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Miniature High Temperature Plug-Type Heat Flux Gauges

Curt H. Liebert
Lewis Research Center
Cleveland, Ohio

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MINIATURE HIGH TEMPERATURE PLUG-TYPE HEAT FLUX GAUGES

Curt H. Liebert
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

The objective of this paper is to describe continuing efforts to develop methods for measuring surface heat flux, gauge active surface temperature, and heat transfer coefficient quantities. The methodology involves inventing a procedure for fabricating improved plug-type heat flux gauges and also for formulating inverse heat conduction models and calculation procedures. These models and procedures are required for making indirect measurements of these quantities from direct temperature measurements at gauge interior locations. Measurements of these quantities were made in a turbine blade thermal cycling tester (TBT) located at Marshall Space Flight Center. The TBT partially simulates the turbopump turbine environment in the space shuttle main engine. After the TBT tests, experiments were performed in an arc lamp to analyze gauge quality.

INTRODUCTION

There is a need to more thoroughly characterize the hostile hot gas and high pressure gas environment moving through turbines driving space shuttle main engine turbopumps. In this environment, thermal transients cause durability problems such as material cracking. Heat flux sensors placed in the turbine airfoils can partially characterize this environment by measuring surface heat flux, surface temperature, and heat transfer coefficient quantities.

This paper describes the design and application of a new miniature plug-type heat flux gauge (References 1, 2). The gauge (Figures 1, 2, 3) is used to simultaneously measure surface heat flux, surface temperature and heat transfer coefficient quantities during fast thermal cycling in a simulated space shuttle main engine (SSME) turbopump environment. These measurements are being used to verify SSME turbine vane and blade analytical stress predictions, boundary layer state, and heat transfer design models. Procedures used for fabrication of these gauges, assessment of gauge quality, elements contributing to measurement uncertainty and observations about gauge durability are discussed. An analysis describing how the gauge works, i.e., how these quantities are simultaneously obtained with this gauge, is also presented.

ANALYSIS

A temperature dependent, nonlinear method is devised to obtain solutions for measurement of surface heat flux, active surface temperature, and gas-side heat transfer coefficient quantities. Figure 1 shows a cross-section sketch of the plug-type heat flux gauge. Figure 2 shows a photograph of a gauge (with rear cover on pressure surface removed) mounted for heat flux measurements on the suction surface of a solid SSME blade airfoil. Figure 3 presents a view of a thermocouple mounted close to the active surface of the same gauge.

The well known one-dimensional heat diffusion equation (Reference 3) with no sources or sinks of energy generated within the thermoplug applies for the geometry shown in Figure 1. The cylindrical portion of the thermoplug is insulated with air. This enables the geometrical configuration to be treated as a one-dimensional heat conduction problem. Surface heat flux is obtained by integrating the diffusion equation one-dimensionally over the thermoplug length to give

$$\dot{q} = \int_0^L \left(\rho C_p \frac{\partial T}{\partial t} \right) dZ = \int_0^L \frac{\partial}{\partial Z} \left(k \frac{\partial T}{\partial Z} \right) dZ, \; W/m^2. \quad (1)$$

In Equation (1), $\dot{q}$ is surface heat flux, ρ and C_p are density and specific heat of the thermoplug (Figure 1) material, T is thermoplug temperature measured with thermocouples, t is time, L is thermoplug length measured from the active surface to the rear of the thermoplug, Z is distance measured along the axis of the thermoplug to a thermocouple location and k is material thermal conductivity.

The gauge material is directionally solidified MAR-M-246 modified with hafnium. Thermal property variation with temperature is given in Reference 4.

The integrand of the middle term in Equation (1) describes the rate of thermal energy per unit volume stored at Z within the thermoplug. The integrand of the right hand term is the heat transfer rate per unit volume at Z conducted within the thermoplug. Surface heat flux can rise or fall abruptly. Heat flux values can be either positive or negative. A positive value of heat flux indicates that heat is flowing into the active surface of the gauge; a negative value corresponds to heat flow out of the surface.

