HEAT TRANSFER MEASUREMENTS IN A HOT SHOT WIND TUNNEL

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HEAT TRANSFER MEASUREMENTS IN A HOT SHOT WIND TUNNEL

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A rugged reliable instrument has been utilized for obtaining surface temperature time histories on various aerodynamic configurations in the McDonnell Hypervelocity Impulse (Hot Shot) Tunnel. These instruments are thin film surface thermocouples capable of very rapid response to temperature fluctuations and have been utilized without failure during extended test programs. Some of these instruments, located in stagnation regions, have been exposed to more than 100 runs without failure or change in their temperature EMF calibration. A run is nominally of 100 milliseconds duration.

A computer program has been designed which can accept the raw data temperature time history from the surface thermocouple and compute the resulting heat transfer rate. The program utilizes the theory for conduction of heat in a semi-infinite slab and requires the thermal constants of the substrate as inputs. This program has provided the required versatility for handling the multifarious temperature time history shapes generated by the aerodynamic flow processes of the Hypervelocity Impulse Tunnel.

Heat transfer rates ranging from 0.1 to 900 watts/cm2 have been determined using these instruments. Sensitivity to input heat flux is established by the instrument's temperature-EMF relationship and substrate thermal properties. Low heat transfer rates of 0.1 and 1.0 watt/cm^2 have been determined within ±10 percent uncertainty with instruments utilizing Pyrex and Chromel substrates, respectively.

LIST OF SYMBOLS

k = thermal conductivity

Q= integrated heat transfer

Q_j = a sequence of heat transfer values

Q_t = integrated heat transfer from time
$\tau = 0$ to time $\tau = t$

q = heat transfer rate (heat flux)

T = temperature

t = time

t_i = a time sequence

X = distance

α = thermal diffusivity

τ = a time variable of integration
τ_1 = a time sequence corresponding to temperature data sampling

INTRODUCTION

Determination of heat transfer rates experienced during operation of the McDonnell Hypervelocity Impulse Tunnel has been accomplished through the measurement of surface temperatures on appropriate aerodynamic configurations.

The McDonnell Hypervelocity Impulse Tunnel, Figure 1, is an arc driven impulse tunnel of the Hot-Shot variety having a Mach range of 12 thru 26 and a Reynolds number range of 9×10^5 thru 9×10^6/m. Aerothermodynamic measurements are obtained in an open jet test section of 1.04 and 1.14 meters diameter at the end of contoured and conical nozzles respectively. Run durations range from 80 to 150 milliseconds. Time history measurements of transient surface temperatures in this test facility permit determination of heat transfer rates which provide an input for the calculation of stagnation enthalpy and a method for determining heating of various aerodynamic surfaces.

Transient hypervelocity testing requires a coordinated system of transducers, amplifying and recording equipment, and computing techniques for producing useful data. This requirement has spurred the development of transducers and mathematical programs consistent with accurate measurement and data programming of surface temperatures. Discussion and review of these efforts are contained herein.

Early efforts utilizing slug calorimeters indicated the instruments to be incapable of rapid response to sudden temperature changes. In addition, calibration procedures requiring a standard heat flux proved inconsistent. Efforts to resolve or compensate these difficulties did not provide a satisfactory confidence level in the heat transfer data. Therefore, in order to improve the confidence level and broaden the capabilities for determining heat transfer rates, an investigation of new techniques was initiated. An obvious direction was the exploration of the thin film resistance gages as used by a number of transient test facilities. This type instrument was quickly proven unsatisfactory because of its calibration change or total destruction due to the contamination phenomena associated with the arc driven Hypervelocity Impulse Tunnel and was subsequently abandoned. Further investigation suggested the use of thin film thermocouples. This technique employed by Bendersky (1) for the determination of surface temperatures in machine gun barrels was mentioned by Vidal (2) as having been briefly evaluated by Cornell in their Hypersonic Shock Tunnel in 1956 and abandoned because of the instruments' low temperature sensitivity. Since there are significant differences between arc driven impulse tunnels and shock tunnels in terms of stagnation pressure and run duration, it was decided that surface temperature thermocouples should be evaluated in the Hypervelocity Impulse Tunnel. Surface thermocouples were subsequently obtained commercially from Mo-Re Incorporated[1] and evaluated operationally. They proved to be rugged, reliable, and versatile instruments for measuring surface temperature histories. They are especially reliable with respect to calibration stability and long life under operational test conditions. Some of the instruments incorporating metal substrates have been used for well over 100 runs at the stagnation point of test models with no significant change in calibration.

