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TEMPERATURE AND PRESSURE MEASUREMENT TECHNIQUES FOR AN ADVANCED TURBINE TEST FACILITY

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ABSTRACT

A high pressure ($4x10^6$ N/m^2), high-temperature (2400 K) turbine test facility is being constructed at the NASA Lewis Research Center for use in turbine cooling research. Several recently developed temperature and pressure measuring techniques will be used in this facility. This paper will briefly describe these measurement techniques, their status, previous applications and some results.

Noncontact surface temperature measurements will be made by optical methods. Radiation pyrometry principles combined with photoelectric scanning will be used for rotating components and infrared photography for stationary components. Contact (direct) temperature and pressure measurements on rotating components will be handled with an 80-channel rotary data package which mounts on and rotates with the turbine shaft at speeds up to 17 500 rpm. The data channels are time-division multiplexed and converted to digital words in the data package. A rotary transformer couples power and digital data to and from the shaft.

INTRODUCTION

About 10 years ago, a program was initiated at the NASA Lewis Research Center to improve techniques for measuring temperatures and pressures on gas turbine components associated with turbine cooling research. Means of obtaining experimental measurements of temperatures and pressures under actual or simulated engine environments, particularly on rotating components, was not well developed at that time. Concentrated efforts in this program and from other sources have greatly advanced instrumentation technology for turbomachinery components. This paper will describe the present status of three measurement systems under the NASA-Lewis program. Two are optical systems for measuring metal surface temperatures on stationary vanes and rotating blades in the turbine stage; the third is a rotary data package for transmitting thermocouple and pressure transducer signals from a rotating shaft to a stationary readout. Previous reports on interim or prototype versions of these systems have been made in Refs. 1 and 2.

The specific application for which these instrumentation systems were developed is a NASA-Lewis high-pressure, high-temperature turbine rig reported in Ref. 3. This rig will be used to investigate turbine cooling technology for a representative first stage turbine for advanced turbofan engines.

TURBINE RIG AND INSTRUMENTATON

The NASA-Lewis high-pressure high-temperature turbine rig for which these instrumentation systems were developed was designed to provide a turbine test environment of $4x10^6$ N/m^2 (40 atm) of pressure and an ultimate gas path temperature of 2400 K. This high gas path temperature approaches stoichiometric conditions for current aircraft hydrocarbon fuels. The turbine rig contains a single stage 0.5 m diameter air-cooled turbine with a shaft speed of about 17 000 rpm. These design conditions are representative of an envelope of foreseeable individual maximum levels of operating parameters that might be encountered in the first stage turbine of advanced turbofan engines.

A schematic view of the turbine rig test section (fig. 1) shows the location of the instrumentation systems. A water-cooled retractable turbine vane camera probe for an IR photography system is mounted at the turbine inlet (Station 4) approximately 4 cm forward of the vane leading edge. A rearward-looking viewing port in the probe is purged with nitrogen to keep the optical surface free of any deposits from the gas path. The probe can be rotated by remote control through an arc of 90° to change the field of view. Probe mounting positions at three different circumferential locations are available at Station 4. The probe actuator and the recording camera are attached in tandem to the turbine rig pressure shell along the centerline of the probe and are protected by an environmental enclosure. The camera is directly coupled to the probe and translates and rotates with it.

A water-cooled retractable turbine blade pyrometer probe is mounted at the turbine exit (Station 6) approximately 6 cm downstream of the blade trailing edge. A forward-looking nitrogen-purged viewing port in the probe permits viewing of the rotating blades. The probe contains a fiber optic bundle which extends about 5 m from the viewing port to interface with a sensitive silicon avalanche detector and associated hardware mounted in a protected position removed from the immediate vicinity of the turbine rig. The probe can be rotated by remote control through an arc of 90°. Probe mounting positions at three different circumferential locations are available at Station 6.

The rotary data package, not shown in Fig. 1, is centerline-mounted on an extension of the turbine shaft beyond the right edge of the figure. The rotary data package contains pressure transducers and electronics for handling pressure and temperature measurements. Instrumentation leads from temperature and pressure measurement points on the blades and the turbine disk run down the forward face of the disk and through the bore of the disk and the hollow turbine shaft and its extension to the rotary data package. The temperature sensors are sheathed chromel-alumel thermocouples. The pressure sensors are static taps in small diameter stainless steel tubes. Thermocouples along the radial run of the pressure tubing on the turbine disk provide a temperature distribution measurement for making density corrections to sensed pressure to compensate for rotational effects (4,5).

OPTICAL SURFACE TEMPERATURE MEASUREMENTS

A surface emits radiation as a function of its absolute temperature. By combining radiation pyrometry and precision imaging, it is possible to obtain research quality temperature measurements over a large area of a heated surface with high spatial resolution. Radiation pyrometry techniques currently in use for determining surface temperatures in gas turbines measure the intensity of near IR radiation (0.9 microns) received from airfoil surfaces in one or several narrow bandwidths. Surface temperatures can then be calculated from the measured received radiation by using suitable calibration techniques.

