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E5719

NASA Technical Memorandum 103274

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Prepared for the
Second Annual Conference on Health Monitoring
for Space Propulsion Systems
sponsored by the University of Cincinnati
Cincinnati, Ohio, November 14–15, 1990

NASA

HEAT FLUX MEASUREMENT IN SSME TURBINE BLADE TESTER

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Abstract

Surface heat flux values were measured in the turbine blade thermal cycling tester located at NASA/Marshall Space Flight Center. This is the first time heat flux has been measured in a space shuttle main engine turbopump environment. Plots of transient and quasi-steady state heat flux data over a range of about 0 to 15 MW/m^2 are presented. Data were obtained with a miniature heat flux gage device developed at NASA Lewis Research Center. The results from these tests are being incorporated into turbine design models. Also, these gages are being considered for airfoil surface heat flux measurement on turbine vanes mounted in SSME turbopump test bed engine nozzles at Marshall. Heat flux effects that might be observed on degraded vanes are discussed.

INTRODUCTION

There is a need to more thoroughly characterize the hostile hot 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 (Refs. 1 and 2) placed in the turbine airfoils can partially characterize this environment by measuring surface heat flux. The heat flux, also commonly called heat flow intensity, is a measure of how much heat is flowing through turbine airfoil surfaces. These heat flux data can be used to verify analytical stress, boundary layer and heat transfer design models.

It has been estimated in Reference 3 that the transient blade surface heat flux in the space shuttle main engine (SSME) turbopump turbine environment can appraoch 15 MW/m^2. This is about 50 to 100 times that encountered in aircraft engines. Because the heat flux is very large, durable miniature plug gages were designed and fabricated into SSME first stage turbine blades for heat flux measurement and durability tests in the turbine blade thermal cycling tester (TBT) at NASA/Marshall Space Flight Center.

Plots of transient and quasi steady-state heat flux data obtained in the TBT are presented. In addition, transient temperature histories measured within the gage are plotted. These temperature values are used with a quasi one-dimensional heat transfer analysis (Ref. 1) to calculate the transient and quasi-steady surface heat flux. Elements contributing to heat flux measurement uncertainty are discussed. Also, an estimate of heat flux measurement uncertainty is given. A discussion of the procedures used for fabrication of gages into the airfoil and installation of thermocouples along the length of the thermoplug is included. Observations about the durability of the gage components are presented. Calibration of the gages in a heat flux gage calibration facility at Lewis is also discussed.

SYMBOLS

Bi	Biot number
C_p	specific heat at constant pressure, J/kg K
h	time variant convection heat transfer coefficient, MW/m^2 K
k	thermal conductivity of thermoplug, MW/mk
L	length of thermoplug measured from active surface of gage, cm
$\dot{Q}$	thermal power per unit volume, MW/m^3
$\dot{q}$	surface heat flux, MW/m^2
T_g	measured gas temperature, K
T_w	gage active surface temperature, K
t	TBT operating time, sec
Z	distance along axis of thermoplug measured from active surface to end of plug, m
ΔT	temperature difference, K
ρ	density, kg/m^3

DETERMINATION OF HEAT FLUX, ACTIVE SURFACE TEMPERATURE AND BIOT NUMBERS

Figure 1 shows a schematic of a plug heat flux gage mounted within a portion of an airfoil. The thermoplug (Fig. 1) is cylindrical, and the front or active surface is directly exposed to the TBT gas environment. The thermoplug is insulated by air in the circular annulus. Therefore heat transfer within the gage is one-dimensional. Heat flux is calculated from measured thermoplug temperatures by using a temperature-dependent thermal property, inverse heat conduction method developed in References 1 and 2. A rear view of a gage mounted in a SSME blade is shown in Figure 2. The back cover of the gage is removed to show the thermoplug. A front view of the gage is shown in Figure 3.

At transient and quasi-steady heat transfer conditions, the time rate of heat stored in a cylindrical differential volume of thermoplug mass is

$$\dot{Q} = \rho C_p \partial T/\partial t, \qquad \mathrm{MW/m^3} \tag{1}$$

Heat flux measured at the active surface of the thermoplug is determined by integrating Equation (1) over the thermoplug length. This length extends from the active surface of the gage to the end of the thermoplug. A one-dimensional heat balance on the active surface is,