To obtain the $\partial T/\partial t$ in the middle term of Equation (1), linear or quadratic least square curve fits are calculated to form equations describing the temperature versus time data measured at four thermocouple positions on the thermoplug. These equations are then differentiated with respect to time and evaluated at selected time points. The values of these derivatives are then multiplied by the specific heat and density corresponding to the four local temperature measurement positions. This produces four values for the rate of stored thermal energy per unit volume corresponding to the four thermocouple positions.

Next, these four stored thermal energy values are used to calculate the surface heat flux by numerically integrating these values over the thermoplug length. To help illustrate the numerical integration procedure, plots of these values are shown in Figure 4 at selected times. The four values are connected with straight lines. The extension of these lines to the ordinate and abscissa are then computed to form an irregular polygon as shown in Figure 4. The value of the area formed within the sides of this irregular polygon is equal to the surface heat flux at a specified time. An algorithm for calculating the area of an irregular polygon is used to determine the surface heat flux.

Now that a method for calculating the surface heat flux based on heat stored concepts has been formulated, the active surface temperature can be determined. Evaluating the integral on the right side of Equation (1) at Z = 0 gives an equation for heat flux based on thermal conduction within the thermoplug

$$\dot{q} = -k \left.\frac{\partial T}{\partial Z}\right|_{Z=0}, \quad W/m^2. \tag{2}$$

Equation (2) is obtained from Equation (1) by noting that $k(\partial T/\partial Z) = 0$ at $Z = L$ because the end of the thermoplug is insulated.

Equation (2) may be rewritten as

$$-\left.\frac{\partial T}{\partial Z}\right|_{Z=0} = \dot{q}/k, \ K/m. \tag{3}$$

As indicated in Equation (3), the active surface temperature is associated with the slope of the temperature gradient at Z = 0.

Two temperature gradient profiles established along the entire length of the thermoplug are shown in Figure 5. To obtain these profiles, a continuous French curve line is drawn through data points of measured thermoplug temperature versus temperature measurement location. These data points are plotted on graph paper with a scale large enough to reveal the least significant digit. This curve was drawn while taking into account the physical principles associated with this inverse heat conduction problem. Four conditions are inherently imposed by the mathematical relationships governing this method. First, the value of the slope of the curve at Z = 0 (Equation (3)) must equal the value of surface heat flux (previously determined from heat stored concepts) divided by the thermoplug thermal conductivity evaluated at the surface temperature. Second, as discussed after Equation (2), the curve must be drawn such that the slope is zero at Z = L. Third, within experimental error, (± 7% to 38%, see Uncertainty section) the equality of heat flux determined from stored and conducted energy considerations must be maintained at each thermocouple location associated with this curve. This equality is calculated using the heat balance expressed by Equation (1) with appropriate limits of integration, where $\dot{q}$ is now associated with the heat flux at the local thermocouple position. Finally, positive values of surface heat flux must correspond to gas temperature greater than surface temperature values; and negative values of heat flux should correspond to gas temperature less than surface temperature.

Heat transfer coefficients, h , are calculated from Newton's law of cooling which is

$$h = \dot{q} \Big/ \left(T_g - T_{surf}\right), \ \frac{W}{m^2 k} \tag{4}$$

where T_g and T_{surf} are gas and active surface temperatures.

FABRICATION OF PLUG-TYPE HEAT FLUX GAUGE

A thermoplug (Figures 1, 2) is formed in a specimen material using electrical discharge machining (EDM)) and trepanning procedures. The thermoplug diameter typically ranges from 0.080 to 0.150 centimeter. Thermoplug length is typically 0.100 to 0.200 centimeter. The annulus is typically 0.08 to 0.10 centimeter wide. The wall thickness may be 0.05 to 0.10 centimeter and the cover is nominally about 0.04 centimeter thick. Thermoplug length is measured from the active surface to the rear of the thermoplug. After gauge fabrication was completed, the airfoils were plasma sprayed with a coating similar to that used on blades in SSME turbopumps.

