of the AIA Present In-Service Materials Test were used to provide baseline data on the hydrolyzable products of combustion. As shown in table III, the maximum chloride value in JSC test 2 was higher than the AIA-measured concentration, and the fluoride and cyanide values were considerably lower. Because of slight differences in the test configuration and in the gas sampling and analyzing techniques, no direct comparison of the JSC and AIA hydrolyzable products of combustion has been attempted.

However, two important factors indicated by these data should be pointed out. First, although much greater amounts of fluorine-base polymers were present in JSC test 2 than in the AIA test, the measured fluoride concentration was relatively low, as expected. A fluoride absorber (or scavenger) had been compounded into the Fluorel formulation to capture and convert the reactive fluorine species to a solid ash; this formulation resulted in reduction of the amount of toxic gases, such as carbonyl fluoride and hydrogen fluoride, released. Second, the cyanide concentration reduction was also expected because of the replacement of the urethane-base seat cushion material used in JSC test 1 and in the AIA test with a fire-resistant urethane foam. This new urethane material will not sustain combustion and, therefore, will not release toxic cyanide products of combustion, such as hydrogen cyanide, unless exposed to an external heat source. A comparison of trace components of combustion that were detected but not quantified is presented in table IV.

Analysis of the comparative results of tests 1 and 2 also indicates that more time would be available to combat and extinguish an in-flight cabin fire or an unattended ground fire in an aircraft refurbished with the improved materials. Although comparative results show that a significant improvement was attained in test 2, the unexpected burning of the paper honeycomb ceiling panels (with their additional contribution to thermal and combustion products) resulted in some masking of the real improvement provided by the new materials. As previously stated, there was evidence that a flash fire did occur in test 1; however, for test 2, all evidence points to the conclusion that no flash fire occurred. (See the preceding discussion and figs. 17 and 25.)

New Materials Test With Smokeless Fuel (Test 3)

Test Results.- During test 3, it was visually observed and motion pictures later verified that the smokeless fuel (acetone and methanol) did not produce a fire as dynamic as the JP-4 aircraft fuel fire. More time was required to ignite the smokeless fuel, and more time was required for the fuel to reach maximum burning temperature. In addition, the flames of the burning smokeless fuel were not as large and did not extend outward from beneath the seat to impinge on the adjacent sidewall as much as did the flames of the burning JP-4 aircraft fuel. Consequently, cabin temperatures increased slowly to a maximum value of 533 K (500° F) (at the sidewall adjacent to the fuel pan, at window level) at 200 seconds elapsed time, and then decreased slowly (fig. 26). Smoke production was slight (fig. 18) until 80 seconds, when the smoke began to increase slowly. A level of 55 percent was measured at the ceiling smoke detector 240 seconds after ignition. The test 2 level was 94 percent.

The data indicate that a typical open fire occurred, similar to the fire that occurred in test 2 rather than a rapid-burning flash fire such as that observed during test 1. Damage to the seat above the fuel fire was almost identical to that in test 2, but sidewall damage was less severe. Ceiling damage was also less severe because additional firebreak insulation, which had been added to fill the gap between existing insulation and the sidewalls, prevented propagation of flames to the back side of the ceiling panels. Consequently, major damage was sustained only by the seat directly above the fuel fire; thus, lower cabin temperatures, less radiant heat, and smaller concentrations of combustible products resulted. Because the fire was small, the test was continued for 840 seconds before termination; however, test values beyond 300 seconds are not reported.

Specific fire damage.- Post-test inspection revealed damage to the interior materials similar to, but not as severe as, that sustained during the previous test of the new materials. The extent of damage is summarized in the following paragraphs.

1. Seats: The seat above the ignition source was partly consumed by the fire, and some of the metal structure had melted. All the bottom seat cushion upholstery was charred, and all the fire-retardant foam padding was consumed. The Nomex seatbelt was also completely charred. The front of the seat-back upholstery was 60 percent charred, the opposite side was 20 percent charred and 30 percent scorched, and the foam padding was only slightly damaged. The headrest napkin was scorched but did not burn. Except for slight scorching of the seat adjacent to the damaged seat, the other seats were not damaged.

2. Sidewall: A 930-square-centimeter (1 square foot) section of the sidewall covering adjacent to the fuel pan was charred, and an approximately 10-centimeter (4 inch) square section of the aluminum panel had melted. Additional areas of the sidewall covering were blistered by the heat.

3. Hatrack: The bottom side of the hatrack was slightly scorched.

4. Ceiling: The ceiling panels were slightly scorched and blistered by the heat. Burning did not occur behind the panels as it did in test 2.

5. Passenger service unit: Only one passenger service unit, placed above the middle row of seats, was used for this test; the unit was scorched slightly on the bottom side.

6. Carpet: The wool carpet was scorched around the fuel pan as it was in test 2.

Comparison with other tests.- A comparison of the data from figures 17, 19, 25, and 26 shows that the radiant heat flux and the cabin temperatures measured at the center of the test section for test 3 were approximately half the values for test 2. Examination of the gas analysis results (figs. 10 to 13 and 27 to 29) shows the same general trend of a 50-percent reduction for many of the products of combustion. A comparison of trace combustion products (table IV), detected but not quantified, shows a reduction in the number of those components in test 3 as compared with the number in test 2.

Because identical materials were used in tests 2 and 3, the differences in visibility (94 and 55 percent, respectively, at 240 seconds elapsed time) (fig. 18)) resulted partly from the additional smoke produced by the JP-4 fuel. Some of these differences also undoubtedly were due to the smaller fire and less burning of materials that occurred in test 3. This information also indicates that a significant portion of the reduction in visibility within the cabin for tests 1 and 2 was due to the smoke produced by the JP-4 ignition source. However, even after considering the smoke contribution of the JP-4 fuel, the smoke density of test 1 would still be considerably greater than that of test 2.

Results of tests 2 and 3 also showed that the type of ignition fuel used influenced the results of the tests because of differences in amounts of thermal input and smoke production. The additional burning that occurred in test 2 was possibly a more significant contribution to the reduction in the parameters used for comparing the results of tests 3 and 2. As previously mentioned, this burning occurred because of inadequate insulation behind wall and ceiling panels in test 2. The ceiling burned and contributed to the fire, resulting in higher temperatures and larger quantities of combustion products in test 2 than in test 3.

CONCLUDING REMARKS

Three full-scale aircraft flammability tests were performed to evaluate the effectiveness of new fire-resistant materials by comparing their burning characteristics with those of older aircraft materials. In test 1, pre-1968 materials were tested to correlate with previous tests of similar materials by the Aerospace Industries Association of America, Inc., and to provide a baseline for subsequent tests. The test resulted in significant fire propagation, rapid loss of visibility, evidence of a flash fire (characterized by rapid oxygen depletion and rapid temperature increase), significant quantities of toxic gases, and high temperatures. Major fire damage was sustained throughout the test section.

Test 2, in which newer fire-resistant materials were tested, resulted in less fire propagation, lower temperatures, a longer time lapse before loss of visibility, and a significant reduction of toxic gas concentrations because of the much smaller fire. No flash fire occurred (therefore, minimum oxygen depletion) and the fire damage was very limited. Unlike the materials used for test 1, the fire-resistant materials burned or decomposed only while exposed to the fuel ignition source and did not propagate the fire significant distances from the ignition source. Unfortunately, some increase in temperature and combustion products occurred during test 2 because of the burning from the back side of the flammable paper honeycomb ceiling panels. This unexpected burning probably detracted to some extent from the degree of improvement that could be expected of the new materials.

In test 3, the JP-4 aircraft fuel ignition source was replaced with a smokeless fuel (acetone/methanol). The result was an even greater reduction in temperatures, smoke, toxic gas production, and fire damage than was observed in the previous test of the newer materials. Part of the reductions during test 3 can be attributed to the provision of more insulation to prevent burning of flammable ceiling materials, such as burned in test 2. The results of test 3 documented the significance of the smoke produced by the JP-4 aircraft fuel in reducing cabin visibility and also permitted an evaluation of the smoke produced only by the fire-resistant materials. As in test 2, no flash fire was observed during the 5- to 6-minute visible portion of test 3. Furthermore, analysis of all other evidence indicates that no flash fire occurred at any time during the test.

Results from tests 2 and 3 demonstrated that use of the improved materials would provide some degree of additional safety during aircraft cabin fires. Substantial ignition sources would be required to ignite the improved materials. When ignition from such sources occurs, the fire would remain somewhat subdued for a significant time, thus permitting adequate time for implementation of extinguishment procedures.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, June 25, 1974
501-38-19-01-72

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TABLE I.- PRE-1968 MATERIALS USED IN TEST 1

Part description	Materials used	Comments
Ceiling panel	Vinyl-covered paper-core/wood-edged fiberglass sandwich	Original Boeing 727 part (Current Boeing 727 part is Nomex-core/foam-edged fiberglass sandwich.)
Sidewall panels	Tedlar vinyl/aluminum laminate	Standard Boeing 737 part
Floor covering	None used	--
Hatrack bullnose	Vinyl-covered urethane foam	Standard Boeing 727 part
Hatrack	Paper-core/aluminum-edged fiberglass sandwich; underside of AMS-3570 foam covered with supported vinyl	Original Boeing 727 part (Current Boeing 727 part is Nomex-core sandwich.)
Passenger service unit	Polysulfone	Original Boeing 737 part (Current Boeing 737 part is polycarbonate.)
Seats	Cushions: AMS-3570; cushion fabric: nylon-wool-rayon combination; armrests: foam rubber covered with natural leather; seat back and literature pocket: supported vinyl; seatbelt: nylon	Standard Boeing 707 part

TABLE II.- NEW FIRE-RESISTANT MATERIALS USED IN TESTS 2 AND 3

Part description	Materials used	Comments
Ceiling panel	Fiberglass coated with white Fluorel L-3203-6, overcoated with Kel-F FX703, applied to identical ceiling panels of pre-1968 materials test (test 1)	--
Sidewall panels	Durette 400-5 coated with Fluorel L-3203-6, overcoated with Kel-F FX703, applied to aluminum sheet	--
Floor covering	Wool carpet treated with ammonium dihydrogen phosphate and high-resilience foam padding treated with Fluorel L-3203-6	--
Hatrack bullnose	Fiberglass coated with white Fluorel L-3203-6, overcoated with Kel-F FX703, placed over high-resilience foam treated with Fluorel L-3203-6	--
Hatrack	Paper-core/aluminum-edged fiberglass sandwich, underside of treated high-resilience foam, covered by fiberglass coated with white Fluorel L-3203-6, overcoated with Kel-F FX703	Paper-core/aluminum-edged fiberglass sandwich was original Boeing 727 part
Passenger service unit	PRD-49 felt impregnated with 6113 resin and painted with white Fluorel L-3203-6	--
Seats	Cushions: treated high-resilience foam; cushion fabric: Proban wool; armrests: Durette 400-5 coated with blue Fluorel L-3203-6, overcoated with Kel-F FX703; seat back: Proban wool; seatbelt: Nomex	--

TABLE III.- CONCENTRATIONS OF OXYGEN AND OF GASEOUS COMBUSTION PRODUCTS

Oxygen and products of combustion	Pre-1968 materials test (test 1)	New materials test (test 2)	New materials test with smokeless fuel (test 3)
Minimum concentration			
Oxygen, percent	4.1	15.5	17.8
Maximum concentration			
Carbon dioxide, percent	9.2	2.4	1.5
Carbon monoxide, p/m	3360	623	407
Methane, p/m	15 480	395	147
Ethylene, p/m	3260	232	54
Chloride (as hydrogen chloride), p/m . . .	[1]275	540	281
Fluoride (as carbonyl fluoride), p/m . . .	[1,2]188	65	58
Cyanide (as hydrogen cyanide), p/m	[1]1000	46	23

[1]Data from similar AIA test of pre-1968 materials (ref. 1).
[2]Converted from hydrogen fluoride.

TABLE IV.- ADDITIONAL PRODUCTS OF COMBUSTION

Combustion products	Pre-1968 materials test (test 1)	Newer fire-resistant materials test (test 2)[1]	Newer fire-resistant materials test with smokeless fuel (test 3)[1]
Benzene	X	X	X
1,3-butadiene		X	
2-butanone		X	
1-butene or 2-butene		X	X
Carbonyl sulfide		X	X
Chlorotrifluoroethylene		X	
1,2-dichloropropane		X	
Ethane	X	X	X
Freon 11 (≤25 p/m)		X	
Freon 21		X	
Freon 113 (≤15 p/m)		X	
Hexafluoropropene		X	
Propanone		X	
Propene		X	X
Tetrafluoroethylene		X	
Toluene	X	X	
Trifluoroethylene		X	
Methyl chloride	X		
Propane (≤1130 p/m)	X		
Toluene	X		
Vinyl chloride	X		
Possibly benzofuran and naphthalene	X		
Possibly styrene, o-xylene, and p- or m-xylene		X	
Possibly 2 monohydrofluorocarbons			X

[1]More sensitive analytical techniques were used for the newer materials tests than for the pre-1968 materials test.

