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DEVELOPMENT OF SENSORS TO OBTAIN IN-FLIGHT ABLATION MEASUREMENTS OF THERMAL-PROTECTION MATERIALS

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DEVELOPMENT OF SENSORS TO OBTAIN IN-FLIGHT ABLATION MEASUREMENTS OF THERMAL-PROTECTION MATERIALS

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SUMMARY

Three instruments to measure the ablative characteristics of thermal-protection materials have been developed by the NASA Langley Research Center. The make-wire sensor is designed to measure the recession of the char-layer interface in a charring ablator and the light-pipe and spring-wire sensors are designed to measure ablator surface recession. The results of extensive ground testing in arc-jet and rocket-exhaust facilities show that each of the three sensors can make ablation measurements to an accuracy in the order of 0.01 inch (0.025 cm). The sensors and associated signal-conditioning circuits have been packaged and environmentally tested to qualify them for use in a spacecraft.

INTRODUCTION

As part of a continuing research program at the NASA Langley Research Center to develop and evaluate thermal-protection materials for spacecraft applications, a program was initiated to develop flight-qualified instrumentation to measure the thermal and physical changes that occur in a space vehicle heat shield during reentry. The design goals for this program included objectives which are common to all instrumentation intended for aerospace use, for example, high reliability, minimum weight and volume, and low power consumption. It was also important that the sensing device be designed so that it does not disturb the basic ablative properties of the heat shield. Furthermore, the instrumentation should be unaffected by the external environment, particularly the ionized plasma surrounding the space vehicle during reentry.

Figure 1, a cross section of a typical charring-ablation material representative of thermal-protection systems currently being employed, shows the measurement regions of interest. As heat is applied, the ablation material decomposes or pyrolyzes at a fairly low temperature and gives off gases, leaving a carbon residue or "char." The gases percolate through the porous char, absorbing heat in the process. The gases are injected into the boundary layer and block convective heat transfer to the surface. Because of its very high subliming temperature and emissivity, the char reradiates a large amount of heat away from the ablator. The char finally recedes by sublimation or oxidation or is removed by aerodynamic forces.

In this program, three instruments have been developed; one is designed to sense the location of the interface between the virgin material and char layer, and two are designed to measure ablator surface recession. Each of these devices is a simple and reliable event sensor, that is, when the surface or the char-virgin material interface reaches the location of individual sensing elements, embedded at precise depths in the heat shield, the element is activated. If the depth of each sensing element in the heat shield and the time of activation are known, the rate of ablator recession can be determined. These sensors are described in detail in the following section.

SENSOR DESCRIPTIONS

Make-Wire Sensor

The make-wire sensor is designed to measure char-interface recession by utilizing the high electrical conductivity of the char. The sensing element consists of a pair of electrically insulated wires embedded in the ablation material perpendicular to the front surface. During ablation, the char interface reaches the location of the sensor and the resistance between the wires decreases. This change in resistance actuates electronic circuitry which provides a signal to indicate the occurrence of this event. Several pairs of wires can be stepped in depth in a single plug of ablator to provide a measure of char-interface recession rate.

Figure 2 is a photograph of the various stages of assembly of the make-wire-sensor configuration which has been developed and tested. The sensing elements are fabricated from 0.01-inch-diameter (0.025-cm-diameter),[1] 85-percent-platinum—15-percent-iridium wire. Platinum, alloyed with iridium for strength, was chosen because, when it is heated, it does not form an insulating oxide which would interfere with the wire-to-char contact. Tests have shown that the measurement reliability is improved by forming a 0.03-inch-diameter (0.076-cm-diameter) head on one end of the wire which provides a larger surface area to insure good contact with the char. A plug, machined from the same material as the heat shield or test specimen into which it will be installed, is sectioned lengthwise. Pairs of sensing elements are then installed so that they terminate at

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[1]Measurements for this investigation were taken in the U.S. Customary System of Units, but are also indicated herein parenthetically in the International System of Units (SI). Factors for conversion of U.S. Customary units to SI units are given in the appendix.

precise depths in the material. This installation is accomplished in low-density ablators by jig-locating the wires and pressing them into the soft material. In higher density ablators, the wires are installed in 0.01- by 0.01-inch (0.025- by 0.025-cm) grooves machined to the proper depth. The sections are then bonded together with a thin coat of epoxy resin and machined to form a cylindrical plug. Figure 2 also shows the bakelite cartridge and mounting rings used to contain the sensor wiring connections and resistors which provide a means for checking sensor lead continuity. The entire cartridge assembly is bonded to the sensor plug and filled with epoxy resin. The completed sensor plug is then bonded into a tight-fitting through-hole in the heat shield.

Figure 3 is a schematic drawing of the signal-conditioning circuitry developed for the make-wire sensor. This circuitry was designed around a bistable solid-state switch (Q_2) which becomes conducting with a small positive potential change at its input and thereafter remains conducting regardless of any further positive or negative changes at the input. Transistor Q_1 permits operation of the sensor at ground potential and eliminates the possibility of shorting the power supply should the char become grounded. Use of this circuitry minimizes changes in sensor output due to variations or disturbances at the input, such as changes in char contact resistance or the random variations of the ionized plasma. The signal-conditioning circuitry used with each pair of wires occupies a volume of 0.2 cubic inch (3.3 cm^3), has a mass of 0.2 ounce (5.67 grams), and requires 60 milliwatts of power.

Light-Pipe Sensor

The light-pipe sensor is designed to measure ablator surface recession by using the visible radiation present at the surface of an ablating heat shield. Sensor operation is illustrated in figures 4 and 5. An optical system consisting of a high-melting-point optical fiber and photodetector is embedded in the ablation material. As the ablation process advances, the area above the end of the optical fiber is heated and becomes incandescent. The light radiated from this area is channeled through the fiber to the photodetector. As the ablator surface approaches the end of the fiber, the intensity of the light increases and causes a proportionate change in photodetector output. When the detector output reaches a predetermined level (0_1 in fig. 5), which has been experimentally selected to correlate surface position with the end of the fiber, electronic switch-closure circuitry is actuated.

Figure 6 is a photograph of the light-pipe sensor configuration which has been developed. The optical elements are embedded in a 0.25-inch-diameter (0.64-cm-diameter) plug of the ablation material, which is then bonded into a tight-fitting blind hole in the heat shield at the desired depth. The optical fiber is a 0.016-inch-diameter (0.041-cm-diameter) rod of synthetic white sapphire (Al_2O_3). This material was chosen because of its high melting temperature (3690° F (2305° K)) and mechanical strength. The infrared rejection filter is constructed of Corning glass, specification number 1-69, which was chosen because of the wavelengths to be attenuated (greater than 0.7 micron (0.7 μm)). The infrared filter was employed in the sensor design to reduce the sensitivity of the optical system to the infrared emission from the lower temperature area near the char-layer interface and to improve sensor response to the higher temperature radiation from the ablating surface. The photodetector is an LS-400 silicon photoresistive diode that decreases in resistance with increasing light intensity incident upon a photosensitive crystal. The detector is 0.08 inch (0.2 cm) in diameter, is capable of operating to 250° F (394° K), and has a spectral response of 0.5 to 1.1 microns (0.5 to 1.1 μm).

Another light-pipe sensor configuration, shown in figure 7, permits the installation of up to six sensing elements in blind holes in a 0.5-inch-diameter (1.27-cm-diameter) ablator plug. Tests of this design were quite successful; however, extreme care must be taken during fabrication since calibration of individual sensing elements cannot be checked after assembly of the complete unit.

The signal-conditioning circuitry developed for the light-pipe sensor is shown in figure 8. The principle of operation is similar to that of the make-wire circuitry.

Spring-Wire Sensor

The spring-wire sensor is also designed to measure the recession of the ablator surface. As illustrated in figure 9, this device consists of a metal tube attached to a snap-action switch. The tube is constructed of material which melts at or near the expected ablator surface temperature. A fine tungsten wire, fixed to the end of the tube, is passed through the tube and attached to the leaf spring of the switch so as to hold the spring in tension. The tubing is inserted in the ablator to the desired depth. As the material ablates to the location of the sensor, the high temperature which exists at and just beyond the ablator surface softens the tubing and releases the wire, which allows the switch to close. This switch-closure signal is channeled through a voltage-divider resistance network to provide the proper signal for the spacecraft telemetry system.

Figure 10 is a photograph of the spring-wire-sensor assembly. On the left, a single sensing unit is shown with the cover removed to expose the leaf spring of the switch; on the right is shown a multiple assembly of four sensing units with mounting brackets attached, ready to install in the heat shield. The snap-action switch has a volume of 0.1 cubic inch (1.64 cm^3). The attachment wire is 0.005 inch (0.013 cm) diameter tungsten. The support tube is 0.020 inch (0.05 cm) o.d. and 0.012 inch (0.03 cm) i.d. High-melting-point tubings such as tungsten-rhenium and molybdenum have been used with heat-shield materials having high surface temperatures during ablation. For the condition where surface temperatures are lower, aluminum and stainless-steel support tubes have been used successfully.

An alternate approach to the sensor design is to eliminate the support tube and anchor the wire directly to a fine metal disk embedded at the desired depth in the ablator. The operation of the sensor in this case is the same as that previously described: the ablator surface reaches the location of the sensor, the anchor disk melts and releases the wire which allows the switch to close. This design has been successfully used in materials which do not form a char layer during ablation.

DEVELOPMENT TEST PROGRAM

Preliminary laboratory feasibility tests were conducted with an oxygen-acetylene torch. Subsequent tests were made in arc-jet and rocket-exhaust facilities in environments that were more representative of reentry heating. Each of these tests is described briefly in the following sections.

Feasibility Tests

Oxygen-acetylene torch tests were conducted to obtain an indication of the practicability of various ablation-sensing techniques. Heating conditions were varied by adjusting nozzle size, distance from nozzle to specimen, and gas-mixture ratio. Sensor output was recorded on an oscillograph. Heating rates from about 100 to 300 Btu/ft^2-sec (1.13 to 3.4 MW/m^2) were obtained.