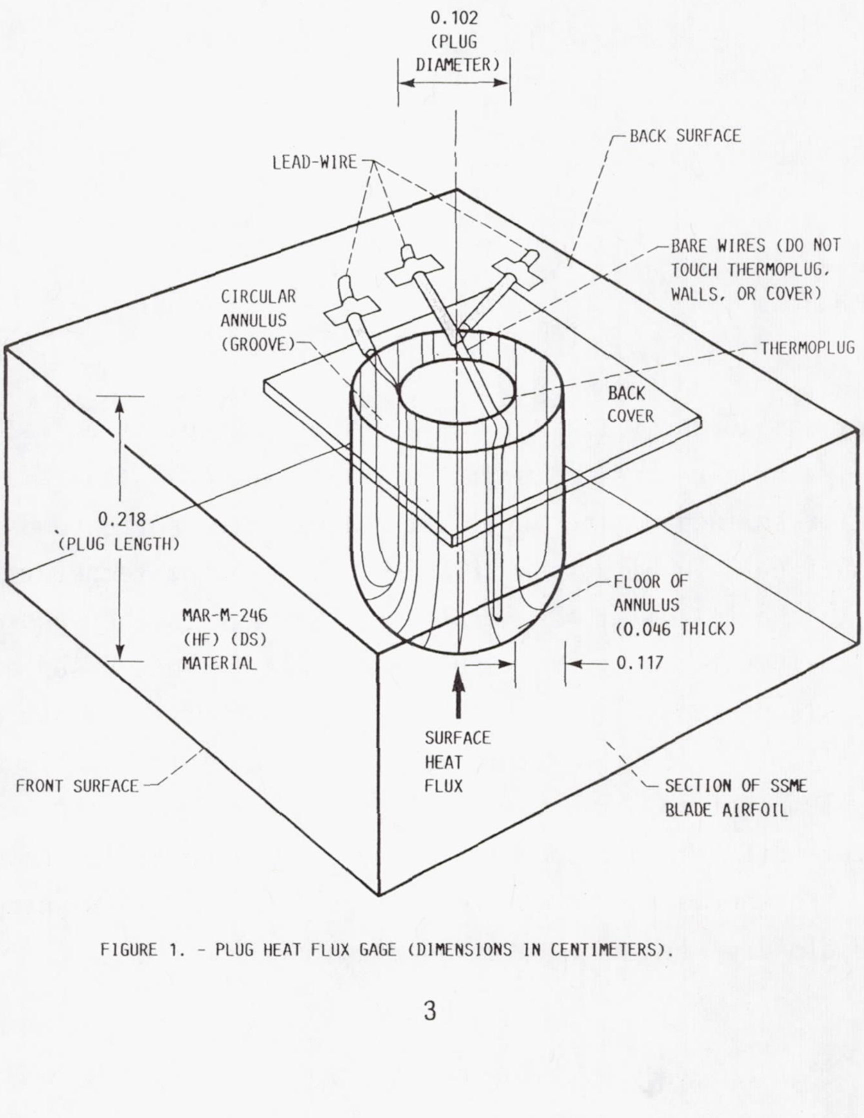

FIGURE 1. - PLUG HEAT FLUX GAGE (DIMENSIONS IN CENTIMETERS).

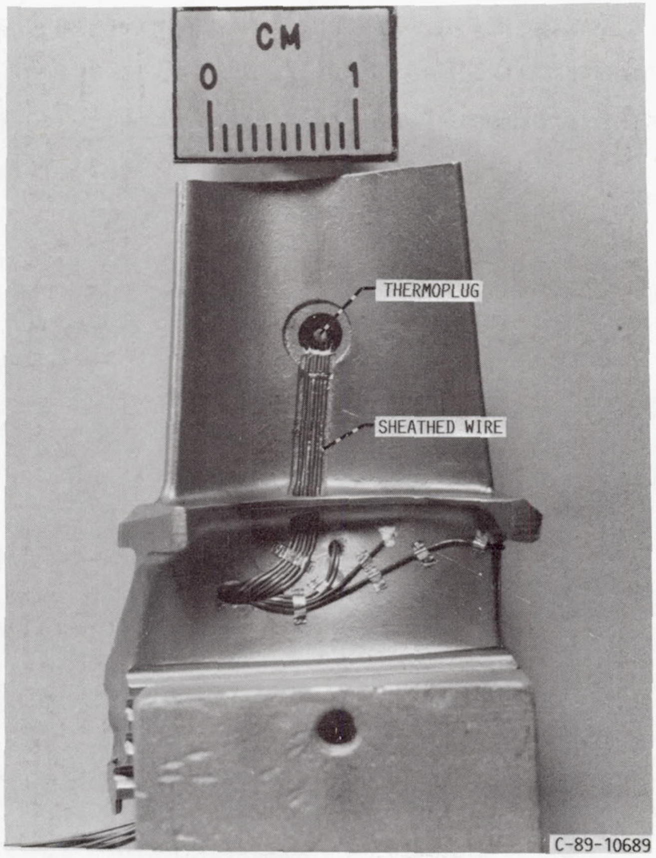

FIGURE 2. - REAR VIEW OF GAGE IN SSME BLADE.

$$\dot{q} = \int_0^L (\rho C_p \partial T/\partial t)dZ, \qquad MW/m^2 \tag{2}$$

$$= h(T_g - T_w), \qquad MW/m^2 \tag{3}$$

The heat flux can abruptly rise or fall. Also, the heat flux values can be either positive or negative. A positive value indicates that heat is flowing into the active surface of the gage; a negative value corresponds to heat flow out of the surface. In high speed flow situations, the temperature difference that drives the heat flow at the surface of the gage is the recovery temperature minus surface temperature. Spot-check calculations based on the thermodynamic analysis presented in Reference 4 suggest that the measured gas temperature, T_g, is, within an uncertainty of about 1 to 2 percent, equal to the recovery temperature. Thus, $(T_g - T_w)$ can be taken as the measured driving temperature difference for heat flow by convection at the active surface of the gage. Furthermore, the spot-checks produced heat flux predictions which agreed closely with measurements.

