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INFRARED PYROMETER FOR HIGH RESOLUTION SURFACE TEMPERATURE MEASUREMENTS ON ROTATING TURBINE BLADES

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ABSTRACT

A high resolution pyrometer was developed and used to obtain temperature profiles of rotating turbine blades at tip speeds up to 366 meters per second (1200 fps). Surface temperature variations from 920 to 1250 K (1200° to 1800° F) can be measured and variations over distances of 0.05 cm (0.020 in.) can be resolved. Temperature profiles were obtained in near real time as hard copies from a computer display terminal. Temperatures measured with the prototype pyrometer and with thermocouples agreed to within 2 percent over the temperature range from 977 to 1144 K (1300° to 1600° F).

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SUMMARY

A high resolution radiation pyrometer, designed at the NASA Lewis Research Center, was tested on an operating turbine engine. This pyrometer was used to obtain temperature profiles of the viewed surface of several turbine blades at blade tip speeds up to 366 meters per second (1200 fps).

A small portion of the infrared energy that is radiated by the blades is collected by an optical fiber probe in the engine and ducted to an external optical detector. The probe consists of a linear array of 80 coherent optical fibers surrounded by a cooling jacket. A lens at the collecting end of the probe simultaneously images eighty 0.05-cm (0.020-in.) spots on the blade onto the ends of the 80 fibers. The opposite ends of the fiber bundle can be mechanically stepped so that each fiber is focused - one by one - onto the optical detector. The detector, a silicon avalanche device, produces an analog output voltage which is digitized at rates up to 2.0 MHz for processing by a minicomputer. The temperature information is presented in near real-time at a computer display terminal in tabular form and also as curves of temperature profile across the blade chords.

Numerous engine tests have been conducted to verify and demonstrate the pyrometer's performance. Temperatures measured with the pyrometer and with blade mounted thermocouples agreed to with 17 K (30° F) at blade temperatures between 980 to 1200 K (1300° to 1700° F). Results of these tests will be presented and discussed. Additional tests including calibration against a black body furnace and dynamic response tests using a light emitting diode as a source will also be discussed.

INTRODUCTION

The performance of a jet engine improves with increased turbine inlet gas temperature, but this results in higher turbine blade temperatures. Present day metallurgy has not produced turbine blade materials that can withstand these higher temperatures so that blade cooling is necessary. Cooling is accomplished by passing some of the engine inlet air through the interior of the turbine blades. Some cooling schemes allow part of this air to flow over the blade surface from numerous perforations in the blade.

The effectiveness of these types of cooling can best be evaluated by knowing the temperature distribution over the blade surface. Historically, thermocouples have been used (and are still used) for these temperature measurements. But there are many problems associated with their use on rotating blades especially where thermal gradient information over a distance of less than 1 millimeter is required.

Radiation pyrometry in conjunction with an optical system utilizing a fiber optic probe is ideally suited for this type of measurement. Radiation pyrometry is noncontacting and thereby eliminates the need to groove and otherwise modify the blade structure for thermocouple installation. It also eliminates slip-rings or other rotating mechanisms which are needed to transfer the electrical signal. The flexible fiber optics allows transfer of the temperature information without the problems associated with a rigid periscope-lens-system. Problems such as image vibration, loss of image resolution, increase of field curvature, and restrictions in location and routing are thereby resolved. The conceptual design of the pyrometer is contained in reference 1.

This presentation will describe the prototype pyrometer made in accordance with the concepts of reference 1 and will also discuss several tests and the results obtained.

TURBINE BLADE PYROMETER

System Design

The design requirements which were established for the pyrometer are as follows:

(1) Obtain a thermal map of rotating turbine blades with tip speeds in the range from 300 to 400 meters per second (1000 to 1300 fps).

(2) Achieve an optical resolution to be able to resolve a spot diameter of 0.05 centimeter (0.020 in.) on the moving turbine blade.

(3) Provide near real time display of temperature.

(4) Measure temperatures over the range from 920 to 1250 K (1200° to 1800° F) with an accuracy of ± 1 percent.

Figure 1 shows a block diagram of the pyrometer system. The single-row bundle contains 80 fibers oriented in a row so that the images are projected to the turbine blade in a vertical line as shown. The purpose of the orientation is to view 4.0 centimeters (1.6 in.) of the blade span in one fixed position of the borescope probe. Each fiber is 0.005 centimeter (0.002 in.) in diameter and is focused on the blade at a magnification of 10. The motion of the blade generates 80 scan lines running across the blade. The radiant energy emitted by the blade is transferred through all the fibers to a microscope assembly. Each fiber is focused on a silicone avalanche detector, one-by-one, in turn, as the actuator moves the fiber across the microscope optics.