The results of these tests indicated the feasibility of make-wire, light-pipe, and spring-wire measurements in several ablation materials and were used to establish the basic sensor designs. To determine precise system accuracies in a more realistic oxidizing environment and one that better simulates reentry heating, tests were conducted in arc-jet and rocket-exhaust facilities.

Arc-Jet and Rocket-Exhaust Tests

Tests have been conducted in the Langley 2500-kilowatt arc-jet (ref. 1). This facility produces a subsonic gas stream at atmospheric pressure having a stagnation temperature of about 7100° F (4200° K). The advantages of these tests include the ability to control test conditions carefully and to use a large specimen which permits the simultaneous test of several sensors, and most important, the facility provides a better ground simulation of the reentry heating environment than the oxygen-acetylene heat source.

Additional tests have been conducted in rocket-exhaust facilities at the Malta Test Station of the New York State Atomic and Space Development Authority. These facilities, described in reference 2, use liquid oxygen and ethyl alcohol as propellants to produce a supersonic stream and high stagnation pressures and temperatures.

Ground-Test Results

Figure 11 is a photograph of a typical 3-inch-diameter (7.62-cm-diameter) test specimen of modified epoxy-novelac ablator instrumented with make-wire, light-pipe, and spring-wire sensors. To date, more than 100 ablation sensor tests have been conducted as part of the sensor development program at heating rates from approximately 100 Btu/ft^2-sec to over 1600 Btu/ft^2-sec (1.13 to 18.16 MW/m^2) in a variety of ablation materials. All these materials were charring composites which consisted of phenolic, epoxy, or other resins filled with organic or inorganic materials in the form of powder, fibers, or microballoons. The results of these tests indicate the general applicability of these techniques to this class of materials. The results of several typical ablation-sensor tests are discussed in the following paragraphs.

Figure 12, a plot of the results of an arc-jet test of a specimen of low-density phenolic-nylon ablator containing light-pipe sensors, illustrates the procedure used to determine measurement accuracy. Thickness of the specimen in inches (cm) is plotted against test time in seconds. The specimen is subjected to the heating environment until all sensors have been actuated. At this time the test is terminated. The depth location of each sensing element is plotted as a function of the time of its activation. A curve is then faired through the data and extrapolated to the "end-of-test" time to predict the final position of the ablator surface. This predicted location is then compared with the actual surface location determined by physical measurements to determine the measurement error – 0.008 inch (0.02 cm) in this test.

Figure 13 illustrates the results of an arc-jet test of a specimen of ablator consisting of a modified epoxy-novelac in fiberglass honeycomb. The specimen was instrumented with make-wire sensors to measure char-interface recession and light-pipe sensors to measure surface recession. For this test, the measured heating rate was 100 Btu/ft^2-sec (1.13 MW/m^2) at a stagnation pressure of 1 atmosphere. As before, specimen thickness in inches (cm) is plotted against test time in seconds. The upper curve represents the recession of the ablator surface from the light-pipe-sensor data, and the lower curve represents the recession of the char-layer interface from the make-wire-sensor data. The vertical separation between the curves represents the thickness of the char layer as a function of time. It can be seen that each curve predicts a final position that agrees well with physical measurements.

A comparison of spring-wire and light-pipe sensors as surface-recession indicators is shown in figure 14, a plot of the results of a test of a 3-inch-diameter (7.62-cm-diameter) epoxy-novelac ablator specimen. This test was conducted at a heating rate of

200 Btu/ft^2-sec (2.27 MW/m^2) in air at a pressure of 1 atmosphere. Both sensors accurately predicted the final surface location. Physical measurements following the test verified that the slight separation between the curves was due to a small difference in ablation rate between the center of the specimen (spring-wire-sensor location) and its outer periphery (light-pipe-sensor location).

The analysis of ablation-sensor performance becomes more difficult when the test specimen does not ablate uniformly. Figure 15 shows the results of a 12-inch-diameter (30.48-cm-diameter) specimen of epoxy-novelac ablator tested in the rocket-exhaust facility. The test was conducted at a heating rate of 650 Btu/ft^2-sec (7.38 MW/m^2) and a stagnation pressure of 13 atmospheres. Because of the severe environment, the specimen did not ablate uniformly but rather eroded unevenly with surface irregularities, in some cases as great as 1 inch (2.5 cm). The upper curve in figure 15 represents recession of the ablator surface from the spring-wire-sensor data and the lower curve represents the recession of the char-layer interface from the make-wire-sensor data. Examination of the specimen following the test disclosed that the char thickness was on the order of 0.005 inch (0.013 cm). The existence of such a thin char indicates that while the make-wire sensor is designed to measure char-interface recession, it was, for all practical purposes, measuring surface recession in this test. Therefore, the curves represent different surface-recession rates at each sensor location. This conclusion is verified by pre-test predictions and post-test measurements of ablator performance in this environment. It appears probable that the deviation of the fourth make-wire data point from the curve was caused by a small chunk of ablation material eroding irregularly. A conclusion that can be drawn from these test results is that, if a specimen is to be instrumented with two different sensors to determine char thickness, they should be located at the same point, or if this is impractical, at least in an area where uniform ablation can reasonably be expected.

Figure 16 is a plot of the results of a test in the rocket-exhaust facility of a specimen of phenolic-graphite ablation material instrumented with two spring-wire sensors. The purpose of the test was to evaluate the performance of different sensor support-tube materials in the phenolic-graphite ablator. For this evaluation, one sensor with a molybdenum support tube (4700° F (2867° K) melting temperature) and the other with a tungsten-rhenium support tube (5600° F (3367° K) melting temperature) were embedded at a depth of approximately 0.2 inch (0.5 cm) from the front surface of the ablator. The heating rate was 1600 Btu/ft^2-sec (18.16 MW/m^2) at a pressure of about 6 atmospheres. Because of irregularities in surface recession, the measured end points at each sensor location differed by more than 0.15 inch (0.38 cm). However, it can be seen that the test data are in good agreement with a straight line connecting the known initial and final thicknesses. In addition, both support tubes were found to be flush with the ablator surface following the test – an indication that they had ablated at the same rate as the phenolic-graphite material. Based on these results, it was concluded that the spring-wire sensor containing either a molybdenum or tungsten-rhenium support tube would make a reasonable measurement of the recession of the phenolic-graphite ablator surface in this heating environment.

The test results presented in the preceding paragraphs are typical of many tests over a wide range of conditions. Based on these results, it is concluded that the make-wire, light-pipe, and spring-wire sensors are capable of making measurements in the order of 0.01 inch (0.025 cm) in several charring ablation materials. In addition, through experience gained while developing these devices, some observations may be made on the application and limitations of these techniques in measuring heat-shield ablation.

The make-wire sensor can measure char-interface recession in charring ablation materials which are not electrically conductive in their virgin state. However, the choice of an instrument for the surface-recession measurement depends upon the specific application. The light-pipe sensor, in its present configuration, can be used in materials which are not transparent. It can provide several measurement points in a small area of the heat shield, but the sensing elements must be installed in a plug of material which will ablate at the same rate as the heat shield. The spring-wire sensor, on the other hand, does not require a plug for installation, but because of its size, it can make fewer measurements in a given area. Also, the spring-wire sensor requires a significantly smaller volume of signal-conditioning circuitry than the light-pipe sensor.

Environmental Tests

As part of the sensor development program, a series of environmental tests has been conducted on the ablation sensors and associated electronic circuitry to qualify them for spacecraft applications. Table I lists the environmental levels to which the sensors and circuit packages have been qualified to date, but do not necessarily represent the environmental limits of these devices.

CONCLUDING REMARKS

Three instruments to measure the in-flight ablative characteristics of a reentry vehicle heat shield have been developed at the NASA Langley Research Center. These instruments are the make-wire sensor to measure the recession of the interface between the char and the virgin material and the light-pipe and spring-wire sensors to measure ablator surface recession. These devices are simple and reliable event transducers which provide a signal as the ablator surface or char interface reaches the location of individual sensing elements embedded at precise depths in the heat shield. The choice of instrument for the surface-recession measurement depends upon the specific application. The light-pipe sensor can provide several measurement points in a small area of the heat shield, but the sensing elements must be installed in a plug which will ablate at the same rate as the heat shield. The spring-wire sensor, on the other hand, does not require a plug for installation; however, because of its size, this device can make fewer measurements in a given area. The results of extensive ground tests in arc-jet and rocket-exhaust facilities indicate a measurement accuracy in the order of 0.01 inch (0.025 cm) for each of the three devices. The ablation sensors and associated signal-conditioning circuits have been packaged and environmentally tested to qualify them for use in a spacecraft.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 15, 1966,
125-24-03-08-23.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution Number 12 (ref. 3). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Heating rate	Btu/ft^2-sec	1.135×10^4	$\frac{\text{watts}}{\text{meter}^2}$ $\left(\frac{\text{W}}{\text{m}^2}\right)$
Length	foot	3.048	meter (m)
Length	inch	0.0254	meter (m)
Length	micron	10^6	meter (m)
Mass	ounce	28.3	gram (g)
Temperature	degrees Fahrenheit ($^{\circ}$F)	5/9 ($^{\circ}$F + 460)	degrees Kelvin ($^{\circ}$K)
Volume	inch^3	1.639×10^{-5}	meters^3 (m^3)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
micro (μ)	10^{-6}

REFERENCES

1. Schaefer, William T., Jr.: Characteristics of Major Active Wind Tunnels at the Langley Research Center. NASA TM X-1130, 1965.
2. Anon: Gas Thermodynamic and Transport Properties of Re-Entry Test Facilities. General Electric Company, MD63-1, Aerospace and Defense Service Eng. Dept., Gen. Elec. Co., Mar. 5, 1963.
3. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.