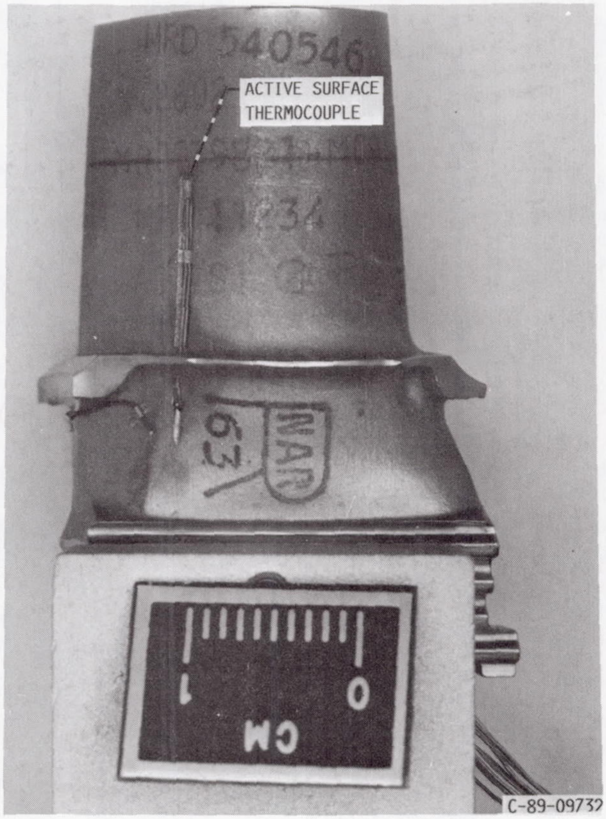

FIGURE 3. - VIEW OF ACTIVE SURFACE THERMOCOUPLE.

Detailed solutions of Equation (2) are given in References 1 and 2. Briefly, in Equation (1), $\partial T/\partial t$ is evaluated by differentiating least-squares curve fit equations expressing measured internal thermoplug temperatures as a function of time at four thermocouple locations. Thermal properties (Ref. 5) are evaluated at local temperatures measured on the thermoplug. Then Equation (2) is evaluated by integration of least-squares curve fit equations expressing heat flux per unit volume (Eq. (1)) versus thermoplug length. As suggested by Equation (3), the ratio of heat flux expressed by Equation (2) to $(T_g - T_w)$ may be taken as a measured time variant heat transfer coefficient.

The temperature of the active surface of the gage is determined by linear extrapolation of temperatures measured by the two thermocouples closest to the active surface.

BIOT NUMBERS

The Biot number (Ref. 6) is considered because of its significance to transient conduction problems that involve surface convection effects. It is applied to these data to establish further credence to the heat flux measurements. The one-dimensional Biot number is generally expressed in the following form

$$Bi = hZ/k \tag{4}$$

Equation (4) may be expressed in a form applicable to one-dimensional transient conduction as

$$Bi = \frac{\dot{q}}{(T_g - T_w)} \frac{Z}{k} \tag{5}$$

The Biot number may also be expressed as

$$Bi = \frac{\Delta T}{(T_g - T_w)} \tag{6}$$

FABRICATION OF HEAT FLUX GAUGES

A gage was mounted in the center blade (Fig. 4, blade position B) at the throat on the midspan portion of the suction surface. Also, a gage was mounted on each of the outer two blades at the midspan, midchord regions with active surfaces facing the center blade.

Trepanning was used to machine gages into each of the three blades. Trepanning is a term used to indicate machining of a circular groove into metals. In this case an electrical discharge machining (EDM) process is used. The thermoplug is naturally formed into a cylinder as the groove or annulus is machined partially through the thickness of the blade (Fig. 1). Since the thermoplug is an integral part of the annulus floor, there is no seam between the thermoplug and the wall. This minimizes thermal distortion by the presence of the gage.

The thermoplug in the center blade was formed into a cylinder with diameter and length of 0.102 and 0.218 cm, respectively. A back cover (304 stainless steel) enclosing the thermoplug and annulus (Fig. 1) was welded flush to the MAR-M-246 (HF)(DS) wall, thus trapping air within the annulus and behind the thermoplug. This trapped air is a thermal insulator that minimizes heat transfer between the thermoplug, the surrounding wall and the back cover. A space of 0.036 cm was maintained between the rear of the plug and the cover. Because of this thermal insulation, heat transfer along the length of the thermoplug can be treated as a nearly one-dimensional case.

