HEAT SHIELD INSTRUMENTATION:

DEVELOPMENT AND EVALUATION

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ABSTRACT

Methods and techniques for monitoring critical heat-shield parameters during spacecraft reentry have been developed and evaluated. The required instrumentation sensors for measurement of pressure, temperature distribution, incident heat flux, char, and ablation are discussed in detail. The calibration and data analysis, human and automatic, applied to the various sensors during simulated reentry evaluation are presented.

INTRODUCTION

When a spacecraft enters the atmosphere surrounding a planet, it has a high initial velocity which must be dissipated prior to impact. The atmosphere acts as a braking mechanism on the vehicle, converting kinetic energy of motion to heat. To protect the spacecraft from localized heating of boundary gas streams in the region of 10 000° F and above, which produce heat rates up to 600 Btu/ft^2-sec, thermal protection systems have been developed. These systems incorporate materials which absorb and dissipate the heat through various methods (re-radiation, decomposition, and insulation). The theoretical efficiency of these materials can be analytically determined with sufficient precision for current spacecraft programs, however, optimization of these systems, from the critical weight standpoint, must be achieved through dynamic information obtained during actual reentry.[1] Until comparatively recent space programs, analysis of the heat shield (thermal protection systems) has been accomplished through trial and error methods, utilizing material information gained from simulation of reentry conditions in ground test facilities and through spacecraft recovery analysis. Computers are extensively used in data reduction and analysis. To apply these techniques of material performance analysis to a nonrecoverable flight vehicle with any degree of accuracy, certain dynamic information must be obtained during actual reentry time. Generally, five material parameters are measured: ablation (surface recession), char (change in parent heat-shield material properties), temperature (surface and subsurface), incident heating rate (total heating rate input at the surface), and pressure (static).

The purpose of this paper is to discuss some of the sensing techniques and problems encountered on the Apollo Program in developing sensors for these measurement parameters.

INSTRUMENTATION

The instrumentation techniques used in measuring these parameters are closely related to the heat-shield material characteristics and the reentry environment variables. However, the basic sensor design and evaluation problems are common to all materials. The Apollo Program heat-shield material (AVCO no. 5026-39) is a phenolic/epoxy-bovalac material, compounded into a fiber-glass honeycomb. A typical measurement system-configuration is shown in figure 1.

Pressure

Static pressure measurements are made by using conventional precalibrated pressure sensors. The outside static pressure is channeled through the heat shield to the transducer, via a small-diameter tube. The major problems initially encountered were hole blockage caused by liquified heat-shield material, excessive erosion at the hole location, heat conduction by the air-tube to the temperature-sensitive pressure transducer, and slow response caused by damping. Most of the problems can be solved by using an alumina tube with a 45° bend for heat absorption, assuming a static or non-dynamic surface measurement is required.

Temperature

Subsurface and surface temperatures up to 5000° F can be measured by using tungsten/tungsten-26-percent rhenium thermocouples which have been flame-spray coated with zirconium diboride or hafnium oxide. The inaccuracy of these thermocouples is less than 3 percent for subsurface measurements and less than 7 percent for surface temperature measurements. The error caused by the thermocouple presence in the material has not been analytically determined; but because of the high char conductivity, it is estimated to account for most of the detectable error found when the thermocouple is exposed on the material surface during testing. Figure 2 shows the most acceptable sensor found for these measurements. The wire diameter is 0.005 inch and coating thickness is between 0.005 and 0.010 inch.

Superscripts refer to references listed at the end of the paper.

Incident surface heating rate

A discontinuous measurement of incident heating rate can be made by using a series of "stacked" calorimeters having an extremely fast response time (less than 100 milliseconds). The technique of heating-rate measurement is derived from the principles of Gardon calorimeters applied to sensing elements fabricated from flame-spray coated tungsten/tungsten-26-percent rhenium wires. A single sensing element is shown in figure 3. These elements are installed into a cylinder of heat-shield material in a manner similar to that used for the thermocouples shown in figure 2. The sensors tested to date demonstrated the technique feasibility, however, the calculated calibration exhibited inaccuracies up to 40 percent in some cases, as a result of inadequate stability of the reference junction. Modified sensor designs can reduce this error to a tolerable level of 10 to 15 percent; however, additional developmental testing is considered necessary prior to spacecraft application.