TABLE I.- ABLATION SENSOR ENVIRONMENTAL TEST LEVELS

Component	Environment				
	Vibration	Shock	Acceleration	Temperature	Vacuum
Make-wire sensor	20 to 2000 cps 3 axes maximum 30g rms	250g 15 milliseconds longitudinal axis	150g longitudinal axis	250° F (394° K) for 45 min	Vacuum equivalent to an altitude of 350 000 ft (10.7 km) for 45 min
Light-pipe sensor	20 to 2000 cps 3 axes maximum 80g rms	250g 15 milliseconds longitudinal axis	150g longitudinal axis	250° F (394° K) for 45 min	Vacuum equivalent to an altitude of 350 000 ft (10.7 km) for 45 min
Spring-wire sensor	20 to 2000 cps 3 axes maximum 30g rms	250g 15 milliseconds longitudinal axis	500g longitudinal axis	250° F (394° K) for 45 min	Vacuum equivalent to an altitude of 350 000 ft (10.7 km) for 45 min
Signal-conditioning circuitry	20 to 2000 cps 3 axes maximum 60g rms	250g 15 milliseconds longitudinal axis	150g 3 axes	200° F (364° K) for 120 min	Vacuum equivalent to an altitude of 350 000 ft (10.7 km) for 45 min

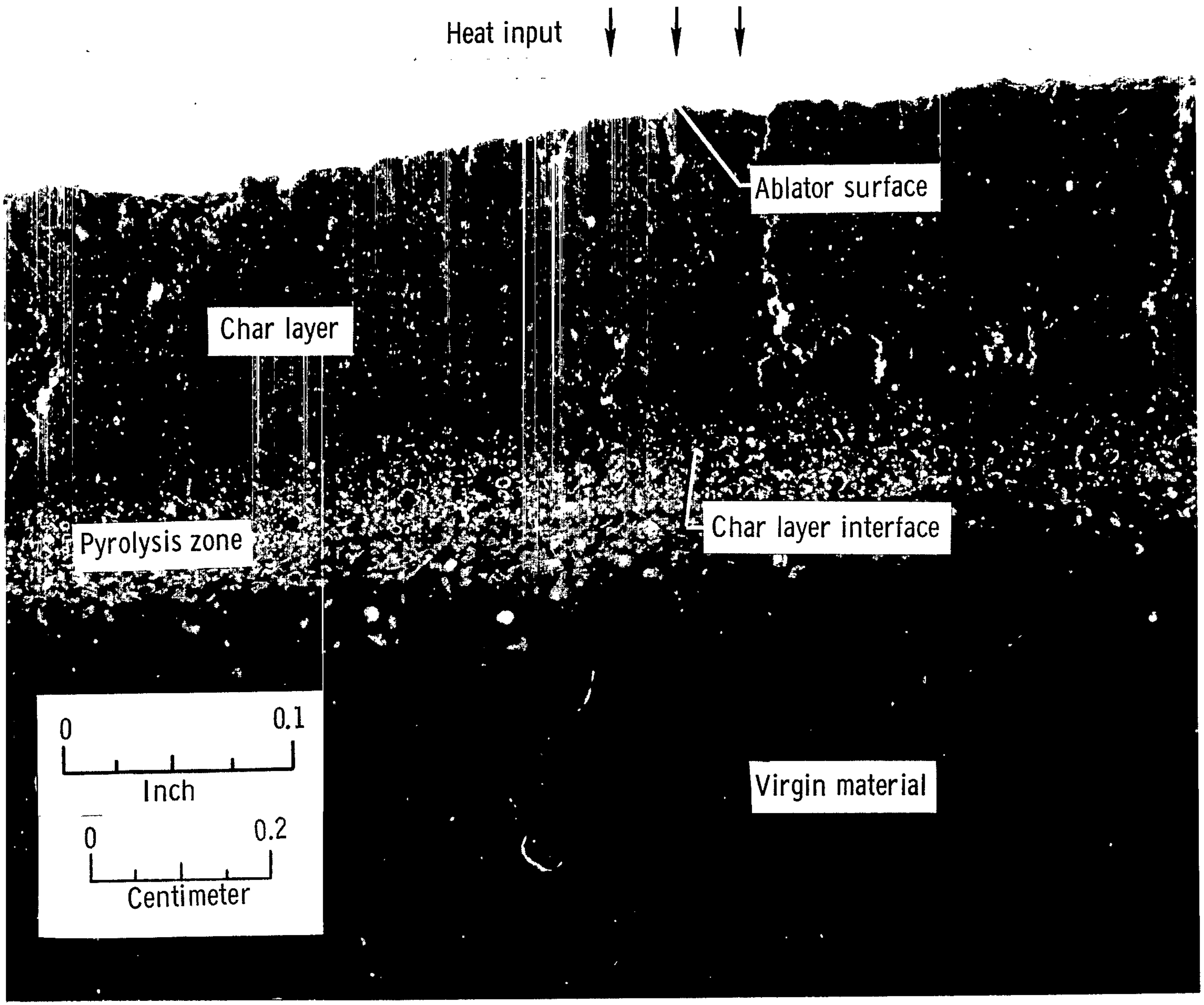

Figure 1.- Typical charring-ablator cross section.