Commercial sheathed thermocouple assemblies with diameter equal to 0.025 centimeter are used for temperature measurement. A length of 2 to 10 centimeters of sheathing is stripped to expose bare thermoelement Chromel or Alumel wire of 0.0038 centimeter diameter. The ends of the bare thermocouple wires are welded to the thermoplug along it's length to form hot junctions. The bare wires are routed through the annulus to the rear of the gauge as shown in Figures 1 and 2. More details of gauge fabrication are documented in References 1 and 2.

Because the thermoplug is an integral part of the specimen material, there is no material discontinuity such as a seam or screw threads between thermoplug and material. Therefore, very large heat flux measurement errors due to material discontinuities present in other plug-type heat flux gauges do not occur with this gauge design. Also, there is no need to determine the uncertainty of heat flux measurement caused by the presence of such a discontinuity.

A heat flux gauge was fabricated into each of three SSME blades and these blades were installed in the TBT at position B shown in Figure 6. These blades do not rotate. On the upper blade, heat flux, active surface temperature and heat transfer coefficient quantities are measured on the airfoil pressure surface at mid-span and mid-chord; for the middle blade, measurements of these quantities are made at mid-span at the throat on the suction surface; and for the bottom blade, measurements are made at the suction surface mid-span and mid-chord region.

TURBINE BLADE THERMAL CYCLING TESTER

The TBT was operated through 2-1/2 cycles for a total test time of 48 seconds. A ruptured seal on a TBT component caused shutdown prior to the usual 5 cycle test series. A single cycle consists of a startup time period where the TBT burns hydrogen and oxygen to rapidly heat the blades, a quasi-steady time period when the TBT operates at nearly constant gas conditions for about 5 seconds and a cooldown time period where the cycle is completed by rapidly cooling the blades with very cold hydrogen and nitrogen gas. A TBT cycle simulates environmental conditions in turbines driving SSME turbopumps.

RESULTS AND DISCUSSION

Figures 7(a), (b), and (c) show plots of gas temperature and thermoplug temperature data measured during the first cycle. In general, gas and thermoplug temperature and gas pressure (not shown) histories follow the same time patterns. That is, during startup, these data measured on all three airfoils increase rapidly and irregularly as valves controlling hydrogen and oxygen propellant flows are manipulated. During cooldown, these data decrease rapidly between 12.48 and 12.78 seconds. This rapid cool down as well as the severe thermal starting transients occurring during startup can cause durability problems such as material cracking.

Heat flux values measured during the first cycle are shown in Figure 8. The largest values of surface heat flux measured on the three blades during startup range from 13.4 to 16.8 MW/m^2. These surface heat flux values are 50 to 100 times those encountered in aircraft engines. Also, within the experimental error discussed below, these measurements agree with prior SSME design calculations. The heat flux histories are consistent with the temperature and pressure transient patterns.

Selected transient heat transfer coefficient values are also shown in Figure 8 for the center blade. These values correlate with the transient heat flux patterns. That is, high values of heat transfer coefficient correspond to high values of surface heat flux and low values of heat transfer coefficient correspond to low values of heat flux.

These consistent results demonstrate that gauges mounted in all three blades are fully responsive to changes in SSME turbopump turbine environmental conditions. This also demonstrates that good quality gauges can be repeatedly fabricated into SSME airfoils.