For stationary vanes, surface radiance distribution can be measured by IR photography. A thermal image of a heated vane is recorded on IR film, the film is developed, and the film density distribution is converted through proper calibration into a surface temperature distribution. Rotating blades can be scanned photoelectrically and the detector output converted again through proper calibration into temperature in near real time. Descriptions of an IR photographic system for vane surface temperature measurements and a photoelectric scanning system for blade surface measurements that were developed for the NASA-Lewis turbine rig are given below.

IR Photography System

IR photography (6) has been used by NASA-Lewis in a number of experimental programs involving turbine cooling and thermal fatigue studies. Experience gained during these experimental programs has resulted in improved borescopes for obtaining quality images and in improved calibration techniques for routinely obtaining accurate relationships between film density and surface temperature. The IR photography system that will be used with the turbine rig was based on these developments.

System Description

The IR photography system for temperature measurements on stationary vanes in the turbine rig is shown in block diagram form on Fig. 2. The system consists of a remote-controlled camera (1) with an optical probe to image the vane radiation through an IR filter onto IR-sensitive film; a film processor (2); a microdensitometer (3) to measure and record film density information over the entire thermal image; and a computer (4) provided with calibration data to calculate the temperature distribution from the film density record. The final result is a turbine vane temperature record (5) consisting of temperature profiles and two-dimensional contour maps of temperature distribution.

The film calibration technique is detailed in Ref. 6. An area of each film is exposed with a calibrated relative energy scale (step tablet on grey scale). This exposure establishes the film (detector) response curve. The film response curve is then correlated with a temperature distribution curve. This latter curve, the distribution of relative radiant energy with temperature, is a plot of Planck's equation integrated over the bandwidth of detection. The detector bandwidth is determined by the filter transmission function and the IR film spectral sensitivity. A thermocouple located on the vane surface in the camera field of view is used as a reference point. At this reference point, one known temperature and one known density are used to correlate the film response and temperature distribution curves. No correction for surface emittance is required with this relative method of temperature calibration.

The advantage of the IR photographic method is that a thermal image of a vane can be recorded in a fraction of a second and the image can be resolved into very small spot sizes with a microdensitometer. A thermal image for a particular camera exposure is limited to an average temperature span of about 200 K. However, this span is more than that required for recording temperature distributions on properly designed cooled vanes. A disadvantage of the method is that temperature data are not available during the time of the test. There is usually a delay of from several hours up to days because of the sequence of procedures required. In most cases this is not a serious drawback, and the detailed information available from a thermal image analysis compensates for the time delay.

Example of Results

An example of a photographic image analysis is shown in Fig. 3. For these tests, a film-cooled turbine vane was heated in a 1530 K gas stream in a thermal stress rig. A conventional photograph of the test vane is included in the figure and is used for dimensional reference and to locate surface features. The thermal image of the heated vane was recorded on 35 mm high speed IR film at a magnification of 0.2. A microdensitometer with a small measuring aperature was used to scan the image in two modes. One mode recorded a density profile scan (10x size) across the image. In this example, it was at the mid span location. The other mode records a contour map (10x size) in equal density increments over the entire thermal image. The density scale on the profile scan was calibrated into a temperature scale using the reference thermocouple and the calibration technique previously described. The contours on the map were converted into temperature by projecting corresponding locations from the mid-span profile curve to the contour map at the mid span location. Generally, all contours can be calibrated from one or two profile scans.

In similar tests, vanes were instrumented with an array of thermocouples. Using one thermocouple as a reference point, the photographically determined temperatures at all other thermocouple locations agreed to within 1 percent of the temperature (expressed in ^{o}C) measured by the thermocouples.

Further Component Improvements

A video densitometry method is being developed to automate and speed-up the film data analysis of thermal images. This method substitutes a commercially available video image processor for the microdensitometer and a computer for the graphs and manual procedures. With the computer-based image processing method, the film frame is indexed over a properly masked light box in a precision film transport mechanism. The light transmitted through the film frame is scanned by a special television camera which was selected by the supplier for its photometric accuracy (shading and linearity). This feature is important since the scanner is the source of the image data that is subsequently processed and analyzed. The output of the scanner is amplified logarithmically. This causes the scanner to operate as a densitometer because, by definition, density is the logarithm of the film transmission factor. The amplified scanner output is then digitized and stored on a magnetic disk.

This information is stored as 480 interlaced lines, each consisting of 620 8-bit picture elements. Each picture element represents one of 256 possible grey values from black (0) to white (255). The image is redisplayed on a television monitor and the grey level of any given point is obtained either from calculated coordinates or from reading the coordinates of a joystick-operated cursor. A calibration scheme to convert grey level to temperature was developed and programmed for the computer.

After further development, this video densitometry method will be added to the current IR photography system to expedite turbine rig film data analysis.