Char

The loss of virgin heat-shield material may be monitored in many ways, all dependent on the final temperature at which the material loses its effectiveness as a thermal insulator. The most effective, accurate, and only continuous method found to date utilizes a radioactive "line" source embedded in the heat-shield material.[2] The source consists of 5 to 10 mc mercuric sulfide (Hg^{203}) suspended uniformly in a filler material (Emcast 31-A) which is contained in a 0.0625-inch-diameter teflon tube. This mixture vaporizes at approximately 850° F (average heat-shield-material char temperature). Once change of state occurs, the source is outgassed along with the material low-temperature fillers. As the source is outgassed, the number of gamma emissions per second decreases proportionally. These emissions are counted by a miniature Geiger-Mueller (G-M) detection package which is remotely located and generates a 0 to 5.0 V-dc output signal. The basic system is shown in figure 4. An embedded source is shown in figure 5.

Ablation

Since the early ICBM reentry vehicles,[3] the most common method for measuring heat-shield-material surface recession (ablation) has been through the use of radioisotopes described in the preceding section on char measurements. The "line" source technique and electronics package are identical. The fundamental difference lies in the source behavior during material char and subsequent ablation. The ablation sensing element must follow the material surface contour as it recedes as opposed to following the decomposition zone as is the case with the char sensor. The complete element (tube, filler, activity) is required to have thermal characteristics similar in behavior to those ascribed to the heat-shield material. Serious deviations in these characteristics result in large measurement errors. The source consists of a 0.0625-inch-diameter alumina tube containing $cobalt^{60}$ or $gold^{198}$ suspended in a silicone filler (Dow Corning 325). The tube wall thickness and melting point are critical for an accurate measurement source, as is the uniform isotope distribution within the tube.

CALIBRATION TECHNIQUE AND TESTING

The validity (and therefore the data accuracy and reliability) of the calibration of a sensor is often misunderstood by the engineer. Since a complete understanding of the sensor calibration and resultant testing is required in the application of these sensors, a brief discussion of each is presented.

Temperature

The thermocouples (tungsten/tungsten-26 percent rhenium) can be calibrated before installation by using a vacuum furnace and checking the output against standard National Bureau of Standards conversion tables.[4] After installation, they can be checked up to 2200° F against chromel/alumel embedded thermocouples, and at 4000° F (or above) when exposed on the sensor surface. A non-emissivity sensitive ultra-violet radiometer, corrected for flame temperature, is used for sensor surface temperature measurement. Exposure time, accurate to 0.10 second, can be attained using motion pictures and good filters. Evaluation tests which are conducted outside of a vacuum furnace should attempt to simulate closely the reentry environment in order to maintain measurement validity gained in non-simulated environmental conditions.

Incident Surface Heating Rate

A Gardon sensor calibration can be applied to the calorimeters, as shown below:

$$Q = C_1 \Delta T = \frac{C_2 e_0 (1 + \beta T)}{k_0 (1 + \alpha T)} + f_1 (T_R, t)$$

Where

Q	incident heat rate in Btu/ft^2-sec
C_1, C_2	constants
e	thermoelectric potential
t	time
k	thermal conductivity
β	constant which defines variation of k with T
α	constant which defines variation of e with T

T   temperature

$f_1(T_R)$ constant dependent on reference junction temperature

0   subscript denotes initial temperature values

At the present time the second term in the equation is used to compensate for decreased sensor output caused by increased reference-junction temperature. This term can be empirically determined using any known radiant heating source by monitoring the rate of change of the reference junction temperature. The addition of this term has reduced the inaccuracy from 40 percent to 15 percent in laboratory tests. Tests conducted outside of a radiant heating facility should simulate reentry-environment conditions to maintain the validity of this calibration when applied to heat-shield measurements.

Pressure

The pressure sensor can be calibrated using a standard "dead-weight" testing facility. The validity of this calibration must be substantiated using the "pressure tube" in simulated reentry environmental conditions.