L-2564-1

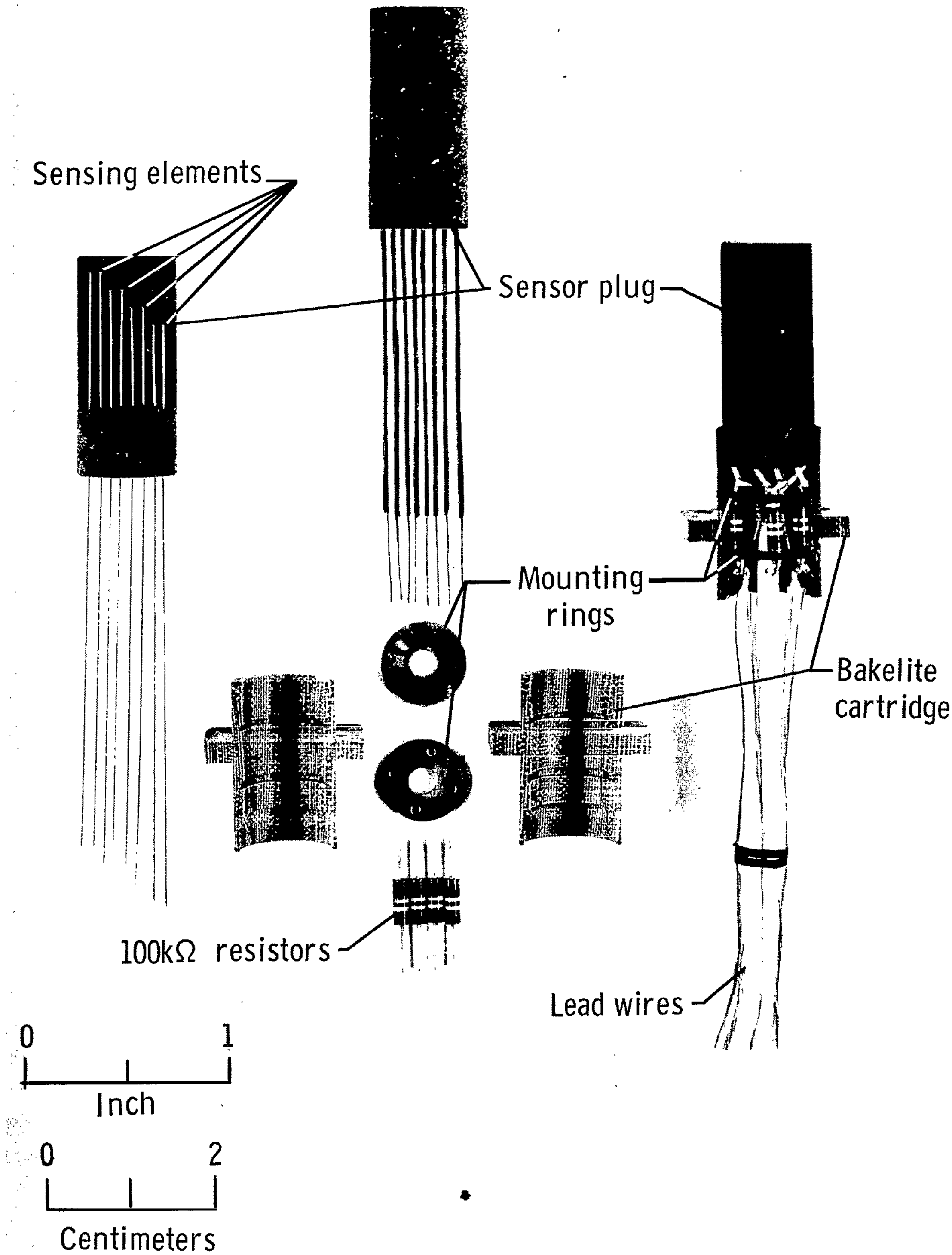

Figure 2.- Make-wire-sensor assembly. L-2564-2

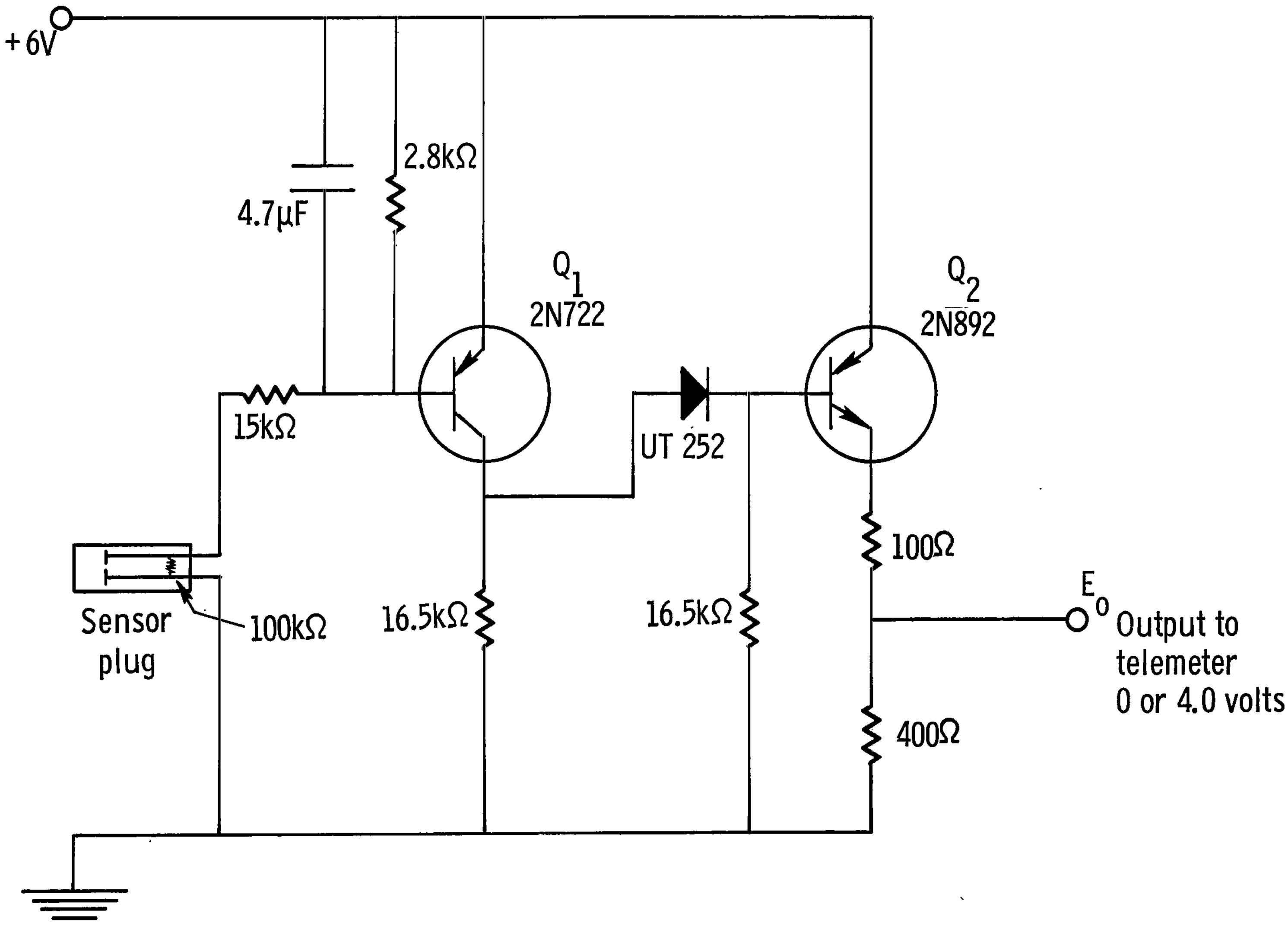

Figure 3.- Signal-conditioning circuitry for make-wire-ablation sensor.

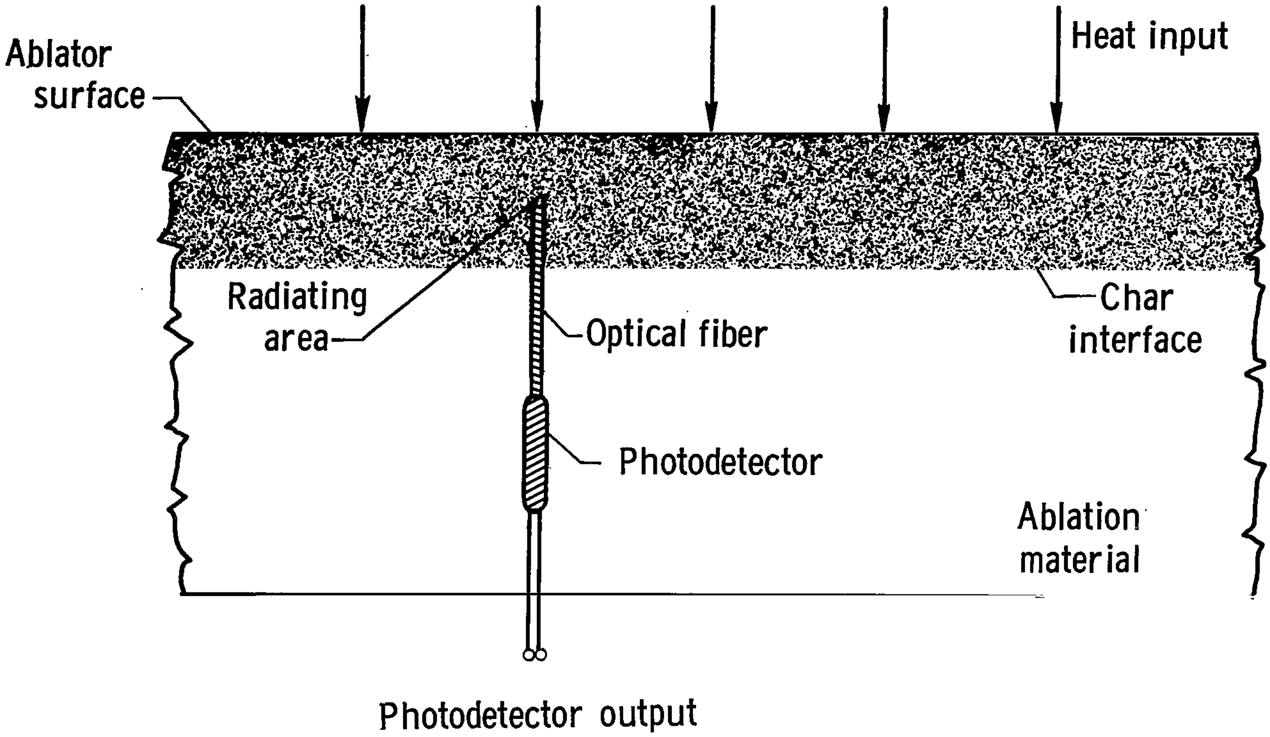

Figure 4.- Schematic drawing of light-pipe ablation sensor.

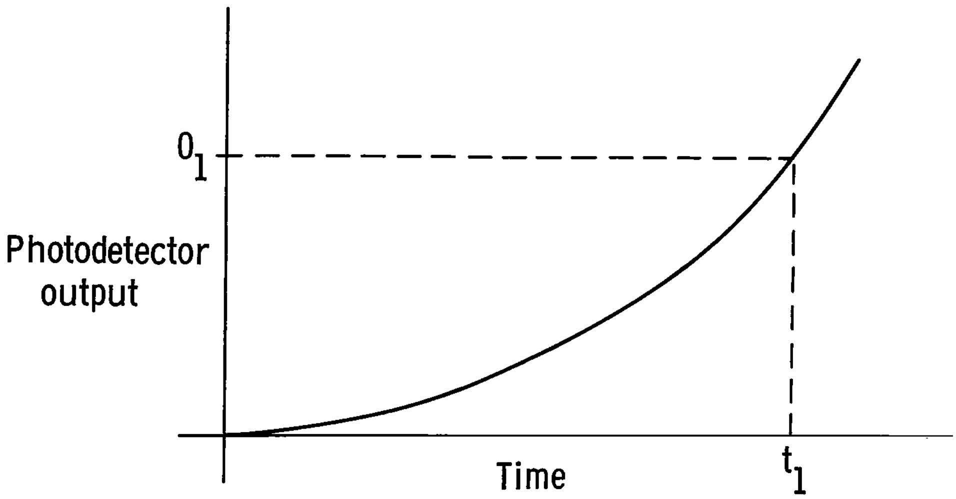

Figure 5.- Variation of photodetector output with time.