Commercial, single-wire Inconel sheathed thermocouple assemblies were used to measure internal thermoplug temperatures. The sheathed thermocouple assemblies were modified by swaging them to a diameter of 0.025 cm and then by stripping them to expose a 0.004 cm diameter Chromel or Alumel thermoelement buried within MgO insulation located under the sheath material.

The swaged thermocouples passed all thermocouple acceptance tests. These tests included measurements of sheath integrity, analysis of electrical insulation resistance and junction integrity and tests for spurious electromotive force.

The bare wires (thermoelements) were spot welded to the sides of the thermoplug to form hot junctions positioned at 0.071, 0.119 and 0.218 cm measured from the active surface of the gage. The junctions were located circumferentially 120° from each other. The thickness and diameter of the hot junctions was about 0.010 cm. The bare wires were extended from the hot junctions in a direction perpendicular to the cylindrical plug surface and then were routed through the annulus to the rear of the gage. The bare wires were carefully positioned so that they would not touch any metal surface. The sheathed wires were then extended from the rear of the gage (Fig. 2) and laid side by side within grooves EDMed into the pressure surface of the airfoil. The grooves were then covered with 304 stainless steel material welded flush to the wall. Then the sheathed wire was extended through holes EDMed into the blade platform and base (Fig. 2) to connectors (Fig. 5). Finally, connections were made to remote computers for temperature data storage.

Commercial single-wire Inconel sheathed thermocouple assemblies were also used to measure the active surface temperatures. The thermoelements were first welded together to form hot junctions. Then the hot junctions were spot welded to the bottom of grooves EDMed into the airfoil surface (Fig. 3). Hot junctions were located about 0.043 cm below the airfoil surface and were positioned so that they intersected a center line extending from the active surface of the thermoplug to the rear of the plug. The hot junctions and sheathed thermocouples were covered with nichrome material which in turn was covered with a stainless steel cover welded flush to the wall.

Finally, the entire airfoil was plasma sprayed with a 0.025 cm thick coating of NiCrAlY. Coating roughness in Ra ampltiude parameters was about 1120 μcm.

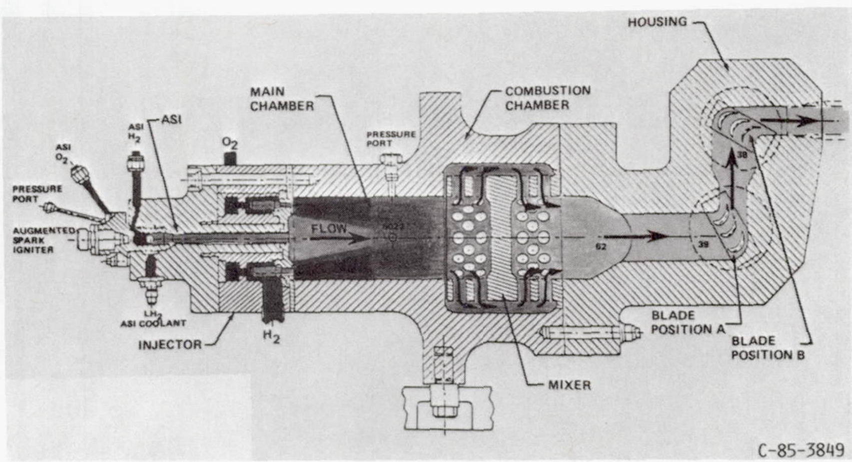

FIGURE 4. - TURBINE BLADE THERMAL CYCLING TESTER.

TURBINE BLADE THERMAL TESTER

Three test blades were instrumented with heat flux gages and installed in the TBT at position B shown in Figure 4. In this paper, only heat flux to the center blade is reported. The TBT is described in Reference 7. The gas temperature was measured with a 0.102 cm diameter Chromel-Alumel thermocouple inserted about 1.3 cm into the gas stream. This thermocouple was located just upstream of the center blade. The upper portion of Figure 5 shows the blades after tests in the TBT. The blades are mounted in a turbine blade holder which is welded to a flange. Sheet metal-ducting within which thermocouple wires and connectors are held is shown extending below the flange. Figure 6 presents an external view of the TBT within which the blades are tested. The sheet metal-ducting holding the connectors is shown extending from the TBT in the upper left-hand portion of Figure 6.

