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DEVELOPMENT OF HEAT FLUX SENSORS IN TURBINE AIRFOILS

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This paper describes the work performed under contract NAS3-23529 "Turbine Blade and Vane Heat Flux Sensor Development." The objective of this contract is to develop heat flux sensors suitable for use on turbine airfoils and to verify the operation of the heat flux measurement techniques through laboratory experiments.

The design of durable turbine airfoils that use a minimum amount of cooling air requires knowledge of the heat loads on the airfoils during engine operation. Measurement of these heat loads will permit the verification or modification of the analytical models used in the design process and will improve the ability to predict and confirm the thermal performance of turbine airfoil designs. Heat flux sensors for turbine blades and vanes must be compatible with the cast nickel-base and cobalt-base materials used in their fabrication and must be capable of operation in a hostile environment with regard to temperature, pressure and thermal cycling. In order to not perturb heat flows to be measured, it is necessary to use the smallest possible sensors.

During the first phase of this contract two sensor designs were identified that met the established criteria for turbine airfoils. These sensors were the embedded thermocouple sensor and the Gardon gage sensor. Both were fabricated into the airfoil wall.

Figure 1 is a schematic of the embedded thermocouple sensor. This type of one-dimensional steady-state sensor determines the heat flux by measuring the temperature drop across a thermal barrier. In this case, the airfoil wall acts as the thermal barrier. The Gardon gage sensor is shown schematically in figure 2. This type of steady-state sensor determines the heat flux from the temperature rise due to radial conduction from the insulated section of the hot side of the airfoil wall.

Both types of sensors were fabricated into turbine blades and vanes. The installation of the sensors required access to the inside wall of the airfoil. The blades used for the heat flux sensor installations were two-piece bonded blades. The instrumentation was installed in one blade half. The two halves were then joined using a 1255K braze material. For installation in turbine vanes, a window, through which instrumentation was installed, was cut into the opposite airfoil wall. Figure 3 shows a vane being instrumented. After completion of instrumentation the window was heliarc welded back in place. The airfoil wall was then smoothed to restore aerodynamic integrity. NASA has fabricated vanes by cutting them in half, installing the instrumentation and then brazing the vane halves back together.

A calibration fixture, shown in figure 4, was designed and fabricated for the calibration of airfoil-mounted heat flux sensors. This fixture was mounted below a quartz lamp bank heat source, shown in figure 5. The fixture allowed positioning of the airfoil so that the surface of the heat flux sensor was normal to the incident radiation. The surface of the airfoil was coated with material having a known and stable absorptance and emittance. The incident radiation was measured with a reference Hy-Cal asymptotic calorimeter. The sensors were calibrated at a number of heat flux levels and over a range of sensor temperatures. The data was then normalized to a temperature of 1200K. Figure 6 shows a typical calibration result for a Gardon Gage sensor. This same apparatus was used for thermal cycle and thermal soak tests as well as the calibration tests.

The sensors developed under the first phase of the turbine blade and vane heat flux sensor program proved capable of measuring the heat loads on turbine airfoils up to 1.6 megawatts/m^2 incident with an accuracy of ± 5 percent. They withstood thermal cycling and thermal soak conditions expected in a real gas turbine engine environment. Sensors must be carefully installed in airfoils with complex internal cooling schemes. In such airfoils there may be regions where strong non-one-dimensional heat flows exist. These non-one-dimensional flows make it difficult to obtain meaningful sensor calibrations. The full details of the sensor development and laboratory testing are contained in references 1 and 2.

The second phase of this program demonstrated a variety of heat transfer measurement methods on a simple test piece in an atmospheric pressure combustor rig. A cylinder in cross-flow was chosen because this configuration has been tested extensively and is well documented in the literature.

The combustor rig selected is a general purpose laboratory combustor shown schematically in figure 7. The mixing and flow in the combustor closely approximated those of many conventional gas turbine combustors, and the critical features of the combustion chemistry were reproduced. The fuel was introduced at the front of the combustor by a pressure atomizing fuel nozzle. The combustion was stabilized in the forward section of the combustor by developing a strong, swirl-stabilized recirculation zone. The hot combustion gases were cooled by dilution jets located at the back of the combustor. The primary and secondary jets have independent air supplies to permit adjustment of the velocity and temperature profiles at the exit. The ignitor, a flame monitor, and instrumentation ports were mounted in an instrumentation rig located between the primary and secondary sections. The 5 cm diameter exhaust could be operated at a temperature up to 1700K at Mach numbers up to 0.7 at this maximum temperature.

The instrumentation cylinder selected was a 1.6 cm diameter tube made of Hastelloy-X with a wall thickness of 0.15 cm. The diameter of the cylinder was a compromise between a size large enough to permit installation of the instrumentation and small enough to cause minimal flow blockage. During test the cylinder will be cooled with channel-flow coolant in the tube. To obtain the required internal heat transfer coefficient, the channel height was reduced by adding a center tube concentric with the cylinder. The cylinder was prepared for instrumentation by slicing a portion of the tube length in half. This allowed direct access to the interior of the cylinder for the necessary Elox operations as well as installation of instrumentation.