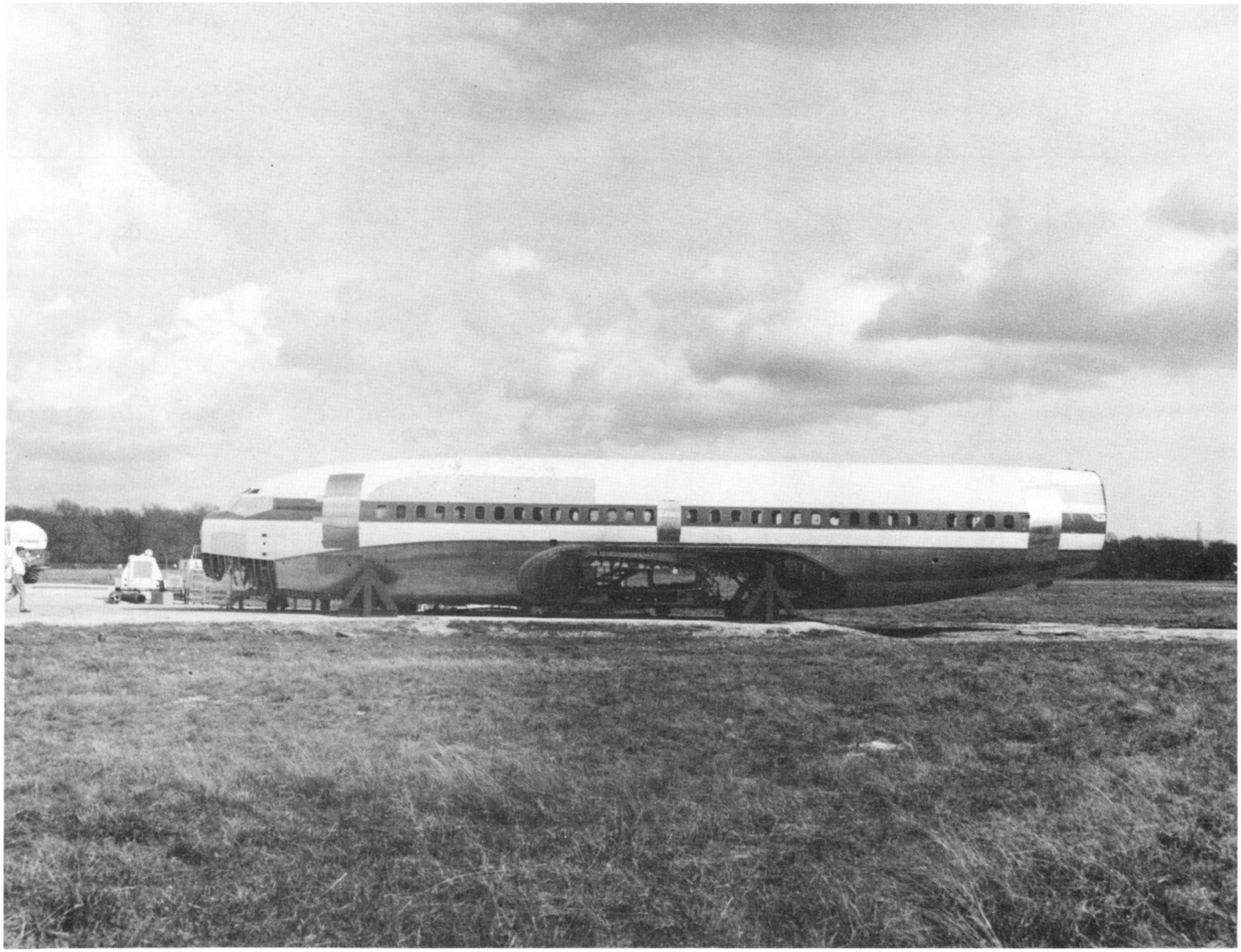

Figure 1.- Boeing 737 test fuselage.

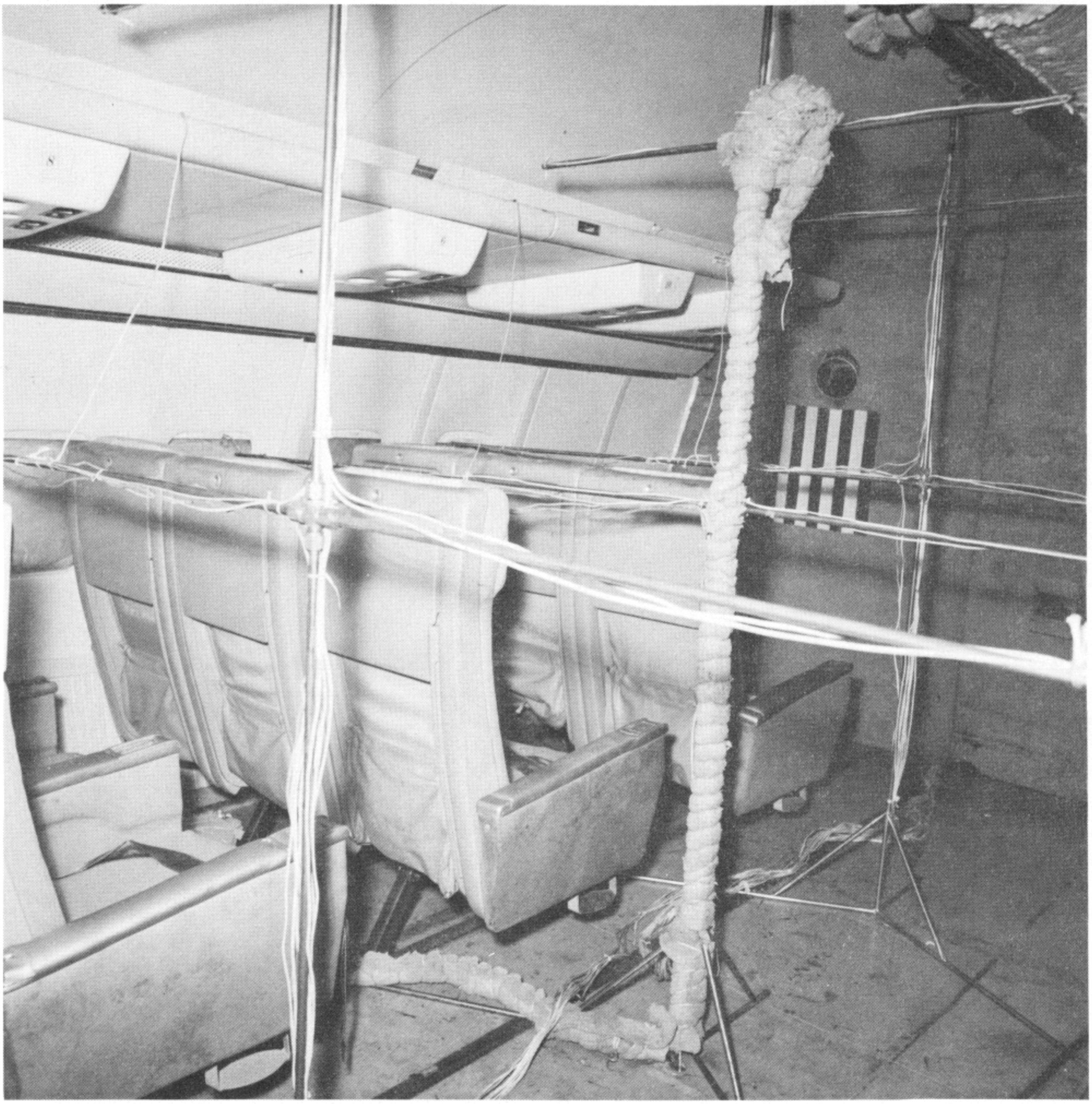

Figure 2.- Typically furnished 4.6-meter (15 foot) test section.

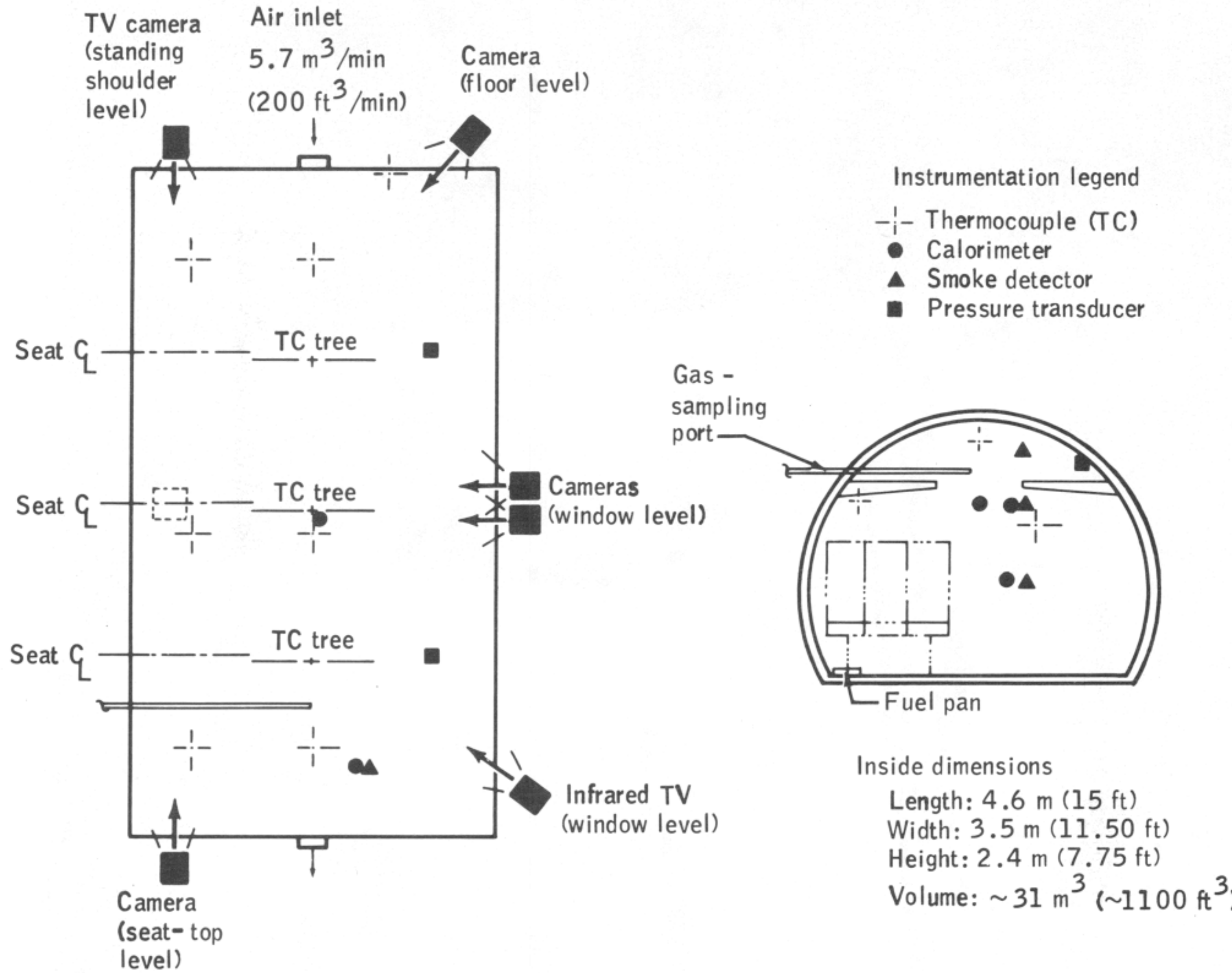

Figure 3.- Test setup and instrumentation locations.

Figure 4.- Test configuration for test 1 using pre-1968 materials, side view.

Figure 5.- Test configuration for test 1 using pre-1968 materials, front view.

Figure 6.- Test configuration for tests 2 and 3 using new materials, side view.

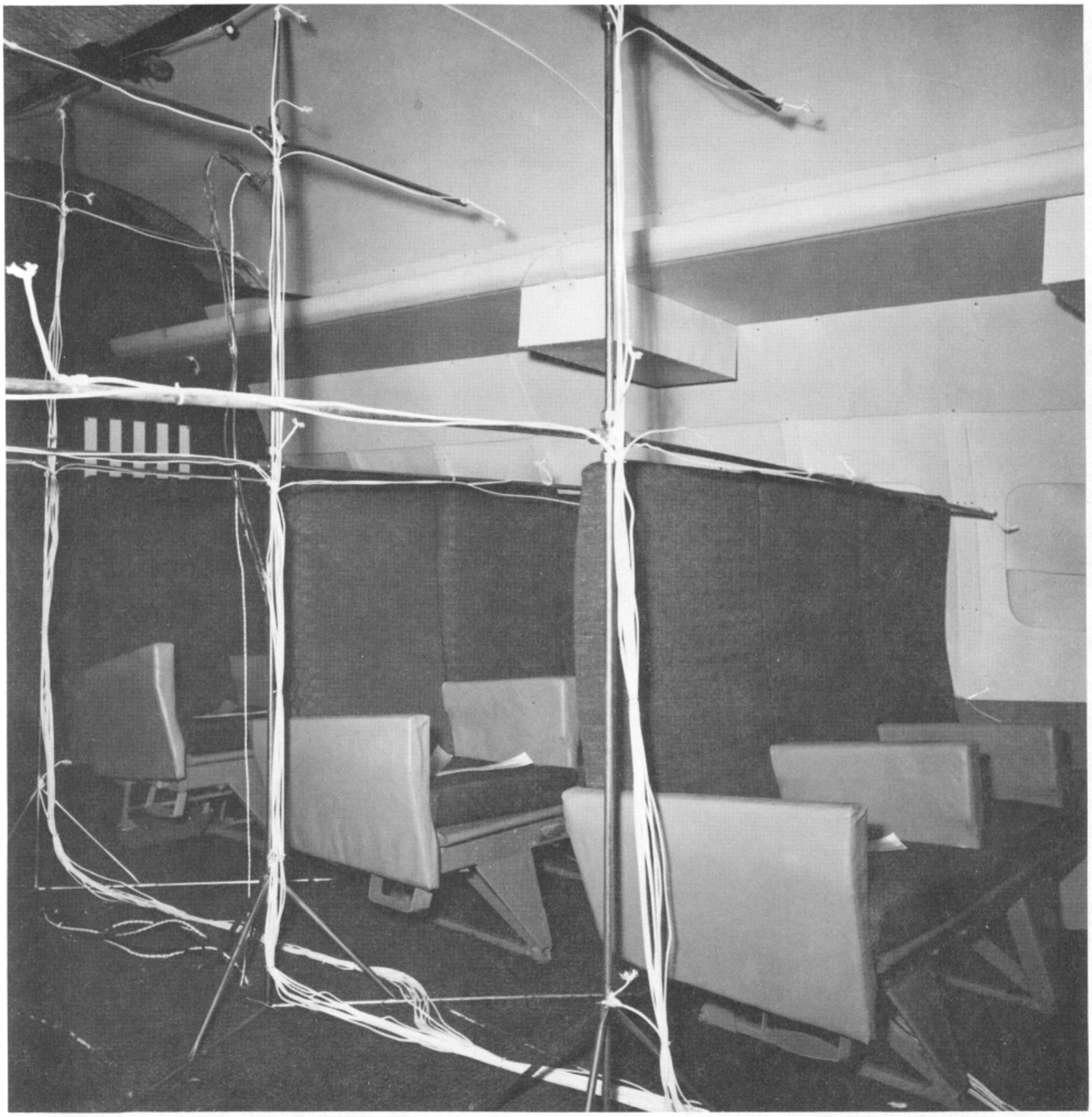

Figure 7.- Test configuration for tests 2 and 3 using new materials, front view.

