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Full-scale aircraft flammability tests are described in which the effectiveness of new fire-resistant materials was evaluated by comparing their burning characteristics with those of other fire-resistant aircraft materials. Two tests were conducted as a follow-on to three previous tests. The later tests used new fire-resistant materials that are more economical and better suited for aircraft use than the previously tested fire-resistant materials. The fuel ignition source for one test was JP-4; a smokeless fuel was used for the other test. Test objectives, methods, materials, and results are presented and discussed. The results indicate that, similar to the fire-resistant materials tested previously, the new materials decompose rather than ignite and do not support fire propagation. Furthermore, the new materials did not produce a flash fire.

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TEST SERIES II

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

TEST SERIES II

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SUMMARY

Two full-scale aircraft cabin flammability tests were performed to evaluate and compare the effectiveness of new, more economical fire-resistant materials to materials tested in three previously reported tests. Sidewalls, windows, ceiling panels, hatracks, a passenger service unit, and three rows of seats, made from materials that meet the end-use requirements of the aviation industry, were installed along one side of a Boeing 737 fuselage section. As in previous tests, a fuel ignition source was located beneath the outboard seat of the middle row of seats and was ignited electrically. The fuel used for one test was JP-4; a smokeless fuel was used for the other test so that smoke produced by the fuel ignition source would not mask the burning of the cabin materials and preclude a determination of the contribution of the materials to the smoke produced. The results of these two tests revealed that the newer, more economical materials decompose rather than ignite and do not support fire propagation; however, these materials also produced undesirable quantities of hydrogen cyanide.

INTRODUCTION

This report, the second in a series of reports on continuing full-scale aircraft flammability tests, presents the results of two tests conducted in a Boeing 737 fuselage as a follow-on to three previous tests to evaluate improved fire-resistant materials for passenger aircraft. The tests discussed in this report are identified as tests 4 and 5. The test configuration and results of the first three tests are presented in reference 1. The three tests discussed in that report are identified as tests 1, 2, and 3 and were conducted to evaluate older flammable aircraft materials and newer fire-resistant materials. The new materials used in tests 2 and 3 were also installed in four NASA Gulfstream executive aircraft for in-use evaluation. Although these materials met stringent test requirements, such as low flammability, low smoke production, and thermal stability, and fulfilled usage criteria, they were generally too expensive for commercial aircraft application. Subsequent development resulted in more economical materials that are viable candidates for use in commercial aircraft, and these materials are the subject of the two tests discussed in this report. The changes made in materials between tests 2 and 3 and tests 4 and 5 were significant in scope and involved upholstery, seat-cushion foam, wall and ceiling panels, and decorative skin.

Test 4 was performed using 0.95 liter (1 quart) of JP-4 fuel as an ignition source. Test 5 was identical to test 4 except that JP-4 was replaced with a smokeless fuel so that the smoke produced by the materials alone could be observed and the loss of visibility due to this smoke could be measured.

The discussions in this report (and in ref. 1) are largely limited to the overall aspects of the events and results observed. The enormous complexity of the flammability process combined with the many variables involved in the tests preclude a detailed explanation currently.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Systeme International d'Unites (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 to previously tested, more expensive materials. In this series, two separate tests were performed. For test 4, the primary objectives were to evaluate new fire-resistant materials (that are less expensive but better suited for aircraft use than those previously tested) in a full-scale configuration and to compare the results with those of tests 2 and 3. For test 5, the primary objective was to obtain a better determination of the amount of smoke produced by the new fire-resistant cabin materials by using a smokeless fuel source. For each test, sufficient data were acquired to accomplish the following detailed objectives.

1. To define the magnitude and the degree of propagation 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, carpeting, 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 schematic of the test setup is shown in figure 2.

The ignition source for test 4 was 0.95 liter (1 quart) of JP-4 aircraft fuel contained in a 30.5 by 30.5-centimeter (1 by 1 foot) pan; the burning time was approximately 5 minutes. The pan was placed under the outboard seat of the middle row of seats (fig. 2), and the fuel was ignited electrically. For test 5, the JP-4 fuel was replaced by 1.42 liters (1.55 quarts) of a smokeless fuel (50 percent acetone and 50 percent methanol) in a larger fuel pan (38 by 38 centimeters (15 by 15 inches)) 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, and the larger fuel pan was used to compensate for the slower energy release rate of the smokeless fuel. For both tests, an airflow rate of 5.7 m^3/min (200 ft^3/min) was provided through the 4.6-meter (15 foot) long test section (fig. 2). Two carbon dioxide fire extinguisher systems were installed in the fuselage for terminating the tests. One system was located in the 4.6-meter (15 foot) long 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 duplicated the configuration for tests 1, 2, and 3.

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. Combustion product concentrations were determined by subsequent analysis of these samples as described in the appendix. Color motion pictures were taken during the tests, and still photographs were taken before and after each test. Black-and-white and color television 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.) The instrumentation locations are shown in figure 2, and a brief description of the instrumentation is presented in the appendix.

Tests

Materials used in tests 4 and 5 were newer fire-resistant materials that are more economical and practical for aircraft use than the materials used in tests 2 and 3 (ref. 1). In this report, the materials used in tests 2 and 3 are designated "new materials A," and the materials used in tests 4 and 5 are designated "new materials B." Details of the test interiors are given in table I, and the interior configurations before testing are shown in figures 3 to 6. A smokeless fuel was used in test 5; the rest of the setup was the same as for test 4.

RESULTS AND DISCUSSION

Because the test methods used in this series were selected to enable correlation and comparison with previous NASA Lyndon B. Johnson Space Center (JSC) tests as well as with tests performed by the Aerospace Industries Association of America, Inc. (AIA) (ref. 2), the results of this test series were compared to those of the previous JSC tests and of the AIA tests, as well as to each other. Also, results of Federal Aviation Administration (FAA) fire tests on aircraft passenger seats (ref. 3) were compared to the JSC test results. Flammability testing cannot be considered an exact science, and results of separate test programs can be compared only in general terms. Quantitative values should be interpreted as approximations, not as exact numbers. Gas analysis results, in particular, are acutely affected by variations in test parameters, sampling techniques, and analytical procedures.

New Materials B (Test 4)

The following discussion of test 4 using new materials B includes test results, a description of specific fire damage, and a comparison of results with those of other tests.

Test results.- Smoke was observed about 4 seconds after ignition of the JP-4 fuel source. As in previous full-scale tests using this fuel source, the initial smoke appeared to come mainly from the burning JP-4; however, small amounts of light-colored smoke appeared to come from the seat materials. The size of the fire slowly increased until about 60 seconds elapsed time, when the fire intensified and flames reached seat-top height. This intensification is believed to have occurred as flames charred the Nomex upholstery, which shrinks and separates as it is pyrolyzed and thus exposes the foam to direct flames. These materials will not self-propagate; they burn or decompose only where exposed to a fire source. Also adding to the intensification were the flammable gases released as the fire-resistant materials decomposed; however, the amount of combustible gases released during test 4 was apparently insufficient to result in a flash fire.

After ignition, the smoke density increased (fig. 7), and visibility of the fire was lost at approximately 140 seconds as smoke filled the cabin. Cabin temperatures also increased, reaching a peak of about 755 K (900° F) (at the top of the seat armrest, above the fuel pan) at 160 seconds after ignition, then rapidly decreased to an average of about 422 K (300° F) at 200 seconds (fig. 8). The temperatures again increased at 320 seconds, peaked at 350 seconds, and then decreased to minimum levels at about 400 seconds. Two additional significant temperature increases occurred, with one peak at 460 seconds and the last peak at about 600 seconds. The gradual decrease in oxygen (fig. 9) and the gradual increase in carbon monoxide (fig. 10) are indicative of a typical open fire (very similar to that which occurred during test 2 (ref. 1)) and of the absence of a rapidly burning flash fire. The maximum heat flux measured at standing head level in the center aisle (fig. 11) was less than 2.84 KW/m^2 (0.25 Btu/ft^2 sec) at about 150 seconds.

Figures 12 to 15 clearly show that the fire did not propagate and that major damage was confined to the seat above the fuel pan and to the lower portion of the adjacent sidewall. Because the fire was small and most cabin temperatures were relatively low, the test was continued for 900 seconds before termination using the carbon dioxide extinguishing system.

Specific fire damage.- The extent of damage to the newer fire-resistant materials used in test 4 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 melted. Approximately 50 percent of the bottom seat-cushion upholstery was consumed, and the remaining material was scorched. Approximately 90 percent of the fire-retardant foam padding of the bottom seat-cushion was consumed. The Nomex seatbelt was completely charred. The front of the seat-back upholstery was 30 percent consumed, 30 percent charred, and 10 percent scorched; the opposite side was about 15 percent consumed, 5 percent charred, and 10 percent scorched. The foam padding of the seat back was approximately 50 percent consumed. The armrest covering was about 50 percent consumed, and the remaining material was charred or scorched. The headrest napkin was scorched but did not burn. Except for slight scorching of the center seat adjacent to the damaged seat, the other seats were not damaged.

2. Sidewall: A triangular area of the lower sidewall adjacent to the fuel pan, covering about 0.13 square meter (200 square inches), was completely charred. The sidewall above this area was scorched and blackened up to the hatrack (fig. 12).

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

4. Ceiling panels: The ceiling panels were slightly scorched and blistered by the heat.

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

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

7. Windows: The monolithic epoxy-boroxine windows were not damaged.

Comparison with other tests.- A comparative summary of some important measured parameters for the JSC tests (including a previously conducted JP-4 fuel calibration test) is given in figure 16. Selected results of the tests can easily be compared using this figure because each parameter has the same scale for all tests. This figure is intended for comparing trends only. For detailed or specific data, refer to the other figures referenced in the text.

The material damage for test 4 was very similar to that of test 2 (ref. 1), except that more ceiling and sidewall damage occurred during test 2. The test 4 seat damage was also similar to that of full-scale tests conducted by the AIA and the FAA (refs. 2 and 3). Both the AIA test (improved materials B) and the FAA seat test (test 28B) were performed using fire-resistant polyurethane foam and Nomex upholstery, as was JSC test 4. In addition, Nomex honeycomb was used in the ceiling and hatrack panels for the AIA test and for JSC test 4.

Although the material damage was comparable for the four tests discussed previously, the test 4 ceiling temperature, which reached a maximum of approximately 450 K (350° F) (fig. 8), was much lower than for the AIA test and about 55 K (100° F) lower than for JSC test 2 and the FAA test. Oxygen depletion for JSC tests 2 and 4 and for the FAA test was similar, but the depletion for the AIA test was much greater. In addition, the smoke-density levels of test 4 followed the same pattern as the levels recorded for JSC test 2 (ref. 1) and for the FAA seat test (ref. 3); however, smoke buildup and reduction in visibility for the FAA seat test were more rapid, probably because of the smaller test chamber volume. Smoke production was not continuously measured during the AIA tests; therefore, no smoke-density comparisons for JSC test 4 and the AIA test can be made.

In general, the concentrations of the major gaseous products of combustion produced by the fire-resistant materials in JSC test 4 were similar to those obtained in JSC test 2 (table II and figs. 10 and 17 to 23) but were significantly less than those measured for the AIA test on comparable materials (ref. 2). A comparision of trace combustion products that were detected but not quantified is presented in table III.

The measured levels of cyanide represented one notable exception to the concentrations compared. The cyanide levels for JSC tests 2 and 4 (table II and fig. 20) were almost as high as values reported by the AIA for the test of its improved materials B (ref. 2). It is possible that the ignition fuels for tests 2 and 4 contributed significantly to the hydrogen cyanide production during the early portions of the tests (<180 seconds), and the differences in concentrations during the early time frame may be due to flame parameter variations for the two fuels. Hydrogen cyanide production in rich hydrocarbon flames has been reported previously (ref. 4). The high concentrations of cyanide were first determined from infrared scans of the gas samples obtained in test 4, and were found to be much greater than values indicated by the cyanide specific-ion electrode. An analysis of previous infrared scans from JSC tests 2 and 3 for hydrogen cyanide also revealed significant differences, apparently due to cyanide electrode interferences. Consequently, infrared spectroscopy was used to determine the hydrogen cyanide concentrations of tests 2 to 5 shown in table II and figure 20. These concentrations for tests 2 and 3 should be used in lieu of the cyanide values reported in reference 1.

The other major exception consisted of the measured low chloride concentrations for test 4 as compared to those for tests 2 and 3. Extremely high chloride readings were indicated by the chloride electrode in test 4. Analyses revealed that the presence of bromide was interfering with the operation of the specific-ion electrode, which was indicating much greater chloride concentrations than actually existed. Because of this bromide interference, chloride and bromide concentrations for test 4 (and test 5) were determined from silver nitrate titrations. Although no bromide was detected in tests 2 and 3 by means of mass spectrometric or other techniques, small amounts sufficient to affect chloride measurement may still have been present. Therefore, the chloride concentrations reported for tests 2 and 3 in reference 1 and listed in table II should be considered as upper limits.

Although the results of test 4 (new materials B) were very similar to the results of test 2 (new materials A) concerning degree of damage, the materials of test 4 represent a significant advancement in the technology of fire-resistant materials. In general, these materials are economically, esthetically, and physically better suited for aircraft use than are the materials used in JSC test 2. Furthermore, although both tests 2 and 4 resulted in about the same material damage, test 4 was allowed to continue for 900 seconds, whereas test 2 was terminated after 280 seconds because of a fire that occurred in the paper honeycomb behind the ceiling panels (ref. 1).

New Materials B With Smokeless Fuel (Test 5)

Test 5 was performed using new materials B with smokeless fuel. Detailed test results, specific fire damage, and comparisons with other tests are presented in the following paragraphs.

Test results.- Test 5, using the same smokeless fuel ignition source as test 3 (but a greater quantity in a larger fuel pan), unexpectedly resulted in a much larger fire and consequently more material destruction in the region of the ignition source and in higher cabin temperatures than test 4, although the thermocouple beneath the seat bottom (above the fuel pan) indicated a lower fuel flame temperature than that measured during test 4.

Smoke was observed at about 15 seconds elapsed time and increased slowly until about 150 seconds, at which time the smoke production increased at a higher rate to a maximum value at 240 seconds (fig. 7). Cabin temperatures (fig. 24) increased at a slow rate after ignition, similar to the rate of increase measured for test 3 (ref. 1), until approximately 165 seconds, when the temperatures increased more rapidly as the fire intensified. Before this time, at 80 seconds, the armrest material was observed to be burning and, at about 130 seconds, a piece of flaming material fell from the seat into the fuel pan. By 150 seconds, flames were at seat-top height, and at 180 seconds flames had reached the bottom of the hatrack. The fire continued to intensify and, at 210 seconds, peak temperatures of approximately 1033 K (1400° F) at the seat armrest above the fuel pan and about 575 K (575° F) at the ceiling were recorded. Also at 210 seconds, flaming material was observed to be falling next to the sidewall in front of the seat above the fuel pan. Temperatures began to decrease rapidly soon after 240 seconds, and loss of visibility occurred at 255 seconds. Except for a minor peak of 7.94 KW/m^2 (0.7 Btu/ft^2 sec) at 265 seconds, the radiant heat flux for test 5 averaged approximately 6.81 KW/m^2 (0.6 Btu/ft^2 sec) from 210 seconds until 240 seconds.

Figures 25 to 29 clearly show that the fire did not propagate, although the seat above the fuel pan and the adjacent sidewall sustained major damage. The only damage to the third row of seats was the scorched headrest napkins; the rest of the damage was sustained in test 4. (Between tests 4 and 5, the middle and back rows of seats were exchanged to provide an undamaged row for test 5.) Figure 5, a pretest photograph for test 5, shows some of the damage resulting from test 4. Although the initial fire was larger than those in previous tests with new materials, the temperature data indicated that, after 240 seconds, the fire was decreasing in size. The test was therefore contined until 900 seconds elapsed time, when the fire was extinguished.

Specific fire damage.- Posttest inspection revealed damage to the interior materials similar to, but more severe than, that sustained during the previous test.

1. Seats: The seat above the ignition source was almost completely destroyed by the fire. Damage included

much of the metal structure, which melted and caused the remaining portion of the seat to fall against the cabin wall. About 95 percent of the bottom seat-cushion upholstery was charred or consumed, and all the fire-retardant foam padding was consumed. The Nomex seatbelt was completely charred. The front of the seat-back upholstery was 90 percent consumed and 10 percent charred, the back side was about 20 percent consumed, 20 percent charred, and 20 percent scorched. The seat-back foam padding was completely consumed. About 50 percent of the armrest covering was consumed, and the remaining material was charred or scorched. The headrest napkin was completely scorched. The upholstery of the seat adjacent to the seat over the ignition fuel pan was slightly charred and scorched. The headrest napkin of the adjacent seat was about 50 percent scorched. The back of the seat in front of the ignition source was about 75 percent scorched. All the remaining headrest napkins were scorched to a maximum of approximately 40 percent.