Photoelectric Scanning System

The customized photoelectric scanning system that will be used on the turbine rig is a modified version of a prototype system described in Refs. 7 and 8. The current system incorporates several improvements including: an electronic shaft angle encoder (9) in place of a magnetic pulse pickup for a more accurate trigger pulse, a reference lamp as part of the fiber optic probe to provide a calibration signal, a pulsed light emitting diode to check frequency response and provision for different wavelength (various filters) measurement. In anticipation of a need to correct for reflected gas and carbon particle radiation at high gas path pressures. The problem of interfering radiation is discussed in Ref. 10 along with suggested methods to minimize its effect.

System Description

The customized photoelectric scanning system has optics and high speed electronics that are capable of resolving a spot diameter of 0.1 cm on a blade moving with speeds of the order of 300 to 400 meters-per-second. Near real time displays of temperature profile are generated for a single blade or for small groups of blades at steady state gas path conditions.

A block diagram of the system is shown in Fig. 4. The protected fiber-optic probe (1) is positioned in the gas path by a remotely controlled actuator and the fiber is focused in the plane of the turbine blades. As the heated blades rotate, the emitted radiation from the spot location (0.1 cm diam instantaneous field of view of the fiber) is transferred optically to a fast response silicon avalanche detector (2), thereby generating a continuous high resolution intensity profile which is monitored continuously on an oscilloscope (3). The amplified detector output is digitized by an analog-to-digital (A/D) converter (4) at ranges up to 2 MHz rate. A blade position sensor (5) supplies a trigger signal when the chosen blade enters the field of view. Starting with this trigger signal, a 200 point sample of the digitized detector output is stored in a high speed memory (6). This process may be repeated a number of times (equivalent to several revolutions of the turbine) to average out random noise. The number of chosen blades (usually 1 to 8) scanned with a 200 point sample is determined by the digitizing frequency and the speed of the turbine. The 200 data points are transferred at a slower rate from the memory to the computer (7) where each point is converted into temperature using pre-recorded calibration information. This calibration information is obtained prior to testing by focusing the optical probe onto an accurately known temperature source and relating the digital output of the A/D converter to the temperature. A blackbody oven is used as the temperature source. Therefore, a correction for the surface emittance of the blade is required with this absolute method of temperature calibration.

The timing and control logic circuit (8) provides interchange of control between the computer, the memory and the A/D converter. Through the logic circuit, the operator, via the computer, has control over the entire system. Processed data are presented on a CRT display in the form of a temperature profile and a listing of the 200 calibrated points making up the profile. A hard copy of the turbine blade temperature record (9) can be made in about 3 seconds. In addition to generating a single temperature profile scan record, the system can also obtain a series of scans over a range of radial locations, using the probe actuator, and present them in an isometric view. With additional computer processing the data can alternatively be presented as a two-dimensional contour map of temperature distribution.

Examples of Photoelectric Scanning Results

An example of data obtained with a photoelectric scanning system during a previous test in an engine described in Ref. 8 is illustrated in Fig. 5. The air-cooled turbine blades shown in the figure were instrumented with surface thermocouples. One blade had a ceramic coating on the surface in the form of a chevron pattern to examine the spatial resolution of the system. Turbine inlet gas temperature was 1640 K while maximum blade temperature was limited to 1200 K by adjusting coolant flow. The tip speed of the blade was 360 meters-per-second. Typical temperature profiles are shown on figure 5. In the center is an isometric display of temperature profiles made across the chevron pattern at the scan line locations (1 thru 8) indicated on the blades. The origin of the temperature-position plot is progressively offset with each scan. The isometric view is used to obtain a qualitative record of temperature distribution over the area bounded by the scans as well as to observe surface features like the chevron pattern. The apparent lower temperature of the chevron is due to its lower emittance. In the lower part of Fig. 5 is a quantitative temperature profile at scan location number three. Comparison of temperatures measured by photoelectric scanning and by thermocouples agreed within 2 percent of the temperature level (expressed in °C).

ROTARY DATA PACKAGE

The purpose of the rotary data package is to house the pressure transducers, to process temperature and pressure signals and to provide a means of transferring these signals from a high-speed shaft to stationary readout equipment. The rotary data package for the turbine rig is designed to operate at a maximum shaft speed of 18 500 rpm. Earlier developmental versions of the current package have been described in Refs. 11 and 12. These earlier versions, tested at maximum shaft speeds of about 9000 rpm, had separate systems for handling temperature and pressure signals and used slip rings for analog signal transfer and "onshaft" electronic processing and a rotary transformer for digital signal transfer. Extensive engine testing with these units has proven the reliability and accuracy of various system components and has guided the design of the current package.

System Description

The rotary data package for the new turbine rig consists of four main subassemblies or modules as shown in Fig. 6. The package is of modular construction with pneumatic and electrical connectors to facilitate ease of fabrication, assembly and testing. Overall length of the package is approximately 1.0 m and the maximum diam of the stationary outer case is about 0.2 m. At the forward terminal module (1), the data package is coupled mechanically with an extension of the turbine shaft. Pneumatic and pressure tubing and thermocouple leads are routed through this shaft extension.