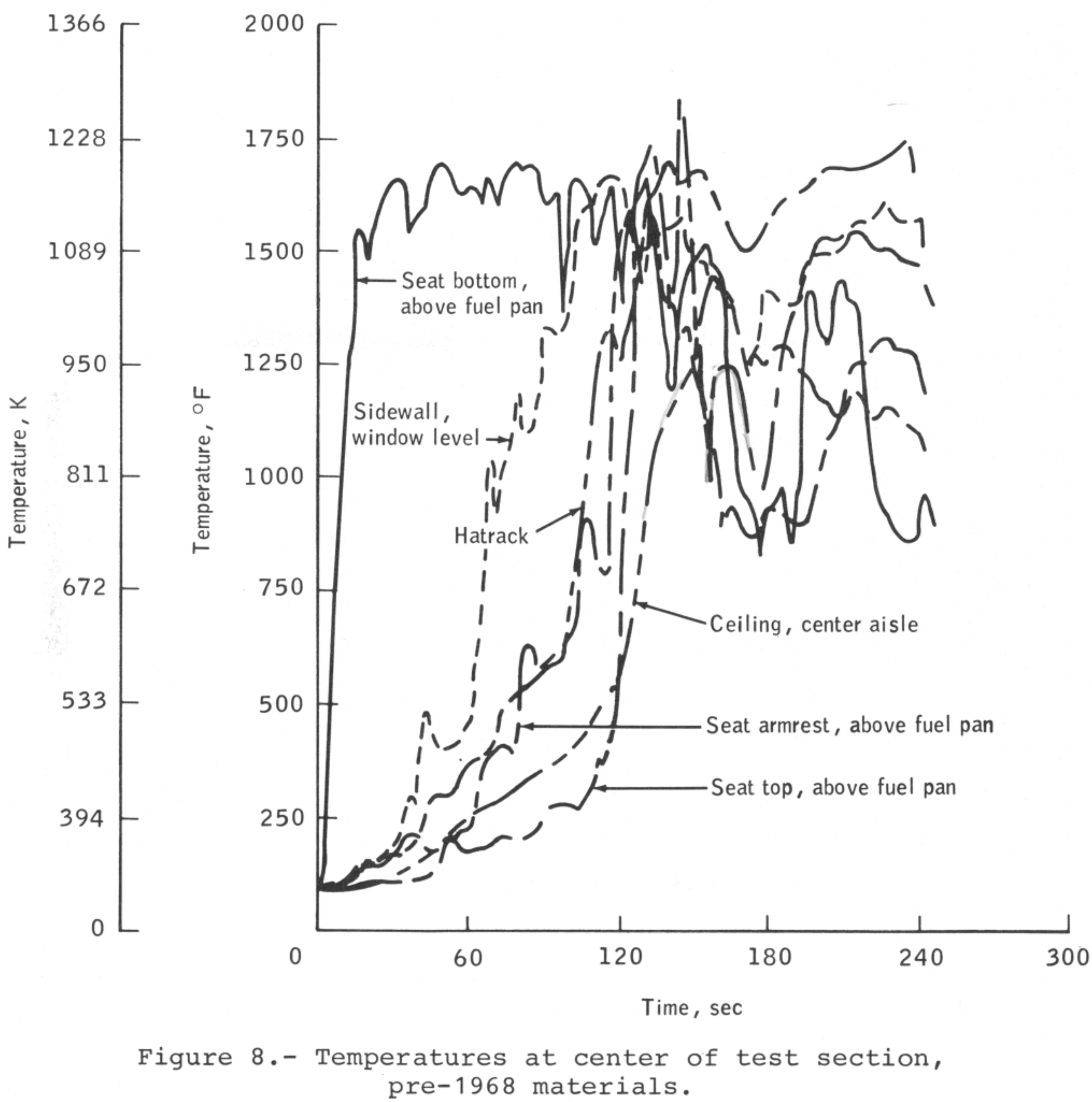

Figure 8.- Temperatures at center of test section, pre-1968 materials.

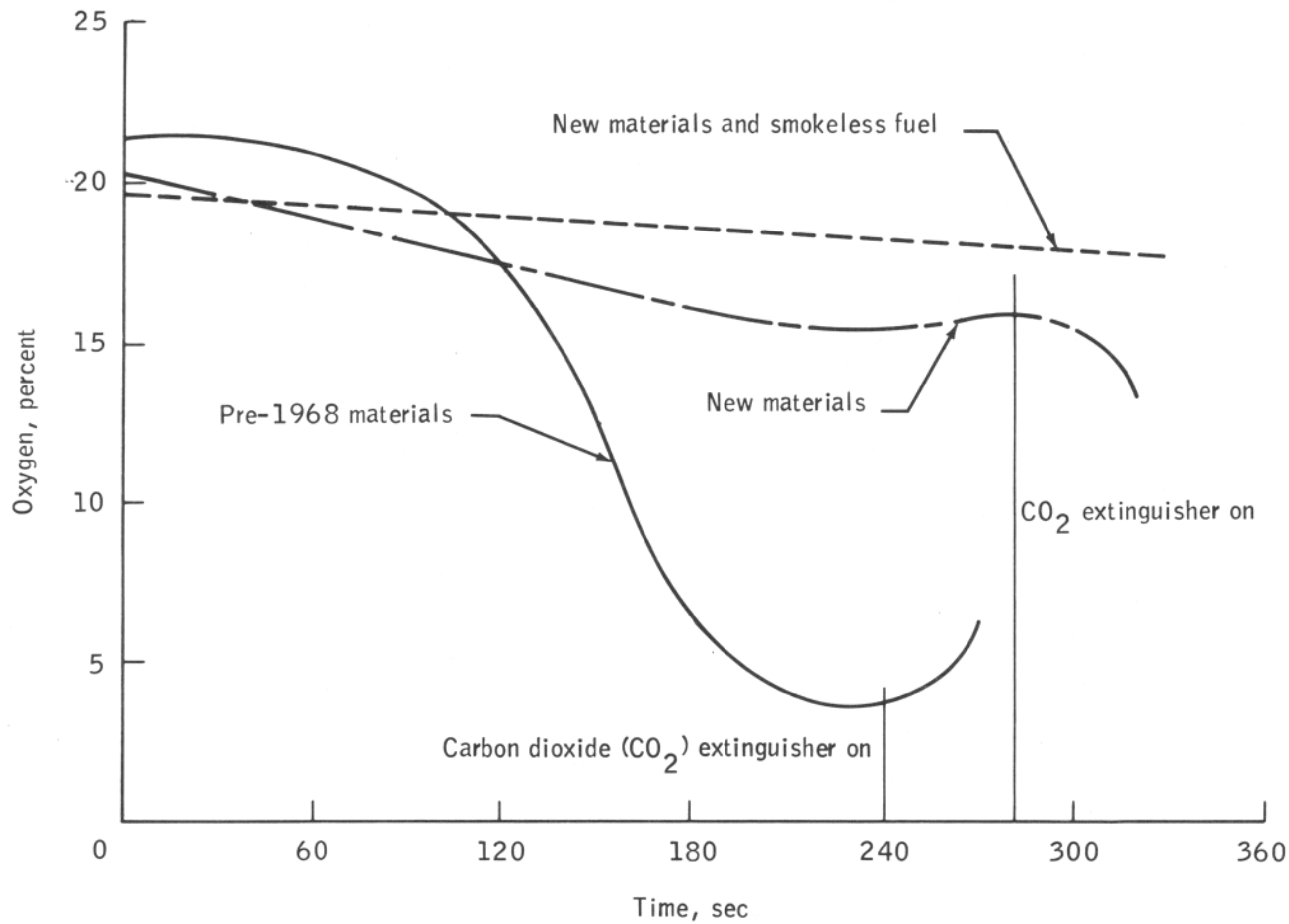

Figure 9.- Oxygen concentration.

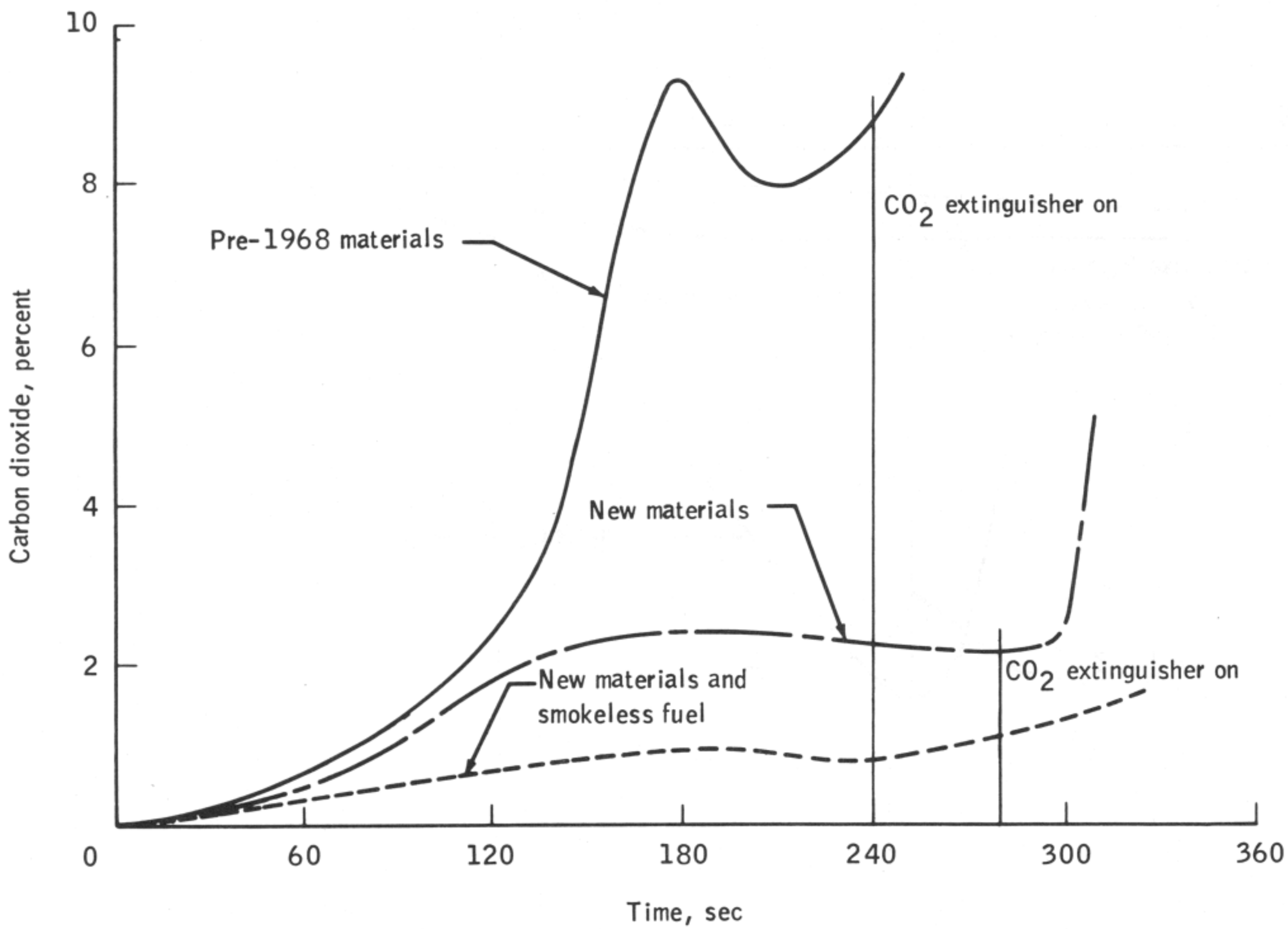

Figure 10.- Carbon dioxide concentration.