MEASUREMENT UNCERTAINTIES

This investigation included use of a Vortek (Reference 5) (model 108) arc lamp at NASA Lewis Research Center to assess maximum uncertainty of heat flux measured with the plug-type gauges. This arc lamp is designed to produce transient and steady-state heat flux measurements in the range of about 0.2 to 5.0 MW/m^2. These arc lamp tests were made after the gauges had been used in the TBT. The arc lamp is especially useful for evaluation of gauge quality because the lamp generates a repeatable, high power, uniform irradiance over a sizeable area (1.5 × 4 cm.). Arc lamp irradiance as a function of input current and associated irradiance uniformity is determined using water cooled, factory calibrated, asymptotic calorimeters (Gardon gauges). These calorimeters indicated an irradiance uniformity of ±4%. The calorimeters are manufactured by Hy-Cal Engineering.

Average surface heat flux measured with plug-type heat flux gauges mounted in the SSME blade airfoils were tested after the TBT investigations were made in the arc lamp. Gauge-to-gauge divergence about the calorimeter data was -16 to +40%. This correspondence suggests that, within experimental error, the gauges did not degrade during TBT operation. This heat flux uncertainty is acceptable for verification of analytical stress predictions, boundary layer state, and heat transfer design models. Also, this correspondence adds credence to the inverse heat flux measurement analysis discussed herein. Wider divergence (greater than 100%) can arise if the blade cracks in the vicinity of the gauge location, if thermocouple hot junctions crack or come loose at thermoplug substrate-junction interfaces, or if the gauge distorts during operation.

Elements and uncertainties contributing to surface heat flux measurement are: (1) Inaccuracy of curve fitting procedures for determination of temperature derivative with respect to time, (±2 to 20%), (2) errors in determination of surface heat flux based on numerical integration of the rate of thermal energy per unit volume stored within the thermoplug, (±2 to 10%), (3) inaccuracy of property values, (±1 to 10%), (4) temperature measurement inaccuracy due to contamination of thermocouple thermoelement materials by thermoplug material during welding, (±2 to 4%), (5) uncertainty of values of derivative of temperature versus time due to noise and temperature gradients along finite thermocouple junctions (±2 to 20%), (6) unaccounted for heat losses

(±1 to 5%), and (7) geometrical variations of plug gauges mounted in various airfoil locations (±5 to 20%). This gives an expected root-mean-square range of measurement uncertainty of ±7 to 38% which compares well with the deviations of plug-type gauge and calorimeter measurements discussed above. Percentage values of the uncertainties were determined by analyzing the experimental data.

For these experiments, application of the mathematical conditions described following Equation (2) provides a narrow envelope of curves which can be fit to the scatter in measured thermoplug temperature gradient data. It was found that the maximum uncertainty of active surface temperature described by this envelope of curves is about ±1 to 10%.

As shown in Equation (3), heat transfer coefficients are inversely proportional to the difference between gas and active surface temperatures. Because the TBT tests produced small differences between gas and active surface temperatures, these temperature differences represent a very small difference between relatively large quantities. This leads to ±50 to 80% uncertainties in heat transfer coefficient measurement. Nevertheless, even though these uncertainties are large, transient heat transfer coefficient values are well correlated with time-varying gas pressure and temperature, thermoplug temperatures, and surface heat flux.

CONCLUDING REMARKS

A miniature heat flux gauge device is used to measure transient surface heat flux, active surface temperature, and heat transfer coefficient quantities on three solid SSME blade airfoils tested in the TBT. These results are being incorporated into turbine design models being developed by NASA Lewis Research Center computational fluid mechanics personnel. The tests demonstrate that the time response of the gauges is compatible with SSME hydrogen-oxygen combustion transients. No deleterious effects on the gauges resulted from fast transients at high and low temperature extremes and hydrogen impingement. These gauges are being integrated into turbine blade airfoils mounted in SSME testbed engine turbopump nozzles at NASA Marshall Space Flight Center. The engine tests will provide additional information for potential inflight engine qualification. Research efforts are continuing for adaptation of plug-type gauges to measurement of these quantities in convection cooled apparatus.