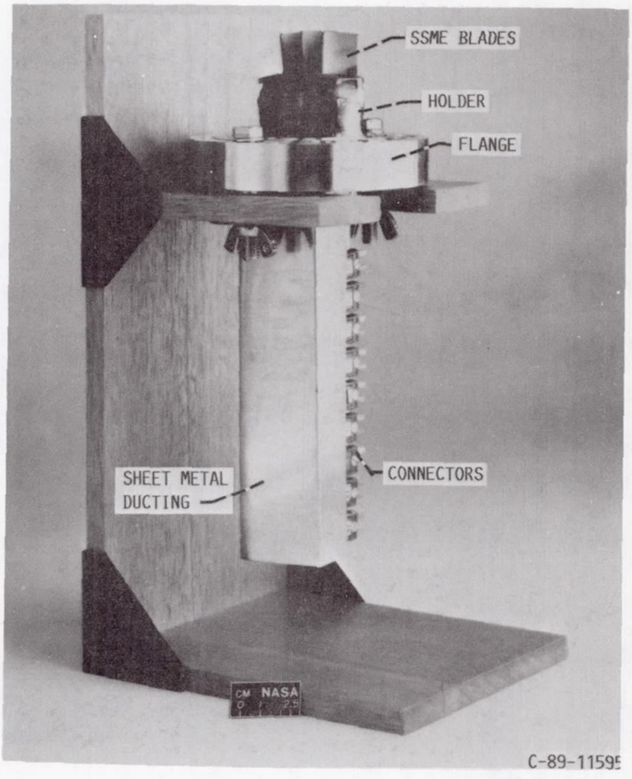

FIGURE 5. - SSME BLADES AFTER TESTS.

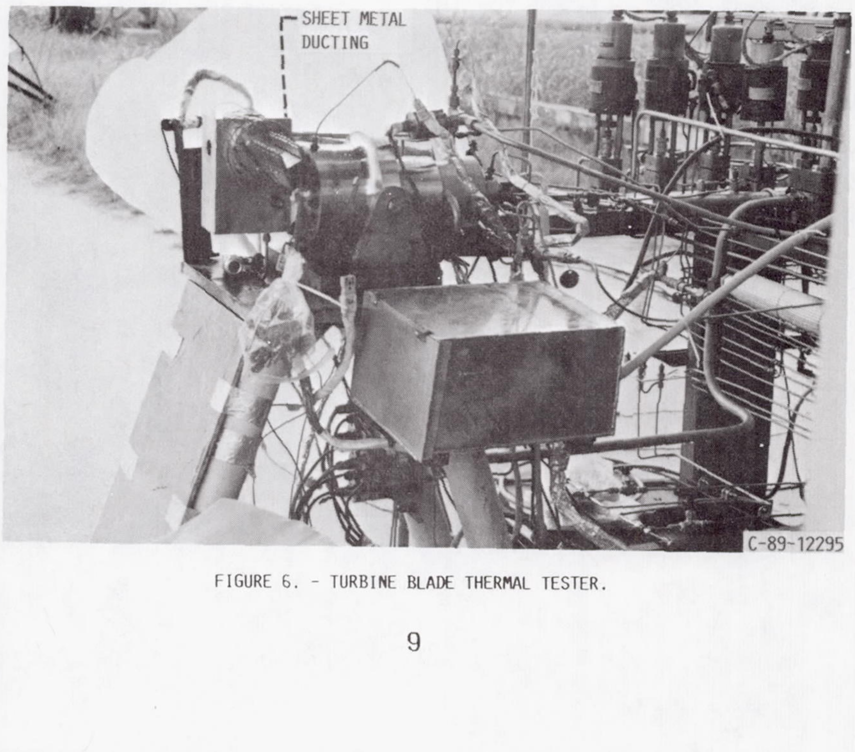

FIGURE 6. - TURBINE BLADE THERMAL TESTER.

RESULTS AND DISCUSSION

TBT Characteristics

The TBT was operated through 2-1/2 cycles for a total test time of 48 sec. A ruptured seal on a TBT component caused shutdown prior to the usual 5 cycle test series. Figures 7 to 9 show plots of the gas temperature and internal gage temperatures measured during the first cycle. In general, gas and thermoplug temperature history follow the same pattern. During startup (Fig. 7), gas temperature increased irregularly from 249 K at 6.28 sec to 1101 K at 7.68 sec. During this time interval, gas pressure (Fig. 10) increased irregularly from 0.8 to 13.1 MPa. After startup, the TBT operated for about 4.6 sec at quasi-steady gas temperature and pressure conditions. During the quasi-steady condition, gas temperature and pressure varied in a more regular manner from about 1101 to 1206 K and 13.1 to 14.00 MPa. After 12.24 sec, combustion was stopped and cooling was initiated (Fig. 9). The next cycle starts at about 17.8 sec (not shown) when measured gas temperature and pressure had decreased to 83 K and 1.8 MPa.