These instruments have been fabricated with substrates of either metal or glass according to the magnitude of heat transfer rates they are expected to experience. Metal substrate gages have been used to measure surface temperatures corresponding to heat transfer rates as high as 900 watts/cm^2 and glass substrate gages to measure temperatures corresponding to heat transfer rates as low as 0.1 watts/cm^2.

Since their diameters are small, 0.16 cm, the gages measure temperatures of a small area and may be placed in many surfaces without introducing significant discontinuities in the surface of interest. If required, the gages can be fabricated with smaller diameters or can be contoured to meet requirements of specific surfaces.

A computer program to reduce heat transfer data was developed to precisely follow arbitrary temperature inputs which correspond to heat fluxes markedly different from a step heat flux. Other desirable features obtained are a simple computing process and a stable output with respect to noise superimposed on the temperature record.

SURFACE THERMOCOUPLES

The surface thermocouples presently employed in the McDonnell Hypersonic Impulse Tunnel were fabricated by Mo-Re Incorporated[1] according to the principles developed by Hackeman (3) and Bendersky (1). The fundamental instrument, Figure 2, is comprised of an insulated constantan wire fixed concentrically within a Chromel-P[2] tube. One end of the concentric tube and wire arrangement is ground and polished until there is no connecting metal between them. The polished surface is then plated with a thin film (1 to 1.5 microns) of chromium using vapor deposition methods. The chromium plating establishes the thermoelectrical junction at the interface of constantan wire and Chromel-P[2] tube.

In the McDonnell Hypervelocity Impulse Tunnel this instrument is used in the flow stagnation regions of the various test configurations where heat transfer is highest. Under these conditions surface temperature rises are from 10 to 100°C depending on model configuration and tunnel flow conditions. Corresponding heat transfer rates of 4 to 900 watts/cm^2 are achieved.

An extension of this instrument concept is shown in Figure 3. This device, with a Pyrex[3] 7740 substrate, is used for determining lower heat transfer rates than can be determined with the previously discussed surface thermocouple. As shown in Figure 3, the two thermocouple leads are extended through the substrate; one end of which is then ground and polished smooth. The thermoelectric junction is subsequently formed by very rapid vapor deposition of overlapping Chromel-constantan thin films. Note that the thermoelectric junction is formed only over the Pyrex substrate. This instrument has been used to determine heat transfer rates of 0.1 watt/cm^2 ±0.02 watt/cm^2. Uncertainty of ±0.01 watt/cm^2 is possible.

This particular technique caused concern for the possibility that vapor deposition of the Chromel constantan alloys would alter their chemical composition and their temperature EMF characteristics. Therefore, a transient calibration was performed with an apparent precision within ±10 microvolts. This test showed no deviation from standard Chromel-constantan thermal EMF and indicated that the gages could be used with confidence.

Figure 4 shows a modification of the Pyrex[3] substrate surface thermocouple which is aimed at eliminating frequent breakage of this instrument particularly during installation in a test specimen. Note from Figure 4 that the actual thermocouple is "floating" above ground in an effort to eliminate electrical noise from the system. Also, it is pointed out that this instrument's substrate need not be Pyrex[3], but can be any homogeneous solid with suitable thermophysical properties and fabrication characteristics.

A photograph of the two types of surface thermocouples is presented as Figure 5.