Figure 8 shows a cylinder following the Elox operation but before installation of the instrumentation. The sensor on the left will be a transient slug calorimeter; the center sensor will be a Gardon Gage; and the sensor on the right will be an embedded thermocouple sensor. Figure 9 shows the same cylinder after installation of lead wires but before the interior wall has been smoothed or the Gardon gage cavity has been filled with ceramic. Figure 10 shows the completed installation, with the center tube installed, prior to cylinder rewelding. The instrumentation is led out through the center tube. Figure 11 is an end-on view of the cylinder following rewelding of the cylinder halves.

Following construction, the heat flux sensors in the cylinder were calibrated using the quartz lamp bank calibration facility. Figure 12 shows typical calibrations for a Gardon gage sensor installed in a cylinder. All of the calibrations were well-behaved. None of the steady-state sensors appeared to be affected by non-one-dimensional flow problems.

Preparations are now underway to test the sensors in the cylinders in front of an atmospheric pressure combustor. Initial tests are being conducted to characterize the conditions at the combustor exit at a number of run conditions. Pratt & Whitney is conducting tests to characterize the thermal and pressure profiles; both the spatial and temporal variations of these quantities are being measured. In a parallel effort, NASA Lewis Research Center is conducting Laser Doppler Velocimeter (LDV) tests on a similar combustion rig. These tests are to characterize the turbulence profiles behind the combustor. Testing will be done both with and without a flow straightener. The preliminary test data looks good. The combustor has uniform thermal profile at the exit, and relatively constant temporal variation and turbulence levels.

When the combustor characterization tests are complete, testing of the cylinder behind the combustor will begin. The cylinder will be mounted 5 cm from the combustor exit. Any free-stream instrumentation will be located upstream from the cylinder, 2.5 cm from the combustor exit. Preliminary test data shows this will put the cylinder in an area of uniform thermal and Mach number profiles, minimizing both cylinder blockage effects and the effect of the cylinder on the free-stream instrumentation.

The cylinder will be mounted on a traverse can. This will allow the various sensor types to be sequentially moved into place behind the combustor, permitting multiple sensor types to be tested at the same conditions. All three sensors (the steady-state embedded thermocouple sensor, the steady-state Gardon gage, and the transient slug calorimeter) will be run over a range of test conditions. The resulting data should allow a good comparison between sensor types as well as between the sensor results and the expected value (which will be calculated from the measured free-stream conditions).

A second cylinder will be tested under a limited number of conditions. That cylinder will be a 1.6 cm diameter NiCoCrAlY tube with wall thickness of 0.48 cm. An array of sputtered thin film thermocouples will be installed on this cylinder. These will be run in front of the combustor rig in conjunction with a high response thermocouple probe (developed under NASA contract NAS3-23154, reference 3). The heat transfer coefficient is calculated from the ratio of the thermal variations of the free-stream gas and the surface thermocouples.

The work done under this contract has yielded accurate durable sensors for use on those sections of turbine airfoils where the heat flow conditions are relatively uniform. It also will yield a data base of high temperature heat flux measurements by several methods on a cylinder in cross-flow. In addition, the requirement for a program to investigate the measurement of heat flux on airfoils in areas of strong non-one-dimensional flow has been identified.

REFERENCES

1. Atkinson, W.H.; Cyr, M.A.; and Strange, R.R.: Turbine Blade and Vane Heat Flux Sensor Development. NASA Contract, NAS3-23529, August 1984.

2. Atkinson, W.H.; and Strange, R.R.: Development of Advanced High Temperature Heat Flux Sensors. NASA Report, CR-165618, September 1982.

3. Elmore, D.L.; Robinson, W.W.; and Watkins, W.B.: Dynamic Gas Temperature Measurement System. Final Report, CR-168167. NASA Contract, NAS3-23154. May 10, 1983.