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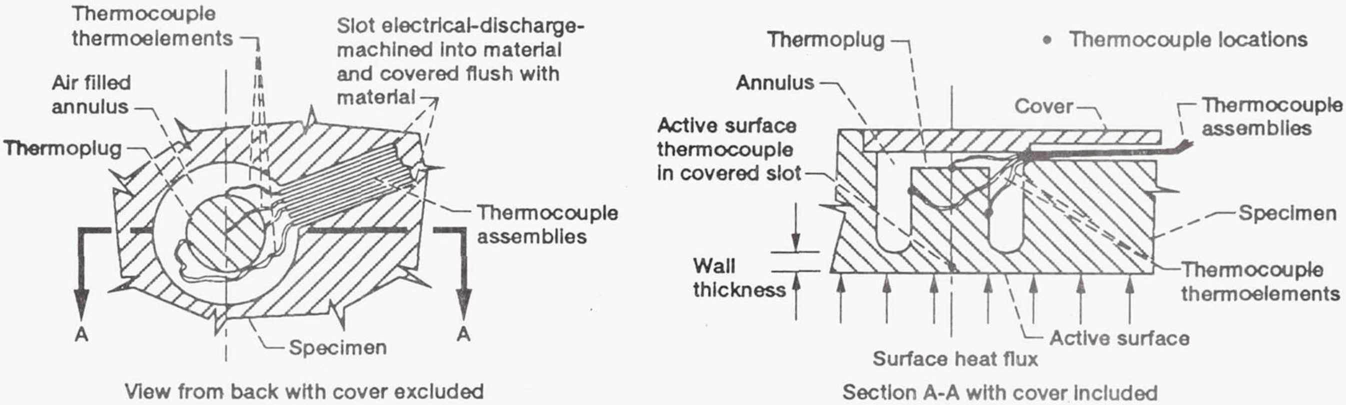


Figure 1.—Heat flux gauge.

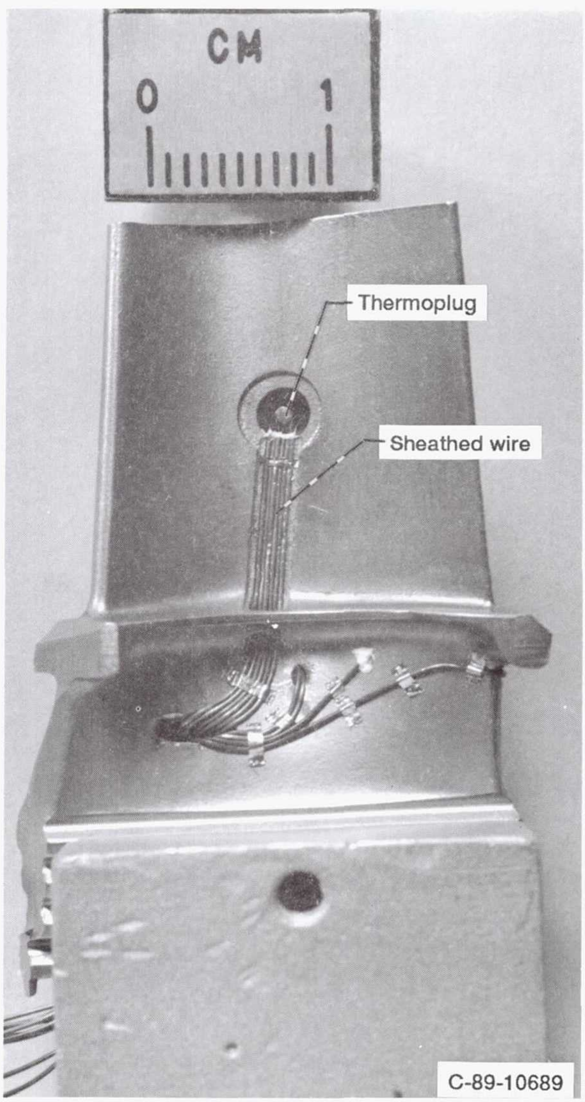


Figure 2.—Rear view of gage in SSME blade (with cover removed).