The detector and amplifier convert the radiant energy to an analog voltage. This analog voltage is digitized by the analog-to-digital (A/D) conversion system at rates selectively variable from 62 kilohertz to 2 megahertz. A 200-point sample of this information is stored in the high-speed memory. The memory (maximum capacity, 200 samples) is used as a buffer to accept the rapid data production which is greater than the computer will accept. Data are transferred to the computer at a slower rate since there is sufficient time in one engine revolution for the memory to unload and be ready for the next passage of the test blade or blades. This process may be repeated many times for the purpose of averaging out the random noise.

The blade position sensor supplies a trigger signal to load the memory when the test blade enters the field of view. This sensor is a phototransistor which senses a reflection from a predetermined blade. A variable delay is available so that the trigger point can be shifted in time to allow the operator to move to another blade or blade grouping. The trigger point must be precise to insure that repetitive samples for signal-to-noise (S/N) enhancement are accurately taken. The sensor also supplies control of the rotational speed of the radiation chopper. The function of the radiation chopper is to provide an ac signal which can be processed by use of an ac amplifier.

The timing and control logic circuitry provides an interchange of control among the computer, the memory, and the A/D converter. Also, through the logic circuit, the computer (and, ultimately, the operator) has control of the entire pyrometer system.

The low-wattage reference lamp, operated from a stable power source, supplies nonchanging radiant energy to the detector as a means of checking system drift. The light emitting diode (LED) is used in the dynamic checkout circuit to test the instrument for response to a rapidly changing signal.

A prototype pyrometer was assembled using commercially available components. The optical-mechanical portion of the pyrometer is shown in figure 2. (A protective cover has been removed to show the parts inside.) Two flexible fiber-optic bundles are used. The longer of the two contains the 80 coherent fibers which are 1 meter (3 ft) long. The rigid portion is a 0.5-meter (1 1/2-ft) long borescope, which is inserted into the engine to view the turbine blades. The borescope is protected from the hot-gas stream by a water-cooled, double-walled enclosure. Nitrogen gas is used to protect and flush the borescope window. The second fiber bundle used for system testing contains the fibers which transmit light from either the reference lamp or the LED.

The computer is a PDP-11 minicomputer. The program is entered into the computer from a tape-deck and is controlled by means of a teletypewriter terminal. At this terminal the operator types instructions for pyrometer operation. Upon completion of instructions the system performs all the required operations and presents data on a cathode-ray tube (CRT) display from which a hard copy may be made. The elapsed time for this operation is about 3 seconds. If the measurement along a scan line is repeated to improve S/N the elapsed time increases to about 22 seconds for 99 measurements. A compromise of 24 measurements was used to obtain a good S/N with an elapsed time of 7 seconds.

Calibration Method

The digital output from the A/D converter cannot be used directly to obtain temperature profiles of the blades. Temperatures are obtained by means of a conversion table stored in the computer memory. Information to make the table is obtained by measuring the radiant output of an accurately known temperature source using the pyrometer system. The A/D counts obtained are tabulated with the temperature and entered into the computer memory. A plot of such a table is shown in figure 3. Each fiber in the 80-fiber bundle has a different transmission factor so that the table described above must be made up for each fiber. This process is the fiber calibration. A blackbody oven is used as the temperature source. Long-term stability of the oven is ± 0.5 K for 8 hours, temperature accuracy is ± 0.5 percent, control accuracy is ± 1 K, and emittance is 0.99 ± 0.01.

Figure 3 shows typical calibration curves obtained for two fibers. The A/D counts are the digital data obtained from the analog-to-digital conversion system. The number of counts is limited by the capacity of the memory which is eight bits (256). A full-range measurement of temperature versus A/D count is made on two fibers to establish the shape of the curve. All other fibers are then calibrated from a single-point measurement at 1089 K (1500° F). This calibration technique is valid because the pyrometer output is linear with radiant flux to within 2 percent. Also, there is no spectral variation within the optical bandpass of the system. Only the transmittance of the fibers is different, which accounts for displacement of the parallel curves.

This calibration remains valid provided the instrument responsivity does not change between the time that a calibration is performed and the time that a measurement is made on an unknown source. Since changes in instrument response can occur, a stable tungsten lamp is used to monitor such changes. Use of this lamp provides a correction for instrument drift.