TESTING AND UTILIZATION OF SURFACE TEMPERATURE THERMOCOUPLES

The standard surface thermocouples (Chromel substrate) were calibrated for their temperature-EMF relationship by maintaining their reference

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[1] Mo-Re is a registered trademark for surface thermocouples now manufactured by Heat Technology Laboratories (HTL) of Huntsville, Alabama. (NOW AT MEDTHERM CORP.)

[2] Registered Trademark, Hoskins Manufacturing Company.

[3] Registered Trademark, Corning Glass Works.

temperature at 0°C and then immersing them into an oil bath of controlled temperatures. The thermocouple output voltages were recorded as a function of oil bath temperature. Final calibrations have shown excellent repeatability and agreement with National Bureau of Standards Calibrations. Repeat calibrations of these instruments after extensive use have shown no significant change.

As pointed out by Marshall et al. (4) the thermal EMF produced by vapor deposited metal-metal alloy film thermocouples is generally less than the thermal EMF produced by bulk materials. In the devices shown in Figure 5 there is no problem unless lateral surface temperature gradients form near the thermocouple wires in the Pyrex substrate, but the possibility of such gradients is the principle reason for forming the junction on the surface between the wires by vapor deposition of thermocouple alloys. If the combined effects of lateral temperature gradients and deviations from standard Chromel-constantan thermal EMF were observable, it would be impossible to define a unique transient surface temperature, Therefore, it is necessary to determine the magnitude of the combined effects or to show that one is zero.

An experimental approach was attempted to resolve the question. Gold-nickel and Chromel-constantan thermocouples of the type shown in Figure 5 were compared under conditions which were identical within ±1 percent. Pure metals were selected for the reference thermocouples on the assumption that 1 micron thick films of pure metals would more nearly exhibit bulk material properties than would alloy films where alloy composition may have changed in the vapor deposition process. Both sets, gold-nickel and Chromel-constantan thermocouples, were statically calibrated in a stable oil bath with 20 calibration points from room temperature to 90°C. The calibration accuracies were within 0.1°C in temperature and 1 microvolt in EMF for each point.

The gold-nickel film thermocouple served as a reference in a transient performance comparison. Equal radiant heat pulses from a projection lamp were applied to the surface thermocouples and amplified output temperature histories were recorded. Based upon the transient responses and the static calibration of the gold-nickel reference, the transient response of the Chromel-constantan film thermocouple up to 2.5 millivolts output agreed with standard Chromel-constantan tables within a 10 microvolt noise band.

Conclusions drawn from the results of this experiment are:

(a) The Chromel-constantan film was equivalent to bulk Chromel-constantan,

(b) No significant surface temperature gradients were produced, or

(c) By coincidence equal deviations were produced in the three gold-nickel and five Chromel-constantan thermocouples tested.

Following calibrations', the surface thermocouples are installed in appropriate model configurations to be used for obtaining pertinent data. An installation in a basic hemisphere cylinder configuration utilized primarily for determination of stagnation enthalpy is shown in Figure 6.

After installation of the surface thermocouples, the model is placed in the wind tunnel test section for testing. Subsequent data in the form of temperature histories is then evaluated by an IBM 7094 computer program in order to obtain heat flux histories from Equation (9) discussed in the following section.

A schematic showing the thermocouple instrumentation system is shown in Figure 7.

Results of a test are shown in Figure 8 which presents temperature-time histories and subsequent heat transfer histories from the experimental measurement and subsequent data analysis. The Chromel substrate gage described in Figure 2 was used to obtain this temperature data which is typical for leading edge positions in the Hypersonic Impulse Tunnel. Note that the heat flux level is of the order of 100 watts/cm^2.

In Figure 9 a small portion of data is shown for a low heat flux condition. A Pyrex[3] substrate gage of the type shown in Figure 3 was used to obtain the temperature curve from which this data was obtained. The heat flux shown here is 2 to 3 orders of magnitude less than the data in the previous figure yet the quality remains high.