2. Sidewall: A 0.6-meter (2 foot) wide section of the sidewall covering (Kynar decorative laminate) adjacent to the fuel pan was charred from the floor to the hatrack. The sidewall extending outward from each side of the charred area was scorched and blistered; because of the direction of airflow, greatest damage was toward the rear of the test section (figs. 26 and 27).

3. Hatrack: The bottom side of the hatrack was slightly more blackened and scorched than that of the previous test. An area of approximately 0.74 square meter (8 square feet) above the fuel pan of the hatrack foam padding was melted and about 50 percent consumed. Again, the damage was greatest toward the back side of the test section.

4. Ceiling panels: All the ceiling panels were moderately scorched and blistered. Again, the damage to the rear half of the panels was more severe than that to the front half (fig. 29).

5. Passenger service unit: Only one PSU was included for this test. This consisted of small samples of polyarylene glued to the simulated PSU from tests 2 and 3 with 3M EC4715 adhesive. The polyarylene samples were only blackened by the fire but fell off because the adhesive failed.

6. Carpet: The Nomex carpet was not damaged except for localized charring around the fuel pan.

7. Windows: The monolithic epoxy-boroxine windows were not damaged.

Comparison with other tests.- Test 5 resulted in a much larger fire with more damage than did test 4 because of the larger ignition source. Furthermore, the test 5 fire and resulting material damage were greater than for any previous JSC tests except for test 1, which was of pre-1968 materials (ref. 1). Although the smokeless fuel resulted in a smaller fire and less damage for test 3 than for test 2 using the JP-4 fuel (both using the same materials), the greater quantity of smokeless fuel and the larger fuel pan used for test 5 exposed more materials to direct flames and thus resulted in more damage than in test 4, as well as in tests 2 and 3. Also, the metal structure of the seat above the ignition source melted sufficiently to cause the remaining portion of the seat to fall against the cabin wall. This collapse did not occur in any of the previous JSC tests and is not known to have occurred in the AIA tests (ref. 2) or the FAA tests (ref. 3). Test 5 ceiling damage was also greater than for previous JSC tests except for test 1 of pre-1968 materials and test 2 in which paper honeycomb of the ceiling panels was ignited from flames that propagated to the back side of the panels. Although there was more damage for test 5 than for the previous JSC tests of fire-resistant materials, test 5 was a more severe test because of the larger ignition source; however, there was no flash fire or propagation beyond the area of direct flame impingement in test 5.

In addition to the increased damage, the cabin temperatures of test 5 were higher than those of tests 2, 3, or 4; however, the peak temperatures occurred about 60 seconds later in test 5 than in tests 2 and 4. The cabin temperature profiles of test 5 (fig. 24) generally were similar to those of test 3 for the first 165 seconds. After this time, the test 5 temperatures increased rapidly, whereas the test 3 temperatures continued at the same rate of increase. A comparison of ceiling temperatures for tests 4 and 5 (fig. 30) shows that the ceiling temperature for test 5, which reached a maximum of about 589 K (600° F) at 210 seconds, was much higher than that for test 4, which had a maximum ceiling temperature of 450 K (350° F) at 120 seconds. In addition, the ceiling temperature of test 5 was higher than that for the FAA seat test (ref. 3) but lower than that for the AIA test (ref. 2).

Another event that had not been observed during previous JSC tests of fire-resistant materials was the direct impingement of flames on the underside of the hatrack. This impingement occurred at approximately 180 seconds, together with a rapid increase of cabin temperature (fig. 24), heat flux (fig. 11), and smoke production (fig. 7). Despite this direct flame impingement, the hatrack panels did not burn through and the facesheets did not delaminate from the honeycomb core. Before 150 seconds, the smoke production of test 5 was about the same as that of test 3 (ref. 1), which also had the smokeless fuel ignition source. A comparison of the minimum and maximum smoke-density levels for tests 4 and 5 indicates the difference in the type of fire that occurred during these two tests. The narrow smoke band for test 4 (about 10 percent after 240 seconds) that continued until the end of the test at 900 seconds indicates continuous burning and the production of smoke, which did occur. Conversely, the wide test 5 smoke band that continued to become wider from about 300 seconds (15 percent) until the end of the test at 900 seconds (35 percent) shows that the smoke production was decreasing and that the smoke was stratifying as fresh air entered the cabin. This observation indicates that the fire was decreasing rapidly after 300 seconds, as was evident from cabin temperatures. Furthermore, at about 240 seconds, the maximum smoke-density value of test 5 exceeded that of test 4, again indicating the larger fire of test 5.

Most of the measured gaseous combustion products of test 5 increased sharply between 160 seconds and 200 seconds, and the oxygen content decreased. These changes coincided with the rapid increase in cabin temperatures and smoke production as the fire intensified at this time. Except for the ethylene concentration, which never reached the level measured for test 4 (table II), and the fluoride concentration, all the concentration levels exceeded the levels of test 4 between 170 and 210 seconds. The fluoride concentration did not exceed the test 4 level until almost 240 seconds. It is significant that the production of large concentrations of combustion products for test 5 occurred later in the test than for test 4 (figs. 10 and 17 to 23). Most of the combustion products in test 4 increased to significant levels in 60 seconds or less, whereas most of the product concentrations in test 5 did not begin to rise appreciably until about 180 seconds after ignition. (It can be deduced from figure 20 that the JP-4 fuel contributed significantly to the early production of hydrogen cyanide, i.e., in tests 2 and 4.) As a result, although most of the maximum concentrations were greater in test 5, most of the product concentrations in test 4 were greater during the first 180 seconds. A similar delay was measured for the cabin temperatures of tests 4 and 5, as previously discussed. The levels of combustion products for test 5 were significantly less than those reported for the AIA test on comparable materials (ref. 2). The levels for test 4 also were less than for the AIA test. (These values may not be directly comparable because of differences in analytical techniques.) An exception was the test 5 maximum cyanide level, which was twice as high as values for the AIA test. This concentration was caused by the larger ignition source that caused more thermal decomposition of the polyurethane seat-cushion foam, which is a known producer of hydrogen cyanide. Trace combustion products that were detected but not quantified are listed in table III.

Because identical materials were used in tests 4 and 5 (except for the difference in seat cushions indicated in table I), the differences in visibility resulted partly from the additional smoke produced by the JP-4 fuel, as also shown by previous JSC tests 2 and 3 (ref. 1). Although previous JSC tests showed that the smokeless fuel resulted in a smaller fire and less damage than did the JP-4, test 5 resulted in a much larger fire with more material damage and production of more toxic combustion products than did test 4. As briefly mentioned earlier, this anomaly resulted from the larger fuel pan used (38 by 38 centimeters (15 by 15 inches)) compared to 30.5 by 30.5 centimeters (12 by 12 inches)) and from the greater quantity of the acetone/methanol smokeless fuel used to compensate for the lower heating value of the smokeless fuel compared to JP-4.

The results of tests 4 and 5 showed that not only did the type and quantity of ignition fuel influence the results of the tests because of differences in amounts of thermal input and smoke production, but the area of the fuel pan also affected the results.

CONCLUDING REMARKS

Two additional full-scale aircraft flammability tests were performed to evaluate the effectiveness of new fire-resistant materials by comparing their burning characteristics with those of other aircraft materials. In test 4, newer fire-resistant materials were tested to determine the benefits or disadvantages of these materials compared with those tested in JSC tests 2 and 3. This test resulted in fire propagation, fire damage, cabin temperatures, radiant heat flux, and toxic gas production similiar to but, in most cases, less than those reported for test 2. Smoke production for test 4 was almost identical to that for test 2. As did the materials used for tests 2 and 3, the fire-resistant materials of test 4 burned or decomposed only while exposed to the fuel ignition source and did not propagate the fire significant distances from the ignition source. Although test 4 was allowed to continue for 900 seconds and test 2 was terminated after 280 seconds, both tests resulted in about the same amount of material damage, a possible indication of a slower decomposition and propagation rate for the test 4 materials.

In test 5, the JP-4 aircraft fuel ignition source was replaced with a larger quantity of a smokeless fuel (acetone/methanol) in a larger fuel pan. The result was a larger fire and more material damage than experienced during any previous JSC tests of new fire-resistant materials (tests 2 to 4). One result of this test that had not occurred in previous tests was melting of the metal seat structure above the ignition source sufficient to cause the remaining portion of the seat to fall against the cabin wall. Another event not previously observed was the direct impingement of flames on the bottom of the hatrack. Despite this direct flame impingement, the hatrack panels did not burn through and the facesheets did not delaminate from the honeycomb core. The results of test 5 again documented the significance of the smoke produced by the JP-4 aircraft fuel in reducing cabin visibility (as did JSC test 3); more importantly, test 5 experience showed that changing more than one test parameter can produce unexpected results. Of major consequence was the use of a larger fuel pan, which exposed more materials to direct flames, and probably accounted for the larger fire and greater damage. Nevertheless, the results of test 5, which was a more severe test than any previous JSC test, showed that the fire-resistant materials tested will not propagate flames under severe fire conditions. In addition, analysis indicates that no flash fire occurred at any time during the test. Test 5 (and test 3) also demonstrated that the JP-4 fuel was primarily responsible for the early high levels (250 p/m) of hydrogen cyanide; when this fuel was not used, 250 p/m was not exceeded for more than 180 seconds.

The new materials still produced undesirable gaseous products of decomposition as most organic materials will; however, because the area affected was limited to the ignition source region (rather than propagating), the quantities of such gases (except for hydrogen cyanide) were reduced when compared to tests involving more flammable materials.

Although the results of test 4 were similar to those of test 2 and the results of test 5 showed more severe damage than that observed following any previous JSC tests of new fire-resistant materials, the materials of tests 4 and 5 still represent an advancement in fire-resistant materials technology. Unlike many of the test 2 and 3 materials, which were too costly, were not durable, and were not esthetically acceptable, the fire-resistant materials of tests 4 and 5 generally are economically feasible and meet the end-use requirements of the aviation industry.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, April 9, 1976
501-38-19-31-72

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2. Fire Suppression, and Smoke and Fume Protection. Rep. AIA CDP-2 (restricted distribution), Aerospace Industries Association of America, Inc. (Washington, D.C.), July 1968.

3. Marcy, John F.: Air Transport Cabin Mockup Fire Experiments. Rep. FAA-RD-70-81, Federal Aviation Administration, Dec. 1970.

4. Haynes, B. S.; Iverach, D.; and Kirov, N. Y.: The Behavior of Nitrogen Species in Fuel Rich Hydrocarbon Flames. Proceeding of the Fifteenth Symposium on Combustion, The Combustion Institute (Pittsburgh, Pa.), 1974, pp. 1103-1112.

TABLE I.- FIRE-RESISTANT MATERIALS USED IN TESTS 4 AND 5

Part descriptions	Materials used
Ceiling panels	PX resin on Nomex or fiberglass honeycomb with skins of PX resin on fiberglass, and a decorative layer of white Kel-F 2401D on fiberglass applied to honeycomb panels with 3M EC4715 adhesive
Dado (lower wall) panels	Light-blue Kel-F 2401B on nylon, applied to aluminum sheet with 3M EC4715 adhesive
Window panels	Kynar decorative laminate, applied to aluminum panel with 3M EC4715 adhesive
Windows	Epoxy-boroxine (developed by the NASA Ames Research Center)
Upper wall panels	White Kel-F 2401D on figerglass, applied to aluminum sheet with 3M EC4715 adhesive
Window shades	White Kel-F 2401D on fiberglass
Floor covering	Nomex pile carpet and pad of Mobay resilient foam 115014-6 treated with ammonium dihydrogen phospate (ADP) and coated with Fluorel L-3203-6
Hatrack	Paper-core/aluminum-edged fiberglass sandwich (original Boeing 737 part), underside a mixture of treated Scott high-resilient foam and treated Mobay resilient foam 115014-6, covered by fiberglass coated with Kel-F 2401D
Passenger service unit	Polyarylene (Stilan) attached to the simulated unit used for tests 2 and 3 with 3M EC4715 adhesive and coated with white-pigmented Kel-F PX 703.
Seats:	
Cushions	Mobay resilient foam 115014-6 treated with ADP and coated with Fluorel L-3203-6 (The seat-back padding for test 5 was treated Scott high-resilient foam.)
Ticking	Modacrylic/polyester Weftamatic fabric, style 6186
Upholstery fabric	100 percent Nomex, Anchorage II blue 69/1211
Armrests	Blue Kel-F 2401B on nylon
Seatbelt	Nomex S/WNX 1856
Seat tray	Polyarylene (Stilan)
Headrest cover	Fire-retardant nonwoven cellulosic S/AMK 770

TABLE II.- CONCENTRATIONS OF OXYGEN AND GASEOUS COMBUSTION PRODUCTS

Oxygen and products of combustion	Test 1	Test 2	Test 3	Test 4	Test 5
Minimum concentration					
Oxygen, percent	4.1	15.5	17.8	17.0	16.6
Maximum concentration					
Carbon dioxide, percent	9.2	2.4	1.5	0.40	0.42
Carbon monoxide, p/m	3360	623	407	368	684
Methane, p/m	15 480	395	147	252	363
Ethylene, p/m	3260	232	54	234	167
Chloride (as hydrogen chloride), p/m	[1]275	[2]432	[2]225	30	89
Fluoride (as carbonyl fluoride), p/m	[1] [2] [3]57	[2]29	[2]26	35	141
Cyanide (as hydrogen cyanide), p/m	[1]1000	796	324	974	2040
Bromide (as hydrogen bromide), p/m	(4)	(4)	(4)	4	42

[1] Data from similar AIA test of pre-1968 materials.
[2] Converted from concentration per unit mass to concentration per unit volume.
[3] Converted from hydrogen fluoride.
[4] Not determined.

TABLE III.- ADDITIONAL PRODUCTS OF COMBUSTION

Combustion products	Test 1 [1]	Test 2	Test 3	Test 4	Test 5
Acetaldehyde					X
Acetone		X	X	X	X
Benzaldehyde				X	
Benzene	X	X	X	X	X
Benzofuran				X	
1,3-butadiene		X			
2-butanone		X			X
1-butene or 2-butane		X	X		
Carbonyl sulfide		X	X		
Chlorotrifluoroethylene		X			
Ethane	X	X	X		
2-ethoxyethylacetate					X
Ethyl benzene				X	X
Ethyl bromide				X	X
Ethyl chloride					X
Ethylene dichloride					X
Freon 11		X			
Freon 21		X			X
Freon 113		X		X	X
Hexafluoropropene		X			
Isopropylbenzene				X	
Methanol			[2]X		[2]X
Methyl acetate					X
Methyl bromide				X	X
Methyl chloride	X				
Methylcyclopentane				X	
Methyl methacrylate					X
4-methyl-2-pentanone					X
Monohydrogenated fluorocarbon				X	X
Naphthalene				X	
Phenyl chloride					
Phenyl cyanide				X	X
3-phenyl-1-propene				X	
Propanol					X
Propane	X				
Propene		X	X		
Propylene dichloride		X			
Styrene				X	X
Tetrafluoroethylene		X			
Toluene	X	X		X	X
Trifluoroethylene		X			
Trimethylbenzene				X	
Vinyl chloride	X				
m-xylene				X	X
o-xylene				X	X
p-xylene				X	X

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[1] Many additional compounds that may have been present in test 1 were not detected because of the sensitivity limitations of the analytical techniques used for this test.

[2] A fuel mixture of acetone and methanol was used in tests 3 and 5.