Differential pressure transducers are mounted on the shaft centerine in the pressure transducer module (2). The electronic data module (3) processes the analog pressure and thermocouple signals and converts them into coded 8-bit digital words. A total of 80 data channels (consisting of 63 thermocouple channels, 14 pressure channels and 3 calibration channels) can be handled in the electronic data module. However, the current pressure transducer module will accomodate only 10 differential pressure transducers.

The rotary transformer (4) couples the coded digital signal train from the rotating electronic data module to stationary instrumentation leads and couples electrical power from a stationary supply to the rotating electronic data and pressure transducer modules.

Pressure Transducers

The differential pressure transducer used in the rotary data package has a four-arm Wheatstone bridge strain gage diffused on a silicon diaphragm. This type of transducer has shown excellent operating characteristics in rotary application testing (13). The ranges of the transducers used are 0.3, 0.6 and 1.7×10^5 N/m^2 (5,10, and 25 psig), the physical size of all transducers is the same (about 0.6 cm diameter and 1.8 cm length).

Each transducer is enclosed in the center of a capsule (fig. 7) which provides two sealed chambers corresponding to the transducer pressure inputs. Each chamber contains an O-ring sealed port that interfaces with the pressure transducer module. The capsule also has four hermetically sealed electrical leads for the power and signal connections to the enclosed transducer. Ten such capsules (with differential pressure transducers enclosed) are mounted in tandem along the centerline of the pressure transducer module.

Temperature Signals

The temperature signals in the rotary data package originate from thermocouples in the turbine section of the turbine rig. These signals enter the package through type K (Chromel-Alumel) leads on the centerline of the hollow turbine shaft extension. The type K leads are soldered to strips in the forward terminal module. All internal wiring in the package is done with copper. A monitoring thermistor is mounted on the part holding the soldered strips where the transfer from type K to copper leads occurs. This thermistor is used to obtain a cold junction reference temperature for the thermocouples.

From the forward terminal module, the thermocouple leads are routed along the outer surface of the pressure transducer module to the electronic data module. After processing and conversion to coded digital words in this latter module, the thermocouple signals are transmitted through the rotary transformer to stationary readouts.

Electronic Data Module

The electronic data module (fig. 8) is an assembly of 10 double-sided printed circuit boards with an overall diameter of about 6 cm and an overall length of 15 cm. Commercially available integrated circuits are used whenever possible and those components most sensitive to acceleration forces are mounted near the center of the boards. Interboard connections are made near the periphery of the boards to facilitate testing of the assembled boards. A clear epoxy is used to hold the components securely to the assembly.

A block diagram of the rotary data package including inputs is shown on Fig. 9. The processing of the thermocouple and pressure signals in the electronic data module consists of a sequence of multiplexing, amplifying, converting from analog to digital and transmitting to stationary readouts through the windings of the rotary transformer. The data output was in the form of a digital train of 8-bit words. Electrical power was fed to the package through two of the transformer windings. The power was rectified and regulated in the electronic data module and distributed to the components of this module and to the pressure transducers. The 12 kHz frequency of the input power is used as a timing (clock) signal in the A/D convertor.

A major improvement to the electronic data module in the current data package is the use of complimentary metal-oxide-semi-conductor (CMOS) circuitry. This permits lower power levels and common power supplies to be used. Total power into the transformer is about 4 watts. The power regulator is a 15 V I.C. (integrated circuit) which replaces the zener diodes used in the prototype versions.

Prototype Performance

System error on the prototype rotary data package reported in Ref. 12 was 0.5 percent full scale. Thermocouple readings transmitted digitally via the rotary transformer were compared to simultaneous analog readings from a slip ring assembly. Agreement was within 2° C. Similar characteristics are anticipated with the current package.

CONCLUDING REMARKS

Efforts at NASA-Lewis to improve techniques for measuring temperatures and pressures on gas turbine components have resulted in the development of several operating instrumentation systems for use on a high-pressure high-temperature turbine rig. An infrared photography system for obtaining thermal maps of the metal surface temperature on the stationary vanes shows agreement with thermocouple measurements within 1 percent of the temperature reading (expressed in degrees C). Continuing developmental work on this system will concentrate on replacing the current manual method for film-image analysis with a computerized video densitometer method.

A customized photoelectric scanning system for blade metal surface temperature measurements will resolve a spot diameter of 0.1 cm on a blade moving at about 400 m/sec. The data can be displayed in near real time as a spot temperature or as temperature profiles on a single blade or on several adjacent blades. Comparisons of temperatures measured by photoelectric scanning and by thermocouples showed agreement within 2 percent of the temperature level (expressed in degrees C).

A rotary data package has been developed that will digitize analog temperature and pressure signals on a high-speed (17 000 rpm) shaft and transfer these digitized signals via a rotary transformer to stationary readouts. Agreement between the same thermocouple reading transferred by a prototype of this system and by a slip ring was consistently within 2° C.