PROGRAM FOR DETERMINING HEAT TRANSFER

Heat transfer, like electric power, is the rate of energy transfer. Heat transfer, however, is not measured as is electric power. Instead, temperature is measured at a point or in a region and the thermal energy transfer is calculated from temperature changes or differences. In order to determine heat flux to a body, temperature sensors are designed with consideration of the thermal and geometric factors which lead to exact or nearly exact solutions to a mathematical model. Mathematical models are classed as either transient or steady state, and in general, the steady state solutions are less complex. Therefore, in heat transfer determinations, steady state measurements are considered first. When steady state measurements are not feasible, much attention is given in the design of test devices for compatibility with minimum complexity of the transient mathematical solutions.

The thermocouple devices described earlier are necessarily transient devices which provide precise data where no steady state devices are applicable. For the surface thermocouples which are used in the McDonnell Hypervelocity

Impulse Tunnel, the one dimensional semi-infinite slab mathematical model is used. This model provides a solution to the partial differential equation for thermal diffusion Equation 1.

$$\partial T/\partial t = \alpha\nabla^2 T = \alpha\,\partial^2 T / \alpha x^2 \qquad (1)$$

Appropriate boundary conditions are stated in Equations (2), (3), and (4), or (5).

$$q = -k\,\partial T/\partial x \qquad (2)$$

$$T(x, o) = 0 \qquad (3)$$

$$T(\infty, t) = 0 \qquad (4)$$

$$q\,(\infty, t) = 0 \qquad (5)$$

Equation (1) states that the partial derivative of temperature with respect to time is equal to the thermal diffusivity times the second partial derivative of temperature with respect to distance and that heat is conducted only in the x direction. Equation (2) defines heat flux as the negative product of thermal conductivity and temperature gradient. Equation (3) requires that the initial temperature is uniform and arbitrarily zero. Equations (4) and (5) state that the heat pulse never reaches the back of the instrument in time t. The model presented is of infinite extent in the x direction which corresponds to the axial direction of the instruments. Obviously, the thermocouples being used are finite in length. Therefore, the time must be short for which the model and thermocouple response are compatible and it is necessary to know the order of magnitude of that time during which the substrate behaves as an infinite slab.

From the extensive discussions by Carslaw and Jaeger (5) and Parker at al. (6) it is observed that the time $t_{0.1} = 0.1\ X^2/\alpha$ may be taken as a rule of thumb for the time which the semi-infinite slab model is applicable, for the thermal pulse at the back of the slab is very weak at shorter times. As an example, t0.1 is about 500 milliseconds for a Chromel-P^2 slab 0.5 centimeters thick. By the time $t_1 = X^2/\alpha$ the semi-infinite slab theory has broken down and the temperature rise at the back of the slab is significant. At this time a transient solution is still applicable, but a different one from the infinite solution presented.

The heat transfer solution to Equations (1) through (5) is given by

$$Q\,(o, t) = \frac{k}{(\alpha\pi)^{1/2}} \int_0^t \frac{T(o, \tau)\, d\tau}{(\, t - \tau\,)^{1/2}} \qquad (6)$$

Equation (6) is the integrated or cumulative heat transfer to a surface from time zero to time t. T(0, τ) is the surface temperature history. The integral is convergent for any continuous temperature function. Where T(0, τ) is analytic, and the heat flux is the time derivative of the cumulative heat transfer function.

$$q\,(o, t) = \partial Q(o, t) / \partial t \qquad (7)$$

The results are easily verified by completing the following integration

$$T(o, t) = \frac{(\alpha)^{1/2}}{k(\pi)^{1/2}} \int_0^t \frac{q\;(o, r)\, d\tau}{(t - \tau)^{1/2}} \qquad (8)$$

which is the temperature solution to Equations (1) thru (5).