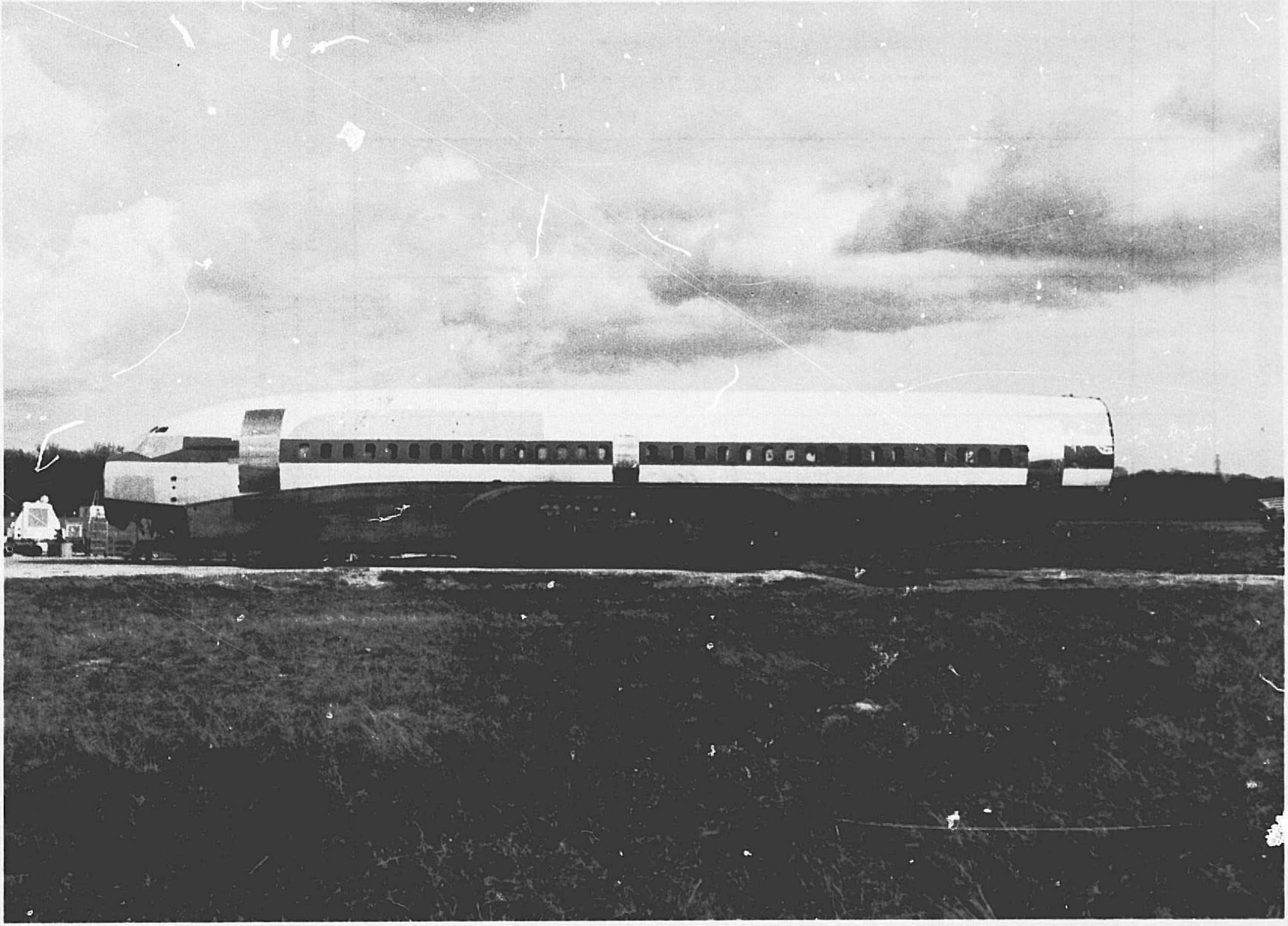

Figure 1.- Boeing 737 test fuselage.

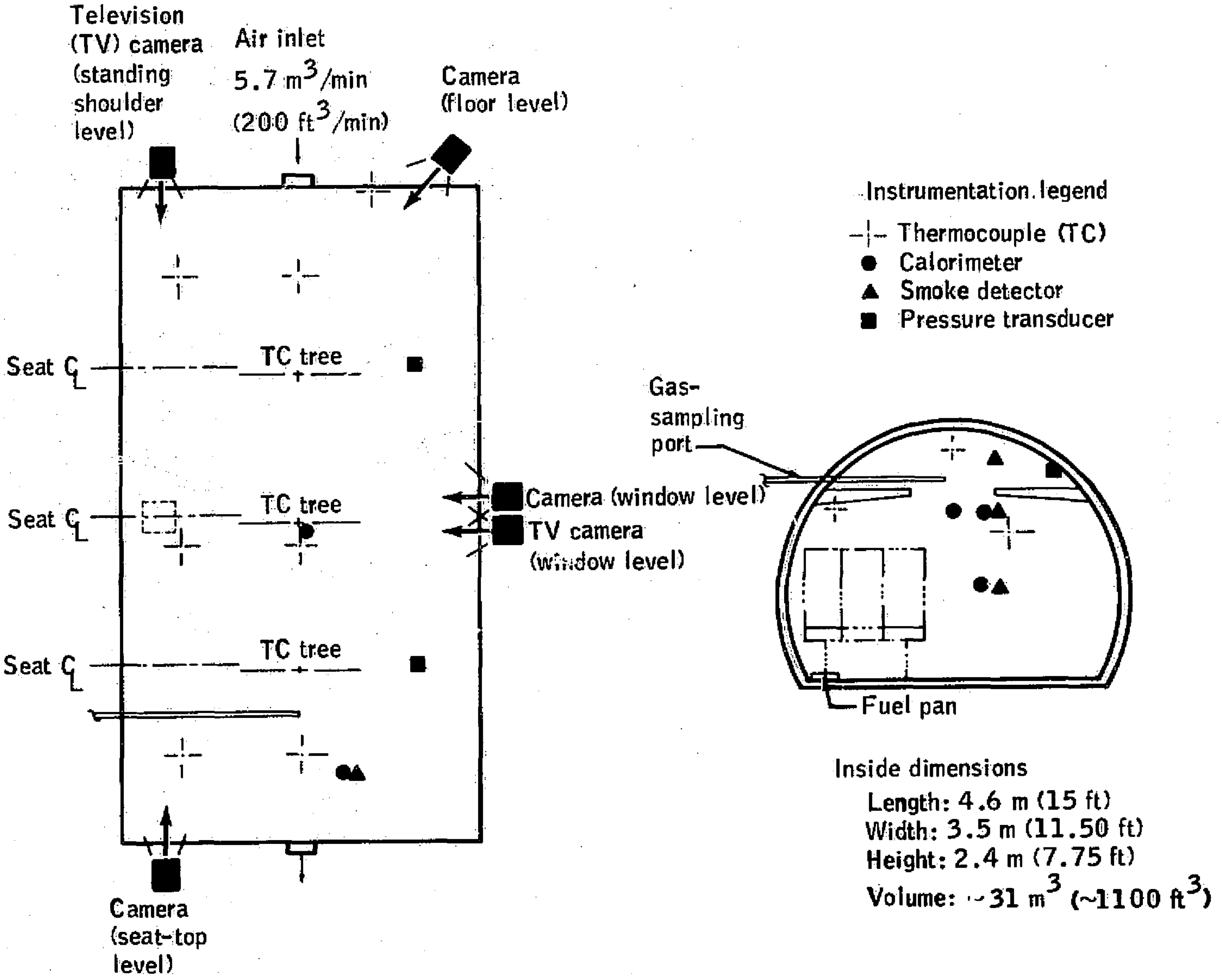

Figure 2.- Test setup and instrumentation locations.

Figure 3.- Test configuration for test 4 using new materials B, side view.

Figure 4.- Test configuration for test 4 using new materials B, front view.

Figure 5.- Test configuration for test 5 using new materials B, side view.

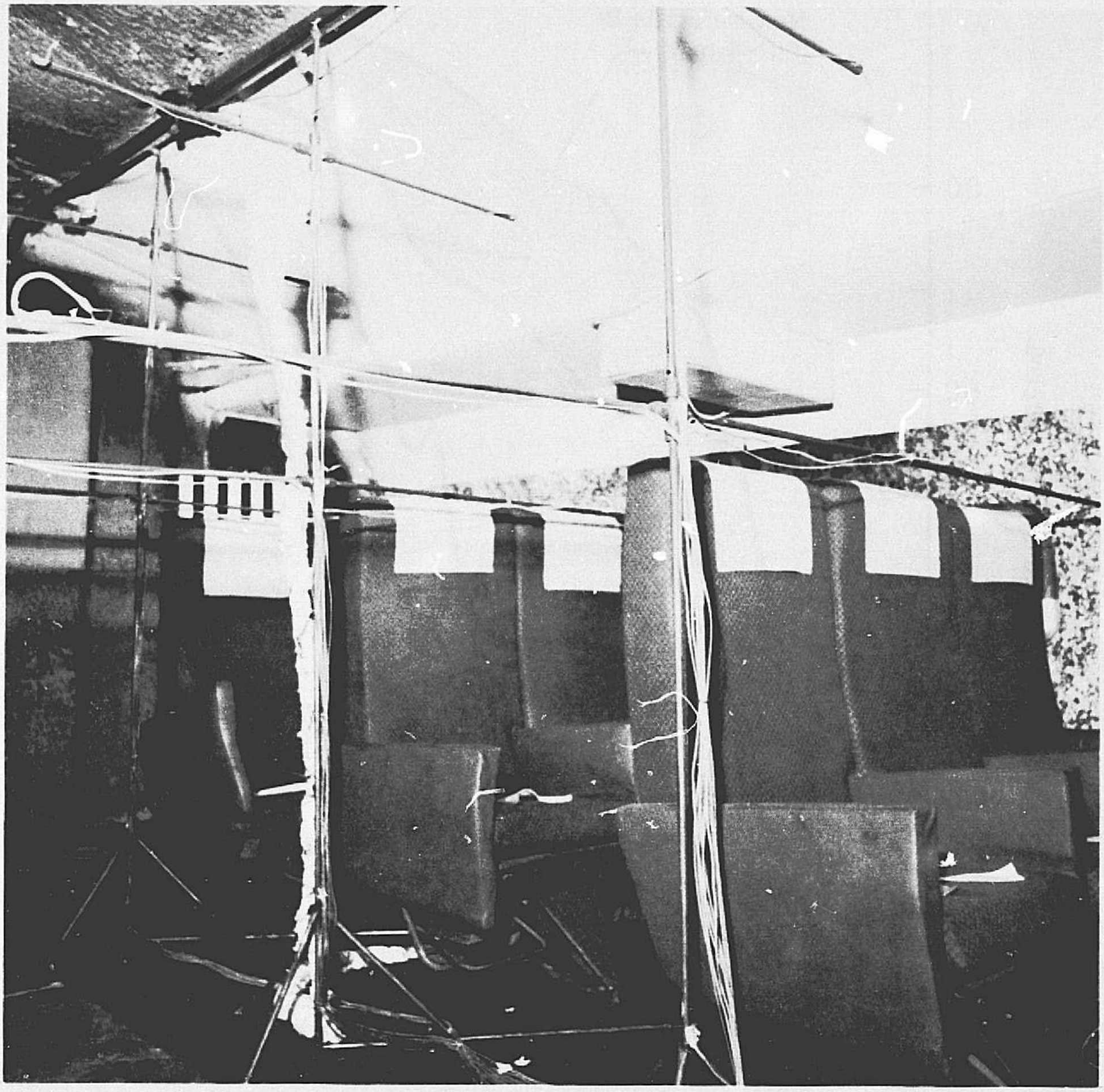

Figure 6.- Test configuration for test 5 using new materials B, front view.

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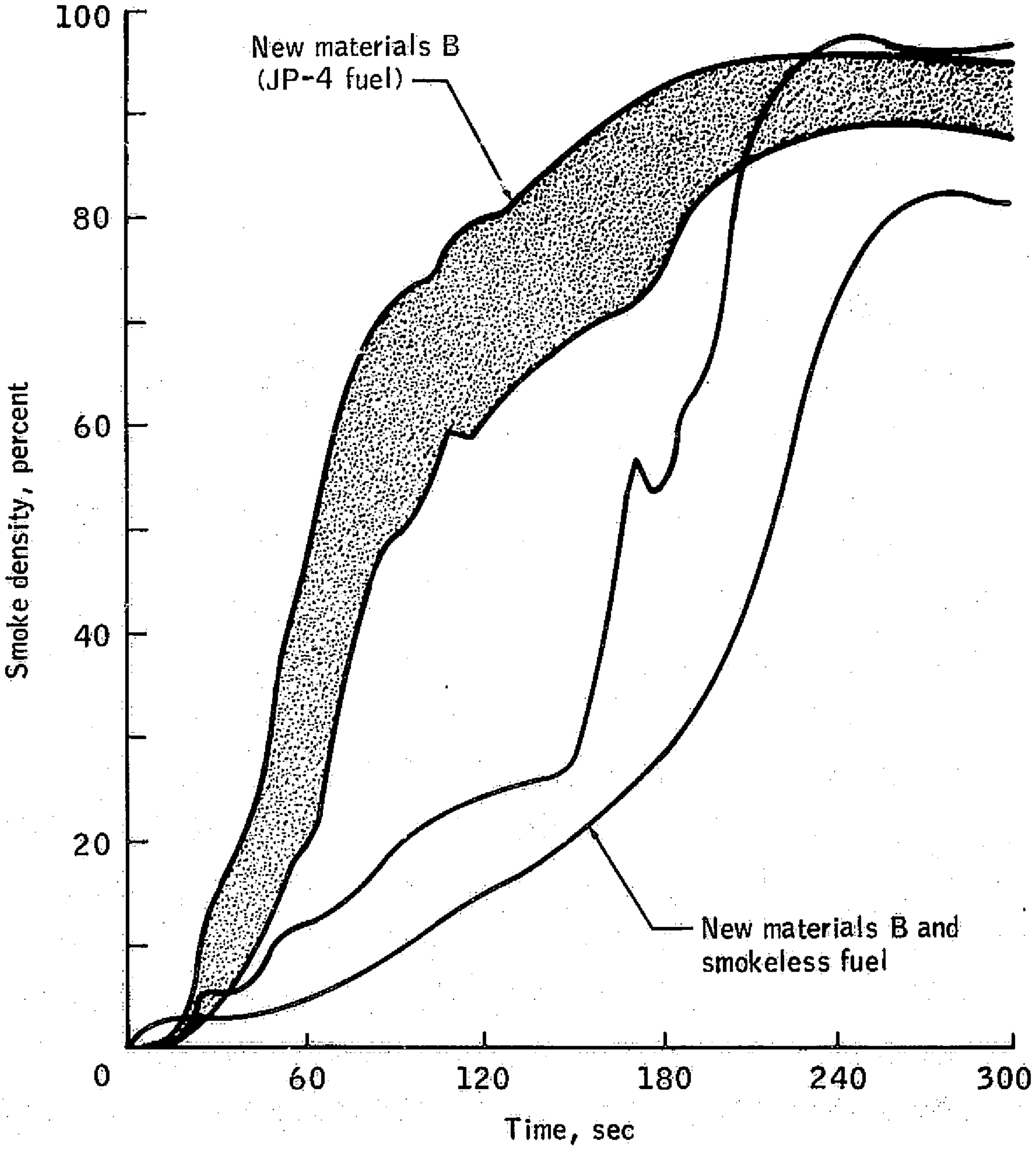

Figure 7.- Minimum and maximum smoke-density levels.

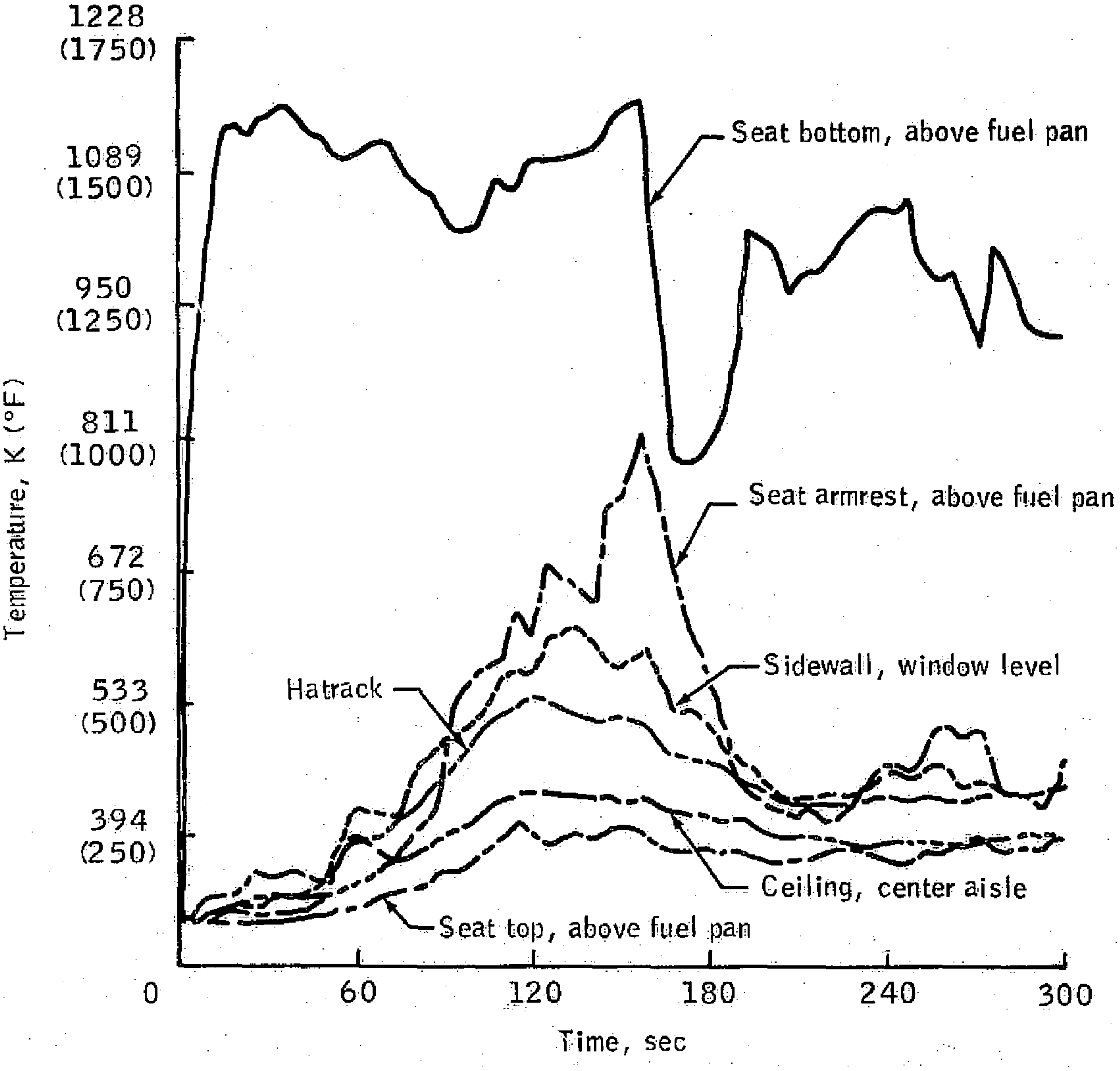

Figure 8.- Temperatures at center of test section, new materials B.