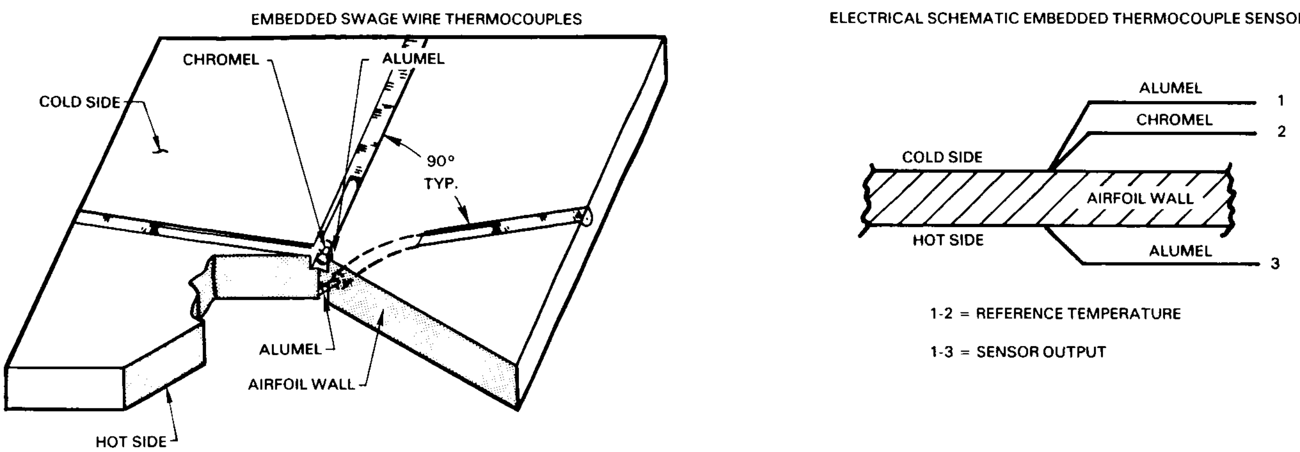

Figure 1   Schematic of the Embedded Thermocouple Heat Flux Sensor

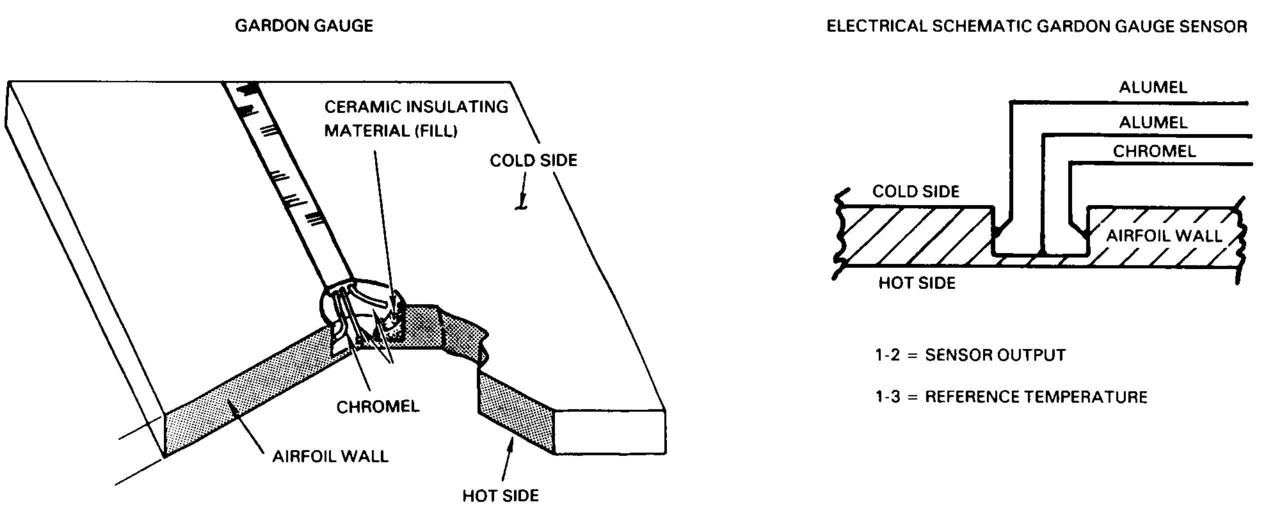

Figure 2   Schematic of the Gardon Gage Heat Flux Sensor

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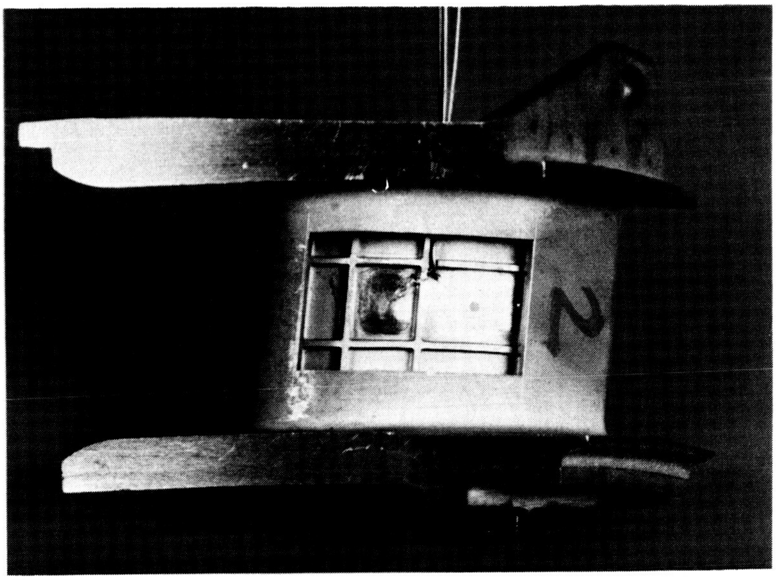
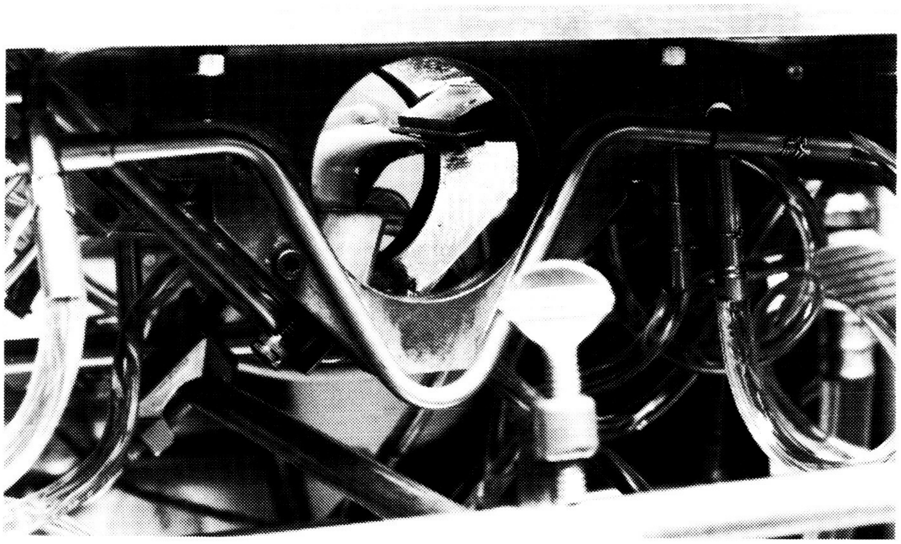