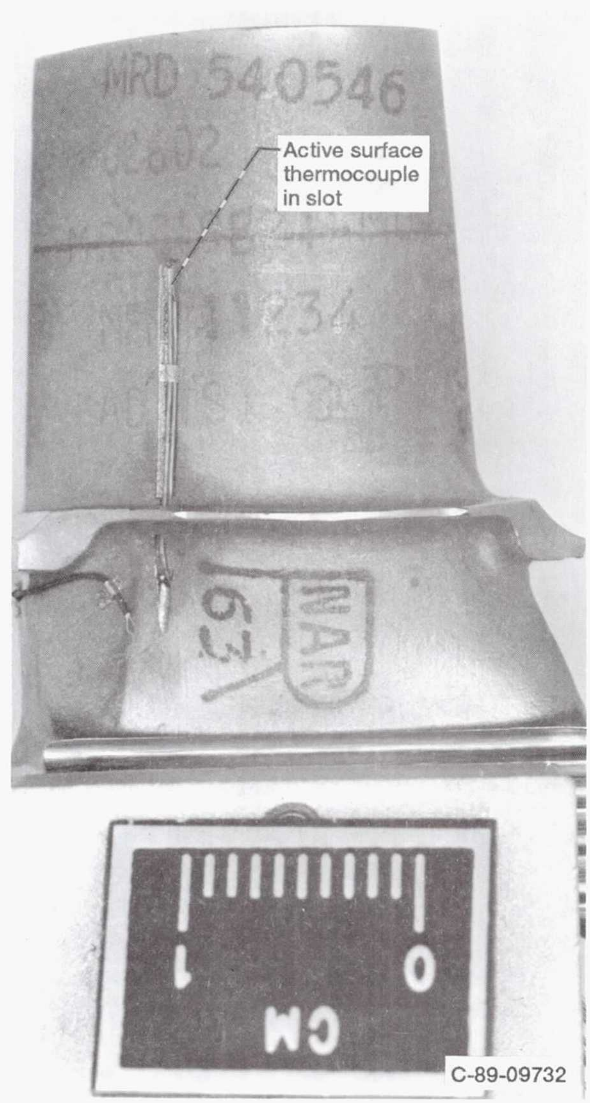
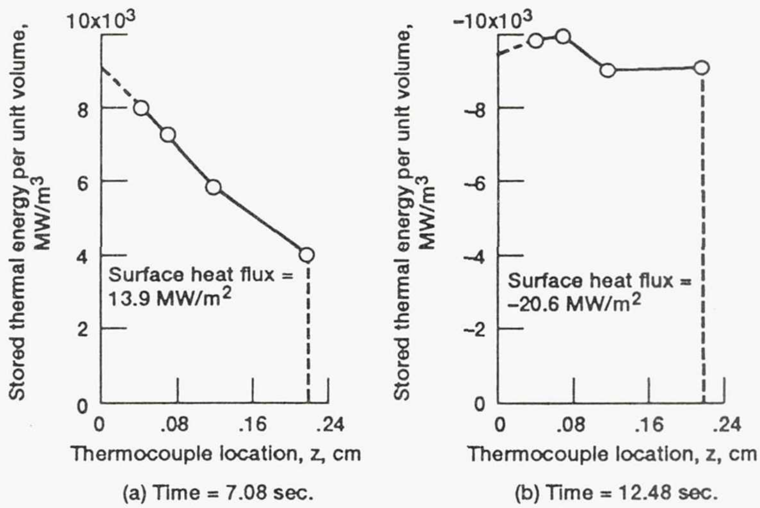
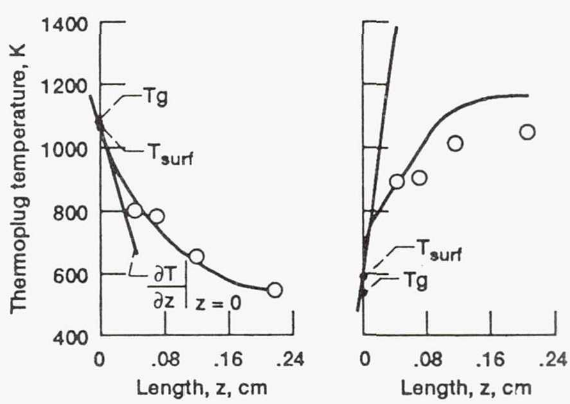