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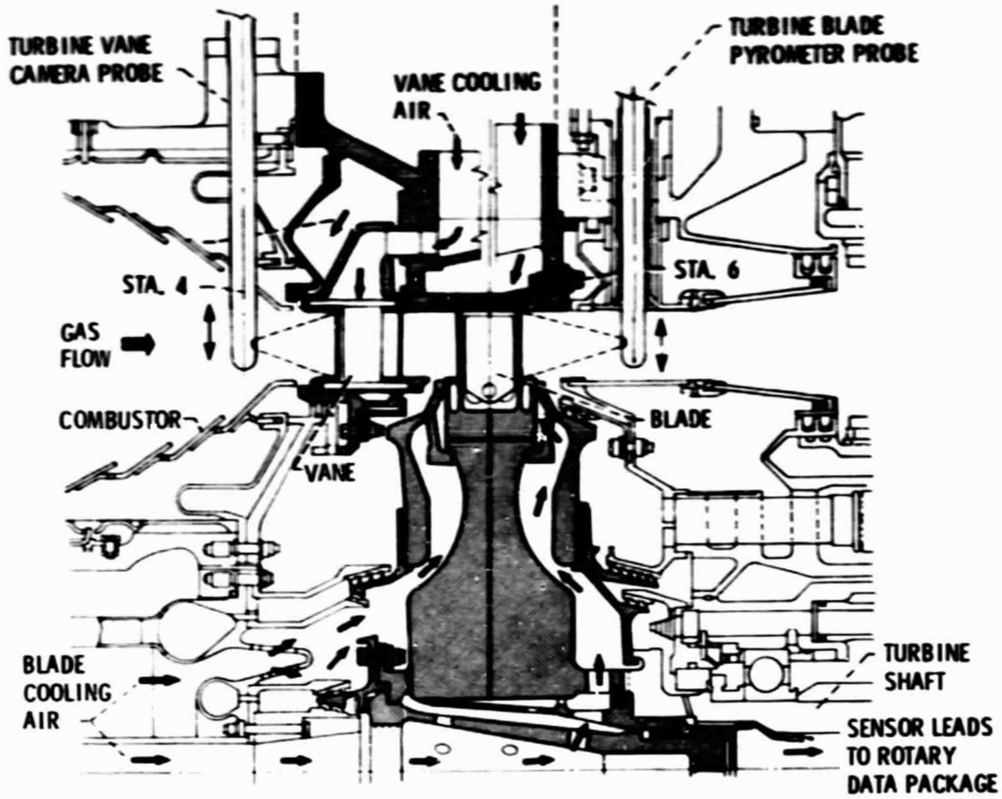


Figure 1. - Turbine rig test section.

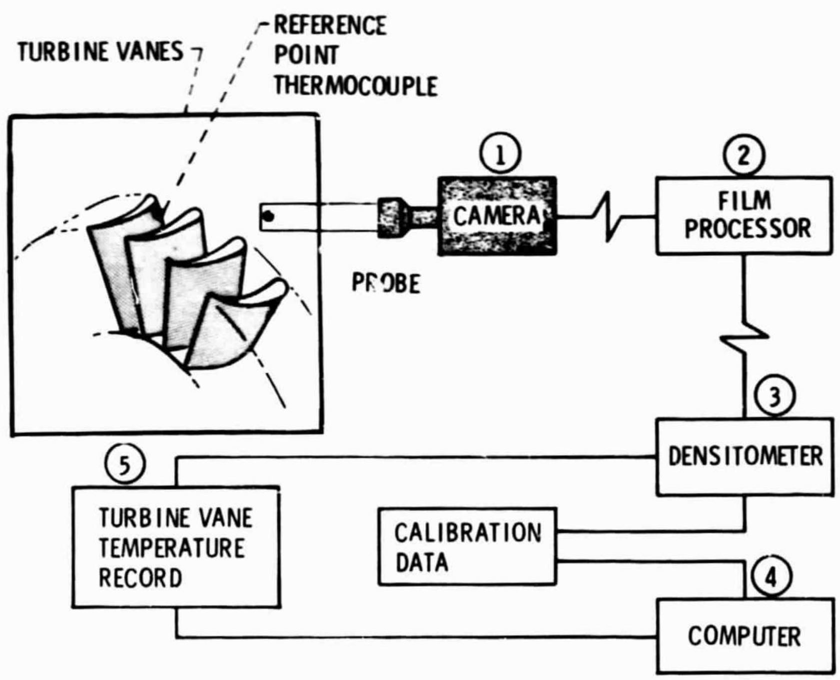


Figure 2. - Infrared photography system for stationary vanes.