Char and Ablation

The char and ablation sensors are calibrated by plotting the source length against radioactivity, and radioactivity against instrument output. The source is cut into 10 equal segments, which are checked for uniformity of radioisotope. The segments are then placed in their original order and mounted on a platform having the required shielding geometry. While monitoring the output continuously, segments are removed, resulting in a series of discrete step functions (0.5 mV per step), with each step representing removal of a known amount of radioactivity. A smooth curve of distances plotted against voltage can be obtained by extrapolation between steps. The sensors can be checked in simulated reentry conditions generated by plasma arcs using non-activated sources and measuring end points by X-ray and sectioning analysis. Activated sensors can be dynamically checked in partially simulated conditions generated by oxyacetylene torches. The inaccuracy σ_r resulting from statistical fluctuation present in any nuclear counting system is given by [5]

$$\sigma_r = \sqrt{\frac{r}{2RC}}$$

where

σ_r counting error per second

r   number of counts per second

RC   time constant of counter

Generally, this error represents less than 0.040 inch (2 percent) for a 3000 count-per-second, 2-inch-long sensor. The error resulting from non-uniform distribution of radioisotope is approximately 3 percent. The total system error is 5 percent or less of the total measurement length.

Sensor Qualification Testing

The qualification testing of these sensors should be designed with two specific purposes in mind. First, to determine the degradation of the calibration curve of the sensor caused by the reentry environment (effects of shear, oxidation, temperature, etc.); and second, to generate a sufficient quantity of experimental data with which to express the measurement parameters in terms of reentry conditions. Since the maximum value of the reentry variables which can be expected to influence the sensor (surface temperature, heating rate, enthalpy, shear, and oxygen partial pressure) occur at different real times, it is possible to use several different types of test facilities for reentry simulation heating. In particular, three facilities lend themselves very well to generation of acceptable environmental conditions for evaluation of heat shield-sensors. They are plasma arc-jets, oxyacetylene torches, and low-pressure rocket-exhaust chambers. Table I lists 24 "test" points obtained from this combination of facilities. The number of test points required to provide sufficient data for parameter analysis of the sensors is determined by the number of environmental variables and their range. It has been found that all four sensors should be subjected to approximately identical test conditions in order to provide adequate correlation between the data. Figures 6 to 9 are typical output signals for temperature, heat-flux, ablation, and char sensors which were tested in simulated environments. Figure 10 is a composite curve using data from all four sensors.

DISCUSSION OF DATA ANALYSIS

The analysis of test data generated by the sensors during simulated reentry conditions can be divided into two separate categories, human and automatic.

Human Analysis

Human analysis uses primarily physical operations (such as sectioning, dimensional measurement, data conversion, and plotting) and visual observations (such as curve slopes, X-ray analysis, output continuity, and motion pictures) based on engineering judgment. From this type of analysis general conclusions may be inferred pertaining to materials compatibility, basic sensor design, accuracy of calibration, reliability within the test environment, and gross environmental effects. It has been observed that during relatively high shear forces (above ¼ lb/sq ft) thin circular disks tend to "pop" out rather than ablate continuously. At low heating rates (less than 50 Btu/ft^2-sec), char formation becomes continuous, and the decomposition "line" becomes a wide band as a result of absence of observable ablation and low surface temperatures (approximately 2500° F). At high heating rates (500 Btu/ft^2-sec) most materials tend to melt or oxidize below the surface, and char and ablation rates approach steady-state values, which tend to remain constant over wide variations of surface conditions. Deviations from the sensor calibration curve can usually be determined in this phase of analysis by complete failure of the sensor or by large errors between sensor data and whatever is used as a standard reference. For example, uninsulated tungsten/tungsten-26-percent rhenium thermocouples repeatedly indicated material surface temperatures of 3000° F. However, optical monitoring devices showed the true temperature to be in the 4000° F to 4500° F range. This difference constitutes a 33-percent error. When measured with insulated thermocouples, surface temperatures recorded ranged from 4200° F to 4500° F, with the observed error being between 5 and 7 percent.

Human analysis can be used to screen designs, determine basic calibration errors, and establish minimum levels of confidence for measurement integrity and reliability. For manned spacecraft applications, higher confidence levels are required.

Automatic Analysis

Automatic analysis implies the use of data processing equipment such as computers and CR plotters. Computer programs have been written to evaluate heat-shield materials in terms of the measured temperature distribution within the material as opposed to environmental parameters. One such program, using "regression analysis" techniques, has been previously used in the Apollo Program. It would appear that similar analysis techniques could be used to increase confidence levels of sensors tested in the partially simulated reentry environments of present ground test facilities and that this same program could be used to establish a "standard" reference with which to compare the output from each type of sensor. A program is currently being written to accomplish these aims, using the Manned Spacecraft Center 7094 computer. The physical aspects of the program are as follows:

1. Each type of sensor is tested in near identical conditions generated by plasma-arc-jets, oxyacetylene torches, and low-pressure rocket exhaust chambers.