The heat transfer solution becomes quite practical when the integral in Equation (6) is converted to the summation given in Equation (9) for computer evaluation.

$$Q_t = \frac{k}{(\alpha\pi)^{1/2}} \sum_{i=0}^{t/\Delta t} \left[\frac{T(\tau_i) + T(\tau_{i+1})}{(t-\tau_i)^{1/2} + (t-\tau_{i+1})^{1/2}} \right] \Delta t \qquad (9)$$

In Equation (9) the T_τ values are the times at which experimental temperatures, T(τ)are given and the value Q_t is the total heat transfer to time t. The summation is repeated at successive times t_j to produce a sequence of heat transfers Q_j which are sectionally curve fitted to produce an analytic function Q(t). Analytic heat functions q(t) are obtained by differentiating the fitted Q(t) functions.

The series given by Equation (9) converges very well, usually to 1 percent within ten data inputs and is stable about a point of discontinuity in heat flux to the surface.

SYSTEM ACCURACY CONSIDERATIONS

Temperature measurement precision is controlled by the recording system noise level and the proper selection of scale factors. The precision obtained using standard thermocouple materials and the present recording system is 2 percent of the selected temperature range with a lower limit of resolution on the order 0.1°C. The scatter in total heat transfer data is proportional to the temperature data scatter and the thermal property term appearing in Equation (9).

The precision in heat flux, however, depends upon a statistical analysis of a curve fitting to a segment of the heat transfer data. Under optimum conditions 3 percent precision in heat flux has been attained as indicated in Figure 10. At the extreme, the 0.1 watt/cm^2 see level, the precision was 20 percent. This reported precision is not a limitation imposed by the gage itself since the noise observed is produced by data recording and processing equipment. The range of measurable heat flux depends strongly on the time scale and the shape of the temperature history.

Three dimensional heat transfer effects are under investigation. However, these effects are expected to be small.

Since the thermal properties of constantan are not very different from Chromel-P[2], and since the mass of the constantan is quite small with respect to the Chromel-P[2], no corrections are made to compensate for the presence of constantan as part of the semi-infinite slab.

The major sources of error characteristic of the system discussed within this paper arise from recording system noise, uncertainties in thermal properties, and thermal conductivity variations with temperature.

RESULTS AND CONCLUSIONS

The surface temperature thermocouple has proven itself to be a useful tool for the determination of heat transfer rates experienced in the McDonnell Hypervelocity Impulse Tunnel. These instruments, their associated support equipment and data reduction procedures have provided the groundwork for the analysis of the system capabilities and limitations outlined in the following paragraphs.

1. Heat transfer rates throughout the range 0.1 thru. 900 watts/cm can be determined within ±10 percent and 5 percent respectively in the McDonnell Hypervelocity Impulse Tunnel.

2. The instruments have proven to be operationally durable. The Pyrex3 substrate gage requires physical protection during handling as suggested by Figure 4. The Pyrex[3] gages have frequently been damaged during their installation because of inadequate protection to the small, fragile substrate.

3. Thermocouple calibration and impedance has not been changed as a result of continued use or contamination deposits on its surface.

4. The data reduction program is providing excellent computation of heat transfer from input time histories. However, problems are occasionally encountered with the technique employed for curve fitting the heat transfer histories for reliable determination of heat transfer rates.

5. An extensive program for precise evaluation of the Pyrex[3] gages has not yet been conducted. The results to date are very encouraging and a complete operational program is being planned for their evaluation.

Thus far this investigation has provided confidence in the utility of the surface thermocouple as an instrumentation concept compatible with the transient measurements associated with the McDonnell Hypervelocity Impulse Tunnel. The "standard" instrument is regularly used as part of the basic instrumentation for determining the test section flow parameters. Further study and evaluation continues in an effort to improve the existing confidence level and expand the capabilities of this instrumentation concept.