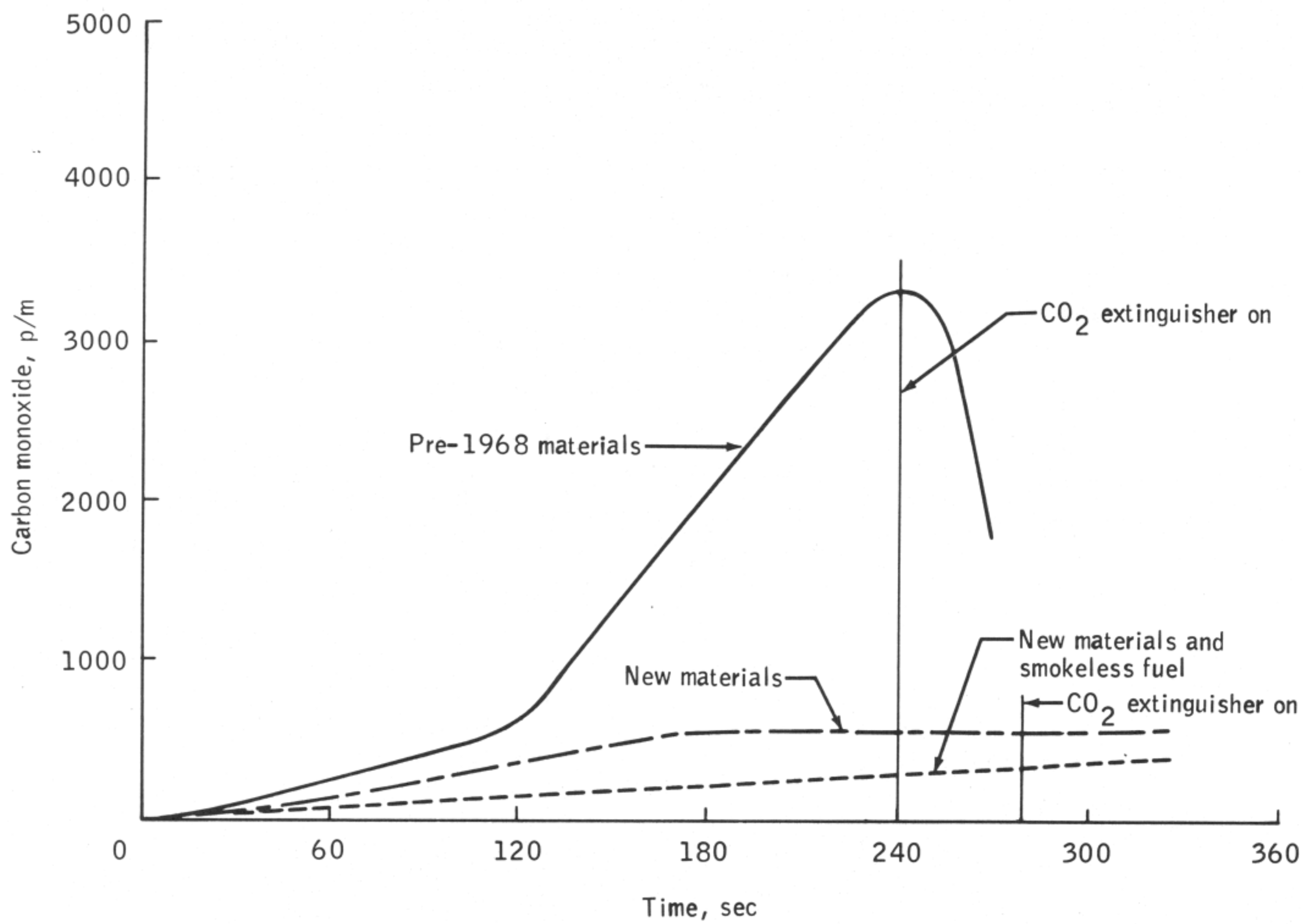

Figure 11.- Carbon monoxide concentration.

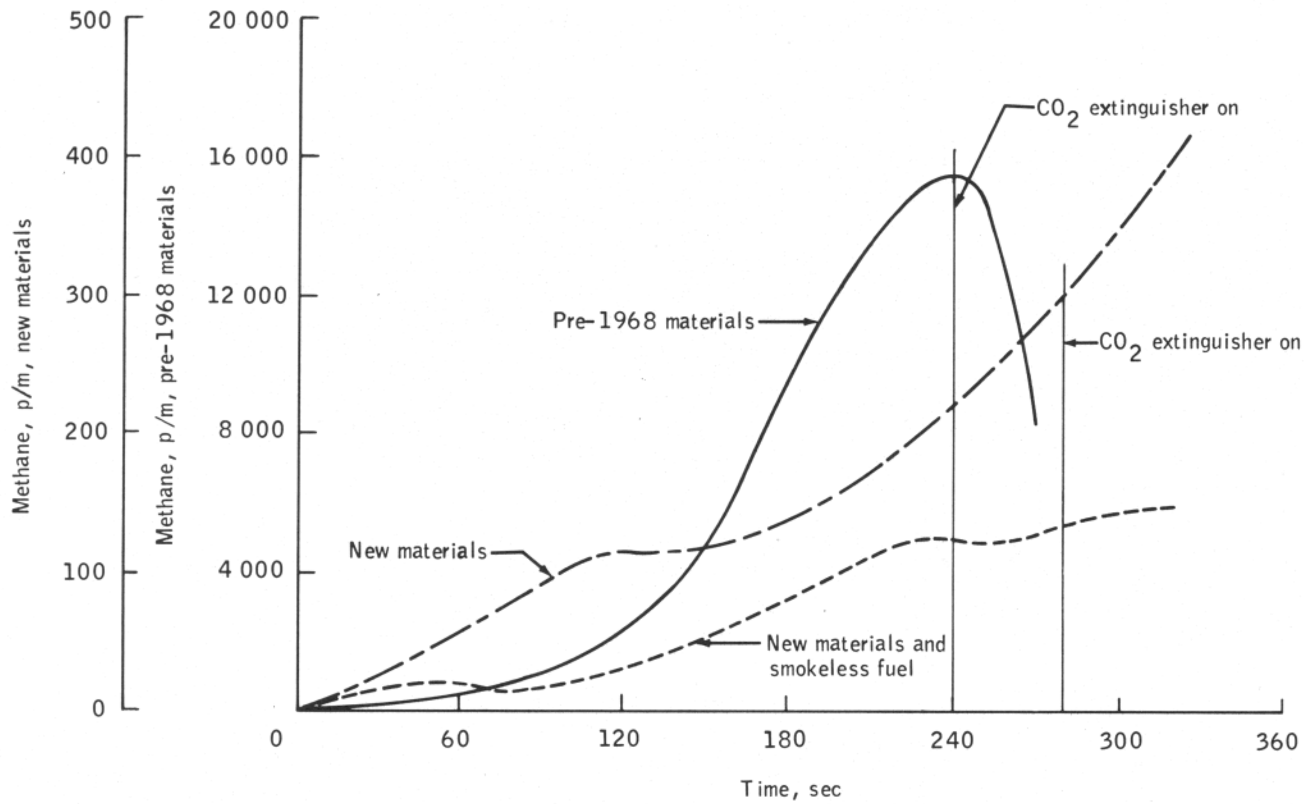

Figure 12.- Methane concentration.

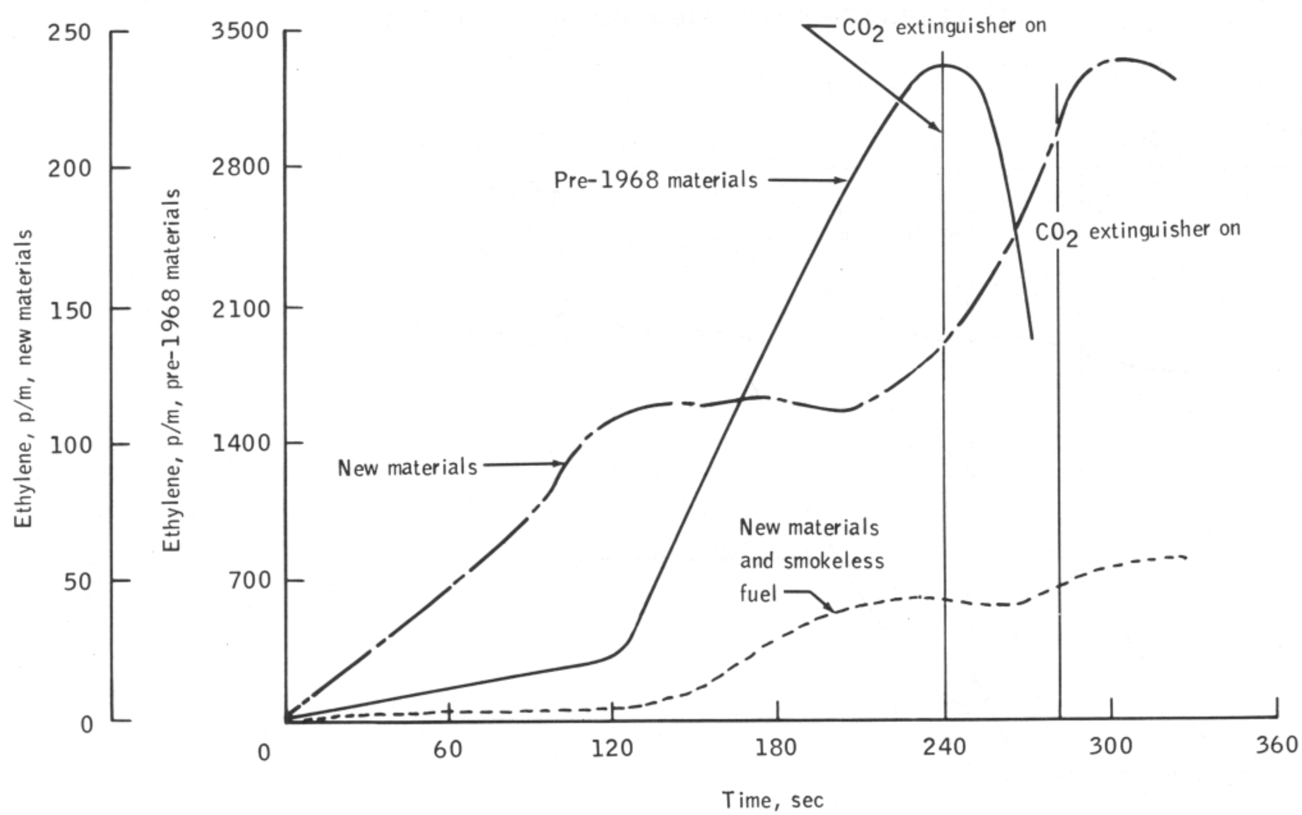

Figure 13.- Ethylene concentration.

Figure 14.- Sidewall fire damage for test 1 using pre-1968 materials.

Figure 15.- Fire damage for test 1 using pre-1968 materials, side view.

Figure 16.- Fire damage for test 1 using pre-1968 materials, front view.

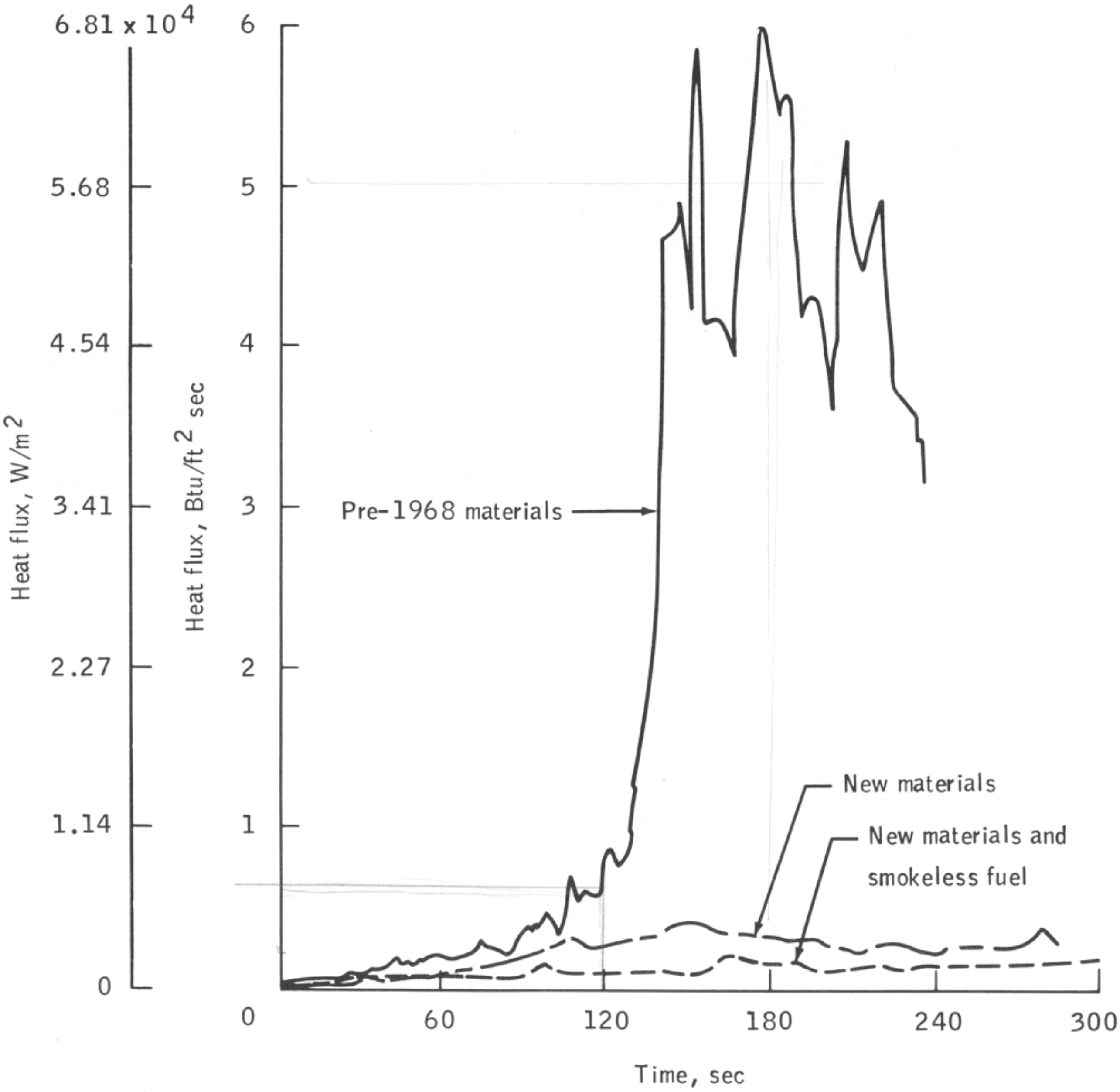

Figure 17.- Heat flux at center of test section, center aisle.