Figure 3 Vane in Process of Being Instrumented



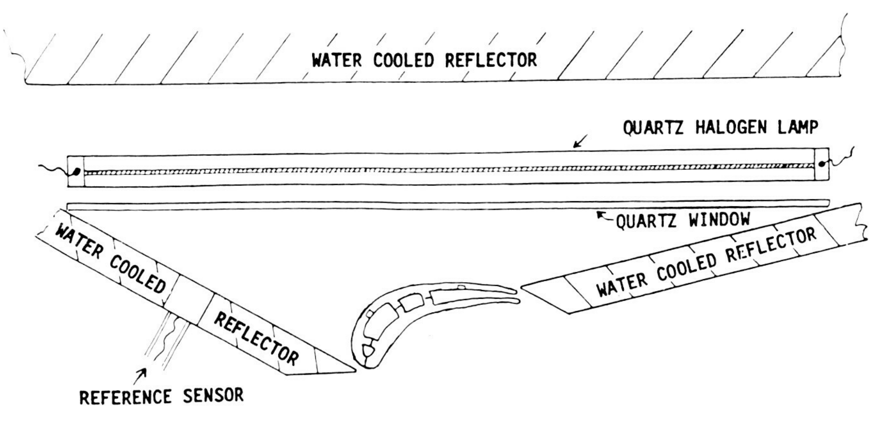


Figure 4 Calibration Fixture

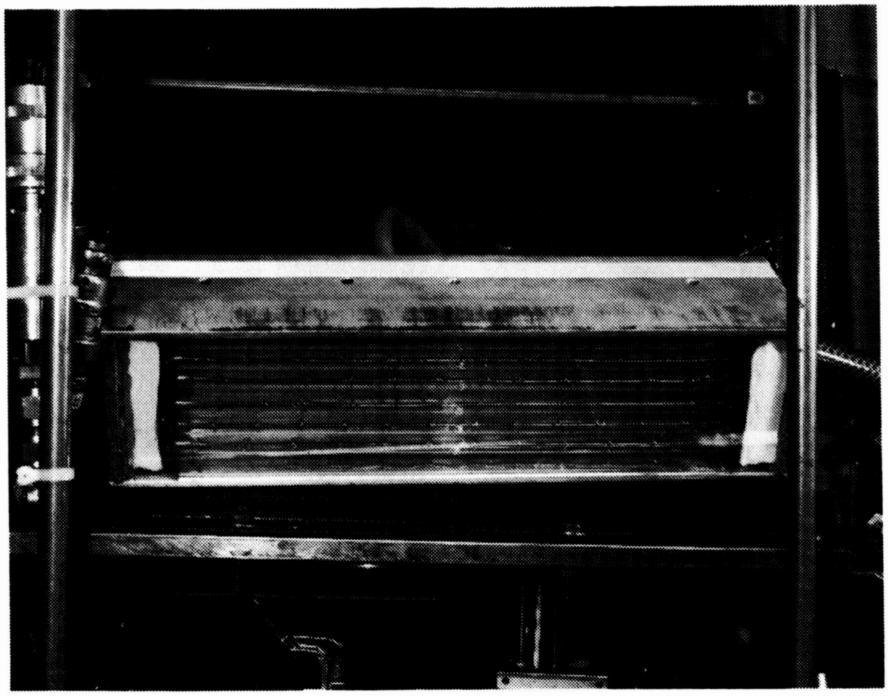


Figure 5 Lamp Face of Quartz Lamp