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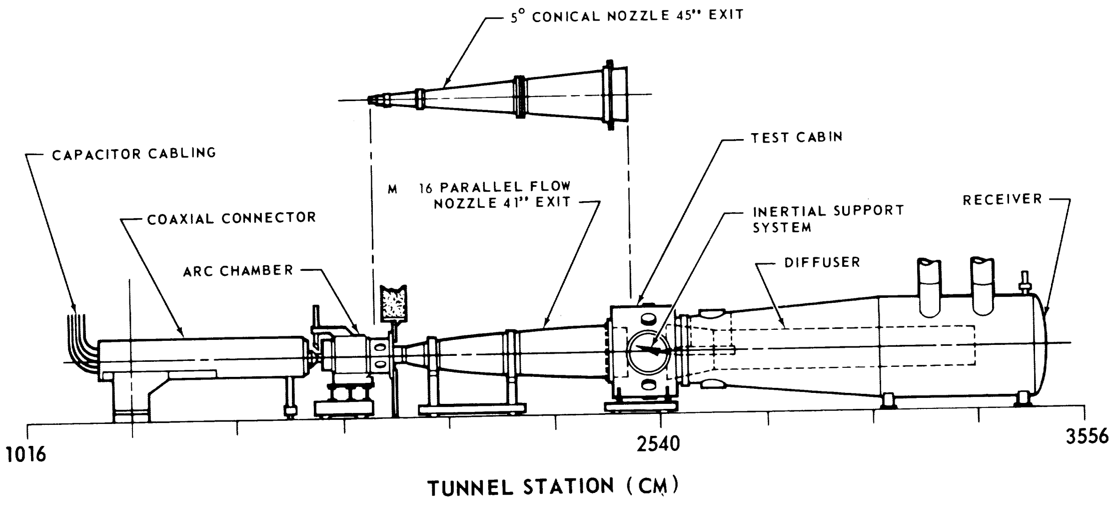

