N91-24321

S14-35
19871

CALIBRATOR TESTS OF HEAT FLUX GAUGES MOUNTED IN SSME BLADES

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Measurements of heat flux to space shuttle main engine (SSME) turbine blade surfaces are being made in the Lewis heat flux calibration facility. This facility was described at the 1987 Structural Integrity and Durability of Reusable Space Propulsion Systems Conference (ref 1). Surface heat flux information is obtained from transient temperature measurements taken at points within the gauge (refs. 2 to 4). A 100-kW Vortek arc lamp (ref. 5) is used as a source of thermal radiant energy. Figure 1 shows a gauge that has been placed at the external focus of an elliptical reflector in a lamp head attached to the side of a service module in the lamp system.

The schematic drawing of figure 2 details the miniature plug-type heat flux gauges being developed for measurement and study of blade surface heat flux. An annulus is electrical discharge machined (trepanned) into MAR M 246 (Hf)(DS) blade material creating a post, or thermoplug. The annulus is machined only part way through the blade thickness. This fabrication method is advantageous because a joining process (welding) is not required between the thermoplug and the gauge. Therefore, no seams are formed between the thermoplug and blade surface; seams can disturb boundary layer flow and heat transfer on the gauge surface. Figure 3 shows the rear of a gauge with the cover removed. Chromel-Alumel thermocouple wires (not shown) with diameters of 0.00254 cm are attached to the front surface of the gauge and along the sides and on the rear of the thermoplug. These wires are routed through the annulus to the back of the blade where they are attached to electrically insulated extension wires. The extension wires are mounted in grooves machined into the airfoil pressure surface (fig. 3), then routed through holes machined into the platform and finally fastened to the blade shank.

Thermoplugs, with diameters of about 0.190 cm and lengths varying from about 0.190 to 0.320 cm, are being investigated. The thermoplug is surrounded on all surfaces except the active surface by a pocket of air located in the circular annulus and under the back cover. Since the thermoplug is insulated, it is assumed that heat is conducted in a one-dimensional manner from the hot active surface to the cooler back side of the thermoplug. A one-dimensional relationship for obtaining surface heat flux is then (ref 2):

$$\dot{q}_s = \int_0^L (\rho C_p \, \partial T/\partial t) dz, \quad W/m^2 \tag{1}$$

where $\dot{q}_s$ is the surface heat flux, L is the thermoplug length, and ρ and C_p are the density and specific heat of MAR-M-246(Hf)(DS), $\partial T/\partial t$ is the partial derivative of temperature with respect to time, and z is a distance along the thermoplug axis.

Values of specific heat as a function of temperature for MAR-M-246(Hf)(DS) and a similar alloy (MAR-M-200) are shown in figure 4. These data were obtained from reference 6. The density of MAR-M-246(Hf)(DS) is 8442 kg/m^3 (ref. 6). Unfortunately, no indication of experimental error associated with property measurement is given in reference 6. Experimental errors of specific heat and density data are assumed as ±20 percent and ±5 percent. These uncertainties of measured property data are typical for many alloys. The curve of specific heat versus temperature used herein to solve equation (1) is shown as a solid curve in figure 4. The solid curve and literature data correspond within experimental error.

The suction surface of an instrumented SSME blade mounted on the calibrator is shown in figure 5. A heat flux gauge is mounted on both the suction and pressure surfaces at midspan and midchord. In figure 5 radiation is incident on the active surface of the suction surface gauge, and radiation is also incident on the back of the pressure surface gauge. Both this and the reverse orientation are being investigated. Welds attaching a cover plate (304 stainless steel) to the suction surface of the blade and a cover plate welded over extension wires buried in grooves machined into the airfoil are discernible in figure 5. Because there is no airflow over the airfoil surface tested in the calibrator, these welds were not machined flush to the surface.