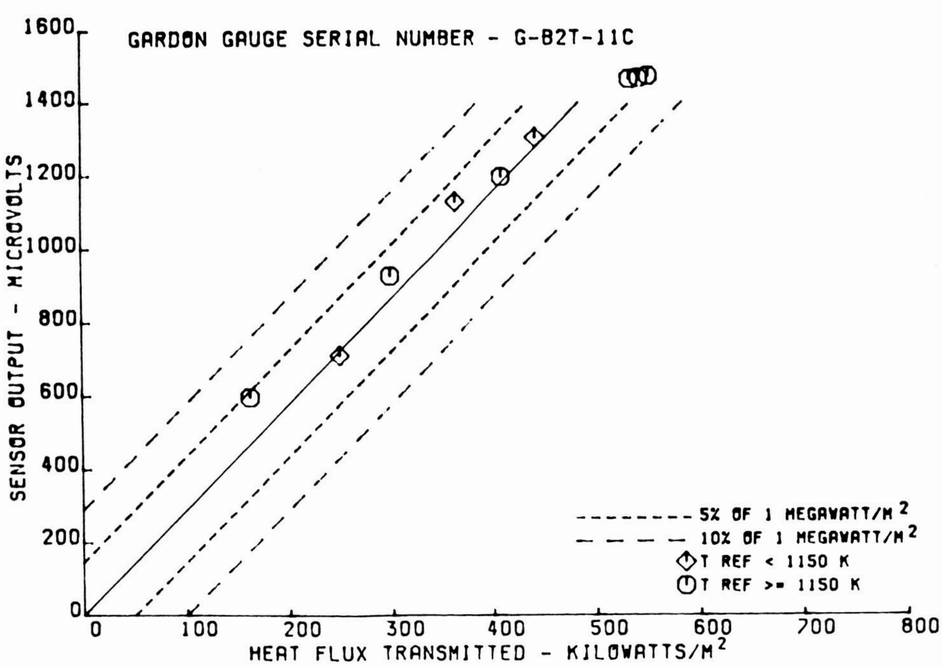


Figure 6 Calibration Curve - Gardon Gage Installed in Turbine Vane

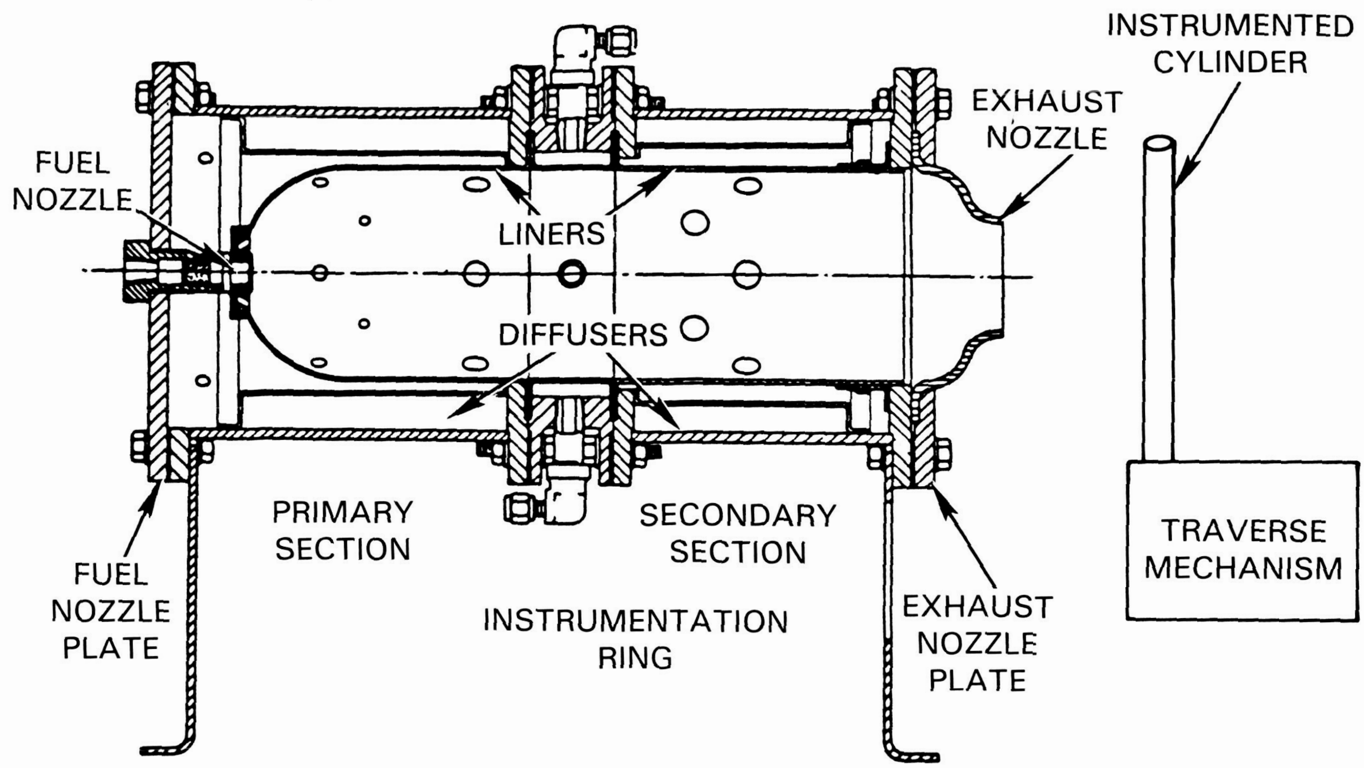


Figure 7 Schematic of Combustor Rig