FIGURE 1 MCDONNELL HYPERSONIC IMPULSE TUNNEL

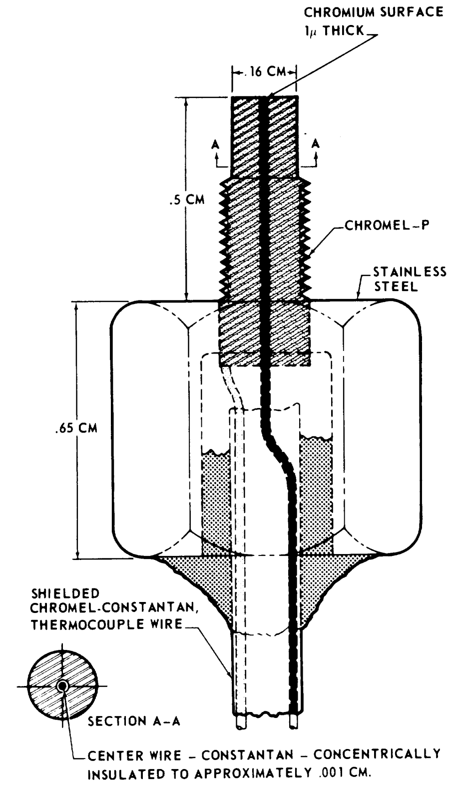

FIGURE 2 CHROMEL CONSTANTAN SURFACE THERMOCOUPLE

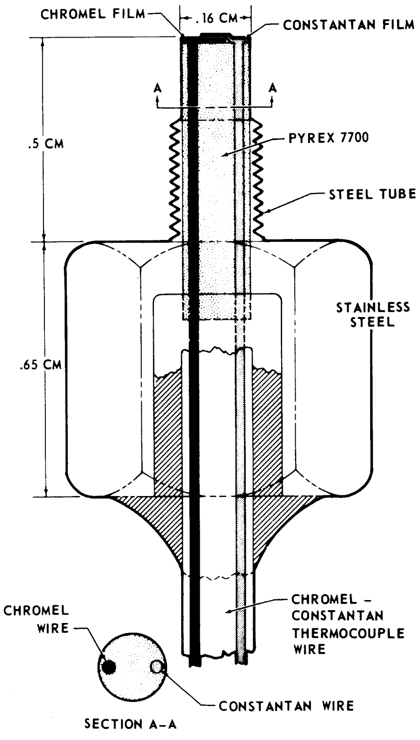

FIGURE 3 CHROMEL CONSTANTAN ON PYREX SURFACE THERMOCOUPLE

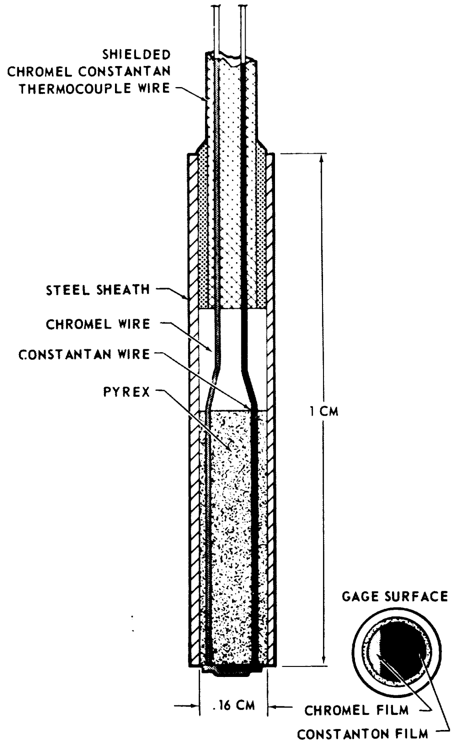

FIGURE 4 CHROMEL CONSTANTAN ON PYREX SURFACE THERMOCOUPLE (MODIFIED)

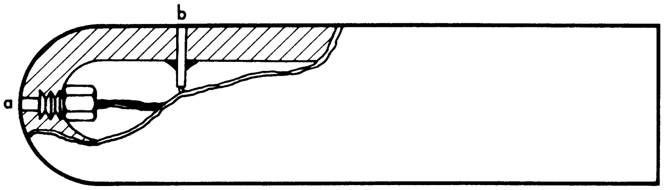

FIGURE 6 TYPICAL INSTALLATION OF a) CHROMEL SUBSTRATE AND b) PYREX SUBSTRATE SURFACE THERMOCOUPLES IN A SIMPLE HEMISPHERE CYLINDER MODEL