The heat flux gauge mounted on the suction surface below the cover is not discernible in figure 5 because the thermoplug and blade at this location are one piece. Thermoplug temperature history measured within the suction surface gauge is plotted in figure 6, and the corresponding heat flux history is shown in figure 7. Blade heat flux data are measured over a temperature range of about 100 to 1100 K at a lamp current of 400 A. This data are compared in figure 7 with data previously obtained with other gauges: (1) four miniature plug-type gauges mounted in MAR-M-246(Hf)(DS) coupons, (2) two commercial factory-calibrated Hy-Cal gauges, and (3) a photocell. The photocell millivolt data show that the lamp intensity rises rapidly during startup (time = 0.3 to 0.6 sec) and then becomes relatively constant at longer times. This trend was also observed when the two Hy-Cal gauges and the four miniature plug-type gauges mounted in the coupons were investigated in the calibrator. Furthermore, the plug-in-coupon data compare reasonably well (-6%) with the Hy-Cal gauge data. Surface heat flux measured on the blade instrumented with a miniature plug-type gauge compares well with both the Hy-Cal and gauge-in-coupon data (fig 7).

Because these comparisons are reasonable, it is concluded that the miniature plug-type gauge concept is feasible for measurement of blade surface heat flux. Reference 7 suggests that it is important to measure heat flux near the hub on the suction surface and at the throat on SSME blades rotating in engines because stress and heat transfer coefficients are high in this region. Nonrotating tests in the calibrator on gauges mounted at this throat location are being planned. Also, tests on gauges with lower thermal conductivity insulation (compared with air) around the thermoplug are planned in the calibrator. Use of insulation with lower thermal conductivity will minimize heat conduction between the plug, the surrounding annulus, and the cover plate. Furthermore, designs for locating heat flux gauges at the leading edge of SSME blades have been started. Finally, plans to test heat flux gauges mounted on nonrotating SSME blades inserted into the Marshall Space Flight Center turbine blade tester are being formulated. The results, in terms of measured gas-side heat transfer coefficients, will be compared with calculations (ref. 7).

REFERENCES

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LAMPHEAD AND POSITIONING ARM