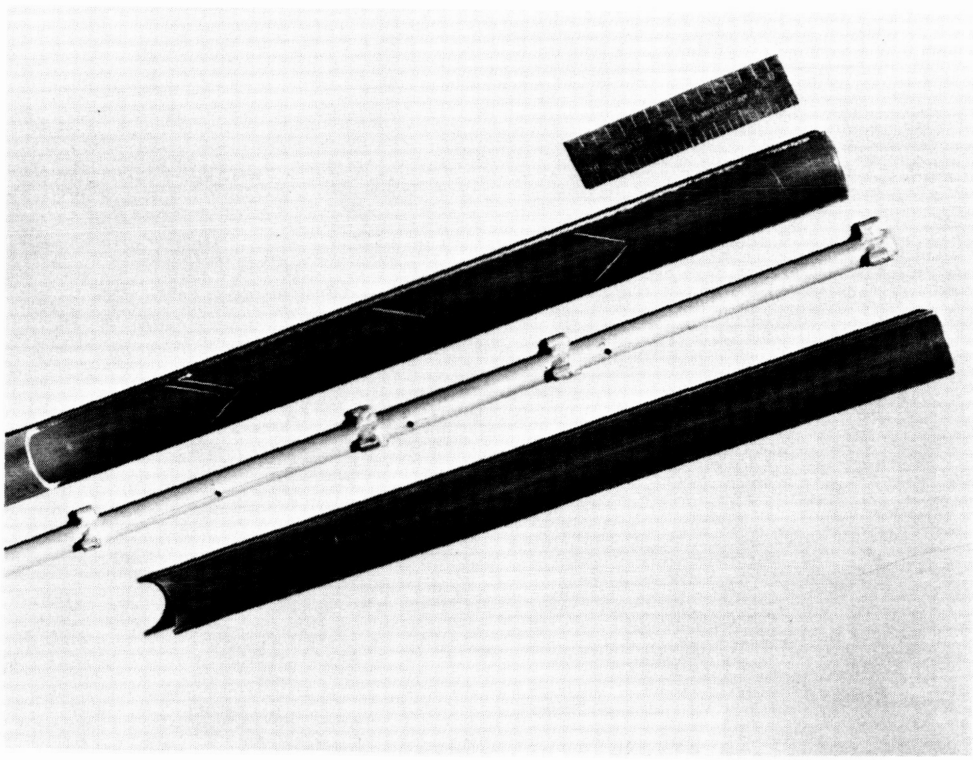


Figure 8 Open Cylinder - Elox Completed

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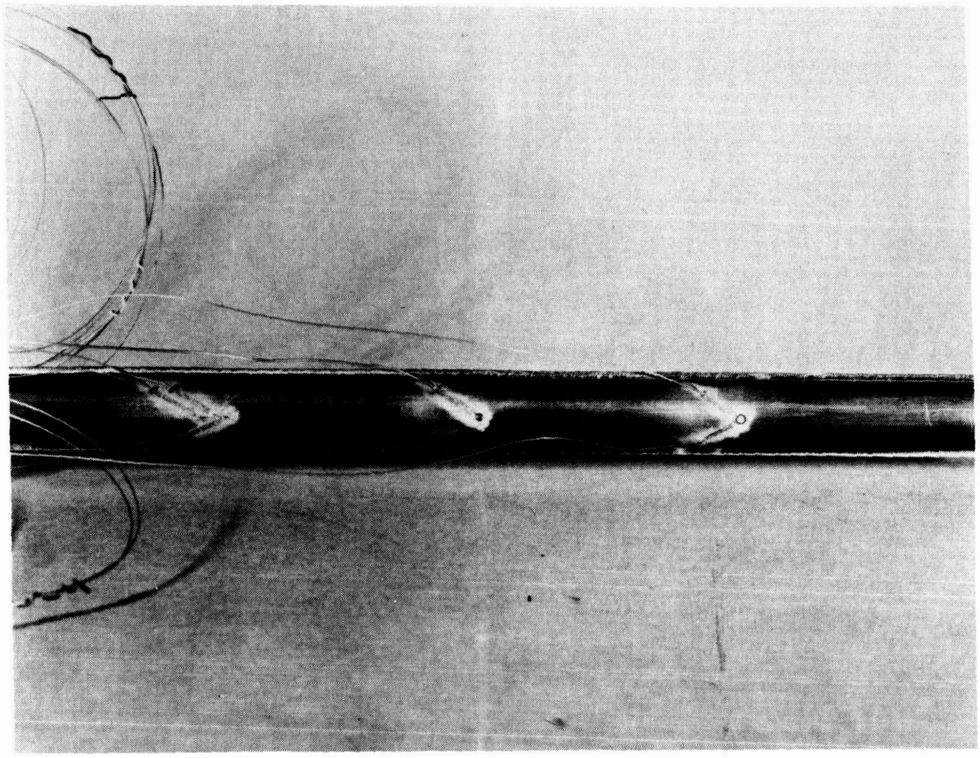