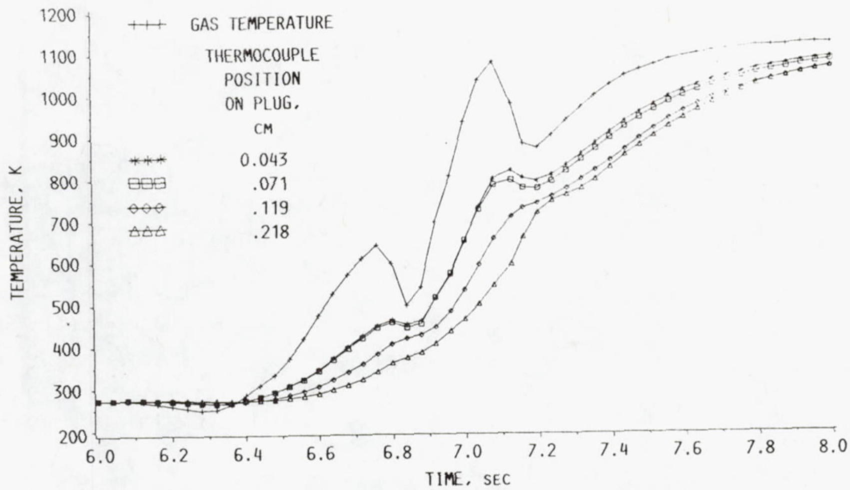

FIGURE 7. - GAS AND GAGE TEMPERATURES, STARTUP, CENTER BLADE.

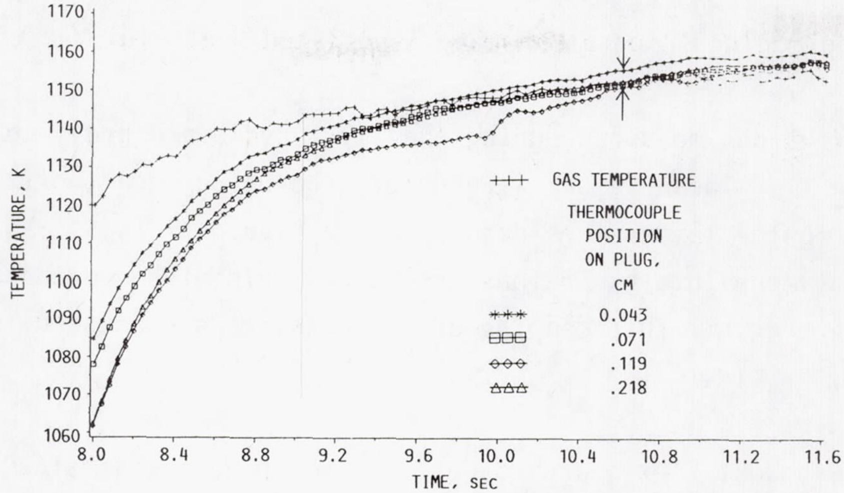

FIGURE 8. - GAS AND GAGE TEMPERATURES, QUASI STEADY, CENTER BLADE.

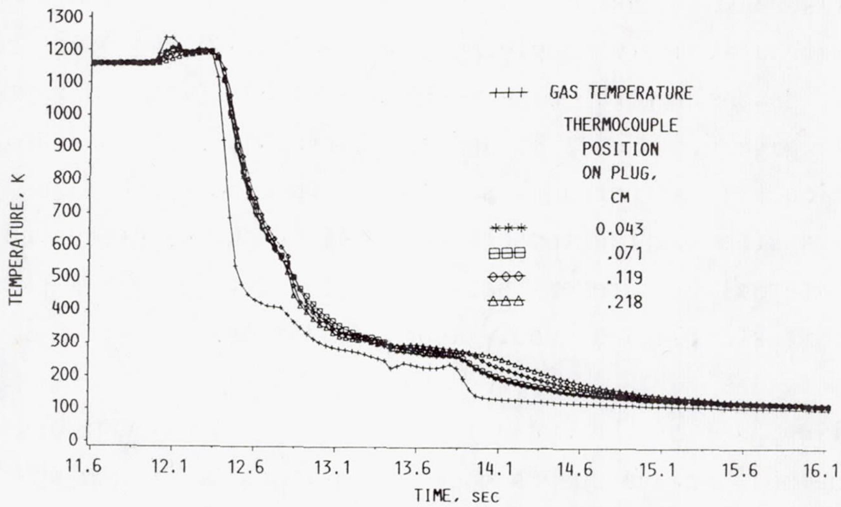

FIGURE 9. - GAS AND GAGE TEMPERATURES, COOLING, CENTER BLADE.

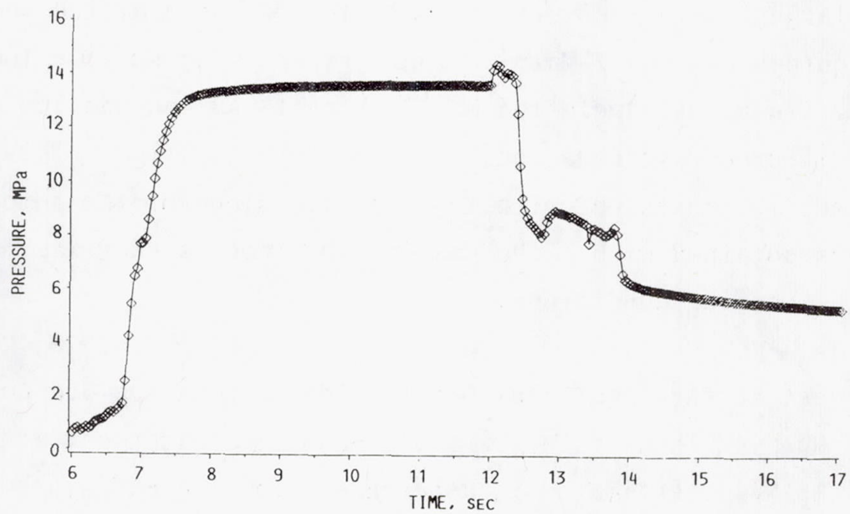

FIGURE 10. - GAS PRESSURE HISTORY - 1ST CYCLE.