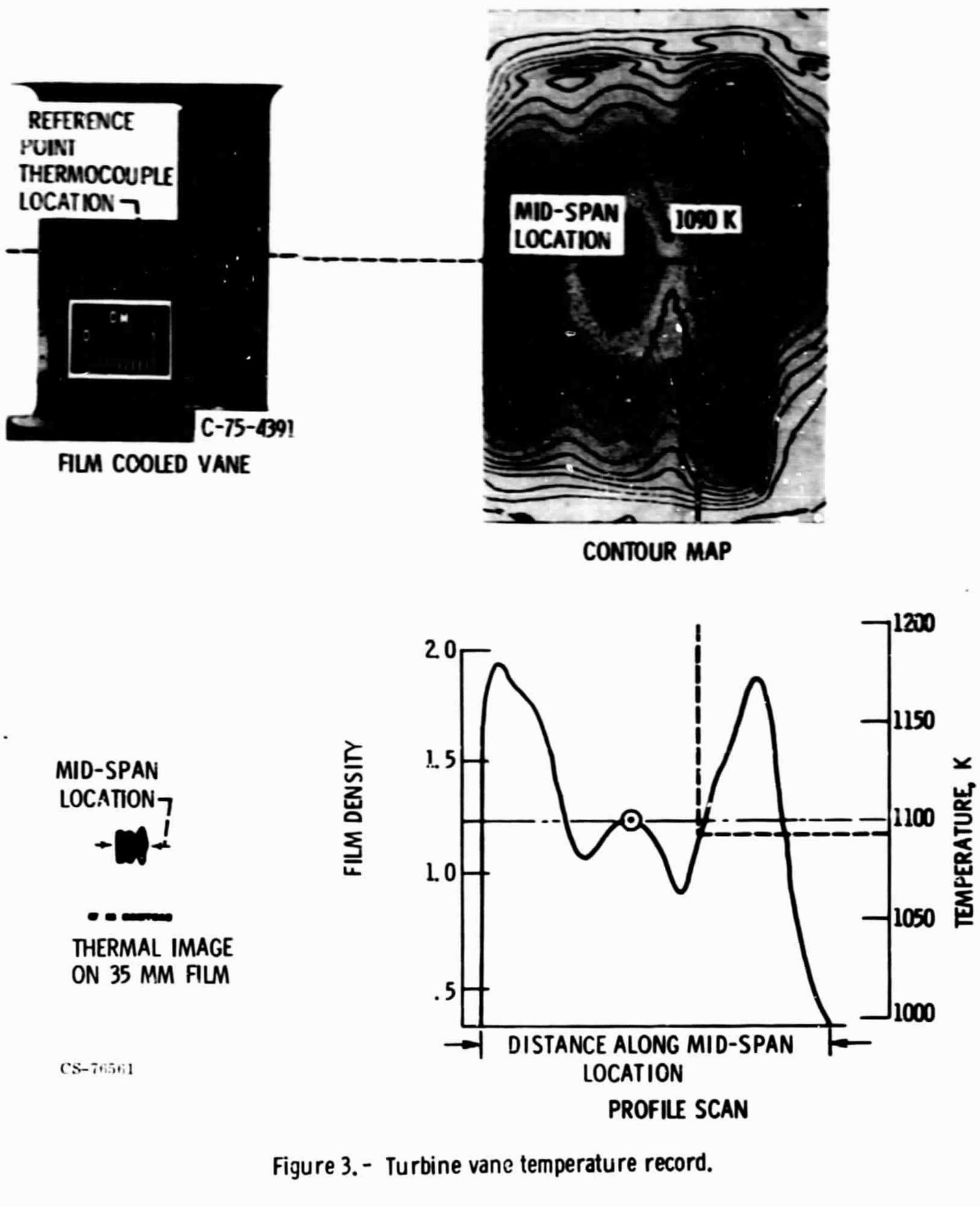


Figure 3. - Turbine vane temperature record.