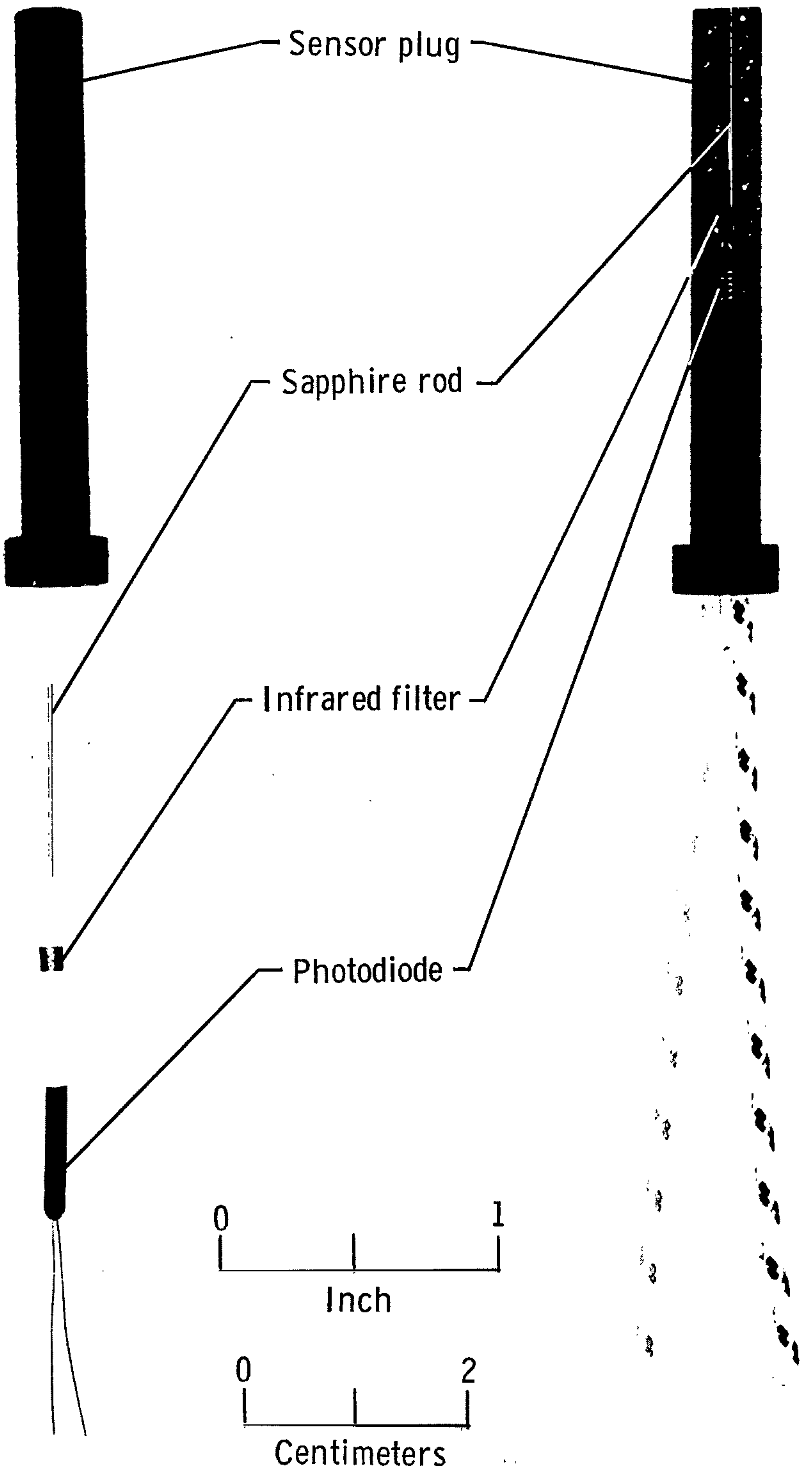

Figure 6.- Light-pipe-sensor assembly.

L-2564-5

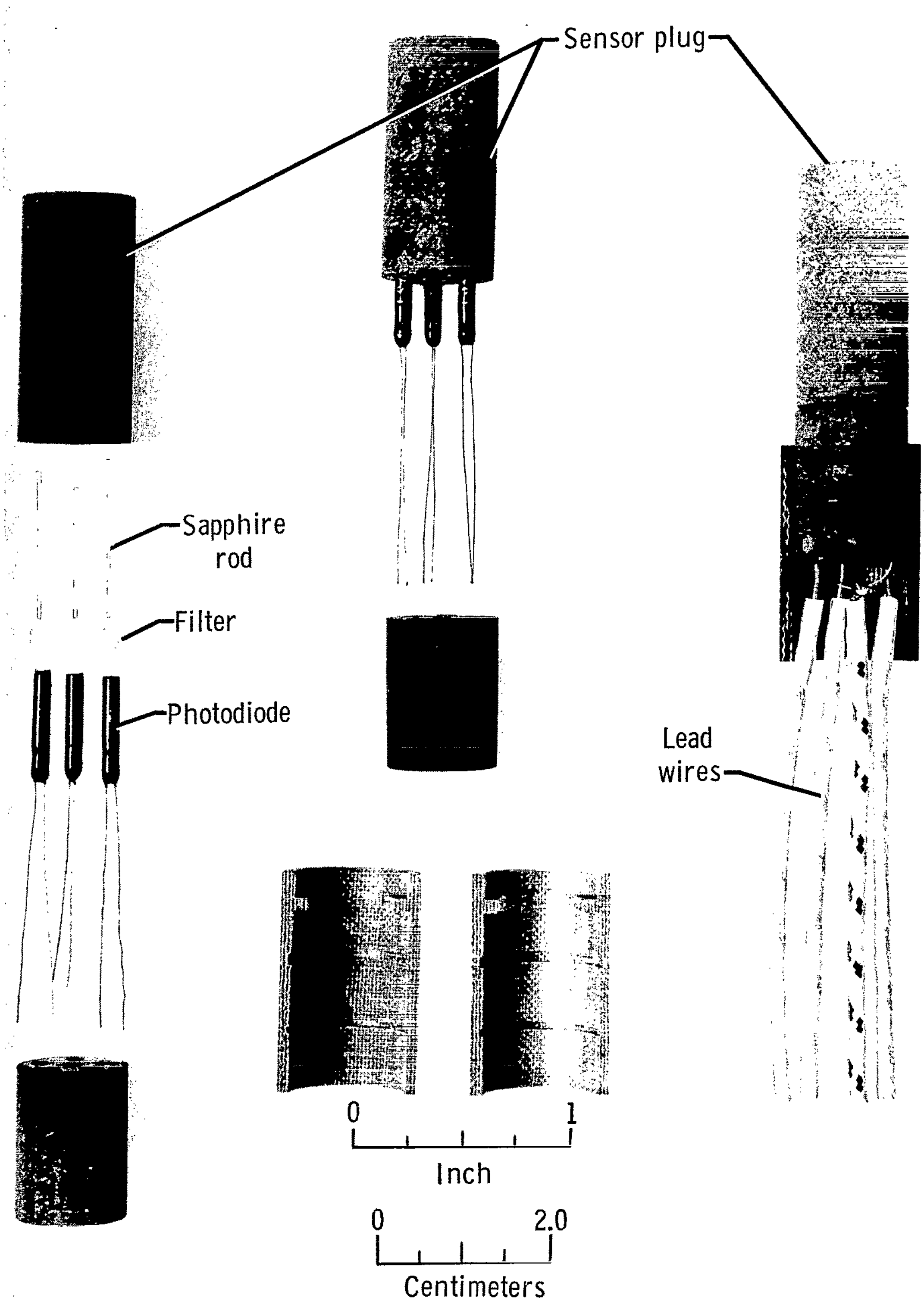

Figure 7.- Multiple light-pipe-sensor assembly.

L-66-4700

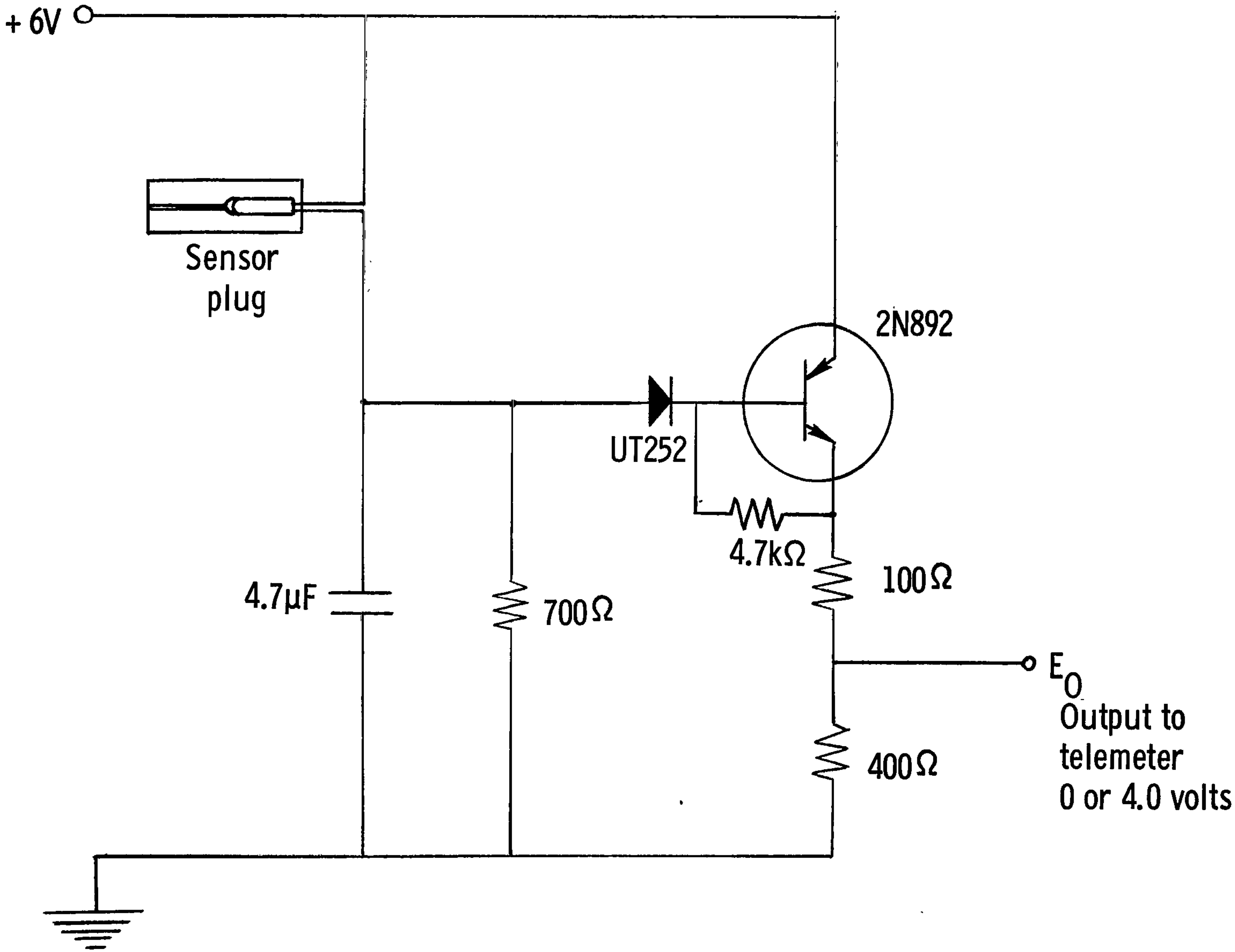

Figure 8.- Signal-conditioning circuitry for light-pipe ablation sensor.