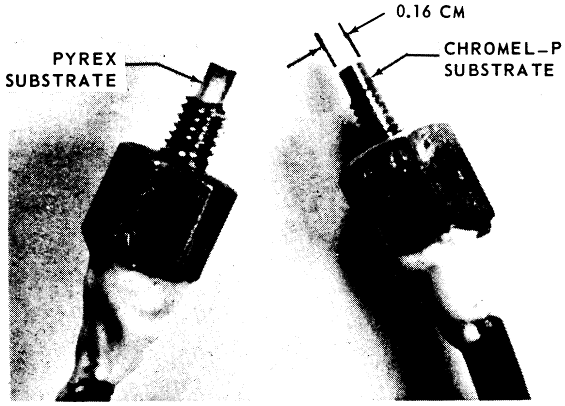

FIGURE 5
PHOTOGRAPH OF SURFACE THERMOCOUPLES

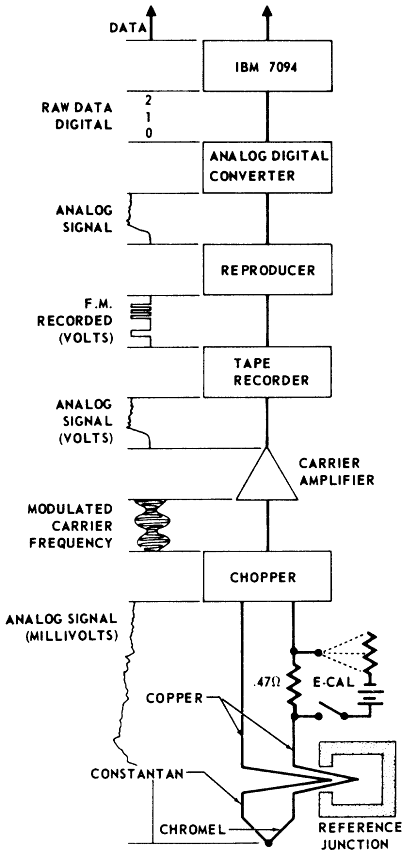

FIGURE 7 SURFACE TEMPERATURE THERMOCOUPLE INSTRUMENTATION AND DATA SYSTEM

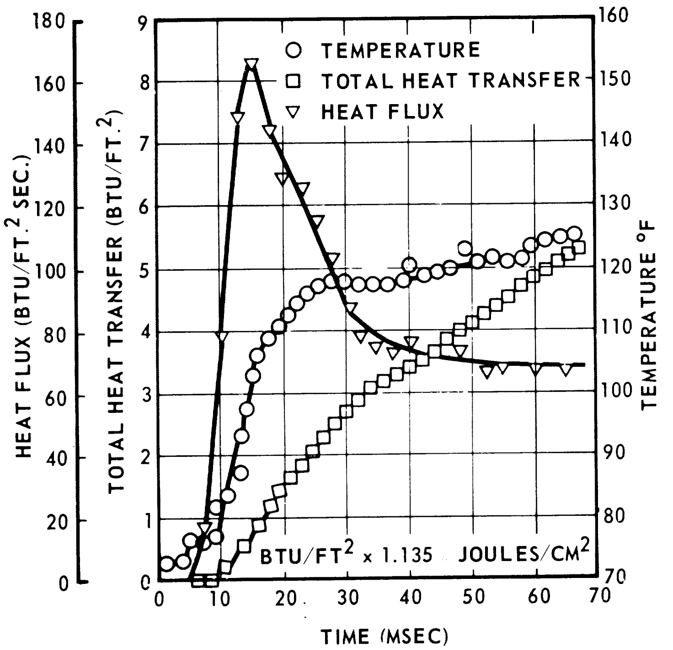

FIGURE 8 HEAT TRANSFER HISTORY AT THE STAGNATION POINT

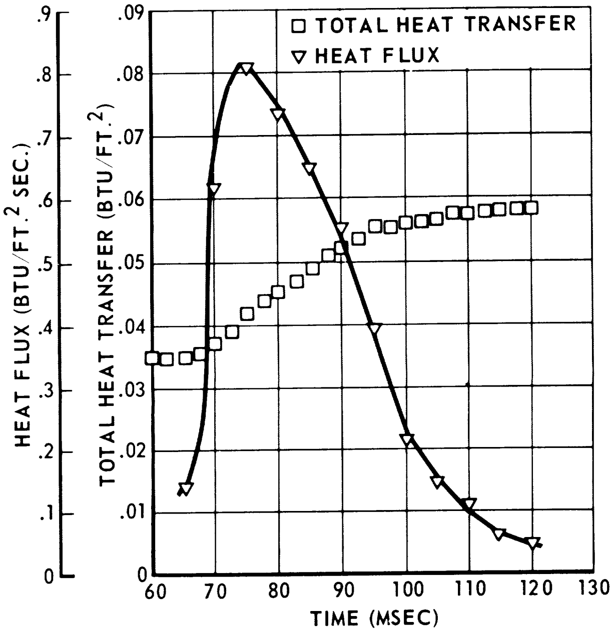

FIGURE 9 HEAT TRANSFER HISTORY ON AN AFTERBODY

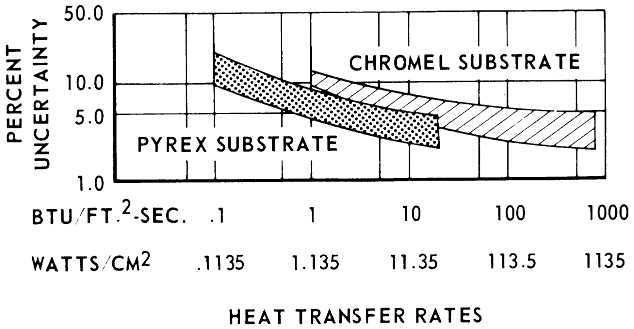

FIGURE 10 RANGE OF EXPERIMENTAL UNCERTAINTY IN HEAT TRANSFER RATES