Dynamic Response Test

A LED is part of a dynamic checkout circuit, which is used to check the dynamic response of the pyrometer. A gallium arsenide diode is used because its light output falls within the spectral bandwidth of the pyrometer. The LED is driven by a signal generator at about 10.5 kilohertz, which is the blade-passing frequency of a turbine wheel with 76 blades rotating at 8300 rpm.

The results of a measurement using a ramp signal from the signal generator are shown in figure 4. These are copies of the output obtained from the CRT display. The curve is a plot of A/D counts, in the range -255 to 255, versus the number of spot measurements along the scan line. The format of this presentation is similar to that obtained on a blade-temperature profile. The abscissa, the number of spot measurements obtained along a scan line (see fig. 1), is actually a time parameter and is the digitizing time required to produce 200 digital values from the analog signal. The total duration of the scan depends on the digitizing frequency. At 2 megahertz (the digitizing frequency used for fig. 4) the time between successive digital values is 0.5 microsecond, so that the total scan time is 100 microseconds.

The purpose of the dynamic response test with the LED was to determine if the pyrometer would reproduce a rapidly changing optical signal. The driving wave shape (current through the LED) was determined to have a decay time of about 1.5 microseconds. The data of figure 4 show the same time, 1.5 microseconds, from peak to base. (The display is generated from right to left so that the sharp drop is decay time.)

The curve of figure 4(b) is the result of a single scan (200 spot measurements). The noise that is present is very evident. Figure 4(a) is the averaged result of 99 scans and shows how noise was averaged out. The exact reproduction of the waveshape for 99 scans also shows that the blade position sensor circuit is supplying a precise trigger. Imprecise triggering of the circuit would produce a rounding effect in the region of sharp changes.

PYROMETER TESTS

Turbine Engine

The pyrometer was extensively tested on a modified jet engine. Approximately 1000 temperature profiles were recorded on this engine.

Figure 5 is a photograph of the turbine rotor looking upstream at the trailing edges of the turbine blades. Figure 6 is a close-up view of the test blades which are located at the top side (12 o'clock) of the rotor in figure 5. The turbine was operated with inlet-gas temperatures of about 1644 K (2500° F). The blade temperatures were limited to a maximum temperature of 1200 K (1700° F) by adjusting the coolant air flow. The tip speed of the blades was approximately 366 meters per second (1200 fps).

Figure 6 shows the direction from which the blades were viewed by the borescope probe. Three of the six numbered blades (numbers 2, 4, and 6) had ceramic coatings applied to their downstream surface. The square patches were used for identification purposes while the chevron was used for the resolution test. Superimposed on the photograph are two lines which represent two scan lines. The upper scanline was made across the chevron pattern to demonstrate resolution; the lower, across the location of the ten thermocouples, to enable temperature comparisons to be made.

Test Procedure

The borescope probe (contained within a water-cooled housing) was located approximately 10 centimeters (4 in.) downstream of the blade row. The probe view angle was oriented nearly normal to the viewed surface of the blades. Some difficulty was experiences with the fiber positioning system. Therefore, for these tests, only one of the 80 fibers in the probe was used. A linear probe actuator positioned the line of sight of this fiber in the radial direction in the desired scan location. This same actuator was used to move the probe into measurement position into the engine. But this was only after the engine had reached a stable operating condition. This precaution reduced window contamination due to the deposition of unburned fuel.

Before beginning a temperature measurement test, four instrument conditions were set: (1) The starting point of the scan line was determined by the amount of delay time applied to the synchronizing pulse from the blade position sensor (the starting position was monitored on an oscilloscope); (2) The sampling rate of the measurement was set by selecting a digitizing frequency; (3) The optical fiber to be used was positioned in front of the microscope lens; and (4) The number of scan repetitions (for averaging) was selected.

RESULTS AND DISCUSSION

Blade Temperature Profiles

Typical temperature profiles made with the turbine-blade pyrometer system are shown in figure 7. The figures are a reproduction of a hard copy from the CRT display. In the upper half of each figure is a listing of the 200 spot measurements (each the average of 25 scans) from which the temperature profile was made. The position of each measurement is indicated along the abscissa. The top row of 10 data points falls between the origin and 10. The second row of 10 is between 10 and 20, etc. The ordinate is a temperature scale for cursory examination of the profile scan. The scan was made with the borescope probe at a radial location that intercepted the chevron on blade 4 as indicated by the sketch in the figure. The peaks represent the temperature at the trailing edges of the blades.