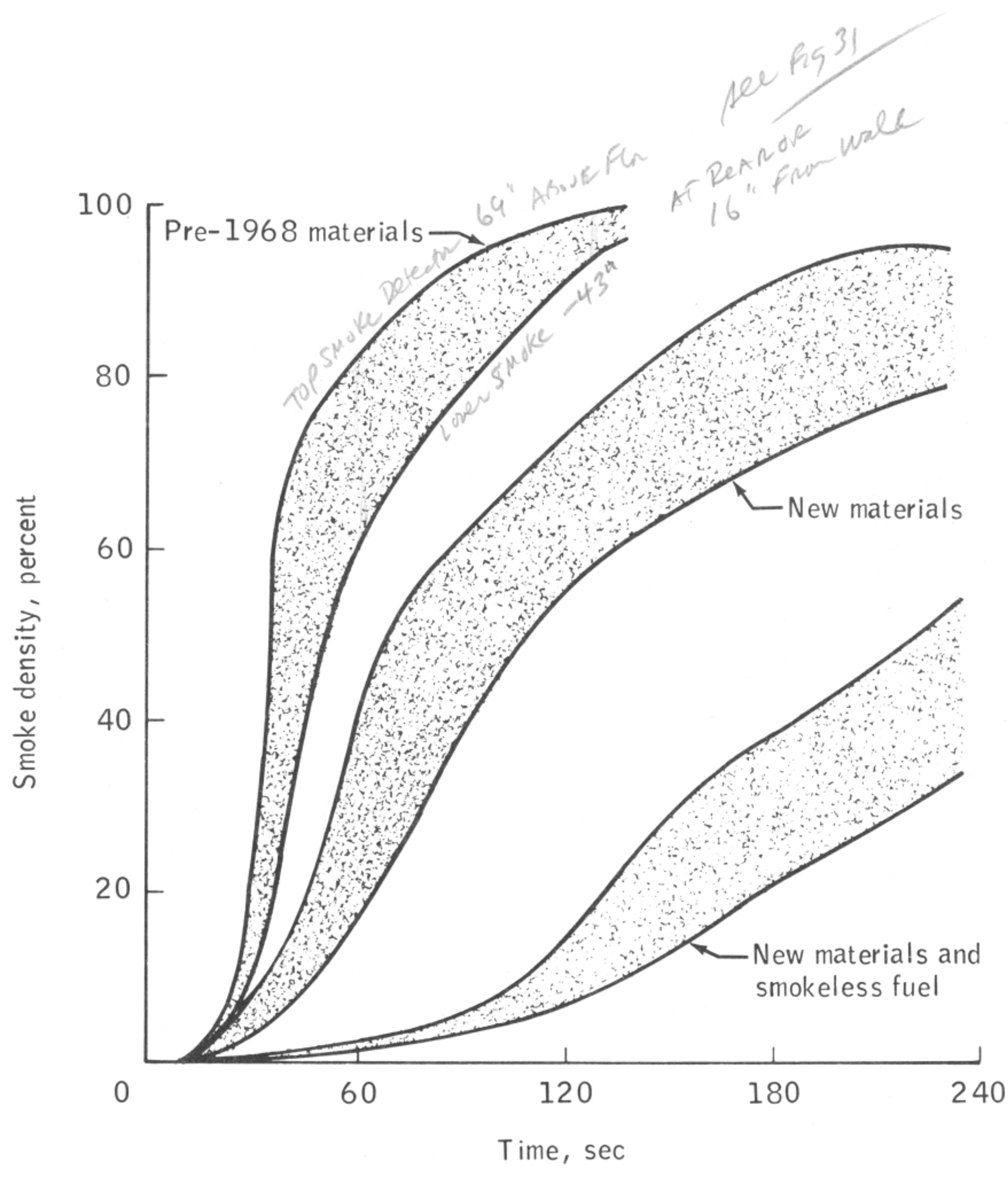

Figure 18.- Minimum and maximum smoke density levels.

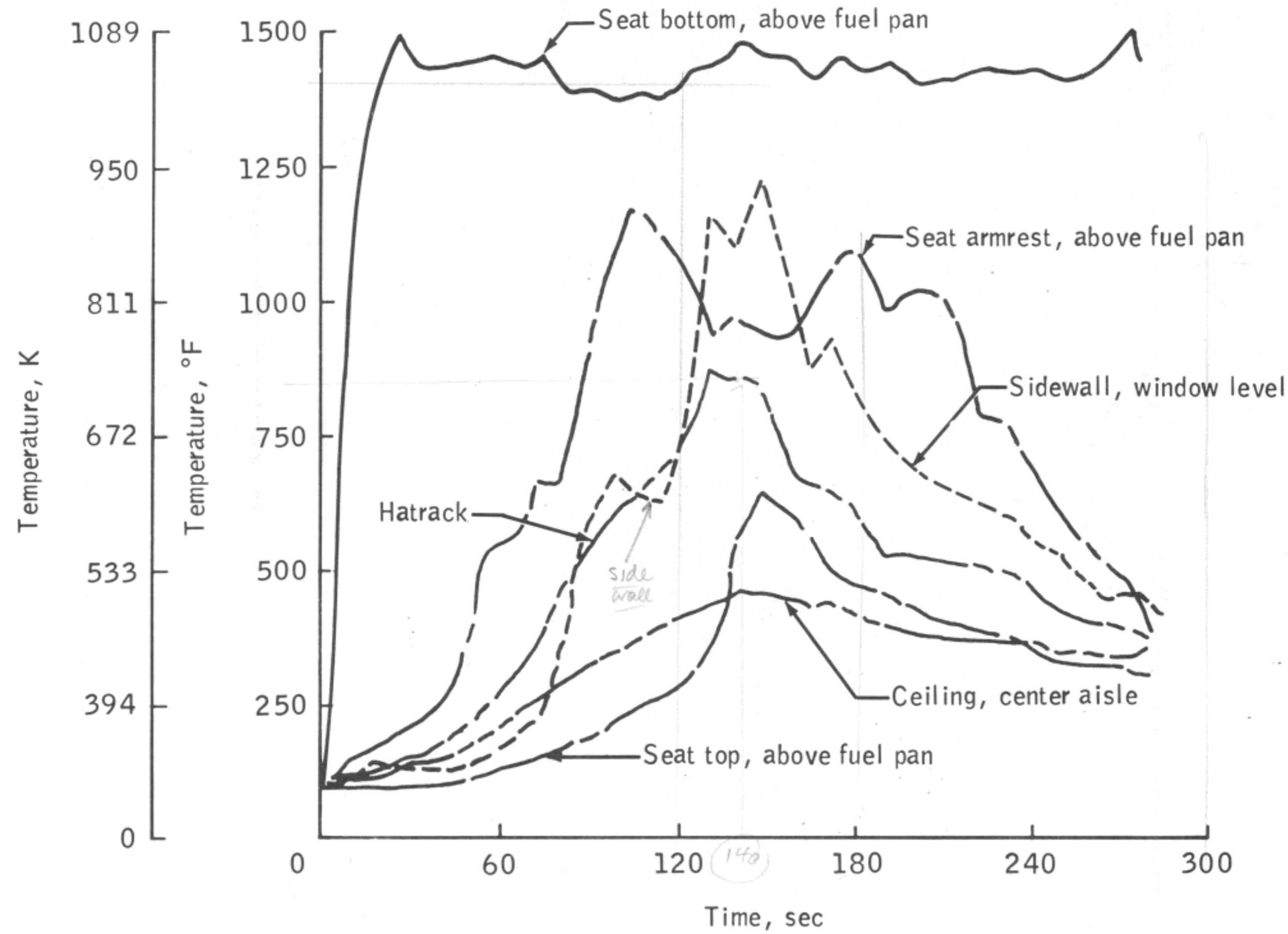

Figure 19.- Temperatures at center of test section, new materials.

Figure 20.- Fire damage for test 2 using new materials, side view.

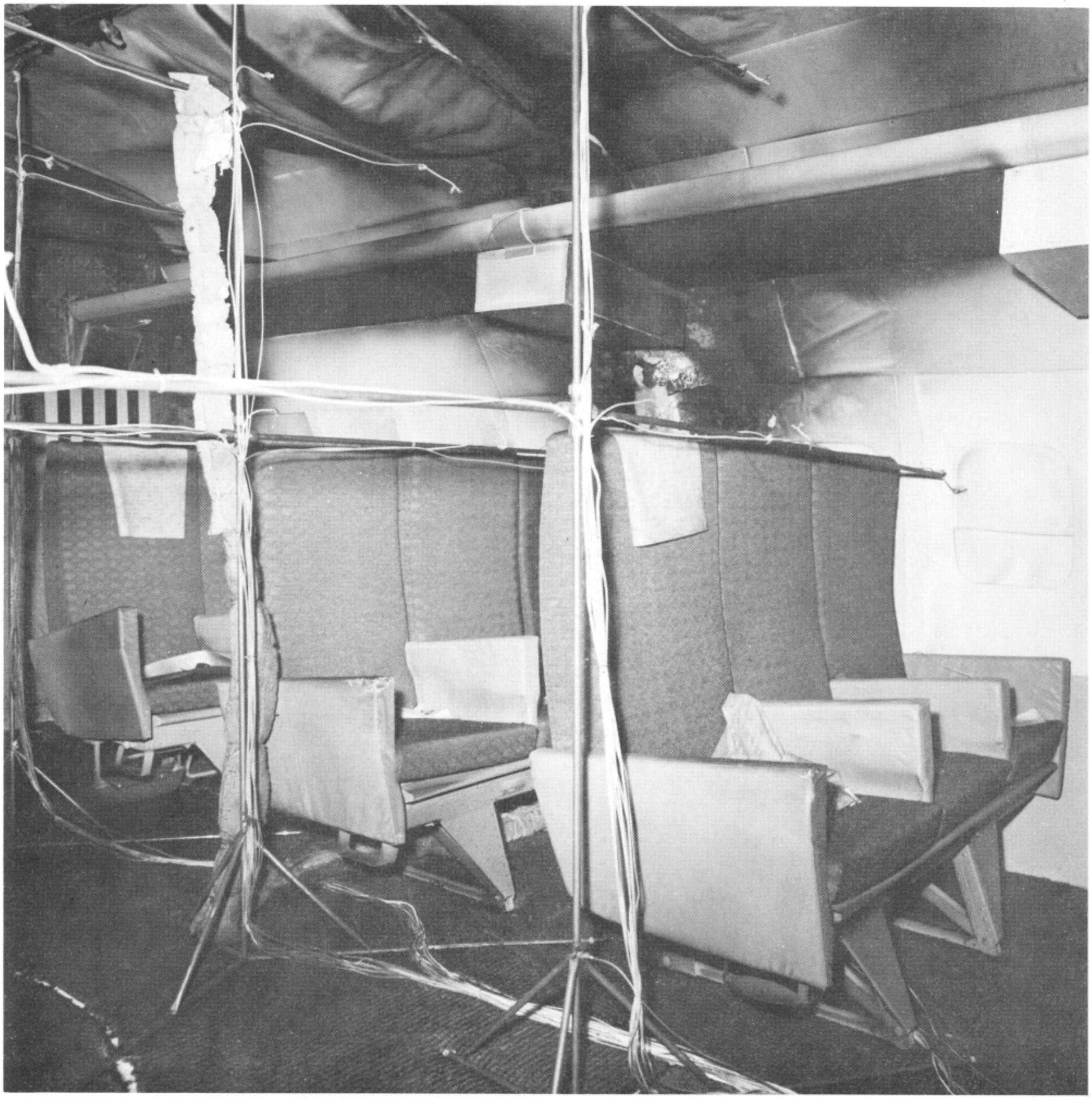

Figure 21.- Fire damage for test 2 using new materials, front view.

Figure 22.- Seat bottom fire damage for test 2 using new materials.

Figure 23.- Seat top fire damage for test 2 using new materials.

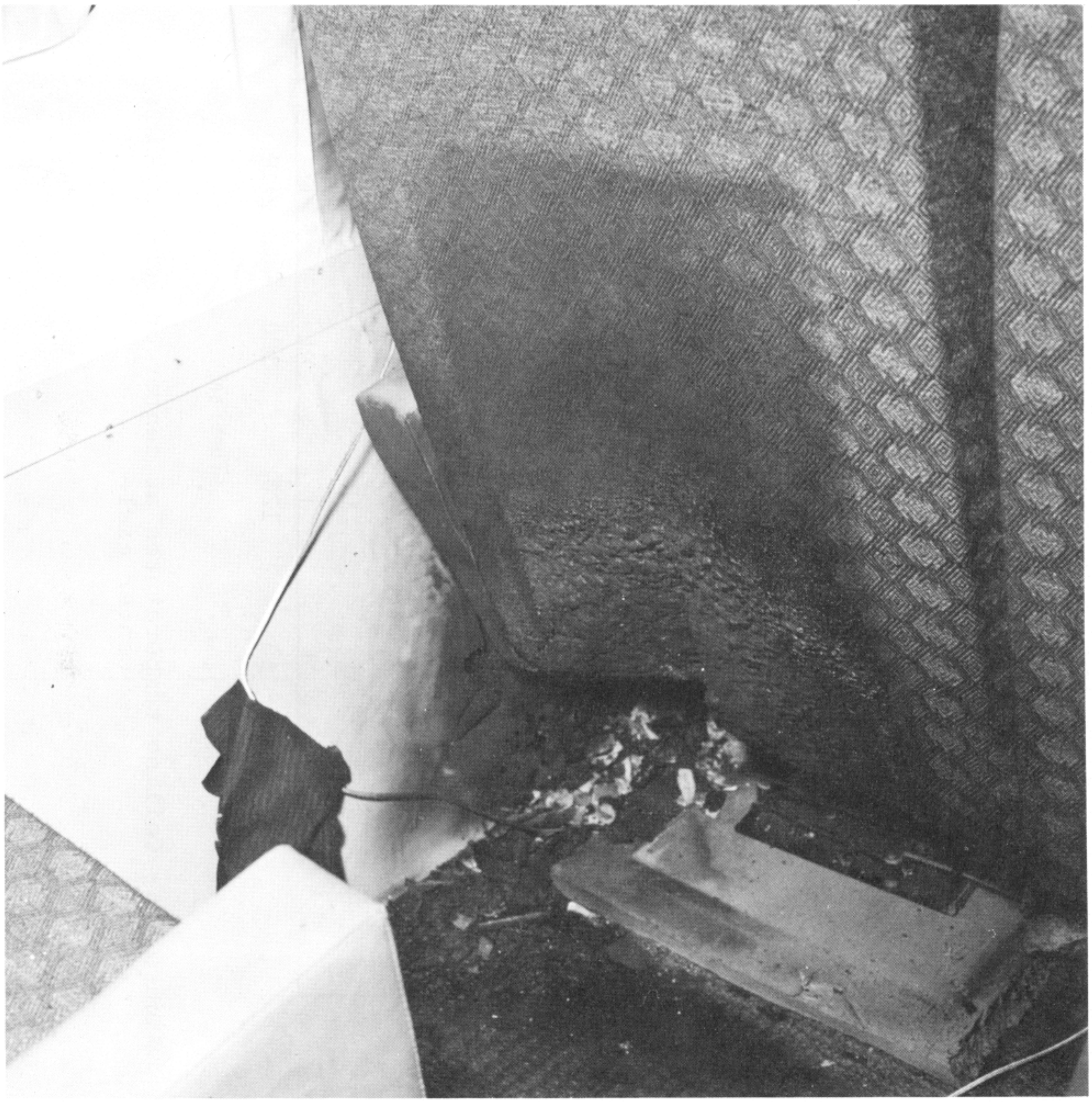

Figure 24.- Seat back fire damage for test 2 using new materials.