Gage Thermoplug Temperatures and Associated Heat Flux Measurement

Heat flux values measured during the first cycle are provided in graphical form in Figure 11. These values were determined using Equation (2) and the transient thermoplug temperature data shown in Figures 7 to 9. Note that the internal gage temperature excursions are usually diminished or dampened along the thermoplug length. This damping characteristic is discussed in References 1 and 8.

The largest heat flux measured during startup and quasi-steady cyclic conditions was about 14.0 MW/m^2. This value was obtained at 7.08 sec when the gas temperature was measured as 1078 K. At this time, the internal gage temperature data measured at thermocouple positions of 0.043 and 0.071 cm was about 800 and 785 K, respectively. Linear extrapolation of this data to the active surface of the gage yields 823 K, and the corresponding temperature difference term in Equation (3) is therefore positive. This positive value is consistent with a positive slope of the temperature history curves presented in Figure 7 at the four internal measurement positions of the gage. This consistency was noted throughout startup and quasi-steady conditions.

The cooling part of the cycle (Fig. 9) lasted for about 6.5 sec. During this time, the most severe quench occurred between 12.36 sec when the gas temperature was 1200 K and about 12.48 sec corresponding to a gas temperature of 538 K. The largest negative surface heat flux measured at the end of this most severe quench was -14.7 MW/m^2. The corresponding surface temperature was determined by linear extrapolation as 868 K at 12.48 sec and the associated temperature difference in Equation 3 is therefore negative. This negative value is correctly consistent with the negative slope of the temperature history curves obtained within the gauge. This consistency was maintained throughout the cooling conditions.

The largest surface heat flux obtained during startup and cooling was 14 and -14.7 MW/m^2. These values are in reasonable agreement with a transient heat flux of 15 MW/m^2 estimated in Reference 3 for the SSME turbopump turbine environment.

Comparison of Figures 11 and 12 shows that the transient surface heat flux and transient gas temperature minus surface temperature values are highly correlated. This correlation demonstrates that the gages are fully responsive to changes in SSME turbopump environmental conditions.

Evaluation of surface heat flux to the other two blades has not been completed. However, examination of the data suggests that the adjacent blades are subjected to very severe heating and cooling conditions.

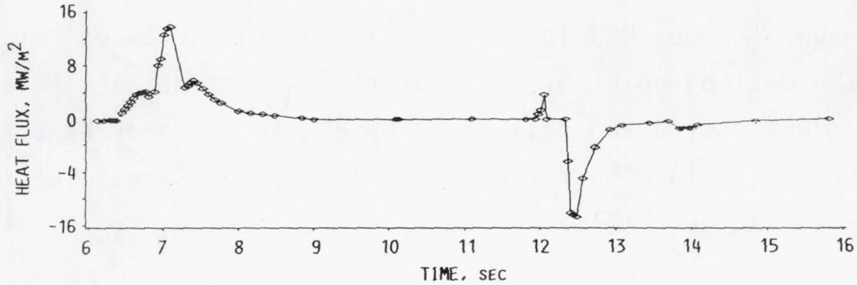

FIGURE 11. - HEAT FLUX.

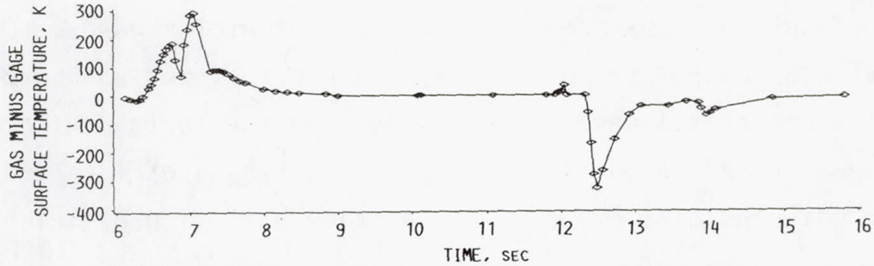

FIGURE 12. - GAS TEMPERATURE MINUS GAGE SURFACE TEMPERATURE.

BIOT NUMBERS

Biot numbers between 0.4 and 0.6 were calculated with Equation 6 at the quasi-steady TBT operation condition. Also, at this condition, essentially uniform temperatures were measured within the gage. Reference 6 observes that, to an excellent approximation, Biot numbers of about 0.5 or less will produce uniform temperatures within solid configurations. The good agreement of the Reference 6 observation with the results obtained herein adds credence to these heat flux measurements. Conversely, as Biot numbers become larger, temperature differences along the length of the gage will theoretically become larger. This latter observation was also experimentally realized herein at startup and cooling conditions. The largest temperature differences measured along the gage length corresponded to a Biot number of about 7.0.