Figure 9 Open Cylinder - Lead Wires Installed

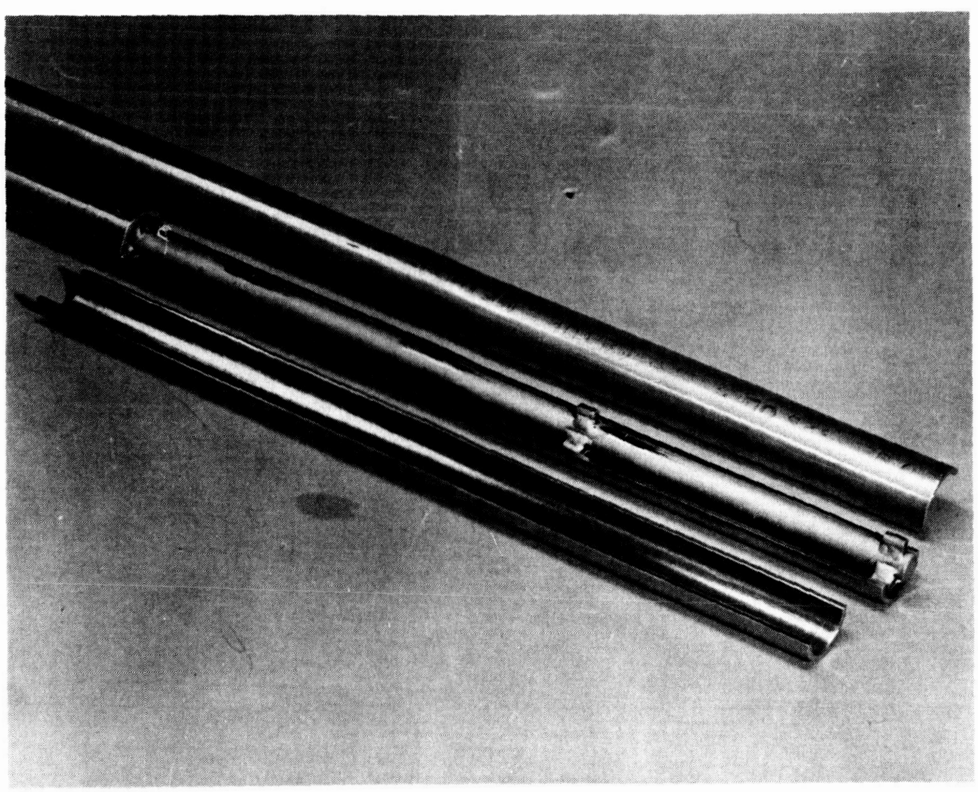

Figure 10 Open Cylinder With Center Tube

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