2. The test conditions selected are maximums, minimums, and several intermediary points of each major environmental variable (shear, heat rate, enthalpy, oxygen partial pressure, and total pressure.)

3. The total test data, environment and sensors output, are processed by the computer to yield an equation of the form

$$f(xt) = a_1 + a_2 (y_1t) + a_3f (y_2t) + . . . + a_nf_i (y_nt)$$

where

x measured parameter variable (temperature, ablation, char, and incident heat rate)

a constants

y environmental variables

t time

For a given set of environmental conditions (y_1, y_2, . . . y_n) operating for a given time interval Δt, the summation has a positive, increasing value as t increases. It is then possible to substitute end-point values for three left-side variables and plot the fourth for a given time interval. This value of $f_4(xt)$, which is computed using the data from the other three sensors, can be directly compared with the data generated by the sensor measuring $f_4(xt)$. This technique has yielded information concerning the influence of environmental parameters on the sensor output. Additional computer time will be required to demonstrate that the summation has unique values for increasing time.

SUMMARY

The necessity for evaluation of heat-shield materials during actual spacecraft reentry has provided the stimulation for developing specialized instrumentation and calibration techniques.

To satisfy these spacecraft requirements, special installation designs, calibration techniques, and data analysis methods have been developed for pressure, temperature, ablation, char, and heat-rate measurements.

From information obtained by these sensors, it may become possible to reduce the time and cost involved in heat-shield material selection and qualification; to understand more accurately the physics of reentry and thereby predict reentry environments with higher confidence levels, and to design other more accurate sensors with which to increase the overall manned spacecraft thermal protection system analysis.

ACKNOWLEDGEMENT

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TABLE I.- SIMULATED ENVIRONMENT TEST CONDITIONS - TEST POINTS AND ENVIRONMENTAL CONDITIONS

Test-point number	Test facility	Heat rate, Btu/ft^2-sec	Enthalpy, Btu/lb	Stagnation pressure, lb/sq in.	Shear lb/sq ft	Source atmosphere	Source gas	Distance, in.
1	Oxyacetylene torch	100	1.4×10^3	15.75	0.180	Oxidizing	O_2-C_2H_2	0.75
2	Oxyacetylene torch	150	1.36×10^3	17.10	0.325	Oxidizing	O_2-C_2H_2	1.00
3	Oxyacetylene torch	200	0.95×10^3	15.57	0.235	Reducing	O_2-C_2H_2	2.00
4	Oxyacetylene torch	250	1.21×10^3	16.20	0.350	Oxidizing	O_2-C_2H_2	3.00
5	Oxyacetylene torch	300	2.23×10^3	16.20	0.225	Reducing	O_2-C_2H_2	3.00
6	Oxyacetylene torch	300	1.30×10^3	16.50	0.345	Oxidizing	O_2-C_2H_2	1.00
7	Plasma-arc	53	5.13×10^3	8.70×10^{-2}	> 5	Oxidizing	Air	3.00
8	Plasma-arc	53	5.03×10^3	8.67×10^{-2}	> .5	Reducing	N_2	3.00
9	Plasma-arc	145	10.24×10^3	17.79×10^{-2}	> .5	Oxidizing	Air	3.00
10	Plasma-arc	145	10.14×10^3	13.07×10^{-2}	> .5	Reducing	N_2	3.00
11	Plasma-arc	261	13.16×10^3	32.00×10^{-2}	> .5	Oxidizing	Air	3.00
12	Plasma-arc	261	13.12×10^3	32.00×10^{-2}	> 5	Reducing	N_2	3.00
13	Plasma-arc	293	20.82×10^3	17.24×10^{-2}	> .5	Oxidizing	Air	3.00
14	Plasma-arc	293	20.21×10^3	17.34×10^{-2}	> .5	Reducing	N_2	3.00
15	Plasma-arc	325	16.11×10^3	27.09×10^{-2}	> .5	Oxidizing	Air	3.00
16	Plasma-arc	400	25.50×10^3	44.10×10^{-2}	> 5	Oxidizing	Air	3.00
17	Plasma-arc	390	24.90×10^3	42.00×10^{-2}	> .5	Reducing	N_2	3.00
18	Rocket engine	60	3.51×10^3	12.87	0.55	Oxidizing	N_2/O_2	*0
19	Rocket engine	97	1.71×10^3	13.07	1.10	Oxidizing	N_2/O_2	*12.5
20	Rocket engine	97	2.68×10^3	14.00	1.17	Oxidizing	N_2/O_2	*12.5
21	Rocket engine	110	3.41×10^3	13.00	1.20	Oxidizing	N_2/O_2	*12.5
22	Rocket engine	200	2.31×10^3	13.11	2.40	Oxidizing	N_2/O_2	*0
23	Rocket engine	200	1.12×10^3	13.75	3.75	Oxidizing	N_2/O_2	*12.5
24	Rocket engine	[illegible]	[illegible]	14.00	[illegible]	Oxidizing	N_2/O_2	*12.5