Figure 3.—View of active surface thermocouple (with cover removed).



(a) Time = 7.08 sec. (b) Time = 12.48 sec.

Figure 4.—Polygon for determination of surface heat flux.



(a) Positive heat flux (7.08 sec) Tg > T_{surf}. (b) Negative heat flux (12.48 sec) Tg < T_{surf}.

Figure 5.—Thermoplug temperature profiles.

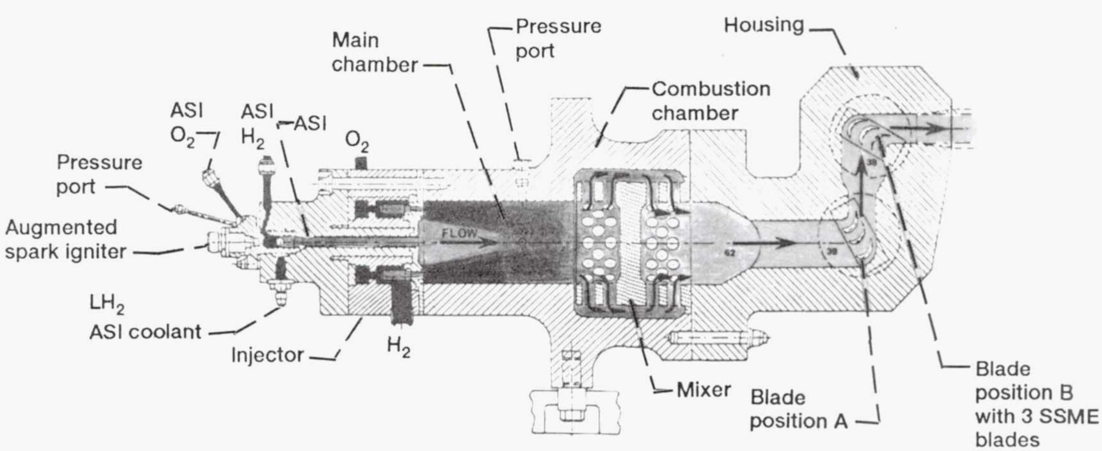
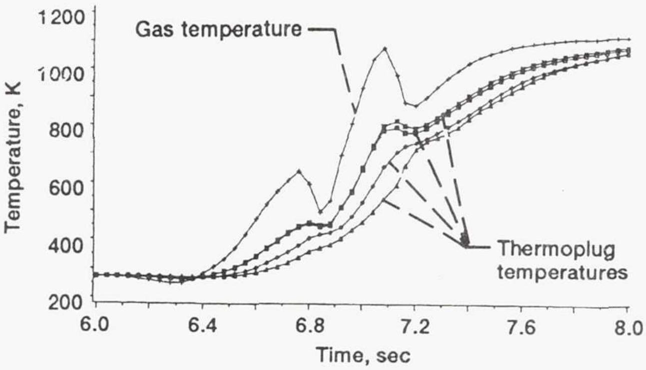
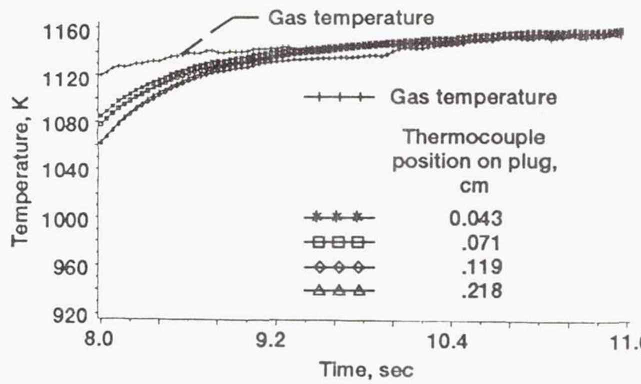