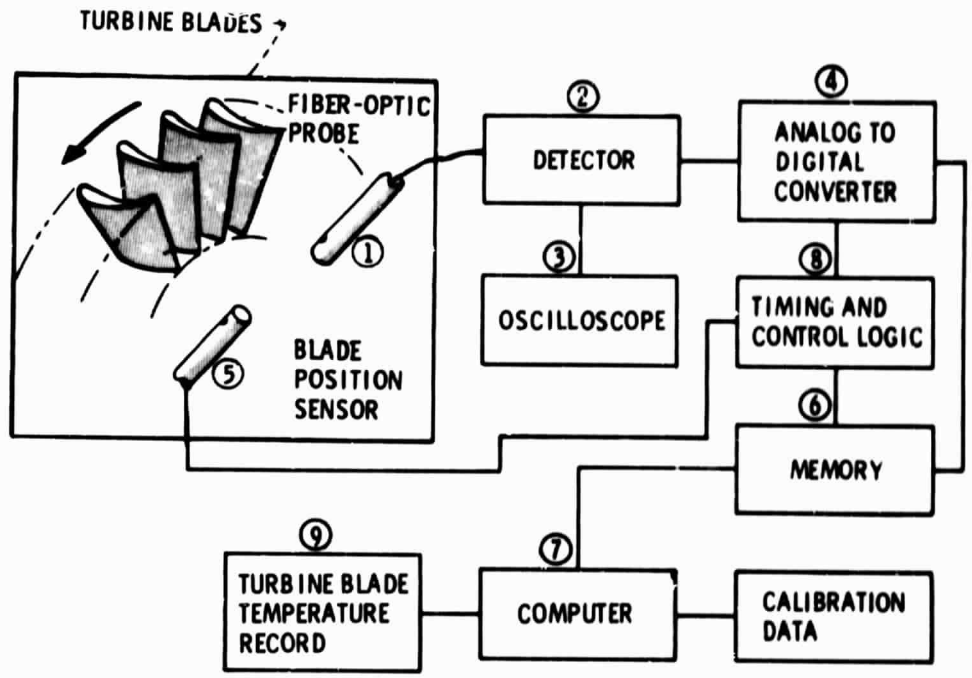
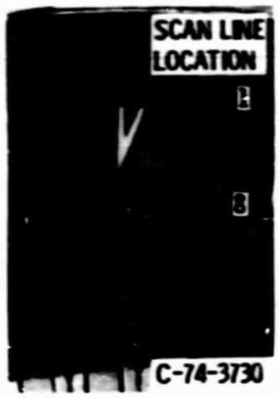
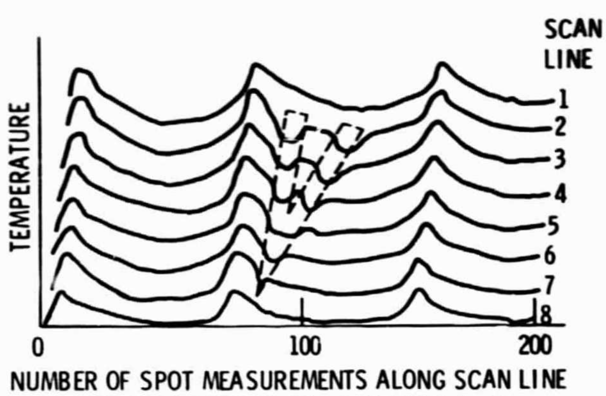


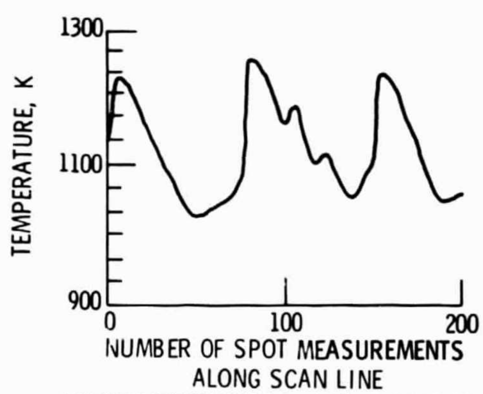
Figure 4. - Photoelectric scanning system for rotating blades.



CONVECTION COOLED
TURBINE BLADES



ISOMETRIC DISPLAY OF SCAN LINES 1 - 8



TEMPERATURE PROFILE ALONG SCAN LINE 3

Figure 5. - Turbine blade temperature record.

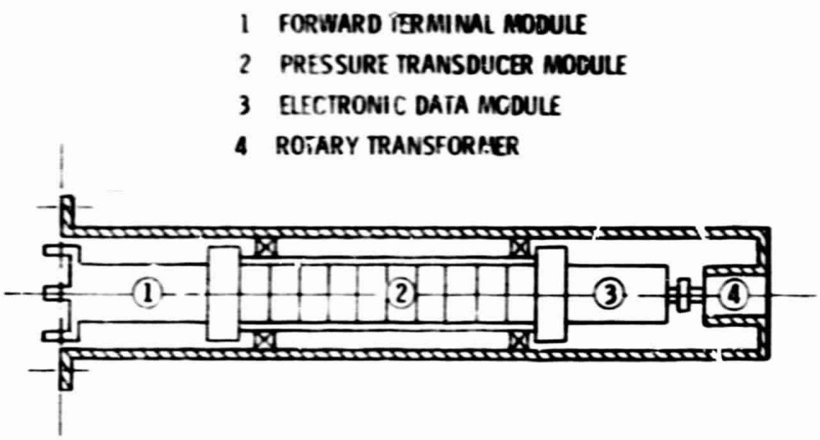


Figure 6. - Rotary data package.