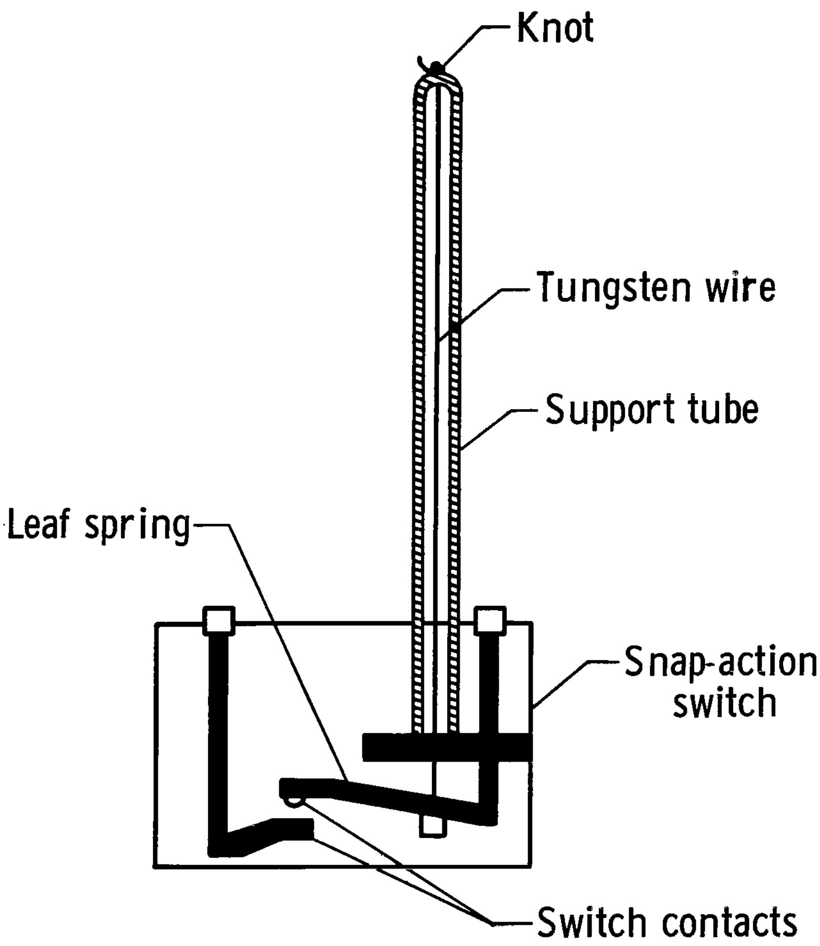

Figure 9.- Schematic diagram of spring-wire ablation sensor.

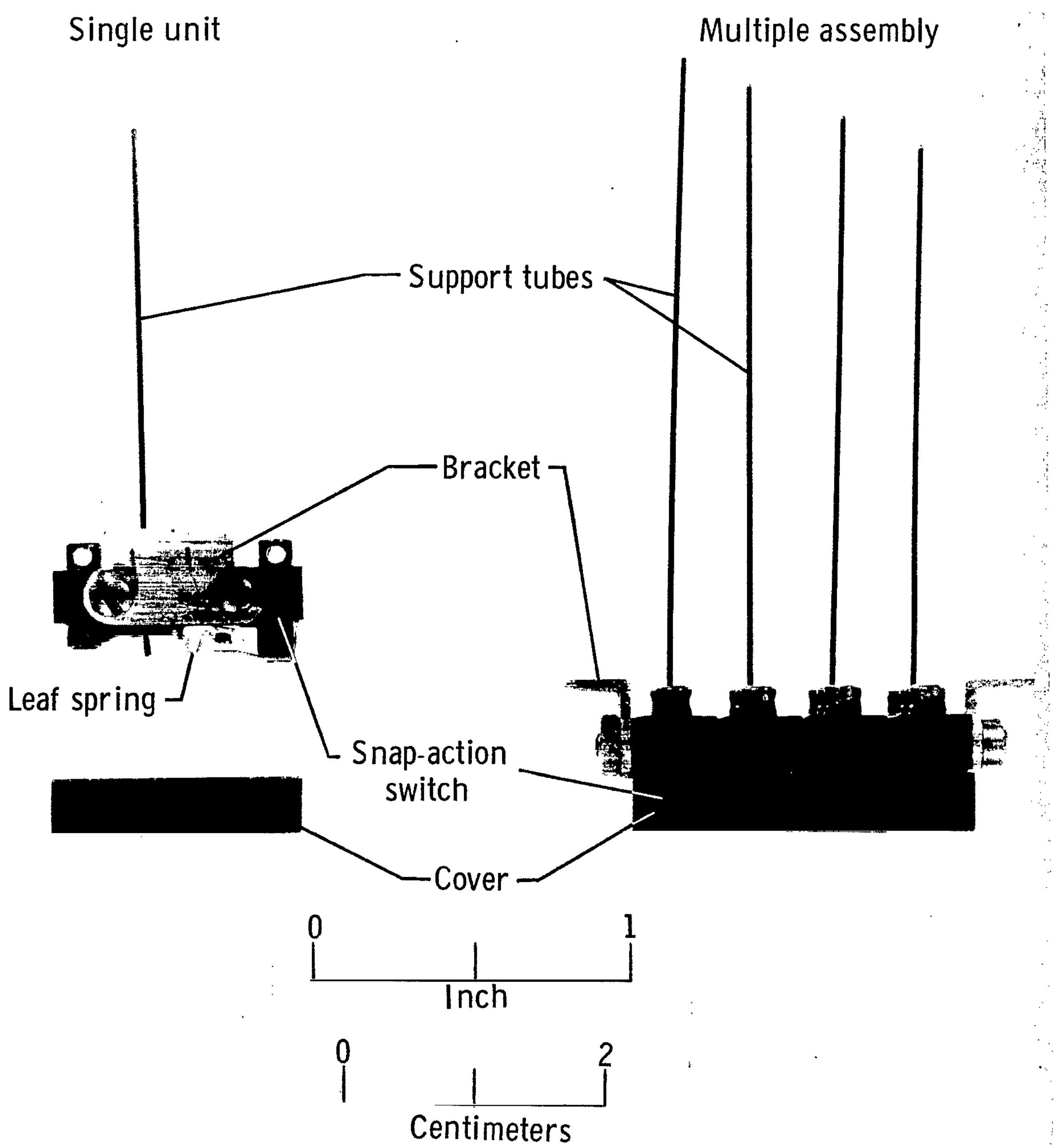

Figure 10.- Spring-wire-sensor assembly.

L-2564-7

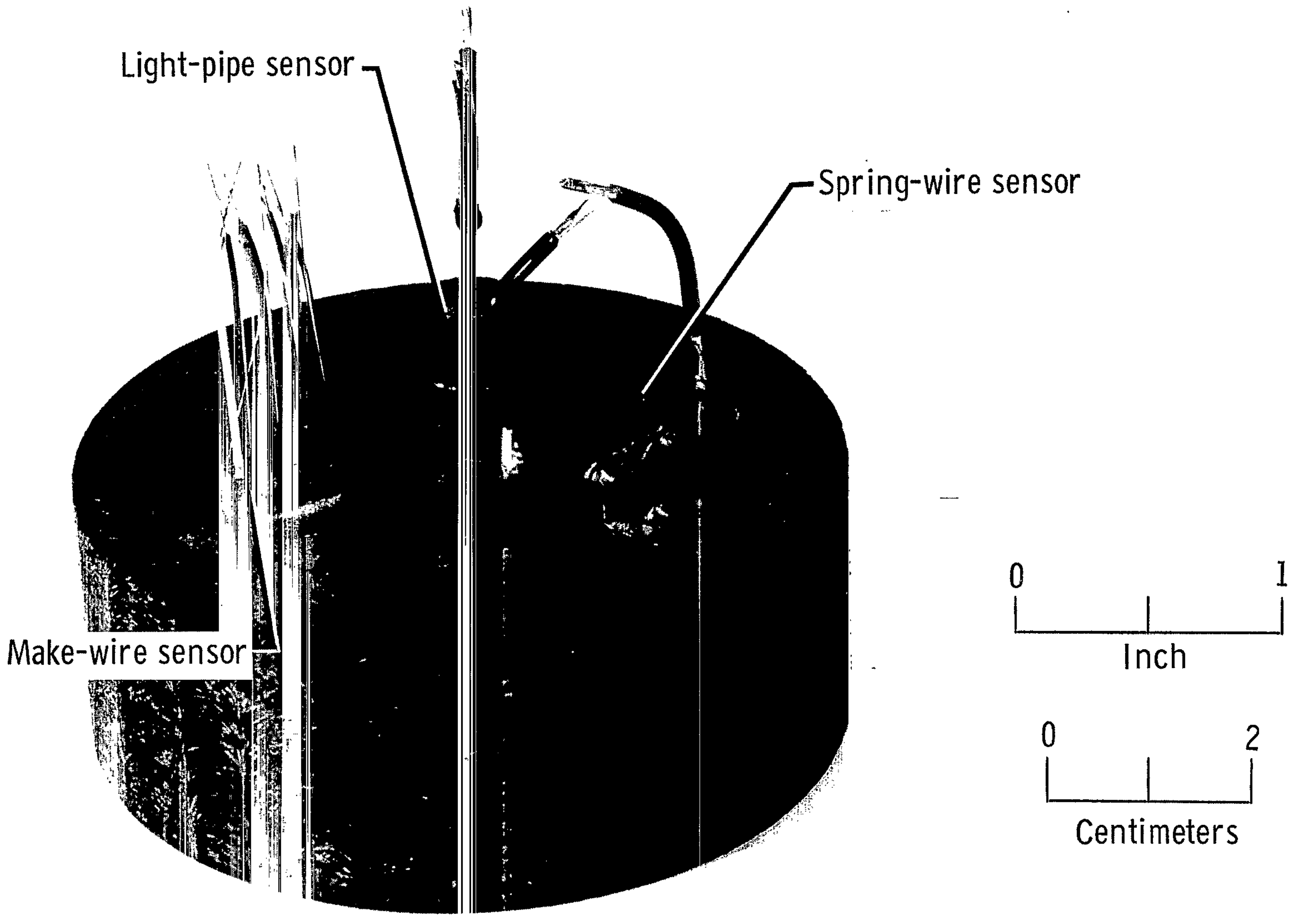

Figure 11.- Typical test specimen instrumented with ablation sensors.