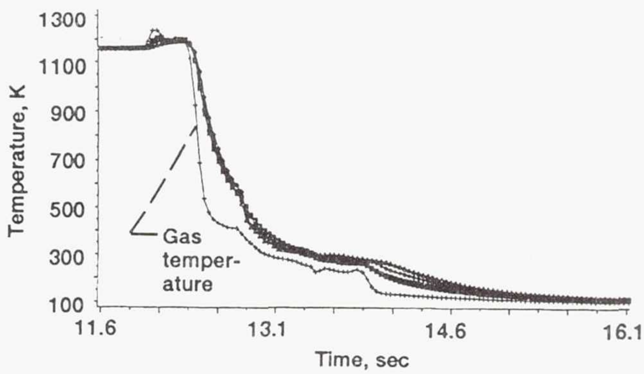
Figure 6.—Turbine blade thermal cycling tester (TBT).



(a) Startup, center blade.



(b) Quasi steady, center blade.



(c) Cooling, center blade.

Figure 7.—Gas and gauge temperature history.

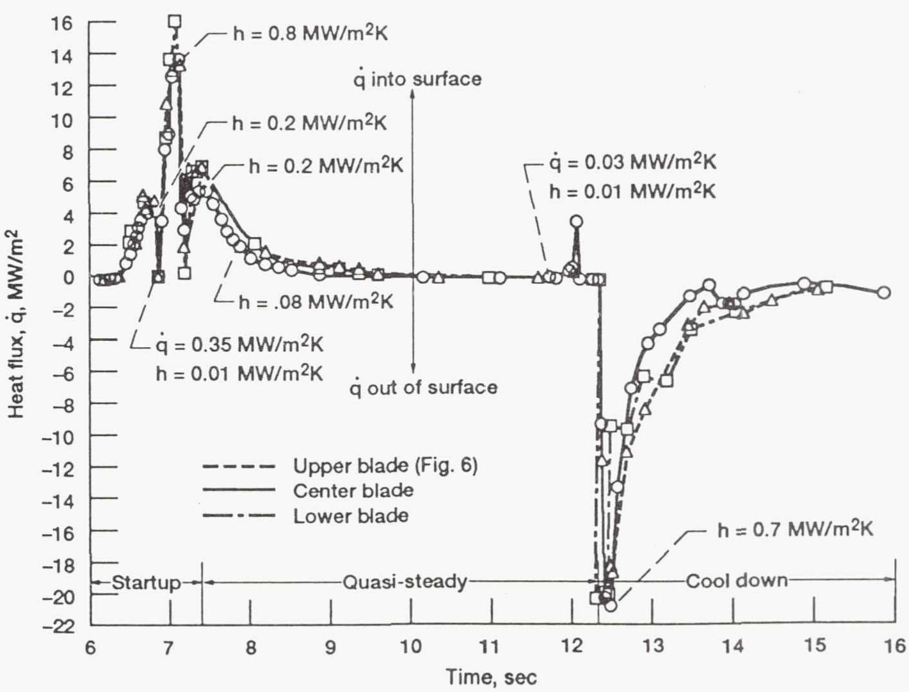


Figure 8.—Heat flux measured in turbine blade tester (h is heat transfer coefficient).

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Lewis Research Center
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13. ABSTRACT ***(Maximum 200 words)***

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