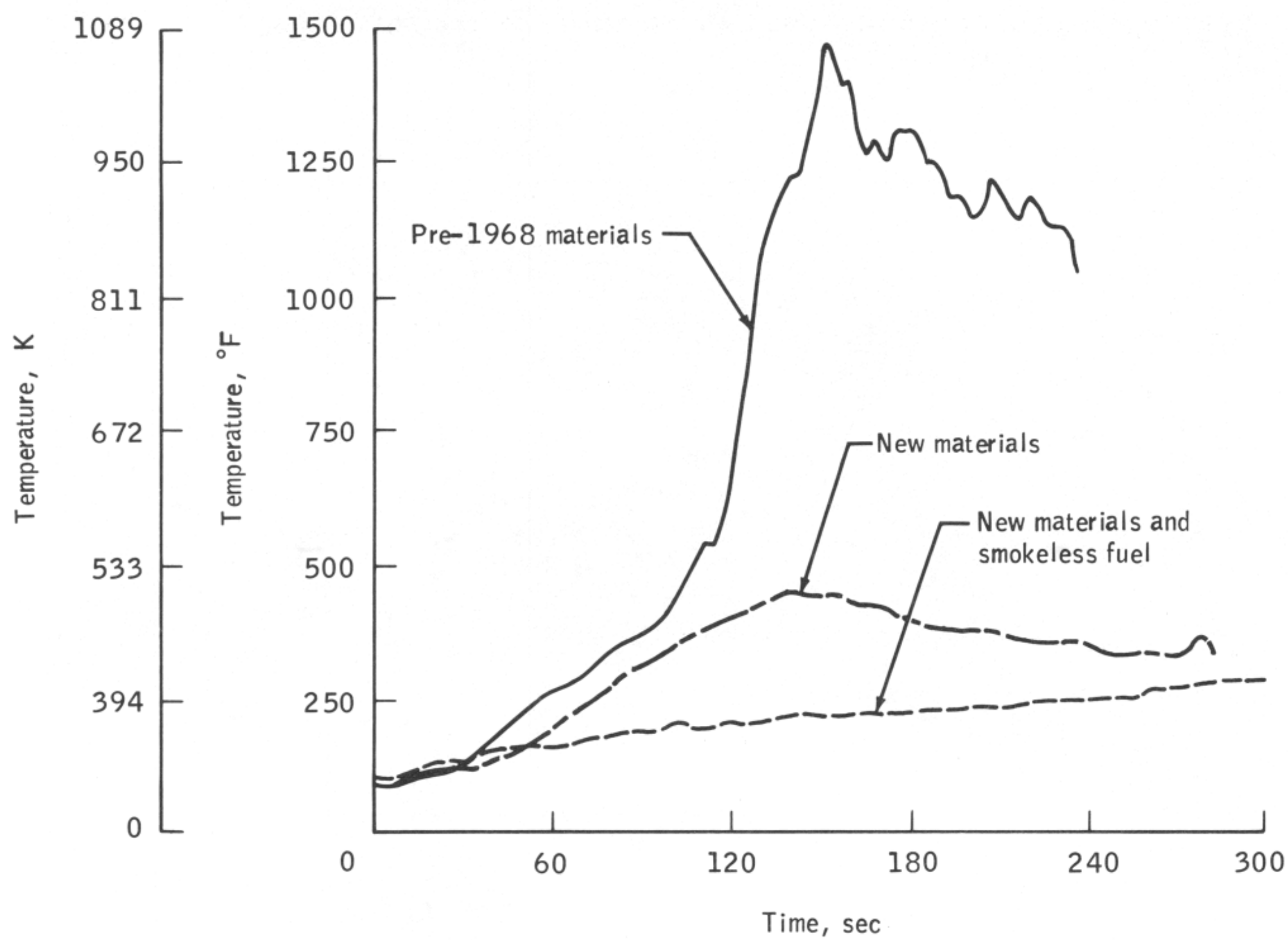

Figure 25.- Ceiling temperatures at center of test section, center aisle.

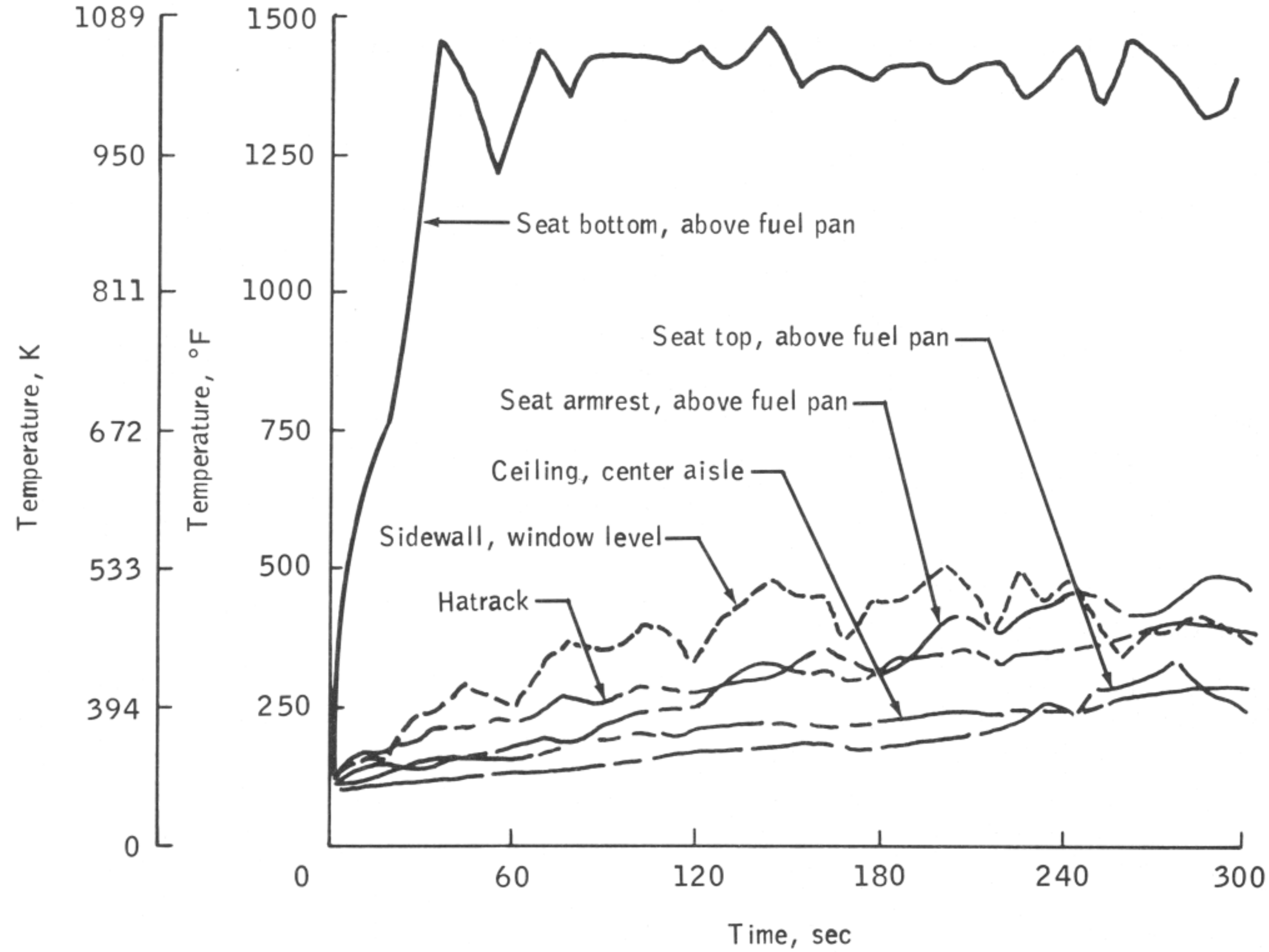

Figure 26.- Temperatures at center of test section, new materials and smokeless fuel.

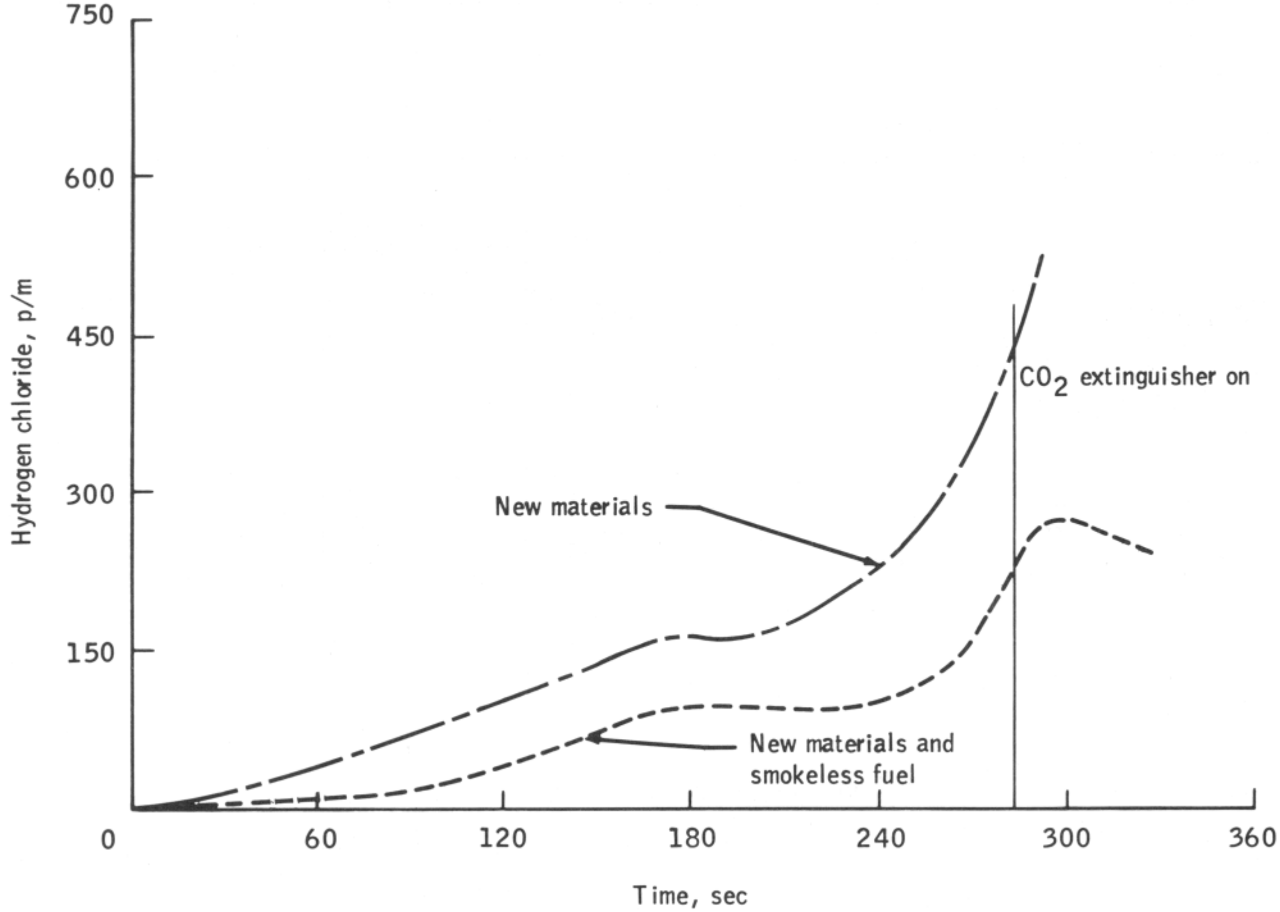

Figure 27.- Chloride (as hydrogen chloride) concentration.