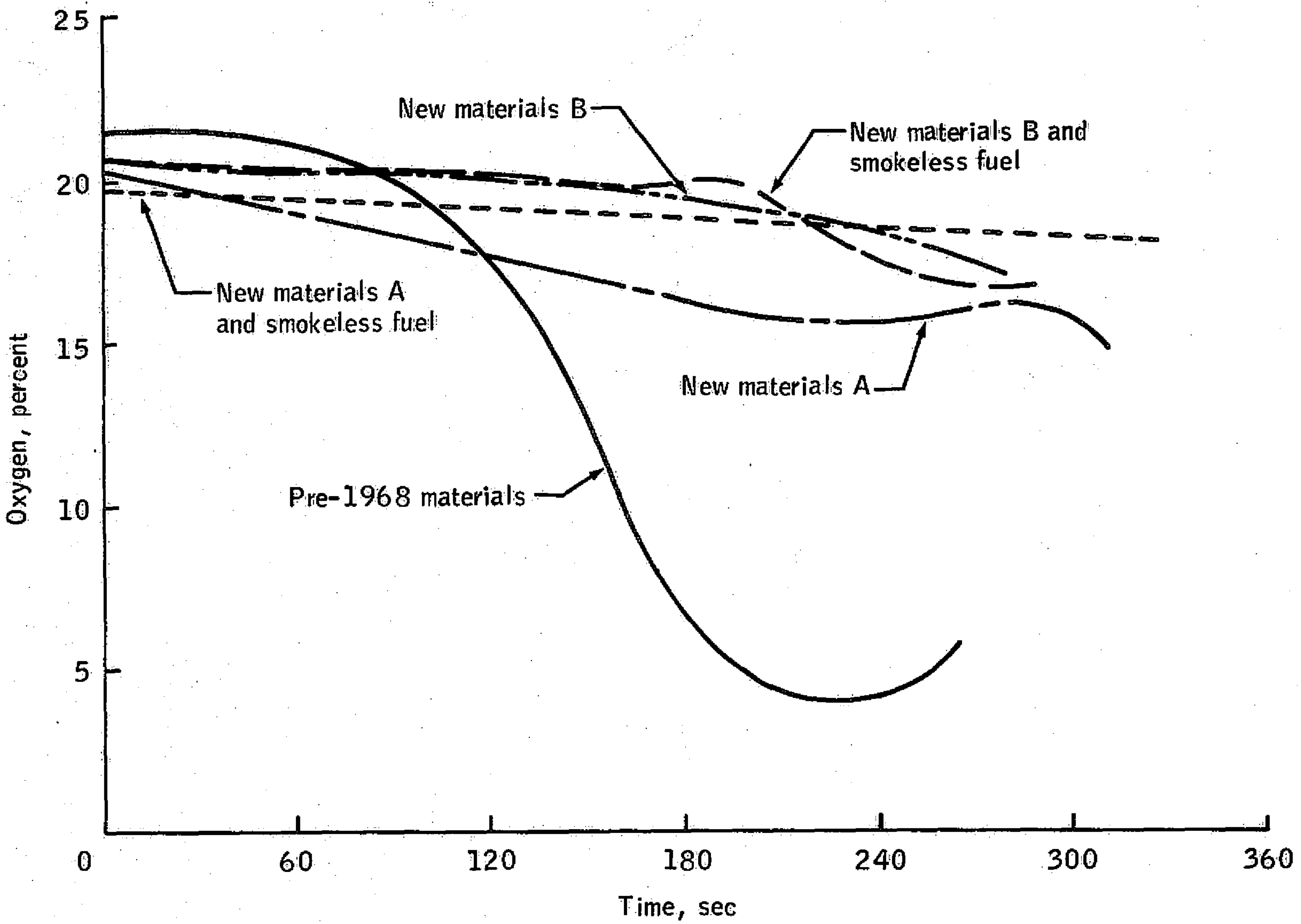

Figure 9.- Oxygen concentration.

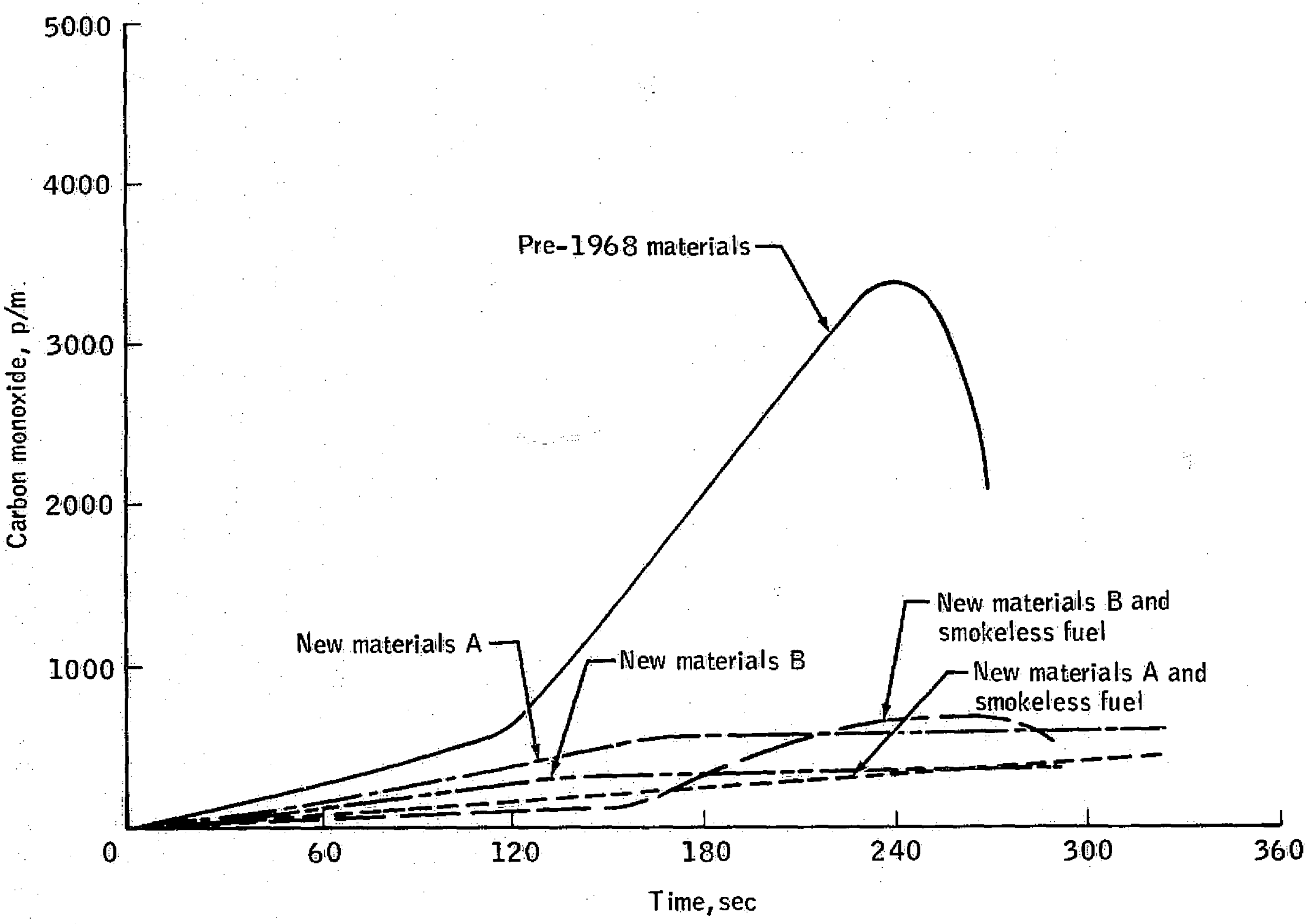

Figure 10.- Carbon monoxide concentration.

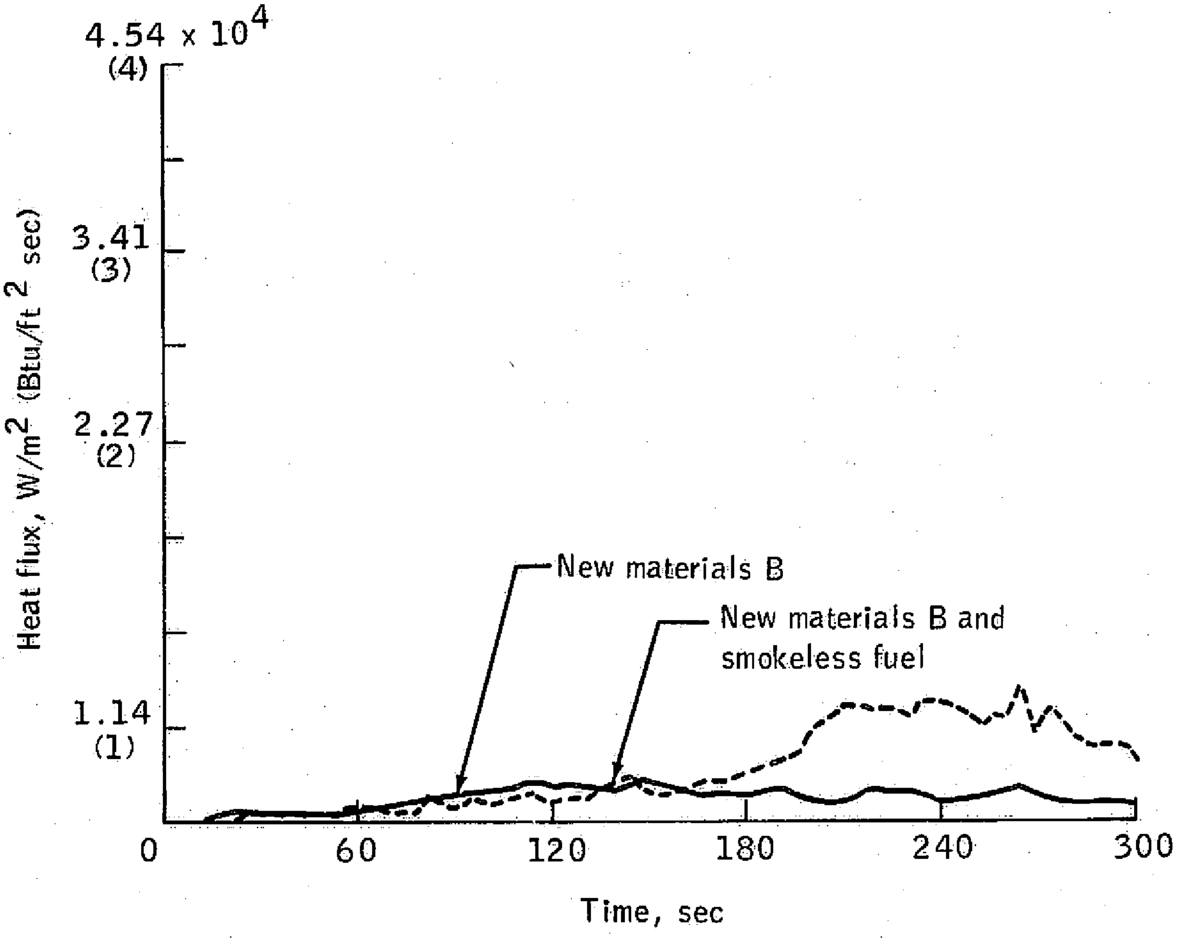

Figure 11.- Heat flux at center of test section, center aisle.

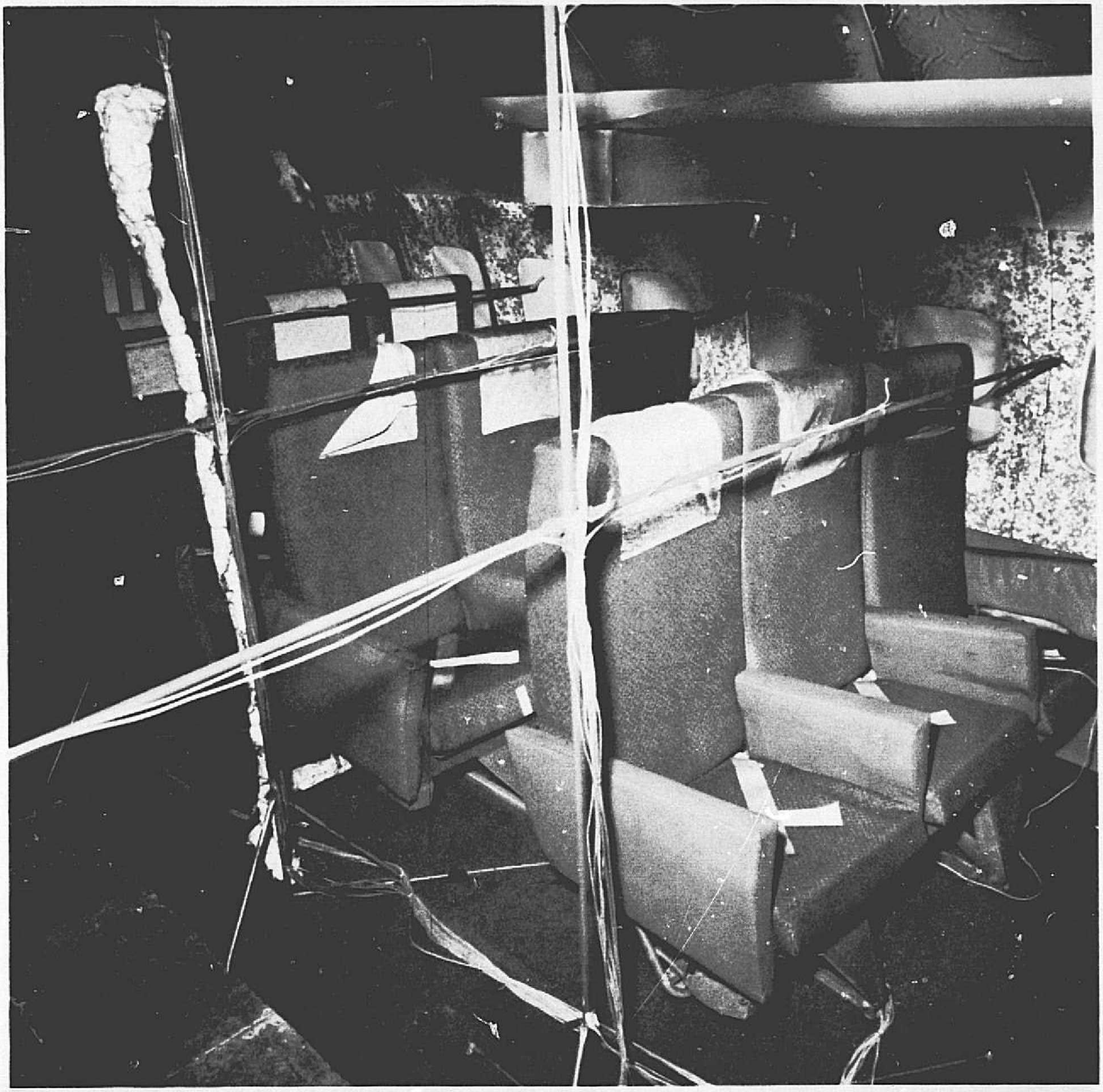

Figure 12.- Fire damage for test 4 using new materials B, front view.

Figure 13.- Sidewall and back of seat fire damage for test 4, using new materials B.