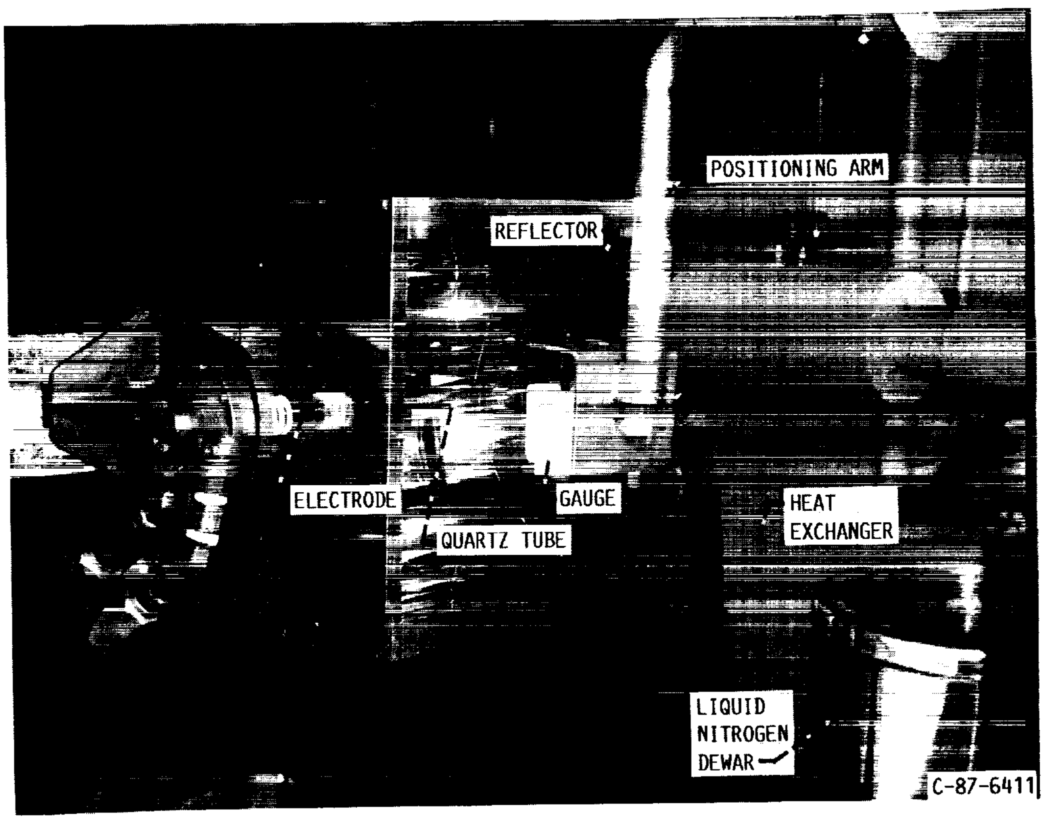

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Figure 1

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PLUG-TYPE HEAT FLUX GAUGE
(DIMENSIONS IN CENTIMETERS)