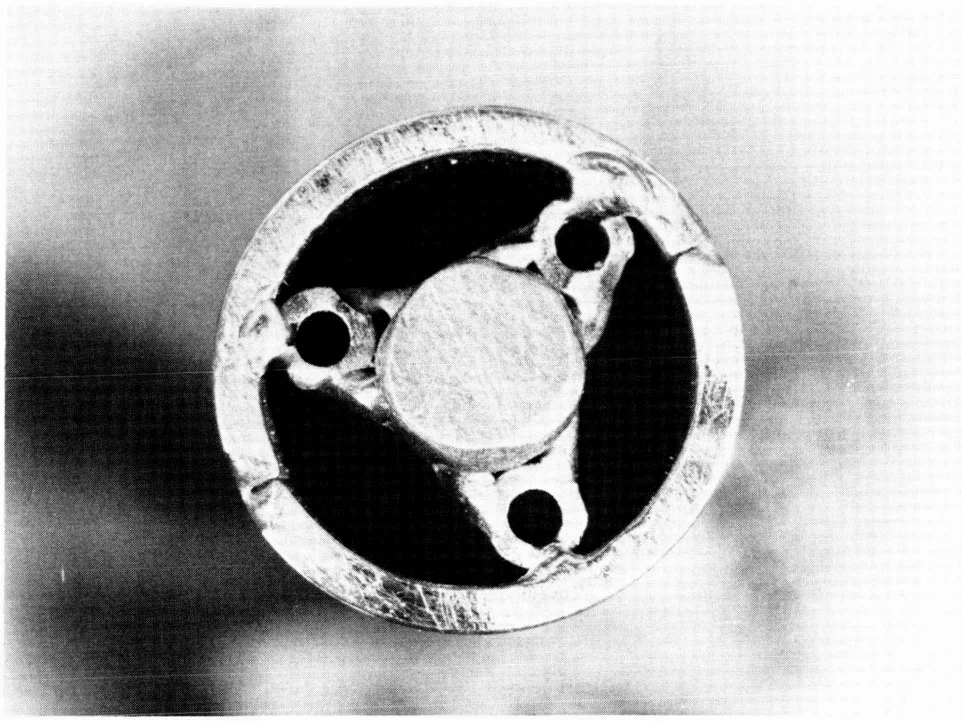

Figure 11 End View of Completed Cylinder

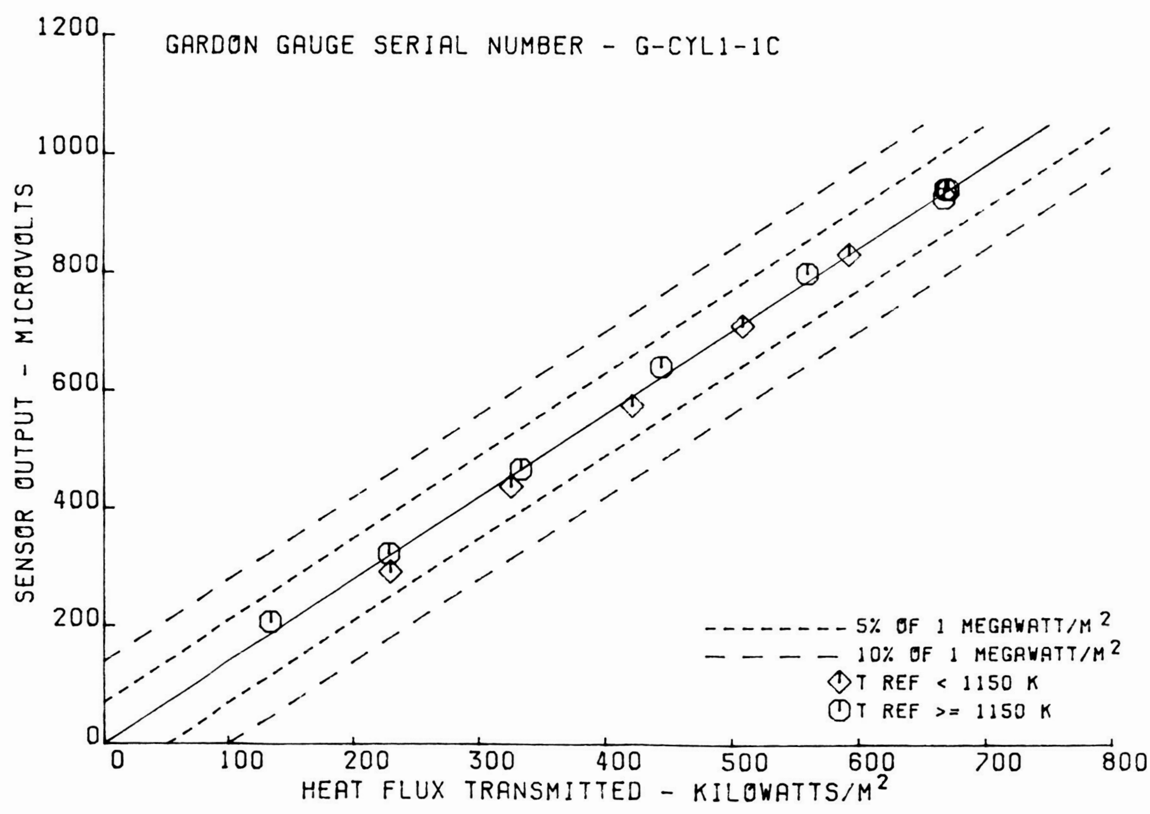

Figure 12 Calibration Curve - Gardon Gage Installed in Cylinder