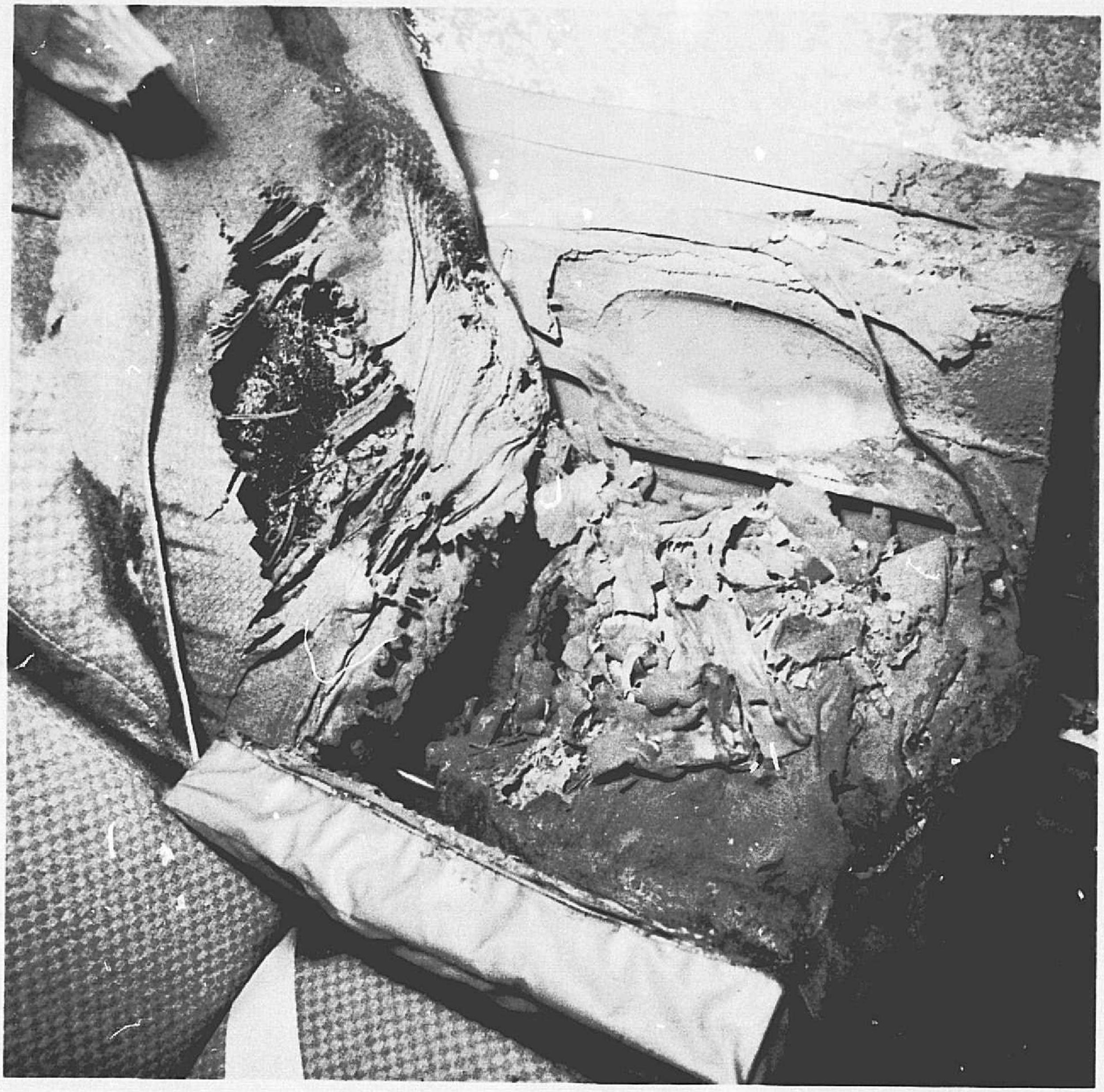

Figure 14.- Seat fire damage for test 4 using new materials B.

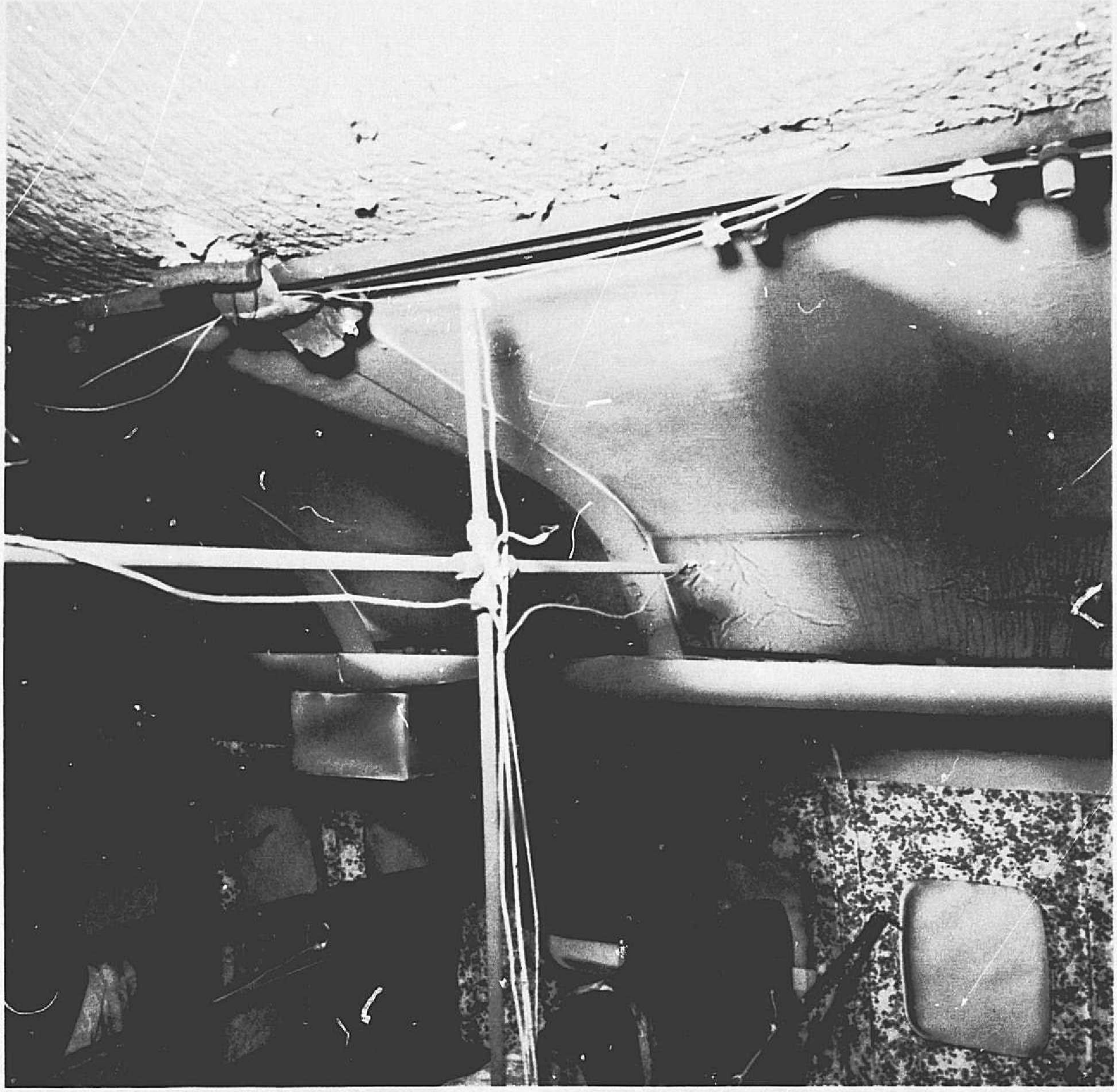

Figure 15.- Ceiling fire damage for test 4 using new materials B.

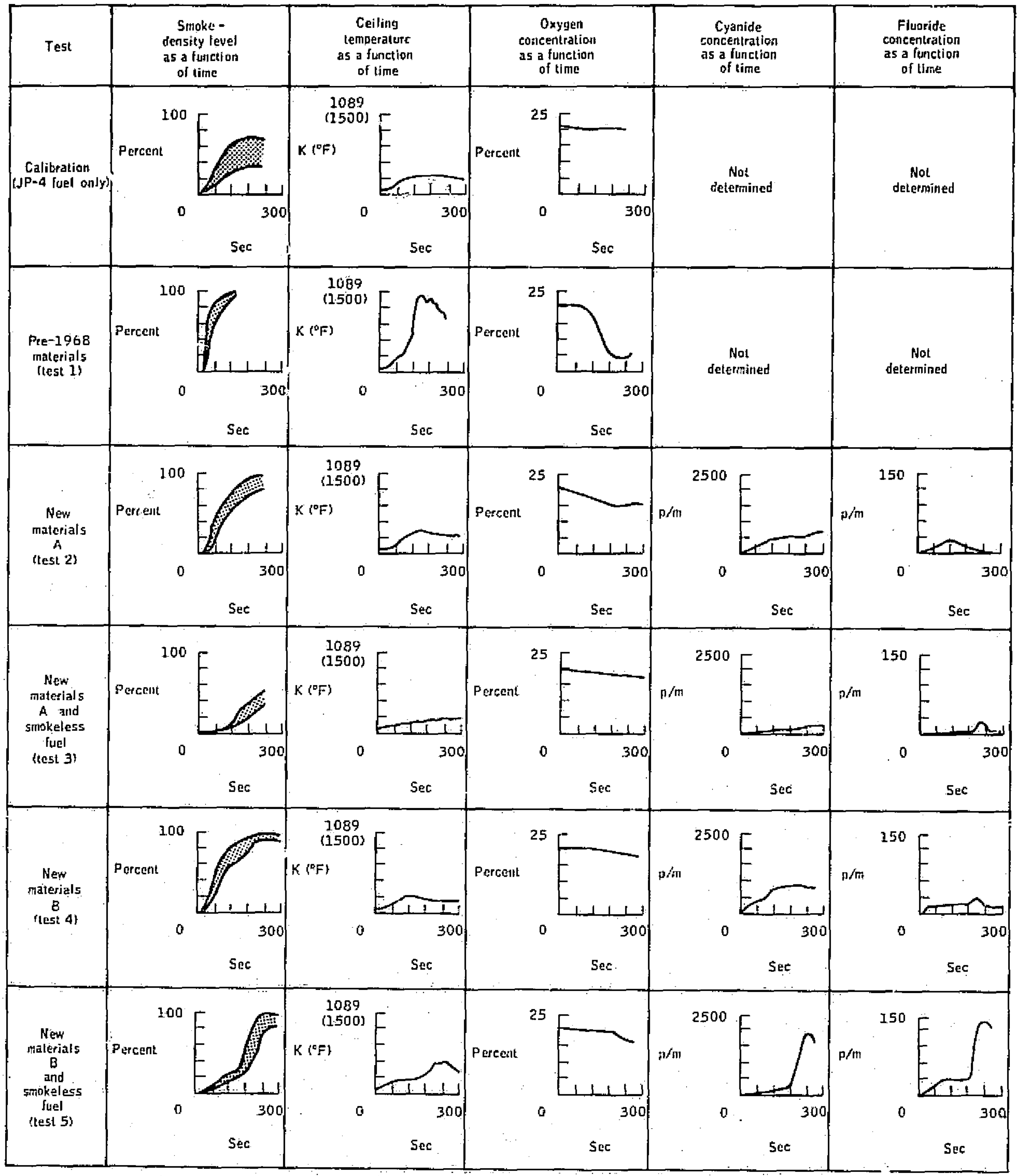

Figure 16.- Comparison of selected results of JSC tests.

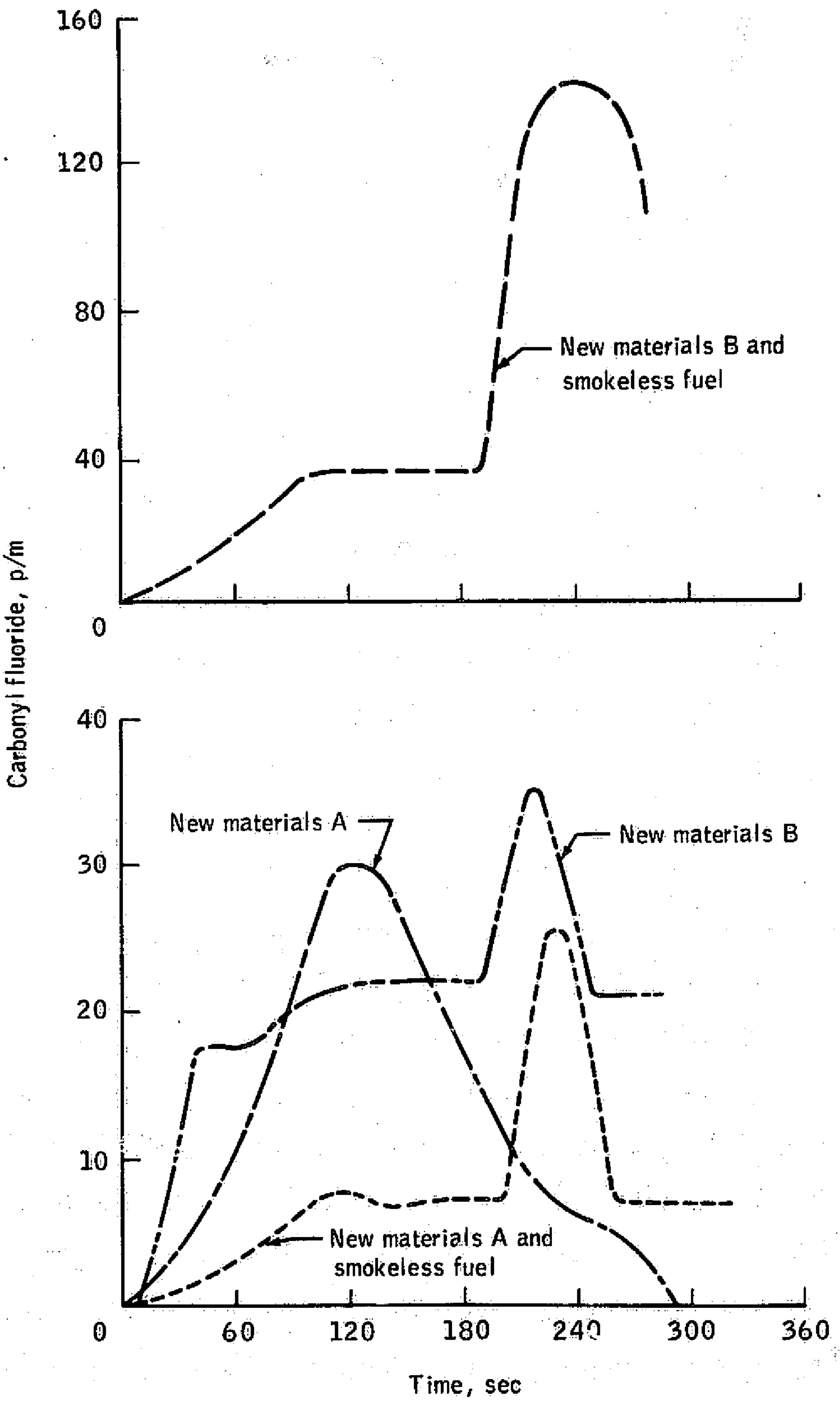

Figure 17.- Fluoride (as carbonyl fluoride) concentration.

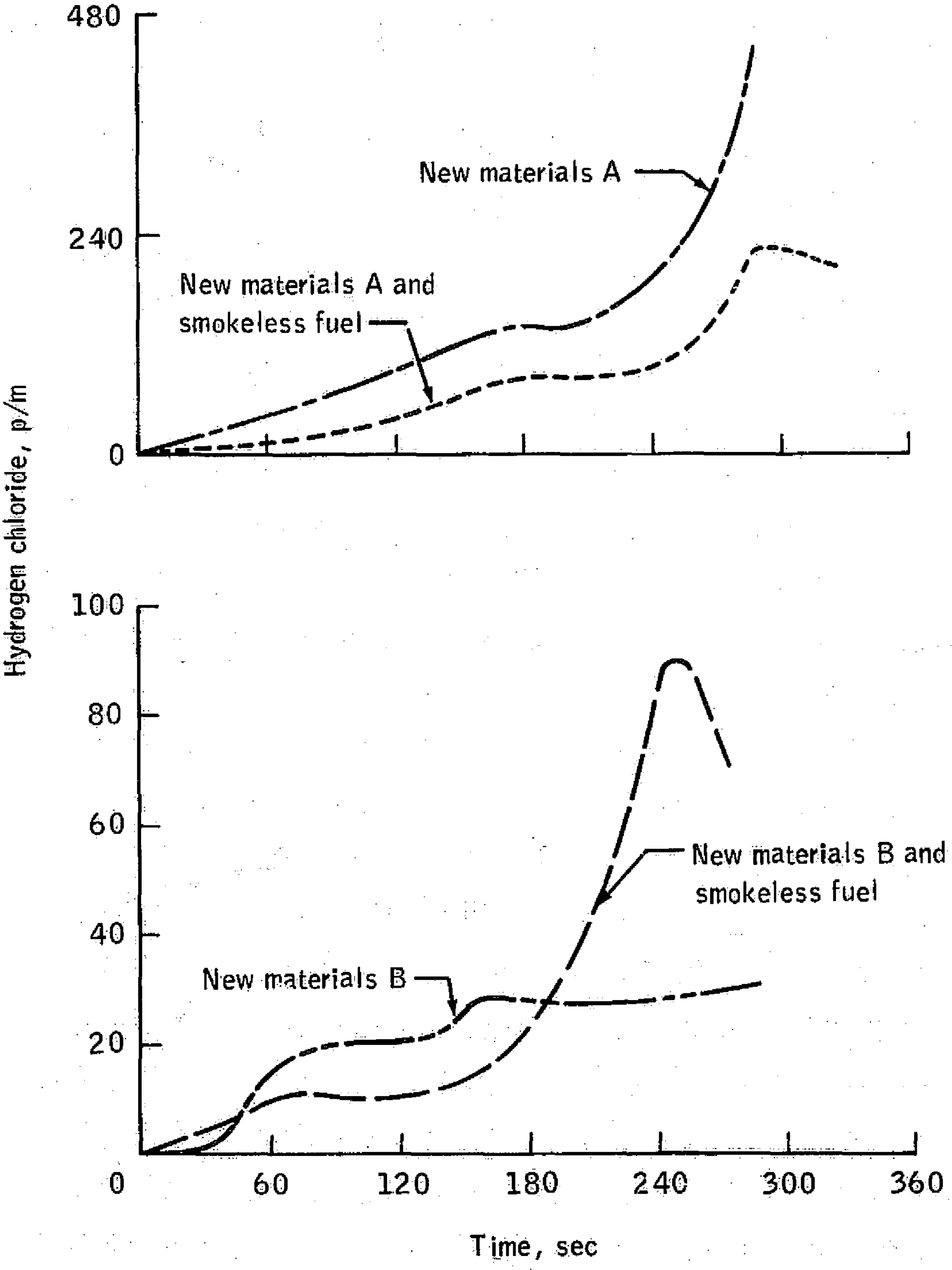

Figure 18.- Chloride (as hydrogen chloride) concentration.