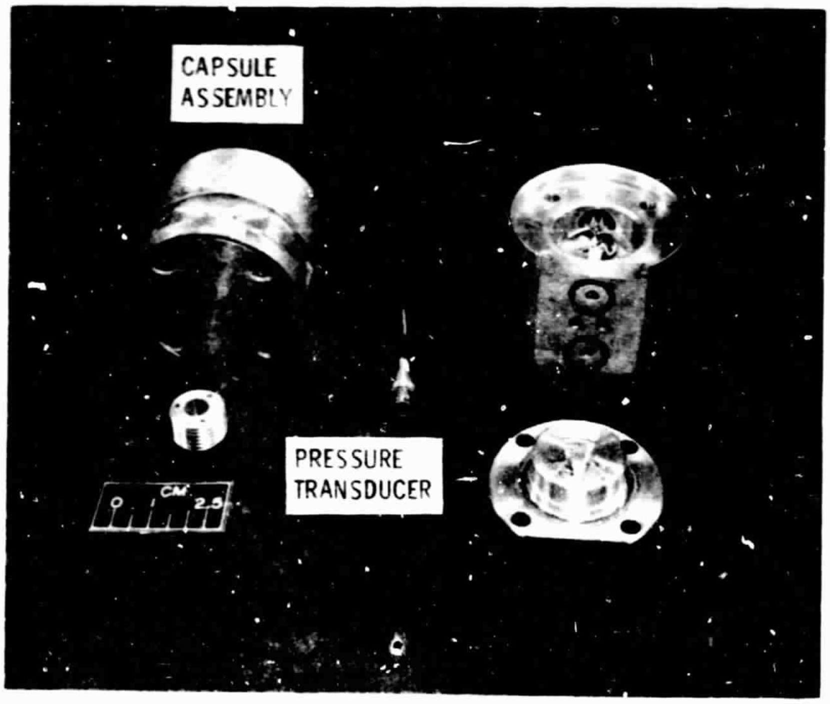


Figure 7. - Pressure transducer capsule.

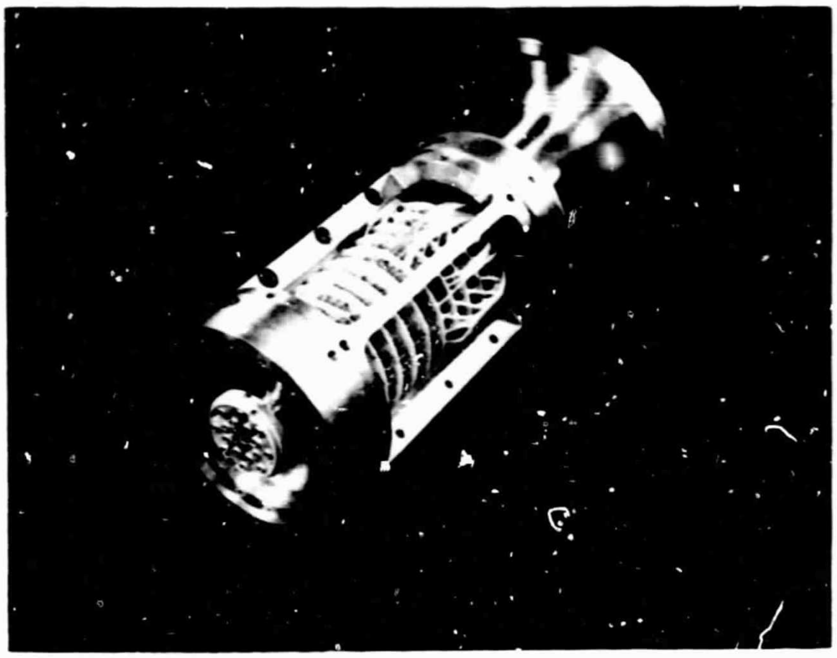


Figure 8. - Electronic data module.

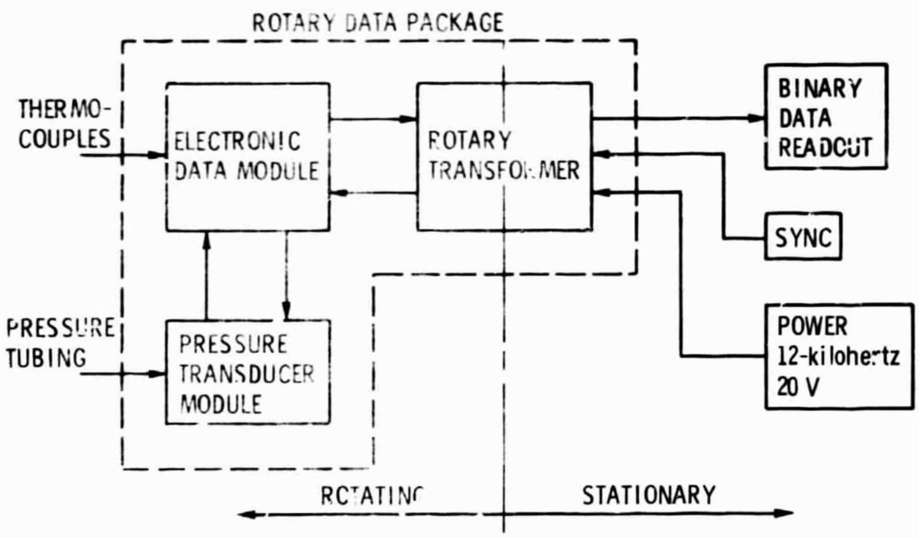


Figure 9. - Rotary data package functional block diagram.