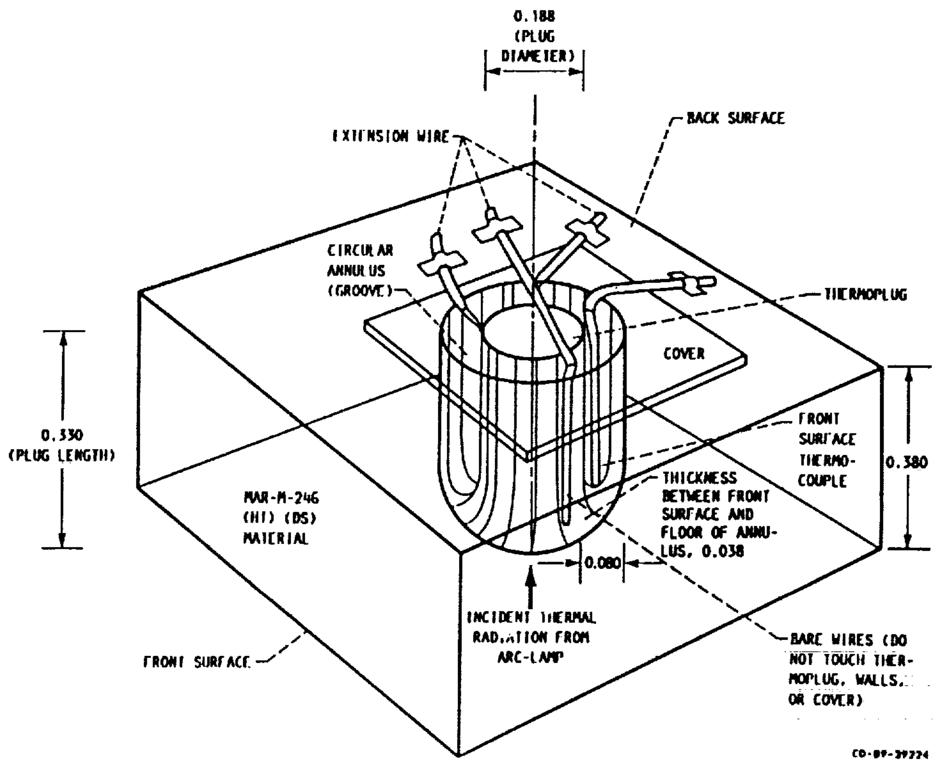

Figure 2

MINIATURE HEAT FLUX GAUGE BEFORE THERMOCOUPLE INSTALLATION

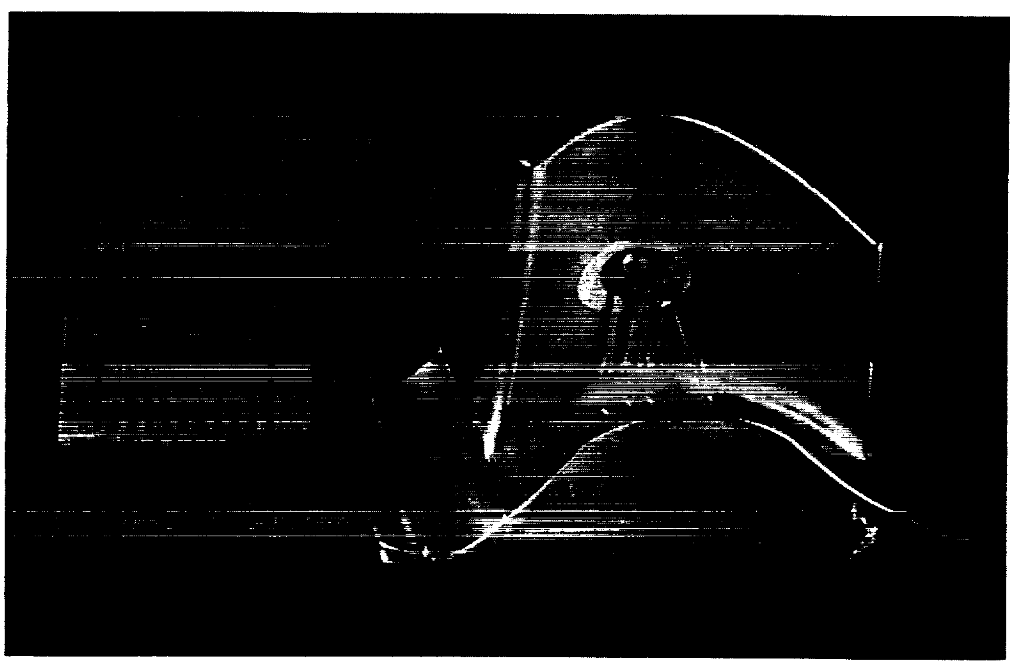

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Figure 3

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SPECIFIC HEAT VERSUS SPECIMEN TEMPERATURE

DENSITY = 8442 kg/m^3; ref. 6

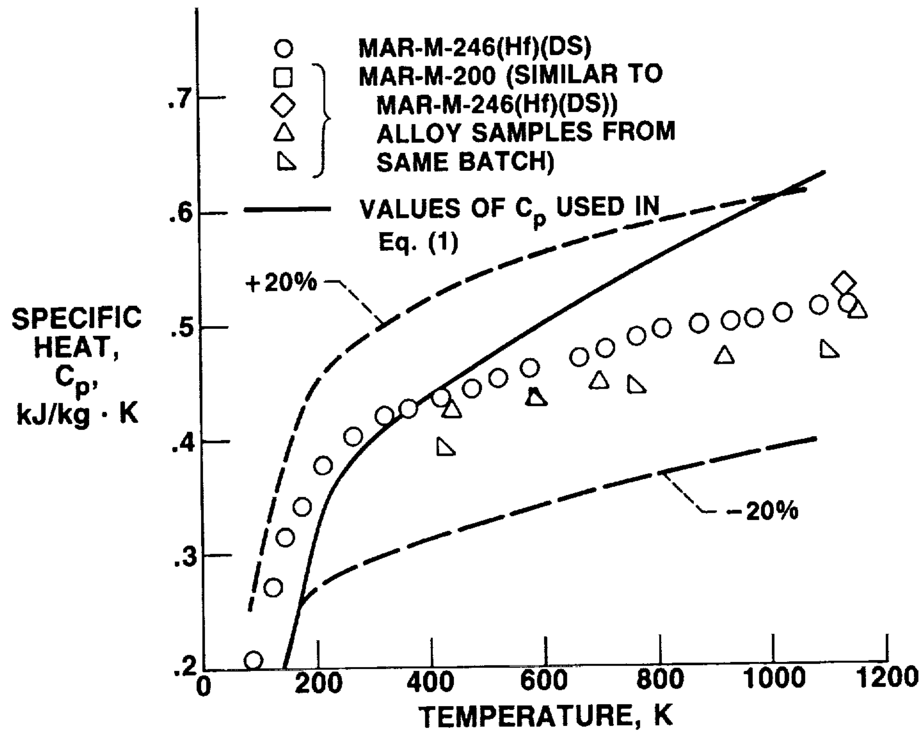

Figure 4 CD-89-39226

INSTRUMENTED SSME BLADE MOUNTED IN CALIBRATOR

Figure 5 CD-89-39227