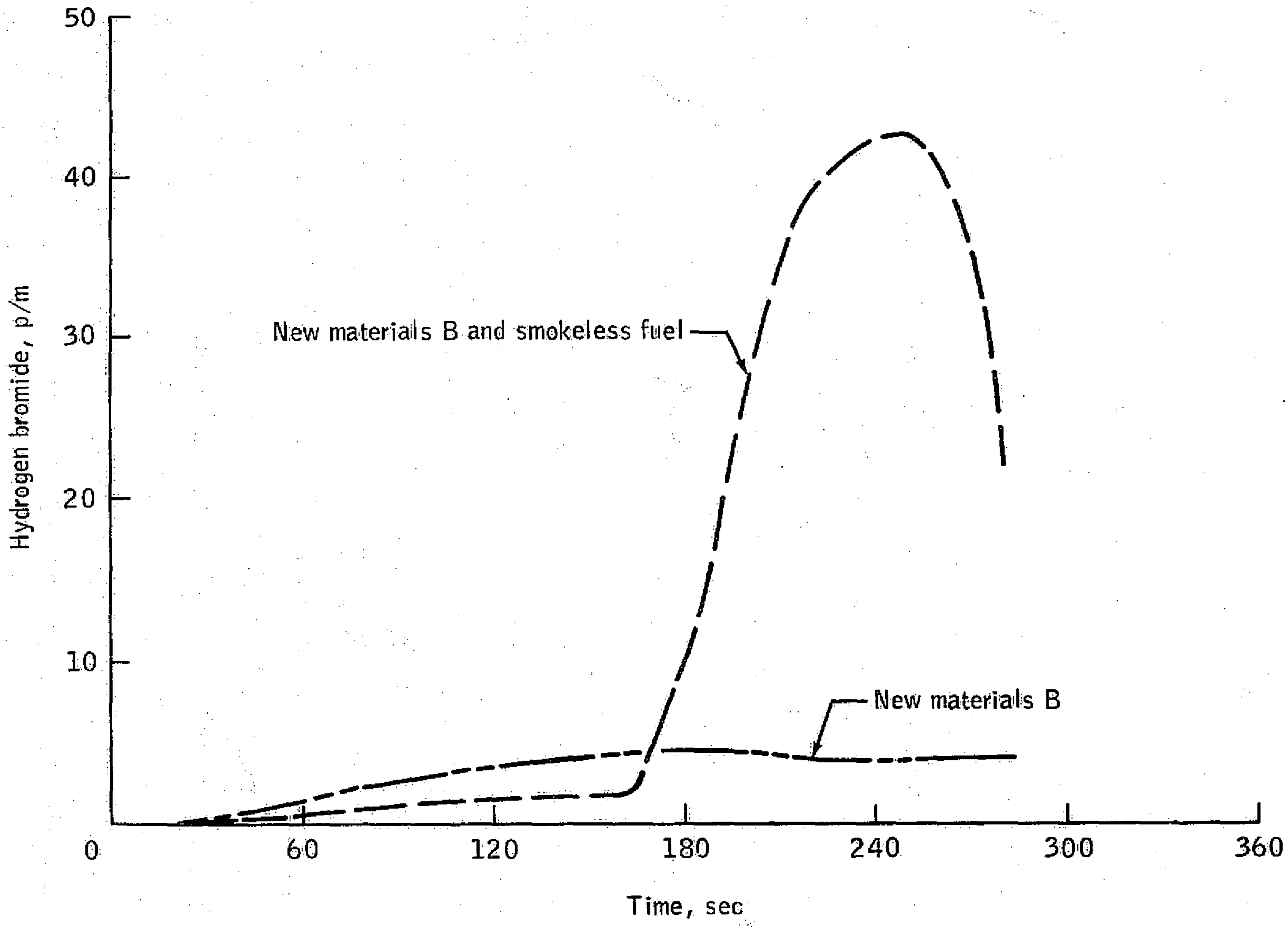

Figure 19.- Bromide (as hydrogen bromide) concentration.

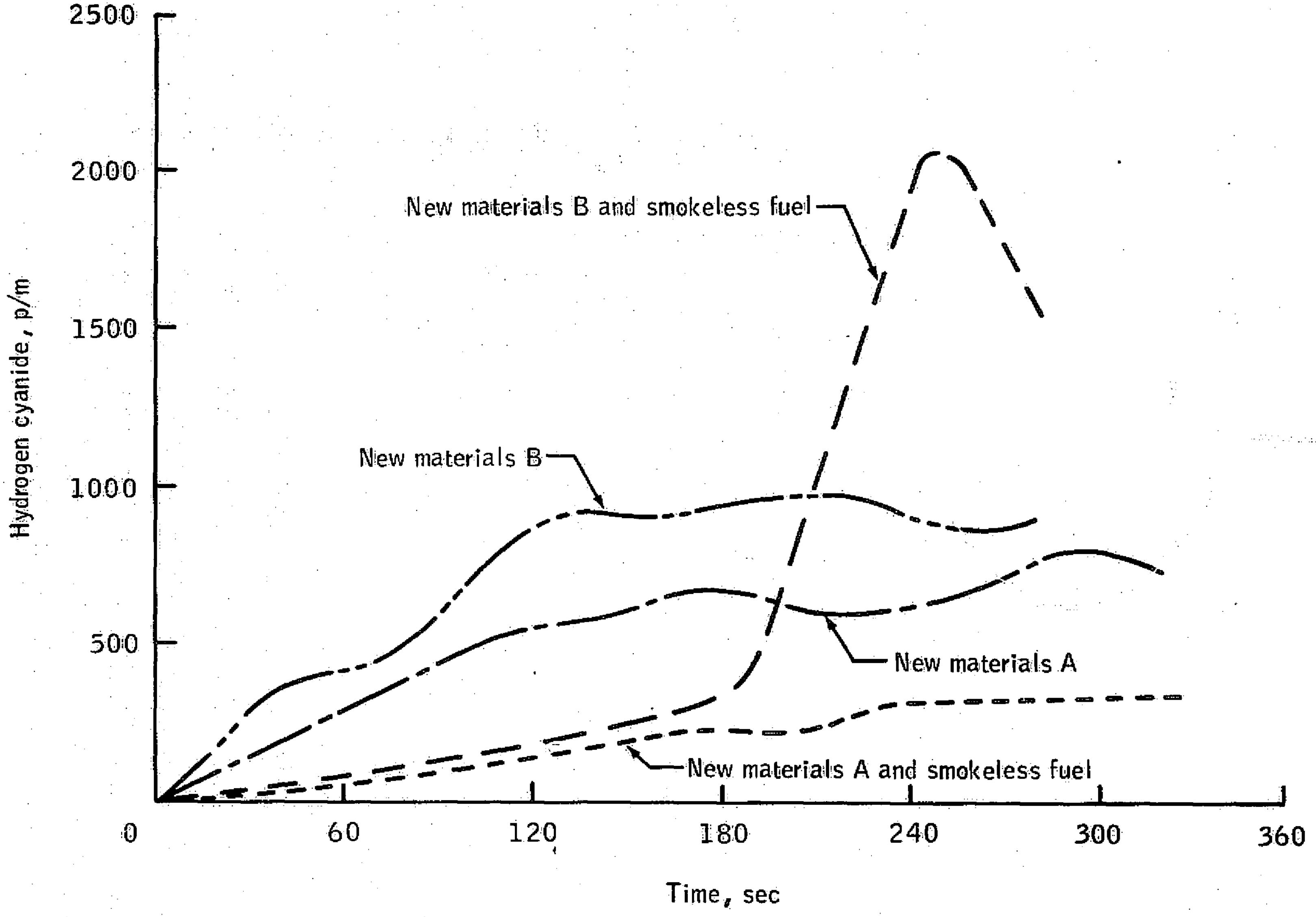

Figure 20.- Cyanide (as hydrogen cyanide) concentration.

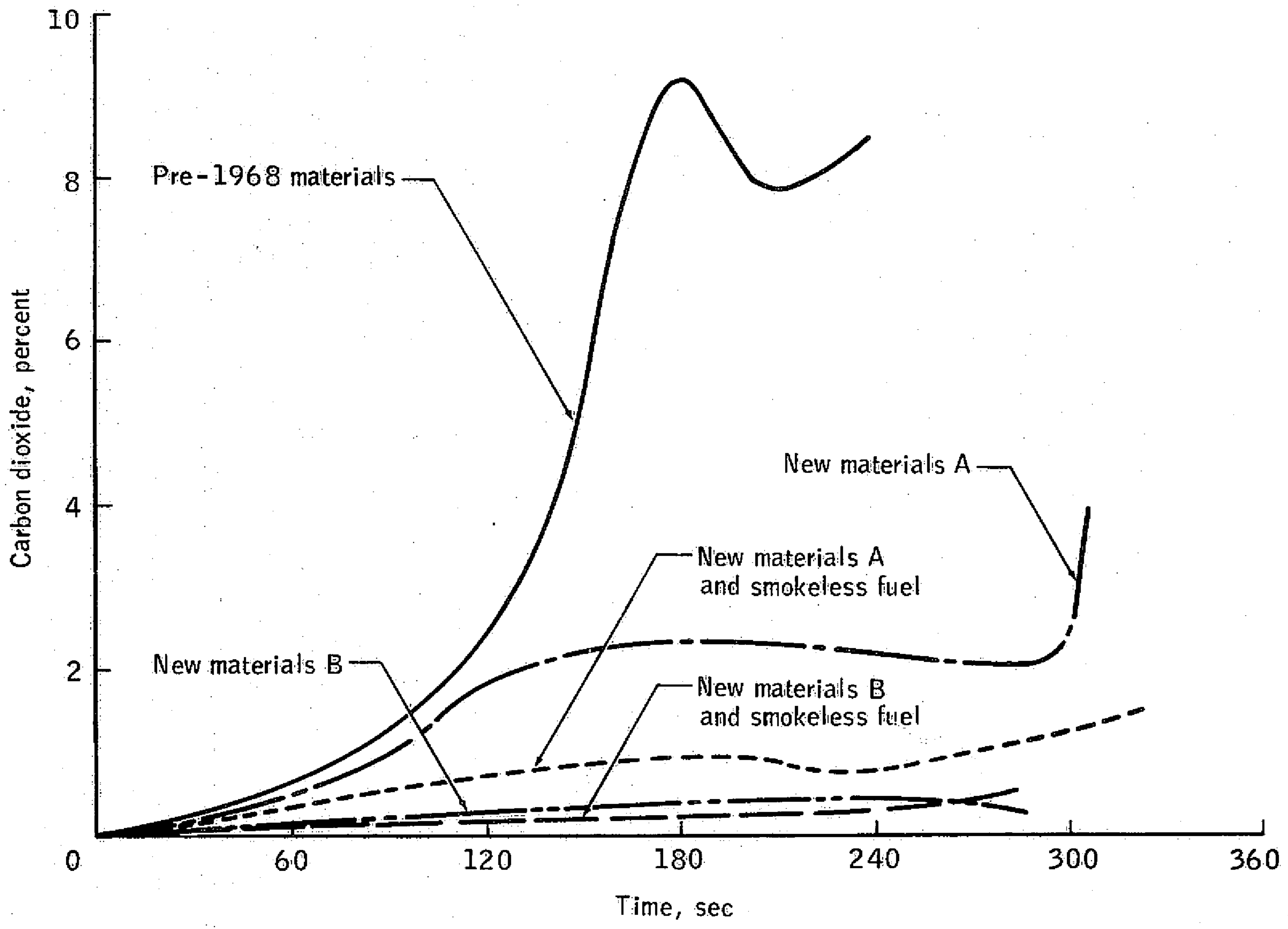

Figure 21.- Carbon dioxide concentration.

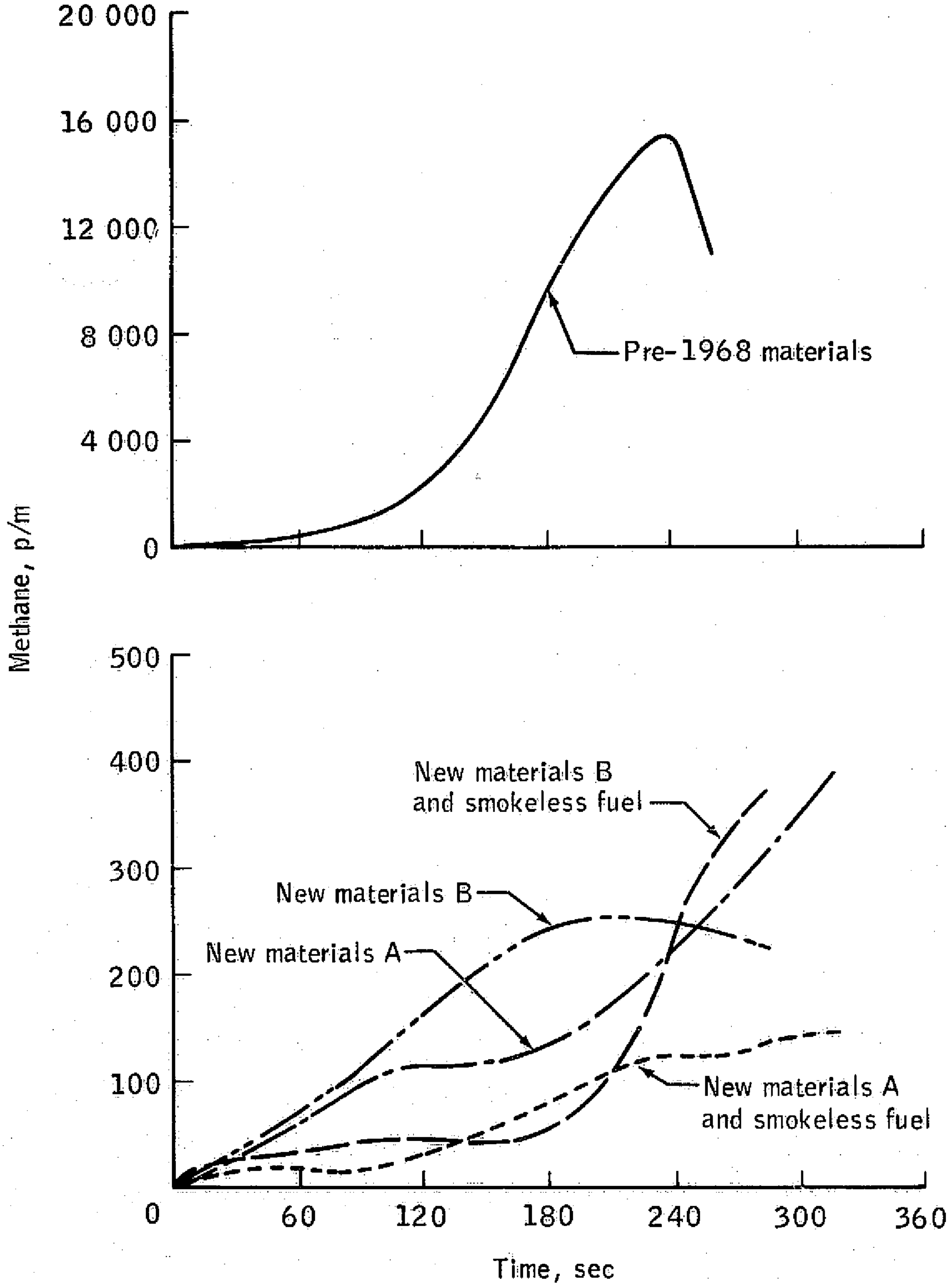

Figure 22.- Methane concentration.