*

NASA-S-65-7442

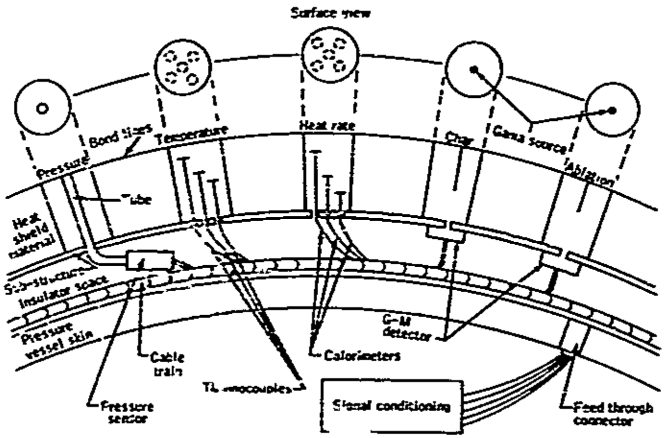

Figure 1. - Heat shield instrumentation system

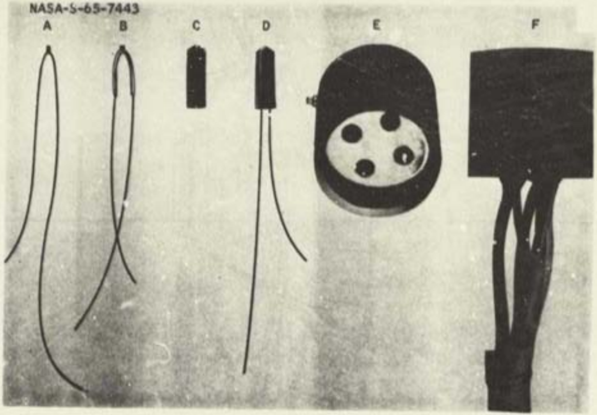

Figure 2. - Temperature sensor

NASA-S-65-7444

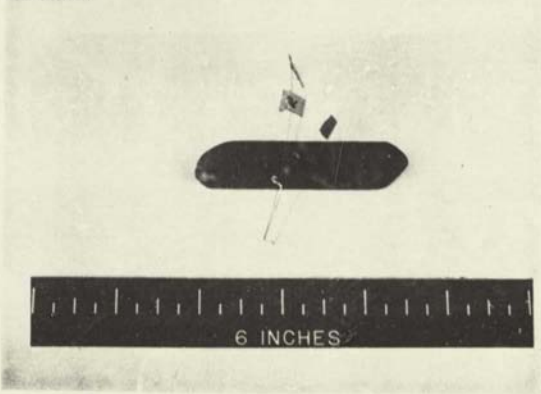

Figure 3. - Calorimeter sensing element

NASA-S-65-7445

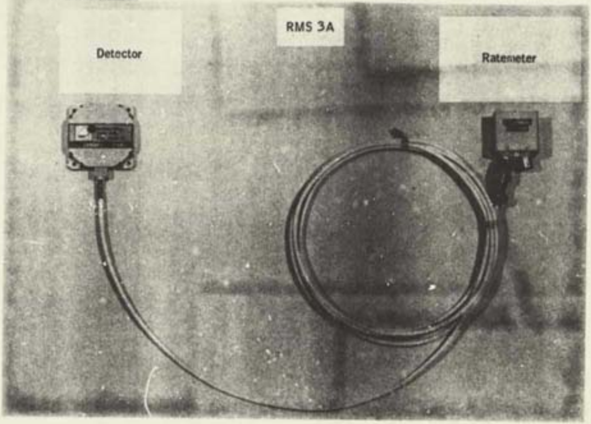

Figure 4. - Ablation/char measurement system.