L-65-7819

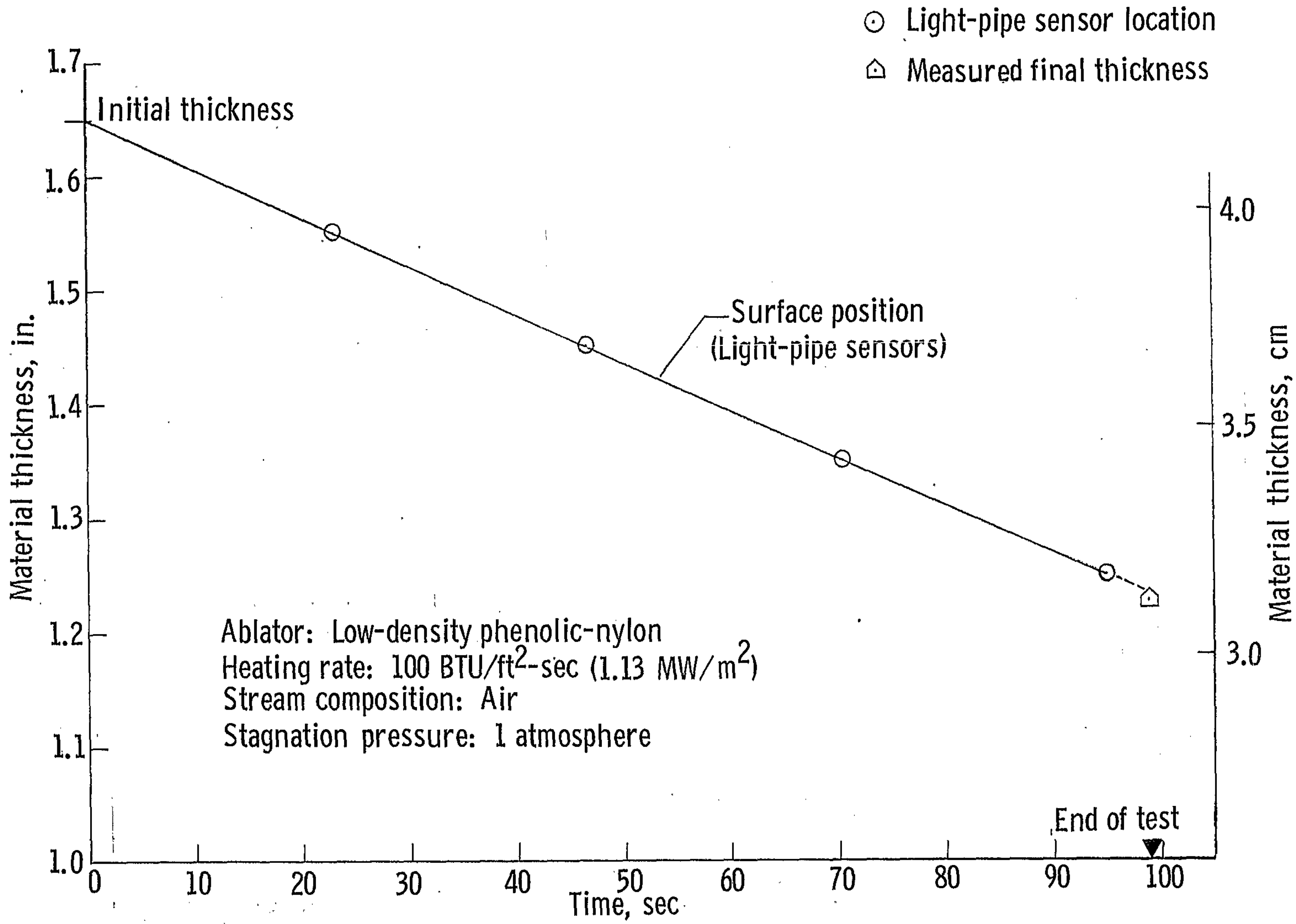

Figure 12.- Arc-jet test results of light-pipe sensors installed in the low-density phenolic-nylon ablator.

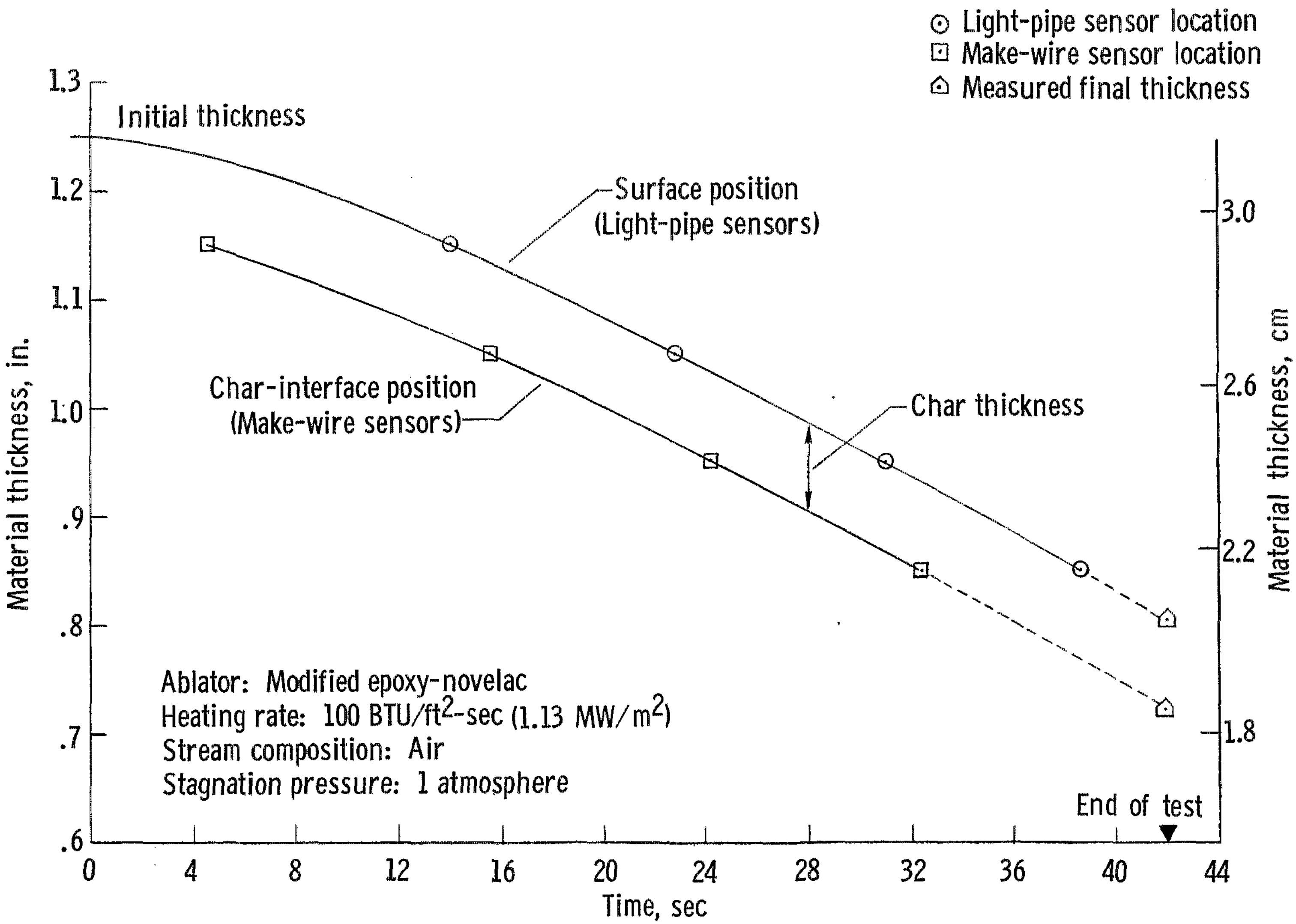

Figure 13.- Arc-jet test results of light-pipe and make-wire sensors installed in the modified epoxy-novelac ablator.