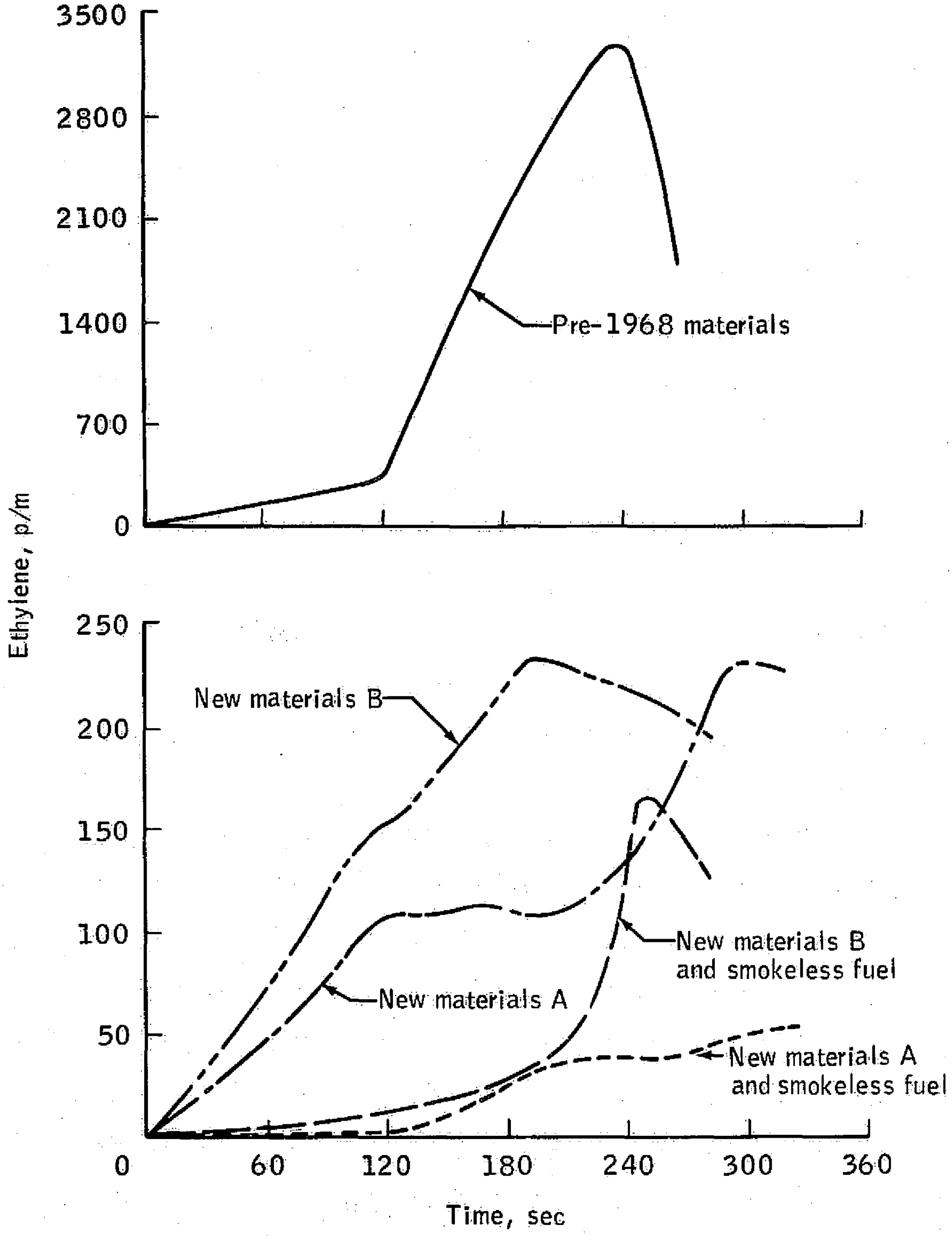

Figure 23.- Ethylene concentration.

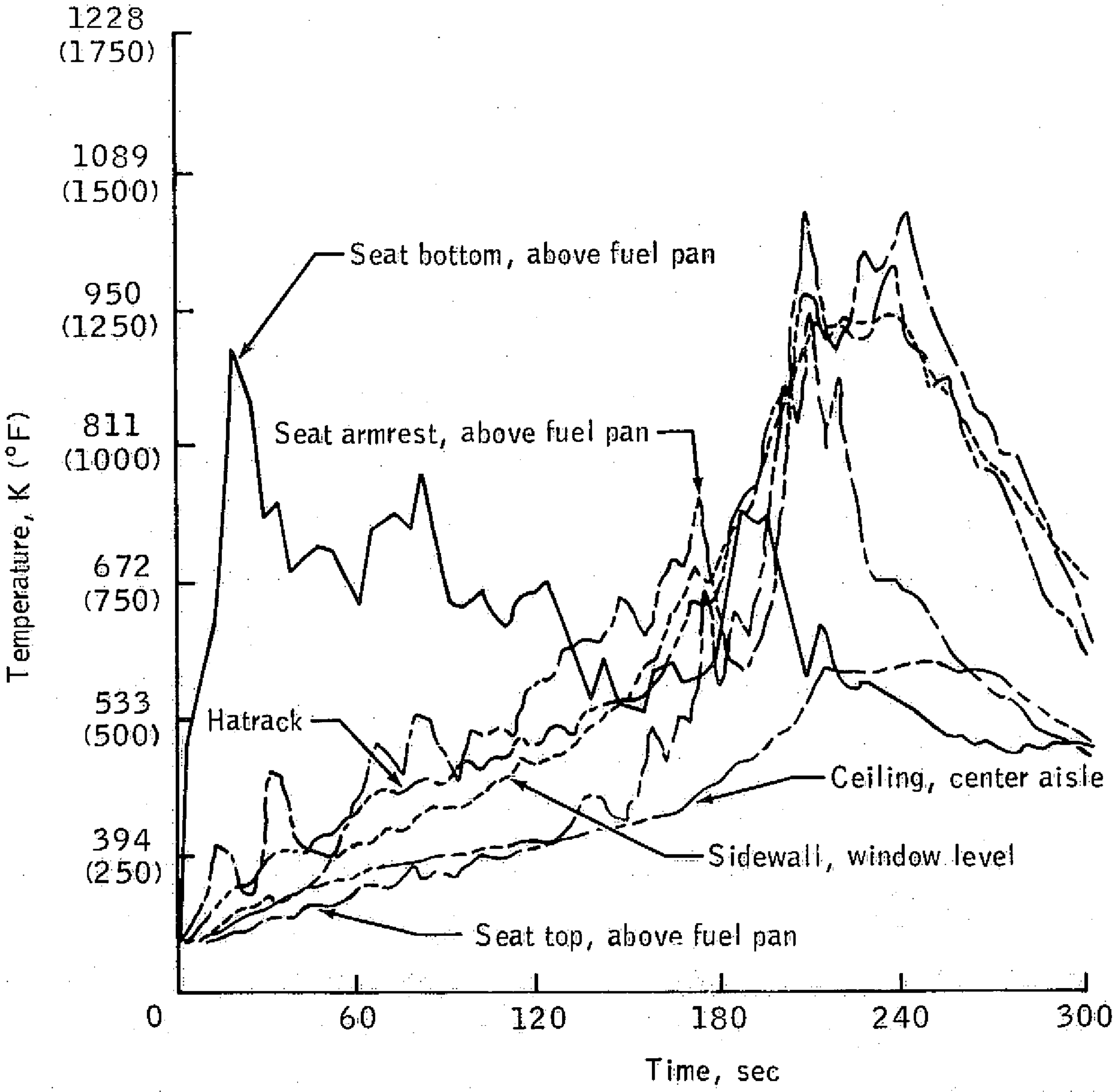

Figure 24.- Temperatures at center of test section, new materials B and smokeless fuel.

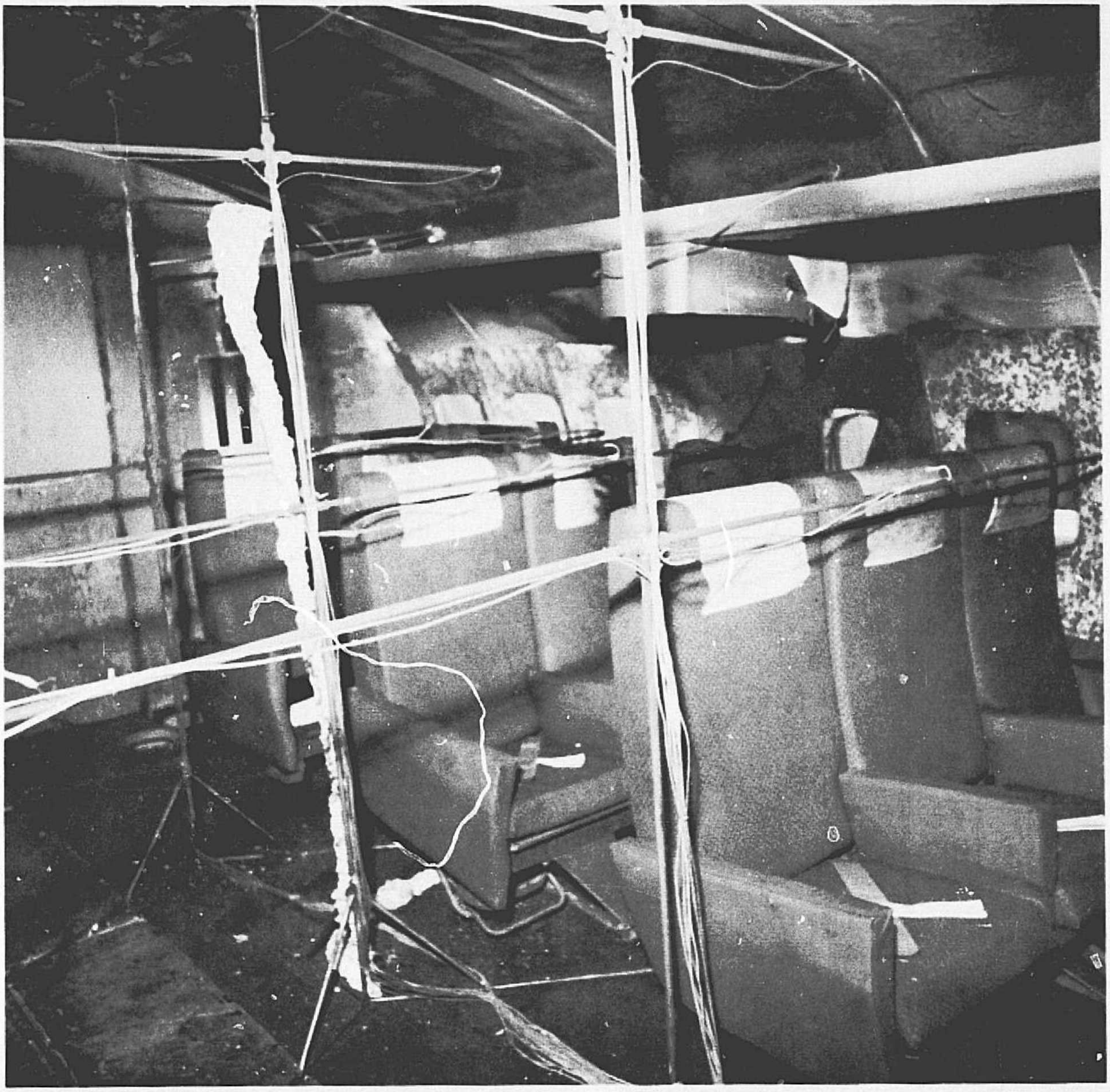

Figure 25.- Fire damage for test 5 using new materials B, front view.

Figure 26.- Fire damage for test 5 using new materials B, side view.

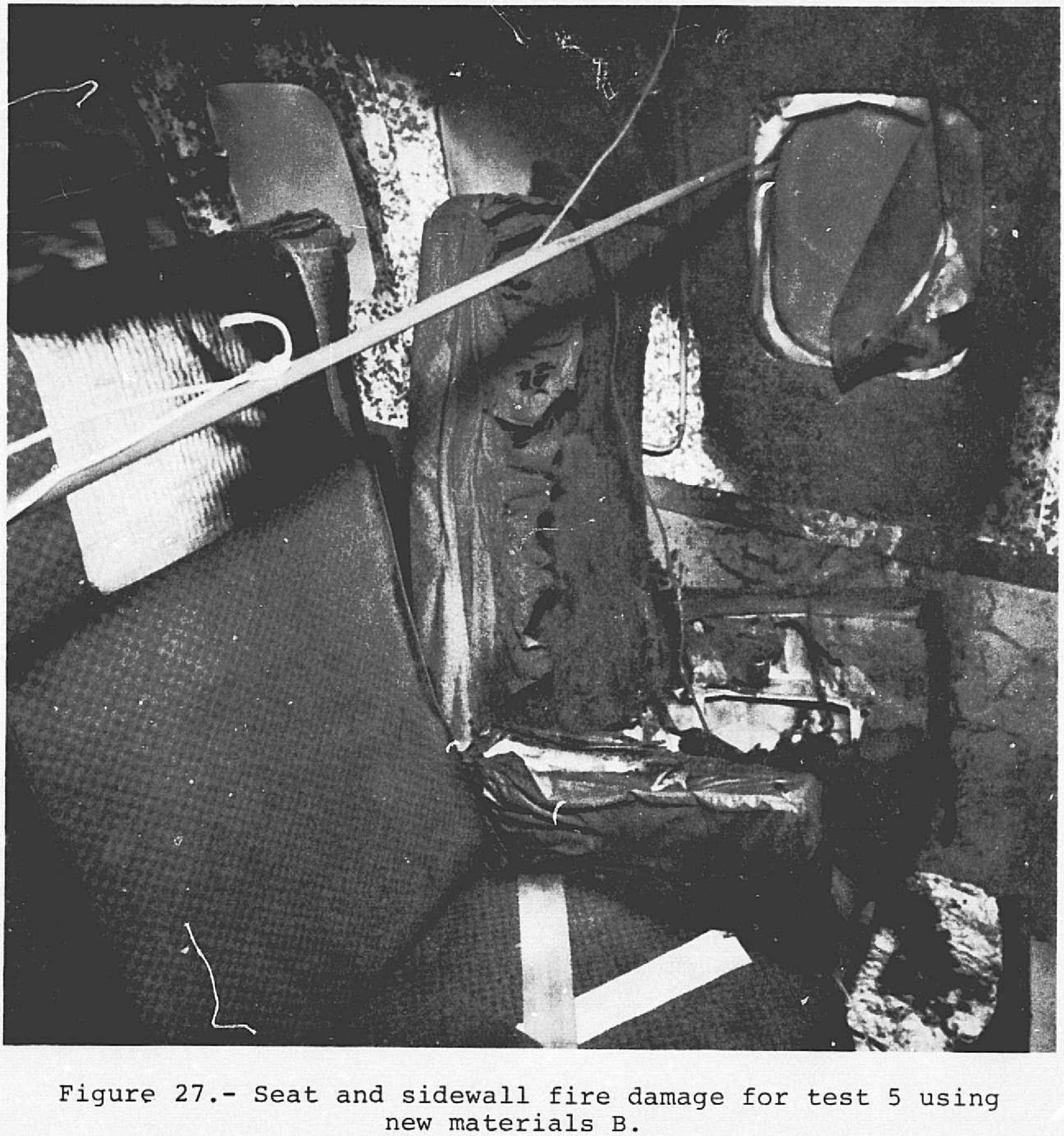

Figure 27.- Seat and sidewall fire damage for test 5 using new materials B.