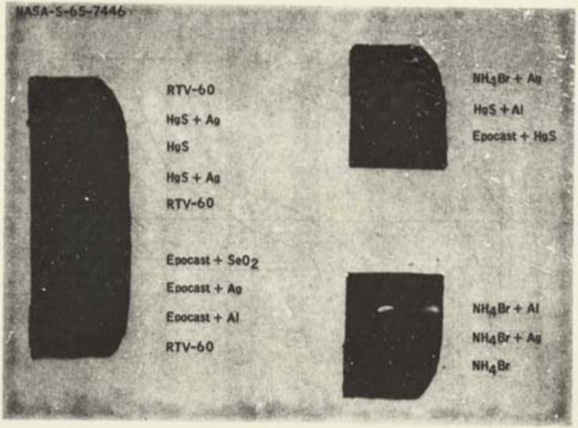

Figure 5. - Radioactive line source

NASA-S-65-7447

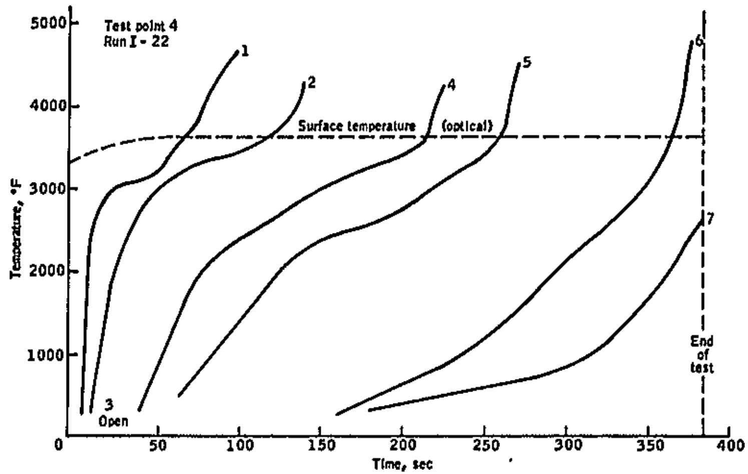

Figure 6. - Typical temperature history of thermal gradient sensor.