Tests in Heat Flux Measurement Facility

Plug gages mounted in the SSME blade airfoils were also tested in a heat flux measurement facility located at Lewis Research Center (Ref. 2). Surface heat flux is generated by an arc-lamp system manufactured by Vortek Industries, Ltd. Transient and steady-state heat flux values can be measured with this system over a range of about 0.3 to 6 MW/m^2 as gage temperatures vary from about 100 K to the melting point of most materials. Commerical, water-cooled heat flux gages manufactured and calibrated by HY-CAL Engineering are used as a reliable measure of surface heat flux generated by the lamp. This heat flux is repeatable within an uncertainty of about ±10 percent.

Values of the SSME blade surface heat flux measured in this facility were compared with surface heat flux measured with the commercial gages. Deviation of plug gage heat flux output from commerical gage output was an acceptable ±25 percent. This comparison was made not only with the instrumented blades after they had been tested in the TBT, but also with gages of identical design mounted in other untested SSME blades with the same airfoil profile.

This comparison suggests that not only are the gages operating properly, but also that the plug gage-in-airfoil system did not degrade during TBT operation. Degradation (in the facility) is associated with heat flux outputs which are more than 25 percent lower than commercial gage outputs. Lower heat flux values can arise if the blade cracks in the vicinity of the gage location or if thermocouple hot junctions crack at gage substrate-junction interfaces.

UNCERTAINTIES

Information about the maximum and minimum uncertainties of selected heat flux data shown in Figure 11 is given in Table I. This uncertainty is determined by combining the uncertainties of appropriate elements contributing to the heat flux measurement in the TBT. The effect of uncertainties associated with the surface heat flux measurement seems to be dominated by uncertainties in curvefitting of the temperature history data, accuracy of literature property values, temperature gradients along finite thermocouple junctions and unwanted heat losses. As shown in the last item of Table I, the overall estimated measurement uncertainty of surface heat flux data plotted in Figure 11 is expected to be 7 to 29 percent. The minimum uncertainty is associated with higher heat flux conditions where the partial derivatives of temperature with respect to time (Eqs. (1) and (2)) are large. Maximum uncertainty occurs when values of the partial derivative are less than 10 K/S.

CONCLUDING REMARKS

A miniature heat flux gage device developed at NASA Lewis was used to measure heat flux on the center blade airfoil in the high-pressure-fuel turbopump turbine thermal cycling tester located at NASA/Marshall Space Flight Center. The results are being incorporated into models being developed by Lewis computational fluid mechanics personnel for turbine designs. The tests demonstrate that the time response of the gages is compatible with the SSME hydrogen-oxygen combustion transients. No deleterious effects on the gages mounted in the center blade and in the two adjacent blades resulted from fast transients at high and low temperature extremes and hydrogen impingement. These gages are being considered for measurement of surface heat flux onto turbine blade airfoils mounted in SSME testbed engine turbopump nozzles at Marshall. The engine tests will provide additional information for potential inflight engine qualification.

TABLE I. - ELEMENTS CONTRIBUTING TO HEAT FLUX MEASUREMENT UNCERTAINTY IN TURBINE BLADE TESTER

	Estimated uncertainty of element	
	Minimum, percent	Maximum, percent
	±	±
TBT facility[a] (Effect of electrical noise from facility components and surroundings on thermocouple temperature measurements; ability to correctly process data; repeatability)	1	5
Uncertainty in calculation procedure for determination of heat flux		
1. Curve fitting		
a. Temperature history	2	20
b. Heat per unit volume versus plug length	2	10
2. Accuracy of literature property values for MAR-M-246 (HF) (DS)		
a. Density[a]	1	5
b. Specific heat[a]	5	10
3. Temperature measurement accuracy after installation of thermocouple on thermoplug (hot junction location, contamination, adherence)	2	4
4. Uncertainty of $\partial T/\partial t$ value due to large temperature gradient along finite thermocouple junction[a]	2	10
5. Uncertainty of $\partial T/\partial t$ due to unwanted heat losses[a]	2	10
Expected root-mean-square of measurement uncertainty	7	29

[a]Difficult estimate.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-103274		

4. Title and Subtitle	5. Report Date
Heat Flux Measurement in SSME Turbine Blade Tester	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Curt H. Liebert	E-5719
	10. Work Unit No.
	590-21-11
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Second Annual Conference on Health Monitoring for Space Propulsion Systems sponsored by the University of Cincinnati, Cincinnati, Ohio, November 14-15, 1990.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Heat flux Measurement High pressure and temperature Hydrogen-oxygen gas	Unclassified – Unlimited Subject Categories 35 and 34

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	18	A03

NASA FORM 1626 OCT 86

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