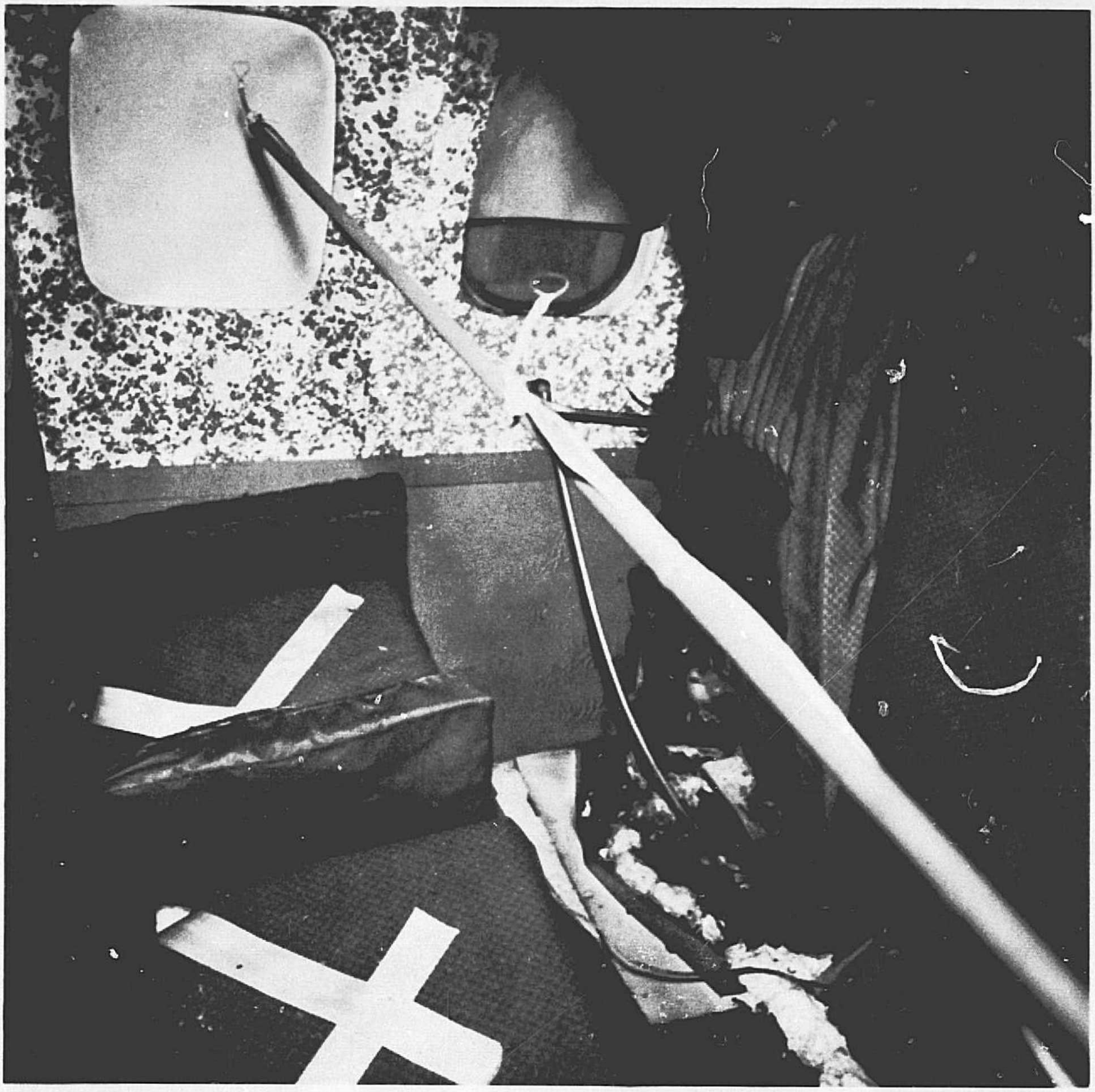

Figure 28.- Back of seat fire damage for test 5 using new materials B.

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Figure 29.- Fire damage for test 5 using new materials B, back view.

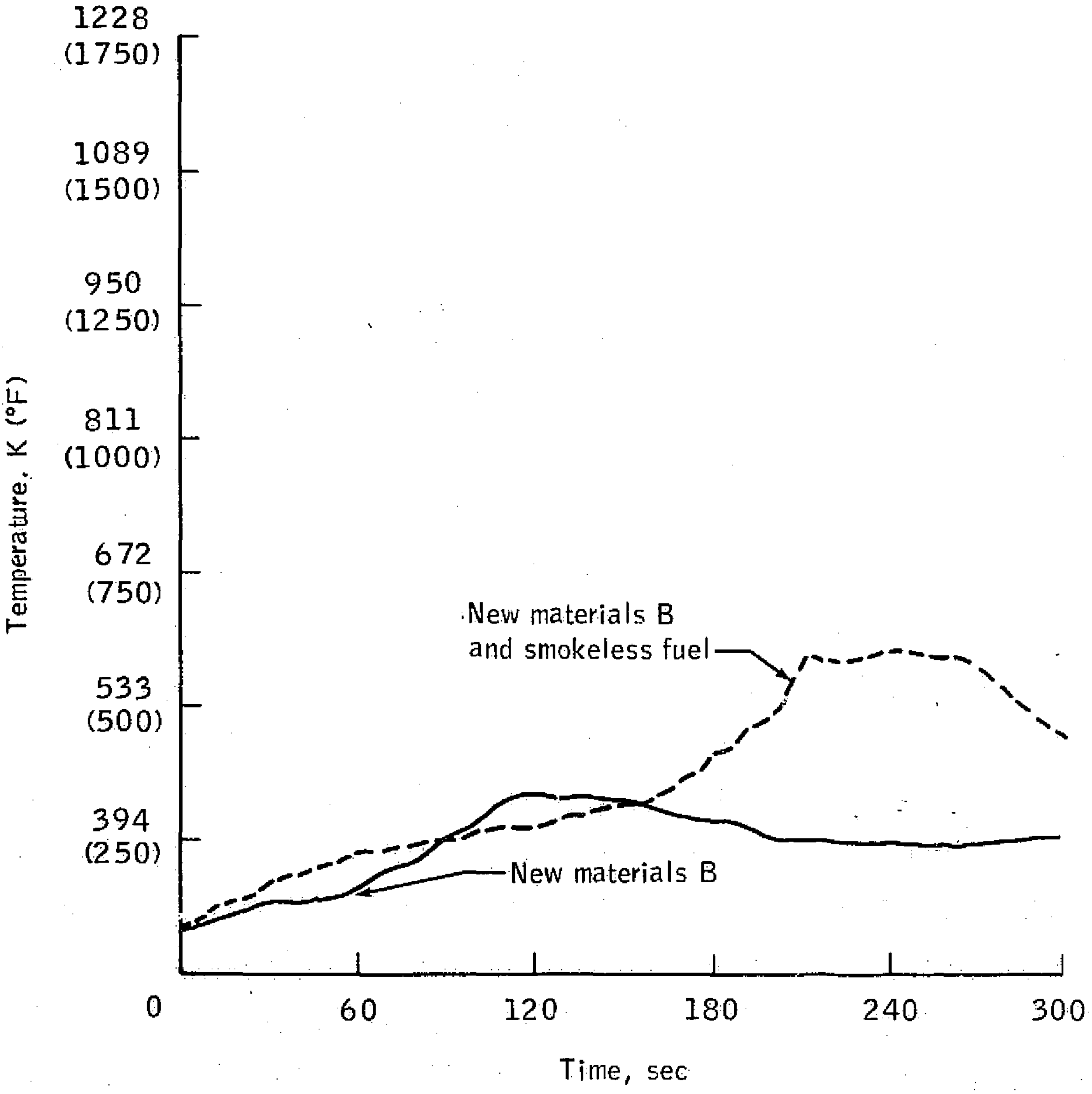

Figure 30.- Ceiling temperatures at center of test section, center aisle.

APPENDIX

INSTRUMENTATION

This appendix contains a description of instrumentation used for the second series of NASA Lyndon B. Johnson Space Center full-scale aircraft cabin flammability tests of new materials. Diagrams of the test setup are included.

TEMPERATURE MEASUREMENT

Forty-nine Chromel-Alumel thermocouples were installed in the Boeing 737 fuselage test section for temperature measurement. Thirty were in the form of thermocouple (TC) trees (fig. 31); each tree contained 10 TC's and one tree was located along the centerline of each row of seats. Six TC's were installed along the ceiling and below the hatrack to duplicate the AIA test setup. Six additional TC's were installed on the seats near 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. The TC locations are shown in figures 2 and 32.

VISIBILITY MEASUREMENTS

Three smoke detectors (fig. 33) were located at the air-exit end of the test section (fig. 32). 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 permit 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. 32). The other two were mounted on the smoke detectors, one at standing head level and the other at seated head level (figs. 32 and 33).

TELEVISION MONITORS

One black-and-white television camera was located at the forward end of the test section at standing shoulder level for real-time monitoring. A color camera was located at window level, as shown in figure 2.

PHOTOGRAPHIC DOCUMENTATION

Three 16-millimeter motion picture cameras with color film were used to record the events, as shown in figure 2. The infrared camera used for previous tests (ref. 1) was eliminated because the color film records events with more detail and for a longer period than the infrared film. The cooler smoke particles produced during the tests obscured the heat spectrum to which the infrared film is sensitive. 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. 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. 32). 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) 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

Infrared spectroscopy was used to determine the concentrations of carbon dioxide, carbon monoxide, methane, ethylene, Freon 113, and hydrogen cyanide in the combustion products. Mass spectroscopy was used to determine the concentrations of oxygen and carbon dioxide, and gas chromatography was used to determine the concentrations of ethane and propane. For nonhydrolyzable products not determinable by these methods, a combined gas-chromatographic/mass-spectrometric interfacing technique was used. This method was used to detect all the unquantified combustion products shown in figure 16. Silver nitrate titrations with a silver specific-ion electrode were used to determine the concentrations of the hydrolyzable chlorides and bromides, and a fluoride specific-ion electrode was used to determine the concentrations of the hydrolyzable fluorides.

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.

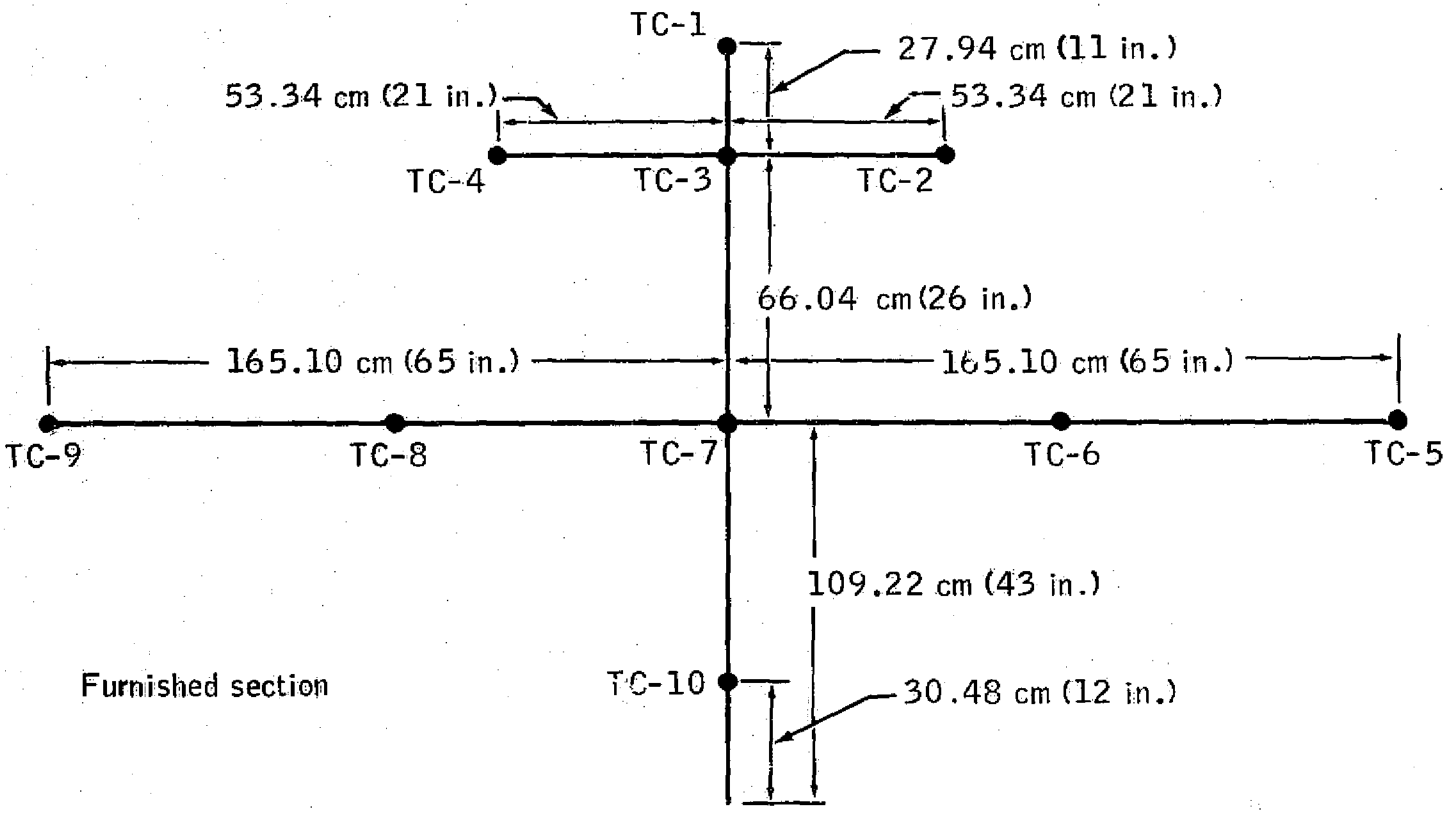

Figure 31.- Typical thermocouple tree.

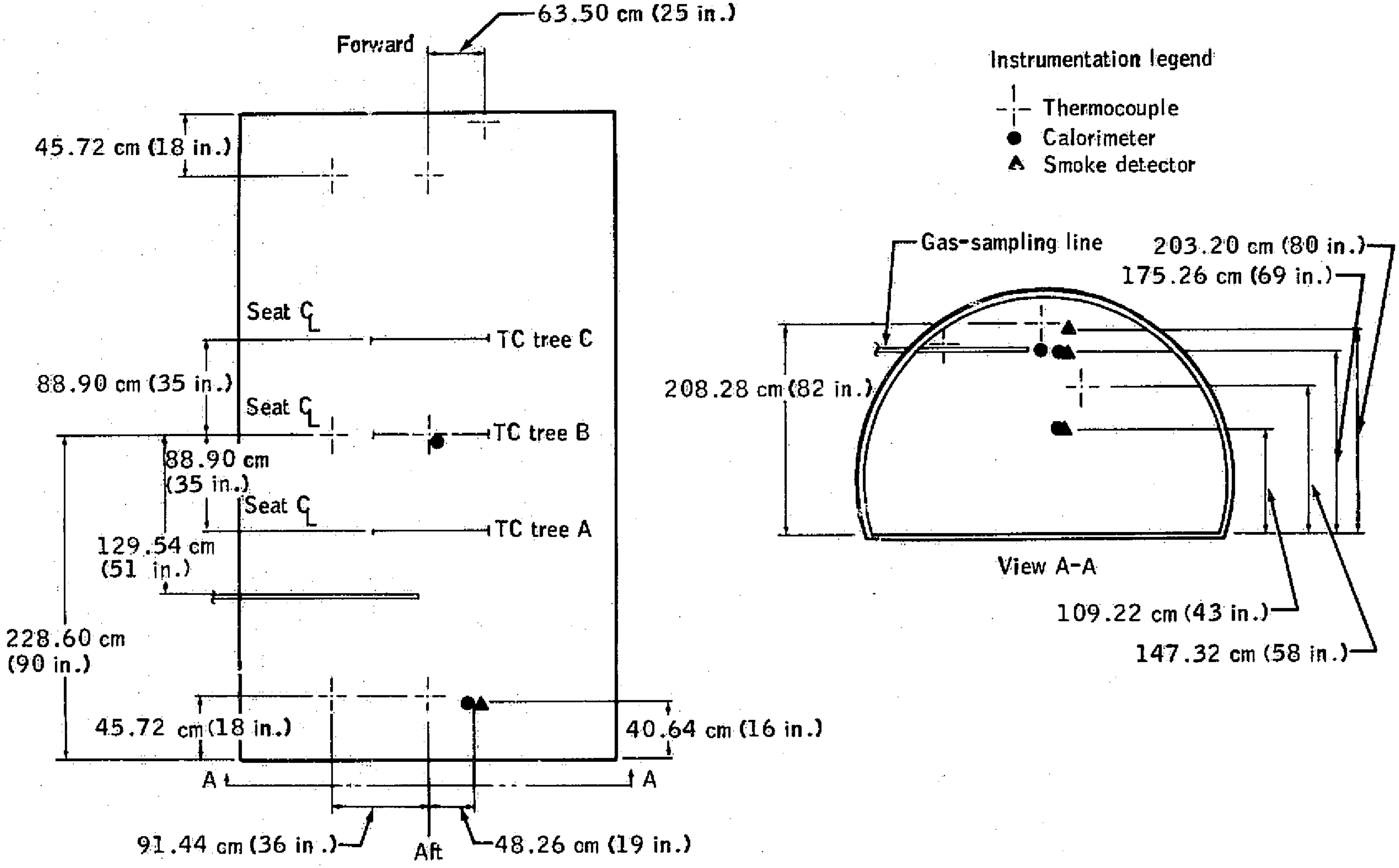

Figure 32.- Instrumentation locations.

Figure 33.- Aft calorimeters and smoke monitors.

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