NASA-S-65-7448

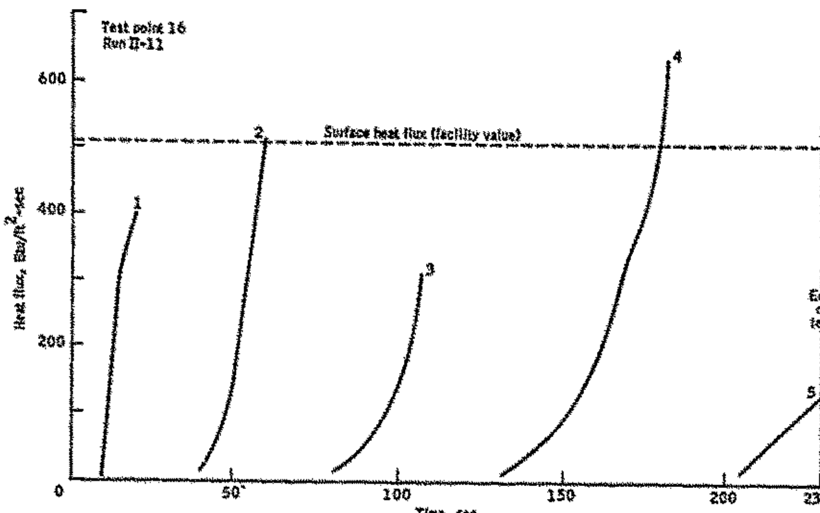

Figure 7. - Typical heat flux history of ablataflux sensor

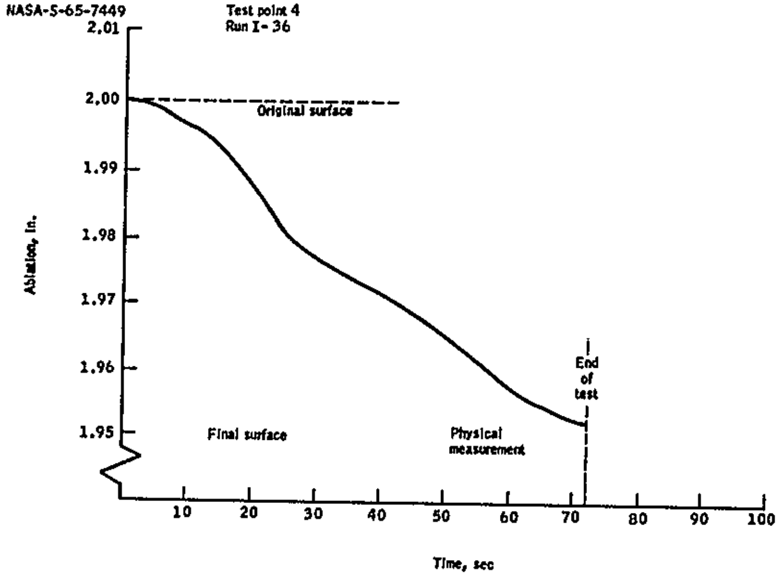

Figure 8. - Typical ablation history of ablation sensor

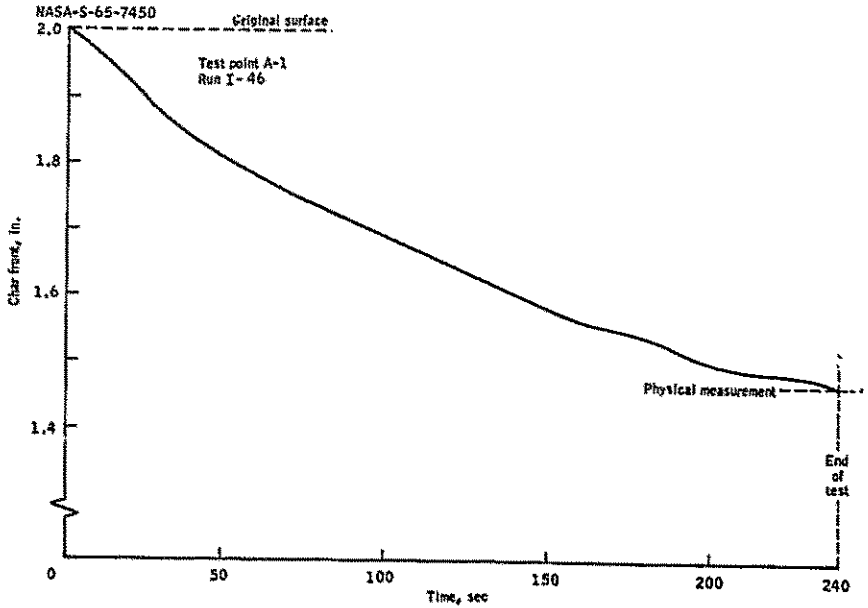

Figure 9. - Typical char history of char sensor

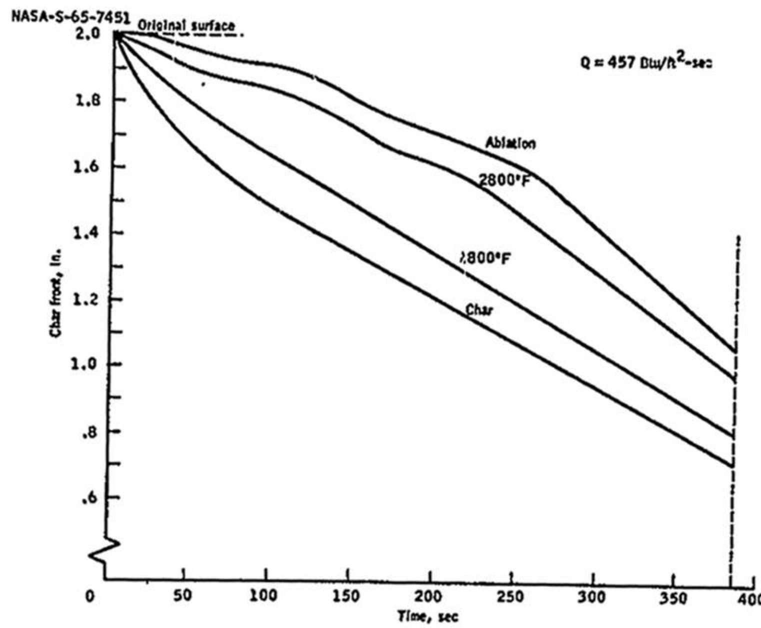

Figure 10. - Composite curve