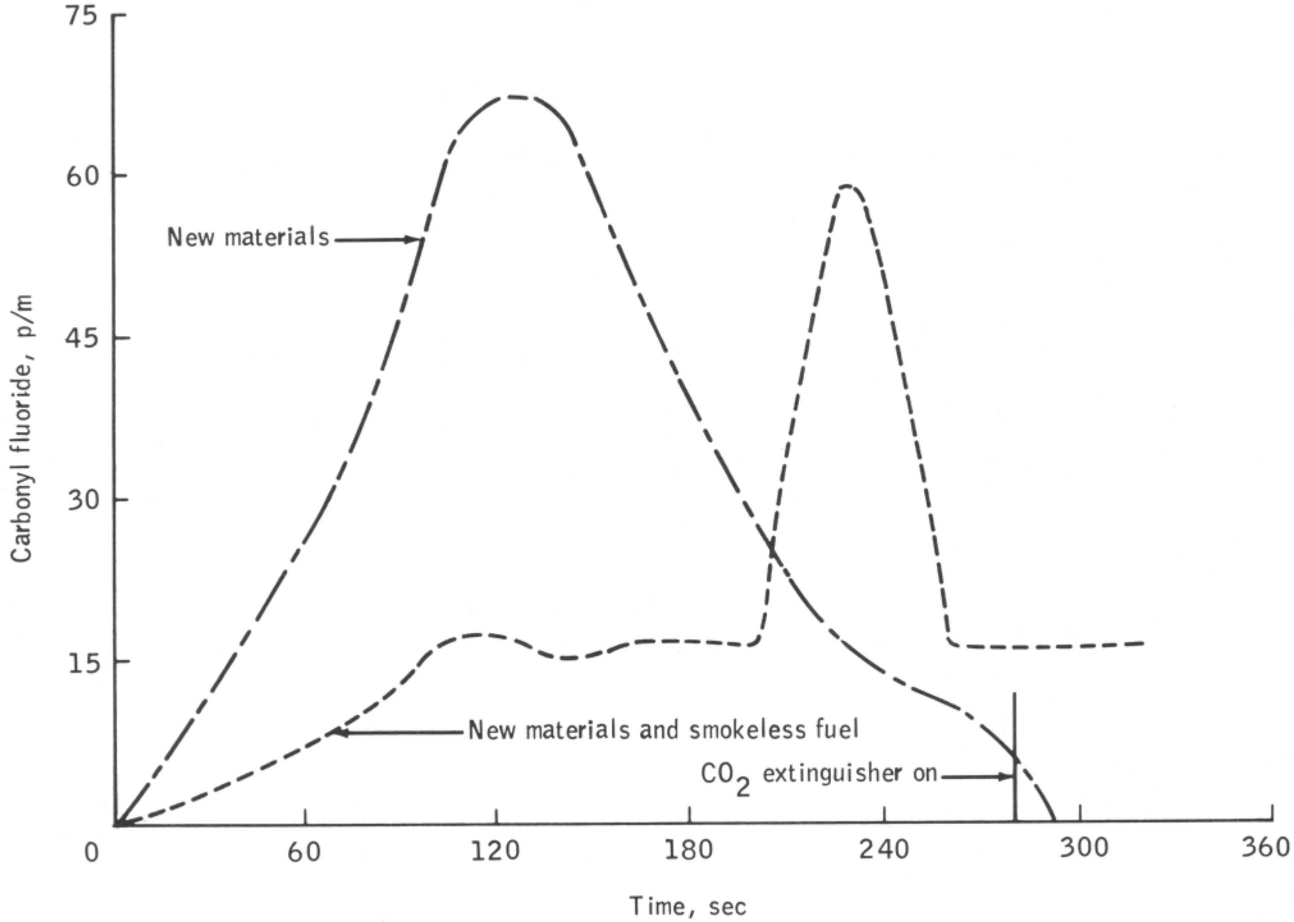

Figure 28.- Fluoride (as carbonyl fluoride) concentration.

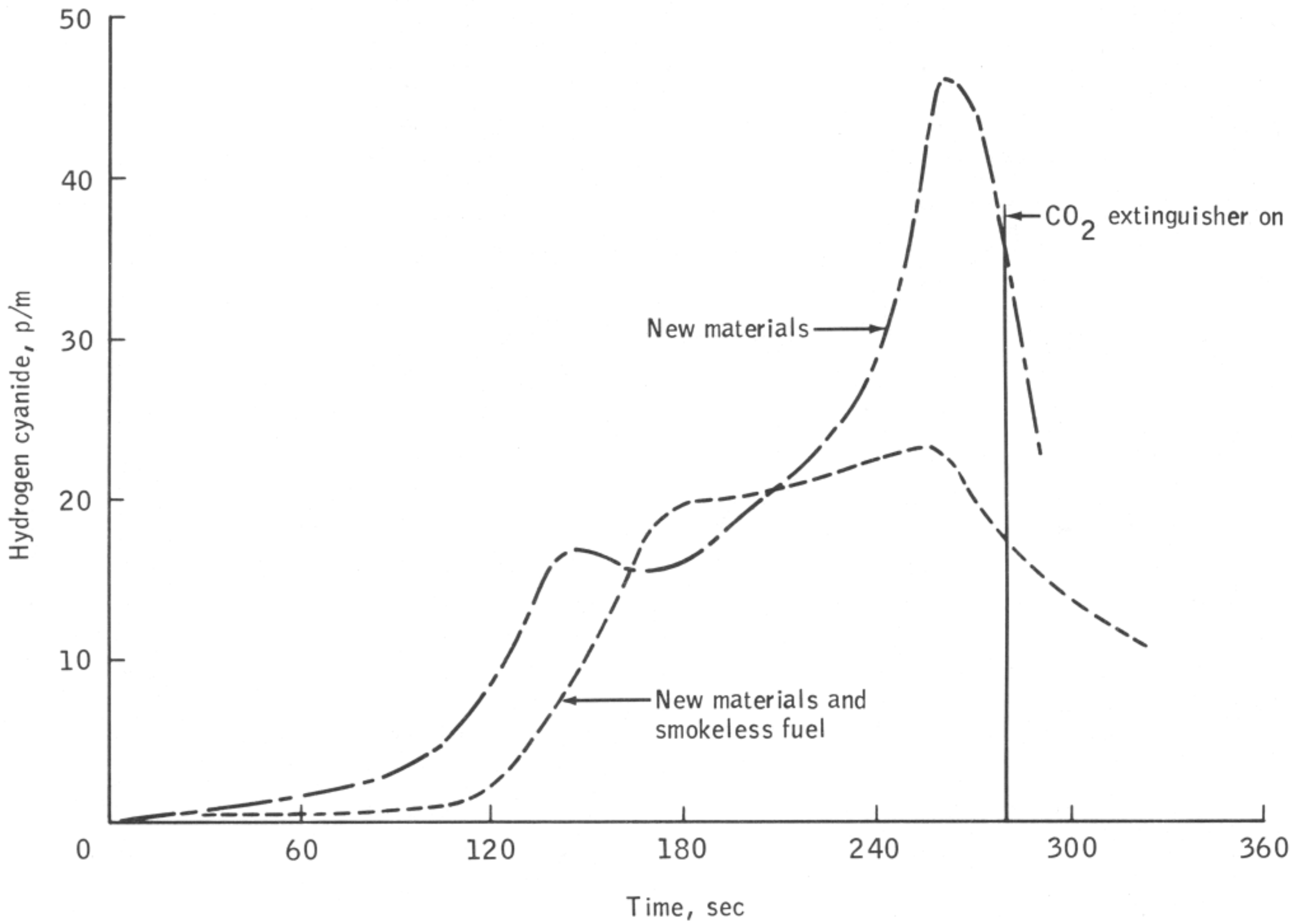

Figure 29.- Cyanide (as hydrogen cyanide) concentration.

APPENDIX - INSTRUMENTATION

TEMPERATURE MEASUREMENT

Forty-nine Chromel-Alumel thermocouples were installed in the Boeing 737 fuselage test section for temperature measurement. Thirty of these were in the form of thermocouple (TC) trees (fig. 30); each tree contained 10 TC's, and one tree was located along the center line of each row of seats. Six TC's were installed along the ceiling and below the hatrack to duplicate the Aerospace Industries Association of America, Inc. (AIA), test setup. Six additional TC's were installed on the seats in the vicinity of the fuel pan. Five TC's were attached to the aluminum structure and skin of the fuselage to enable test termination before the occurrence of excessive damage to the fuselage; a wet-bulb TC and a dry-bulb TC were added for determining humidity. Thermocouple locations are shown in figures 3 and 31.

VISIBILITY MEASUREMENT

Three smoke detectors (fig. 32) were located at the air-exit end of the test section (fig. 31). One detector was located near the ceiling, the second was placed at standing head level, and the third was installed at seated head level. The detectors consisted of a 5.7-centimeter (2.25 inch) diameter steel tube, painted black, having a light source at one end and a Weston photoelectric cell at the other end. Holes were drilled in the tube to allow passage of smoke, and the units were calibrated with Kodak Wratten neutral density filters to provide attenuation, or opacity, from 0 to 100 percent.

HEAT FLUX

Three asymptotic calorimeters were installed to measure heat flux from the burning materials. One was located at standing head level in the center aisle directly across from the fuel ignition source (fig. 31). The other two were mounted on the smoke detectors, one at standing head level and the other at seated head level (figs. 31 and 32).

TELEVISION MONITOR

One black and white television (TV) camera was located at the forward end of the test section at standing shoulder level for real-time monitoring. An infrared TV camera was located at window level near the aft end for monitoring heat paths, as shown in figure 3.

PHOTOGRAPHIC DOCUMENTATION

Four 16-millimeter motion picture cameras were used to record the events, as shown in figure 3. Three of the cameras used color film, and the fourth used infrared film to record heat paths. In addition to the motion picture coverage, still color photographs were taken before and after each test.

GAS COLLECTION

Two separate systems were used to collect the gaseous products of combustion, one for hydrolyzable gases and the other for nonhydrolyzable gases. A schematic of the gas collection systems is shown in figure 33. These systems contained eleven 16-liter and eleven 32-liter stainless steel collection bottles, respectively. Each bottle was connected to a common manifold (one for each system) by a solenoid valve. A stainless steel line was run from each system manifold to the sampling location in the test section (fig. 31). The nonhydrolyzable gas samples were collected in the stainless steel bottles in the gaseous state, whereas the hydrolyzable gas samples were absorbed into a 200-cubic-centimeter sodium hydroxide solution placed in each 16-liter stainless steel bottle. Before each test, the hydrolyzable gas bottles were filled with the sodium hydroxide solution and evacuated to a pressure of approximately 33.3 hN/m^2 (25 torr) (i.e., to remain above the vapor pressure of the sodium hydroxide solution). The bottles for the nonhydrolyzable system were evacuated to a pressure of 4 hN/m^2 (3 torr) or less. Approximately 1 minute before the test, a background sample was taken for each system; following fuel ignition, gas samples were obtained at 30-second intervals.

GAS ANALYSIS

In the analysis of the combustion products, the following analytical methods were employed. The concentrations of the products of combustion were determined by means of infrared spectroscopy for carbon dioxide, carbon monoxide, methane, ethylene, Freon 11, and Freon 113. Mass spectroscopy was used for oxygen and carbon dioxide, and gas chromatography was used for ethane and propane. For nonhydrolyzable products not determinable by these methods, a combined gas-chromatographic/mass-spectrometric interfacing technique was employed. The latter method was used to detect all the unquantified combustion products listed in table IV. Specific ion electrodes were used to determine the concentrations of the hydrolyzable chlorides, fluorides, and cyanides.

DATA ACQUISITION

All data were recorded on magnetic tape and subsequently plotted in engineering units by a computer. In addition, critical parameters were monitored on a cathode-ray tube visual display during testing.

TEST OBSERVERS

During test 1, the observers were two representatives of the NASA Lyndon B. Johnson Space Center (JSC), four representatives of the AIA, and two representatives of American Airlines. For test 2, in addition to one JSC observer, representatives of the AIA, the Federal Aviation Administration (FAA), the National Transportation Safety Board (NTSB), the Air Line Pilots Association (ALPA), and United Airlines served as observers. For test 3, one JSC observer and representatives of AIA, American Airlines, and ILC Industries viewed the test. Non-NASA attendees at the three tests were as follows.

1. Pre-1968 materials test (test 1)

   a. P. J. Lester,[1] Boeing Co.

   b. R. J. Sutton,[1] McDonnell Douglas Corp., Douglas Aircraft Co.

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[1]Representing the AIA.

c. B. Silverman,[1] Lockheed Aircraft Co.

d. S. Parker,[1] Boeing Co.

e. G. D. McManus, American Airlines

f. B. Snoody, American Airlines

2. Fire-resistant materials test using JP-4 ignition fuel (test 2)

a. J. A. Leland,[1] McDonnell Douglas Corp., Douglas Aircraft Co.

b. D. G. Shaw,[1] Boeing Co.

c. B. Silverman,[1] Lockheed Aircraft Co.

d. W. S. Perkowski,[1] Boeing Co.

e. D. A. Heine, ALPA

f. D. R. Mott, ALPA - Stewardess Division

g. M. M. McCormick, NTSB

h. M. Radnofsky, Consultant

i. R. C. McGuire, FAA

j. E. B. Nicholas, FAA

k. H. P. Branting, FAA

l. M. Kuperman, United Airlines

m. A. P. Vance, Monsanto Co.