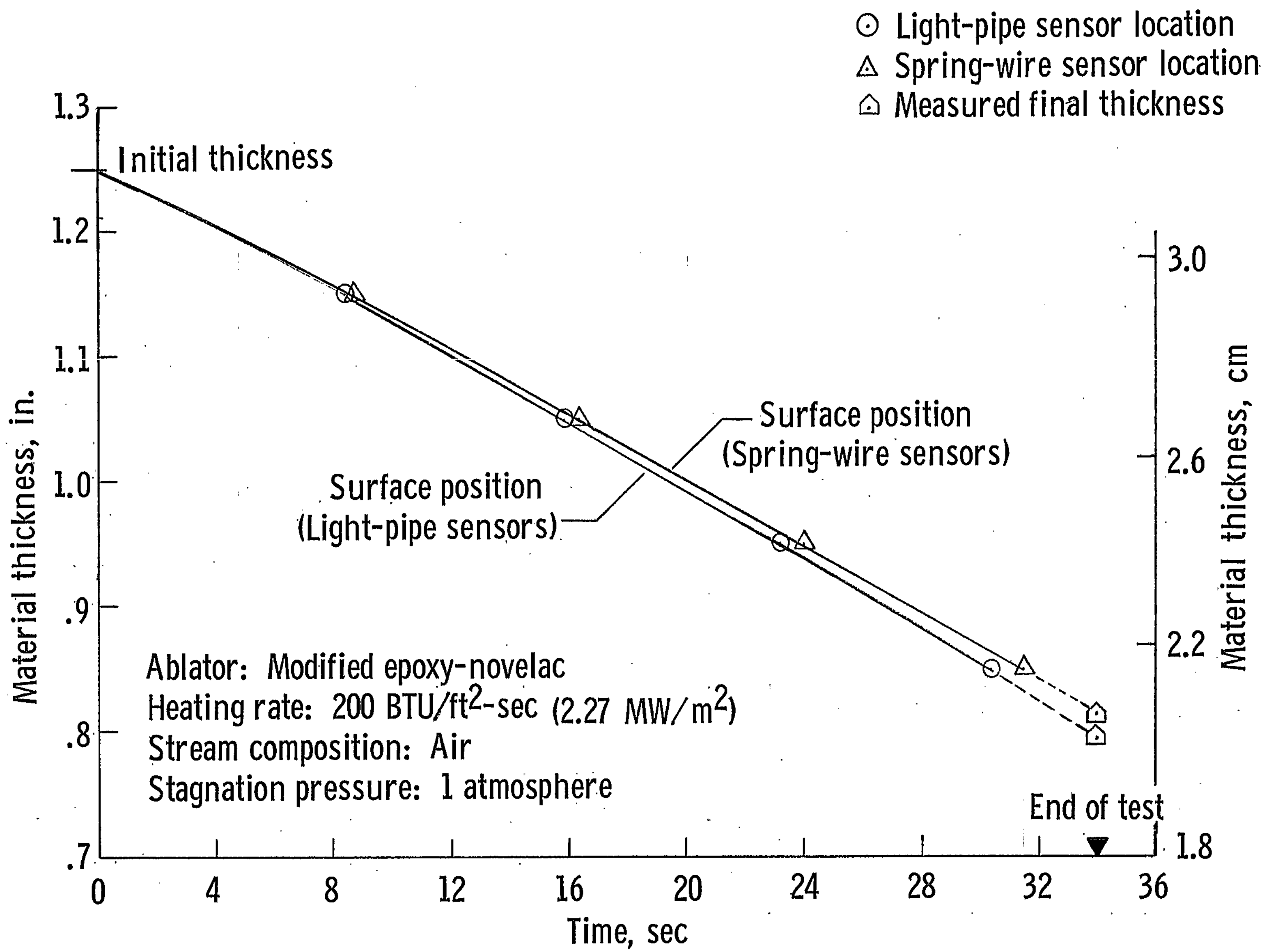

Figure 14.- Arc-jet test results of spring-wire and light-pipe sensors installed in the modified epoxy-novelac ablator.

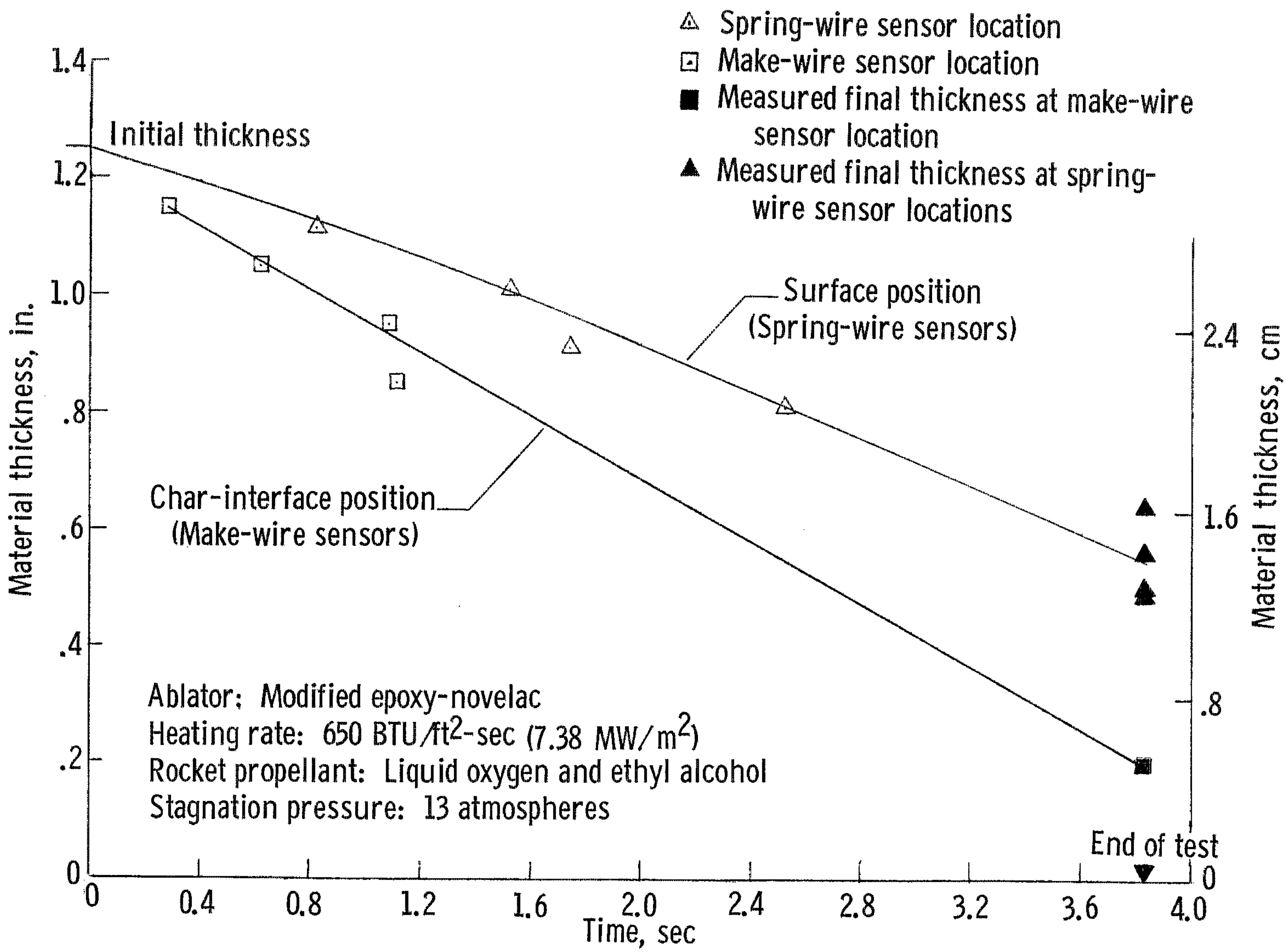

Figure 15.- Rocket-exhaust test results of make-wire and spring-wire sensors installed in the modified epoxy-novelac ablator.

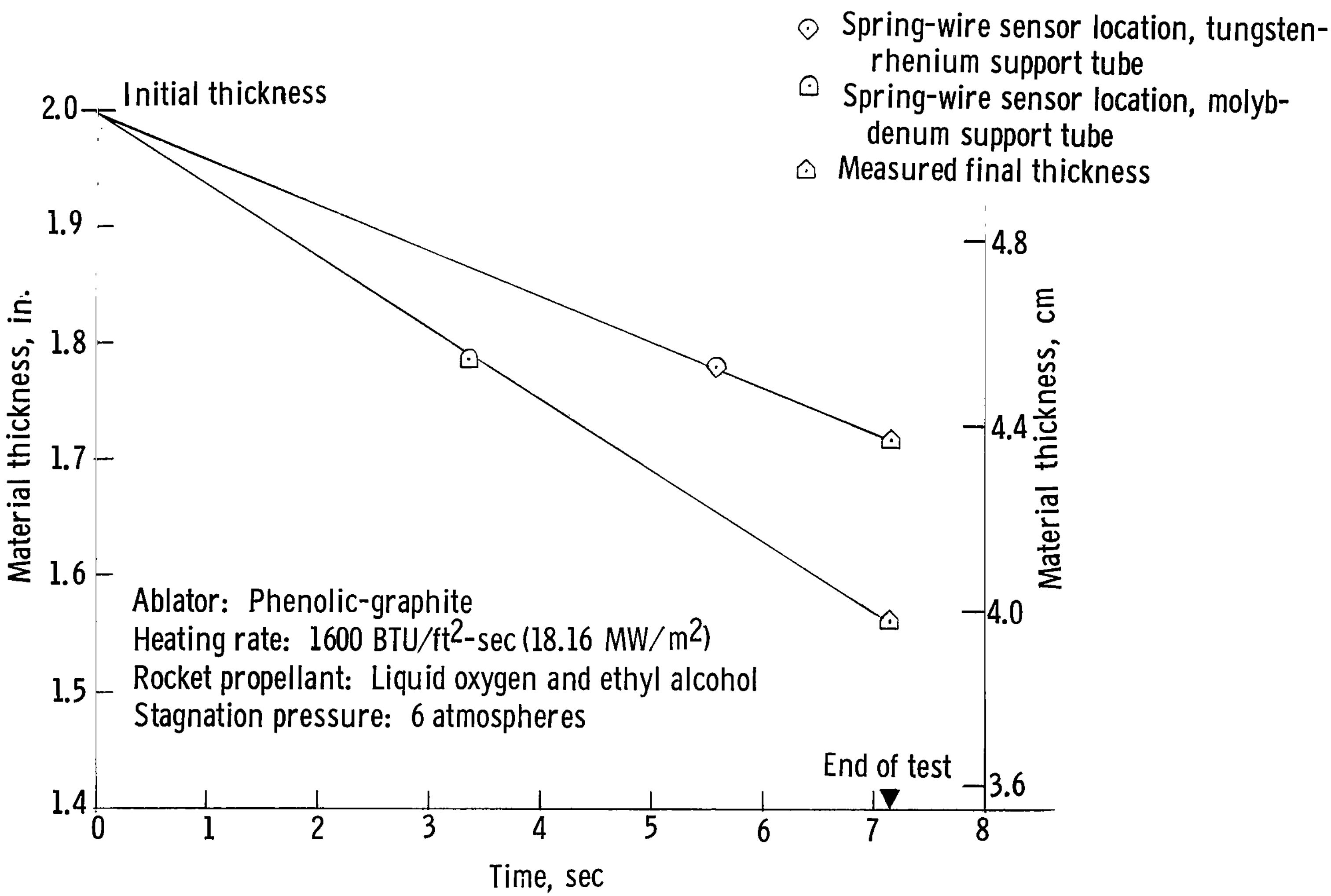

Figure 16.- Rocket-exhaust test results of spring-wire sensors installed in the phenolic-graphite ablator.

NASA-Langley, 1966 L-3681

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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