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TEMPERATURE HISTORY OF GAUGE MOUNTED IN SSME BLADE

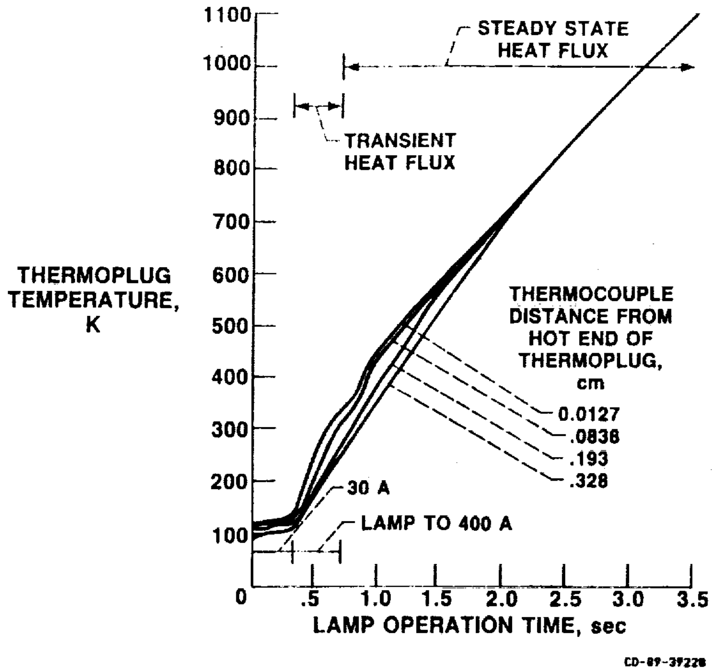
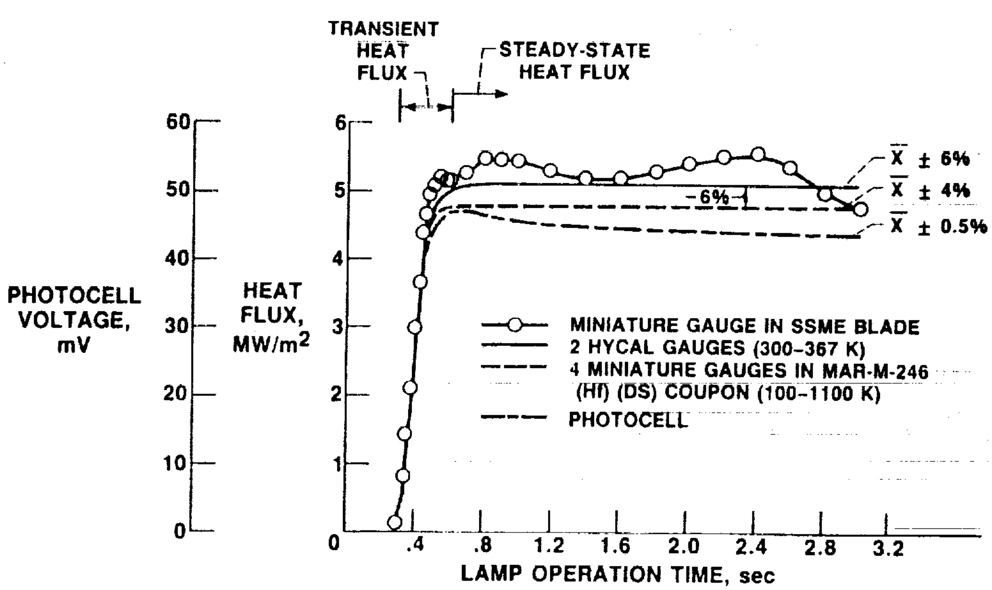


Figure 6

HEAT FLUX MEASUREMENTS WITH GAUGE MOUNTED IN SSME BLADE

LAMP CURRENT, 400 A



$\overline{X}$ EVALUATED AT 95 PERCENT CONFIDENCE INTERVAL:

- STEADY-STATE IS 100 DATA POINTS MEASURED AT t=0.6 – 3.0 sec
- TRANSIENT IS 10 DATA POINTS MEASURED AT SELECTED TIMES

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Figure 7