3. Fire-resistant materials test using smokeless ignition fuel (test 3)

a. B. Silverman,[1] Lockheed Aircraft Co.

b. J. A. Leland,[1] McDonnell Douglas Corp., Douglas Aircraft Co.

c. R. Anderson,[1] Boeing Co.

d. V. Pools, American Airlines

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[1]Representing the AIA.

e. B. Lapham, ILC Industries, Inc.

f. M. Radnofsky, Consultant

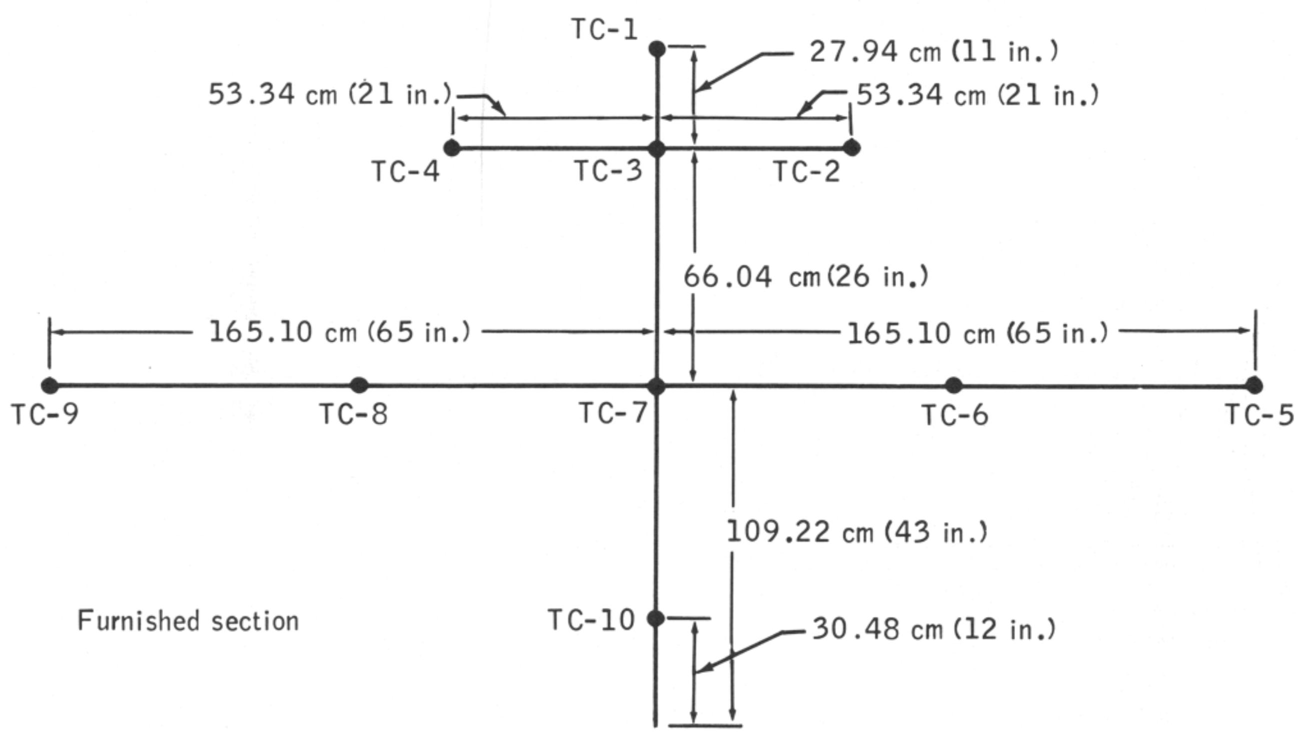

Figure 30.- Typical thermocouple tree.

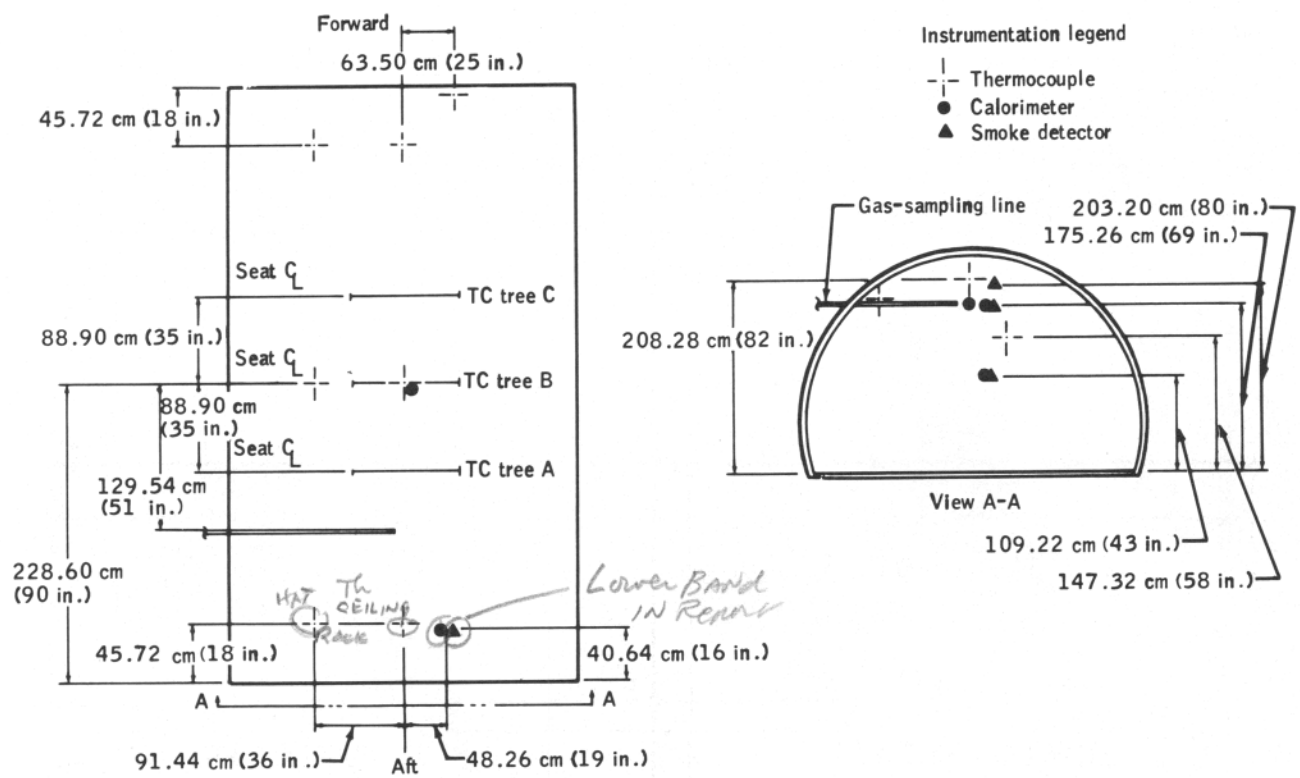

Figure 31.- Instrumentation locations.

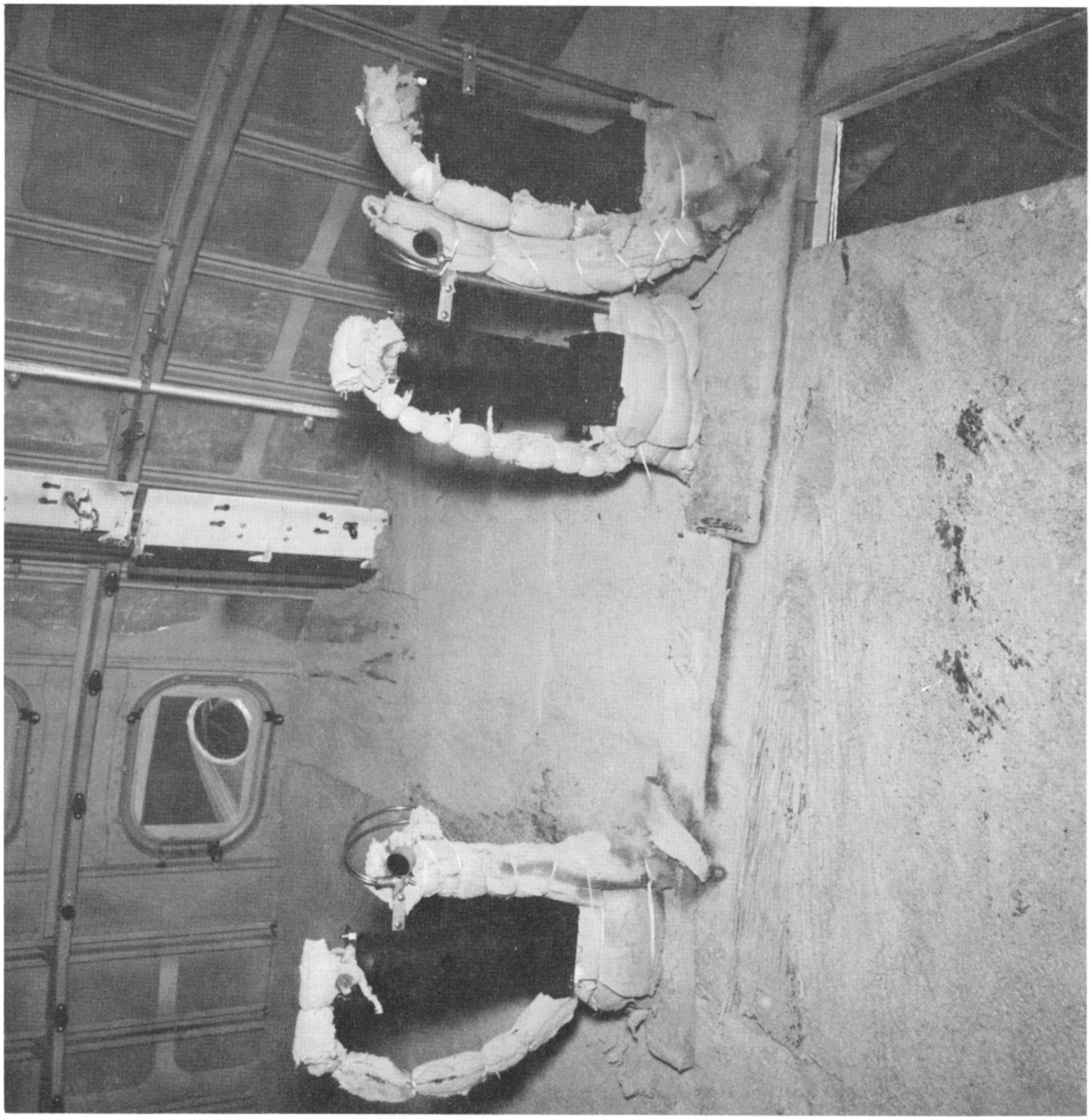

Figure 32.- Aft calorimeters and smoke monitors.

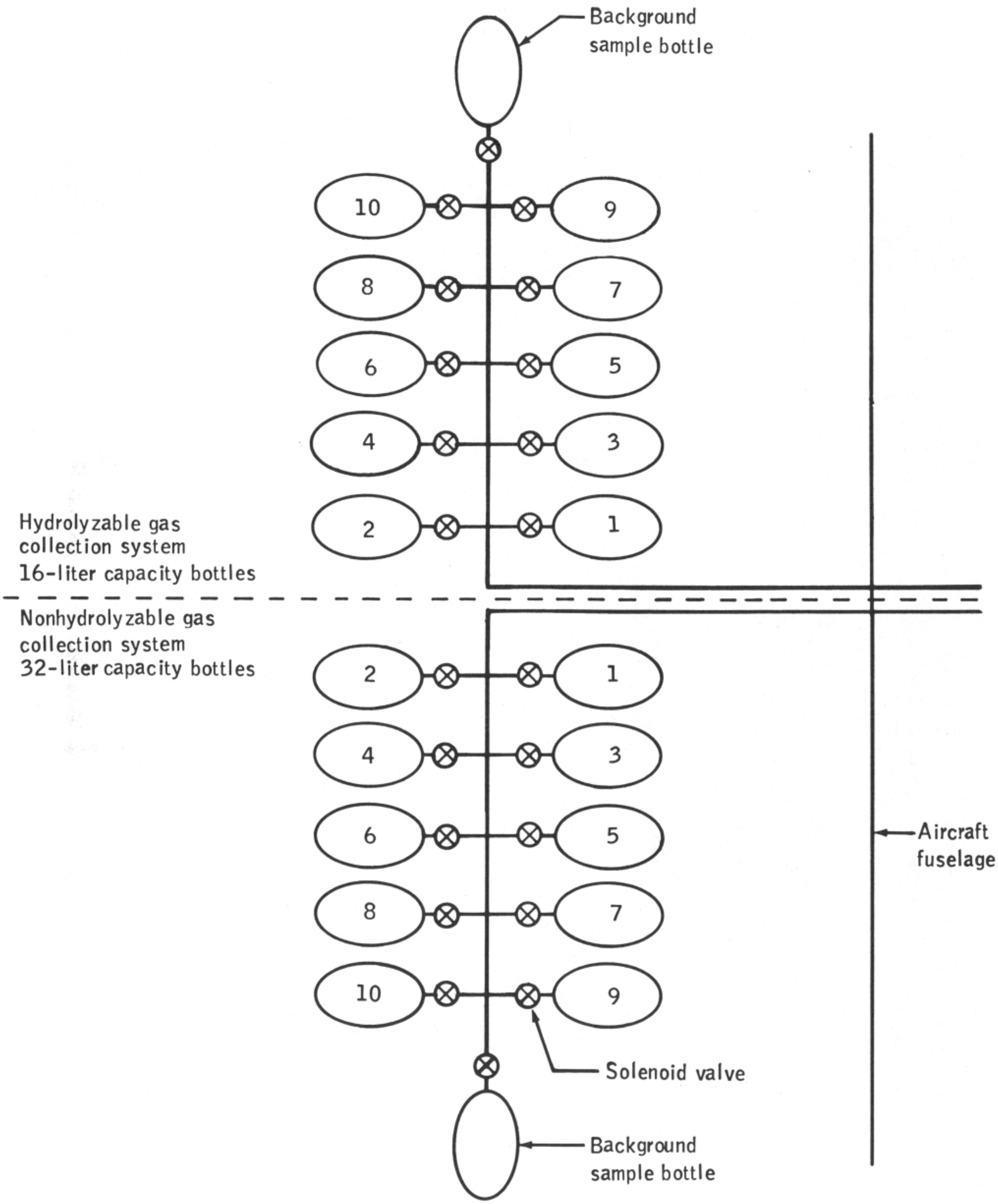

Figure 33.- Schematic of gas collection systems.

NASA-JSC