For the profile shown on figure 7(a) the digitizing rate was 0.25 megahertz. This rate, combined with the speed of the blades, resulted in a 200-point temperature profile scan across approximately eight blades. This results in about 25 spot measurements across the viewed surface of each blade (see fig. 6). The viewed surface of each blade chord was about 2.8 centimeters (1.1 in.) wide; therefore, the 200 spot measurements were 0.11 centimeter (0.045 in.) apart. From this, it can be determined that three spot measurements were made across each leg of the coated chevron. The resolution is apparent in the figure. (The lower indicated temperature of the coating was due to the lower emittance of the coating.)

Other temperature profiles were recorded at various digitizing frequencies. The higher measurement rates result in increased spatial resolution over shorter path lengths. Figure 7(b) shows the temperature profile of a single blade obtained using a 2 megahertz digitizing rate. This is the blade with the chevron pattern.

Measured Temperatures

Several temperature profile scans at various sampling frequencies were made across the test blades at the thermocouple location (as shown in fig. 6). The locations of these ten thermocouples were accurately determined on these profile scans.

The data of table I are a comparison of thermocouple measured temperatures and temperatures measured with the turbine blade pypometer system at steady-state engine conditions for one run. The data of this table, however, are typical of the results obtained for several engine runs. The pyrometer measured temperatures were corrected for a blade emittance of 0.87. The thermocouple measured temperatures were not corrected for the small errors associated with their use on turbine blades. These corrections, based on heat-transfer calculations, would increase the thermocouple measured temperatures about 5 to 8 K (10° to 15° F).

All the compared temperatures for this run agree to within 2 percent. The same agreement was observed during other test runs (with various sampling rates) in which hundreds of temperature profiles were generated. The temperature comparison testing was limited to the range between 977 to 1144 K (1300° to 1600° F) because of engine operating safety considerations.

Isometric Display of Temperature Profiles

A useful mode of presentation which is available from the system is an isometric display of temperature profiles. This is a grouping of temperature profile scans with the origin progressively offset with each scan. Figure 8 is such a plot made across the single blade with the chevron pattern. In this example a single fiber was used to generate the profiles. The borescope probe was positioned along the blade span in increments of 3.6 centimeter (0.14 in.) to generate the 8 scans. Each of the 8 scans is the average of 25 repetitive measurements along the same scan line to improve the S/N. An alternative way to generate this display is to keep the probe location fixed and use different fibers within the optical probe. The eight temperature profiles shown cover a span height of 2.5 centimeters (1 in.). The isometric view can be 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.

CONCLUDING REMARKS

The turbine-blade pyrometer described in this report can generate temperature profiles of turbine blades in an operating jet engine. Spatial resolution on an individual blade surface is of the order of 0.05 centimeter (0.020 in.). Temperatures were measured over the range from 977 to 1144 K (1300° to 1600° F) and agreed with thermocouples to about 2 percent. The temperature profiles can be plotted as hard copies from a computer terminal within 7 seconds of the measurement. Also, profiles could be obtained by using any or all the fibers in the bundle. The prototype pyrometer had 80 tangent fibers to allow viewing 4 centimeters (1.6 in.) of the blade surface in a fixed probe location. The system is designed so that each fiber would be positioned in turn to generate scan-lines at 0.05 centimeter (0.02 in.) intervals upon a command from the computer. After all 80 fibers are so positioned, the 16 000 (80×200) measured temperatures would be transferred from storage to form a two-dimensional thermal map of the blade surfaces. During the testing programs described in this report the fiber position actuator often failed to accurately locate the individual fibers at the microscope lens. To overcome this difficulty, a single fiber was used and the borescope probe was actuated radially to view different scan lines. A second generation pyrometer has been assembled and is being tested. This improved pyrometer will incorporate features which increase reliability while decreasing size without sacrificing any of the original design requirements.

REFERENCE

1. Buchele, Donald R.; and Lesco, Daniel J.: "Pyrometer for Measurement of Surface Temperature Distribution on a Rotating Turbine Blade" in Progress in Astronautics and Aeronautics, vol. 34, Mass. Inst. Tech. Press, 1974, pp. 347-354.

TABLE I. - COMPARISON OF MEASURED TEMPERATURES

Thermo-couple	Temperature, K, measured by -		Difference in temperatures, ΔT
	Thermocouple	Pyrometer	
1	1021	1030	+9
2	1016	1033	+17
3	1108	1102	-6
4	1032	1041	+9
5	994	1008	+14
6	1034	1047	+13
7	1044	1049	+5
8	1122	1111	-11
9	1037	1041	+4
10	1035	1038	+3

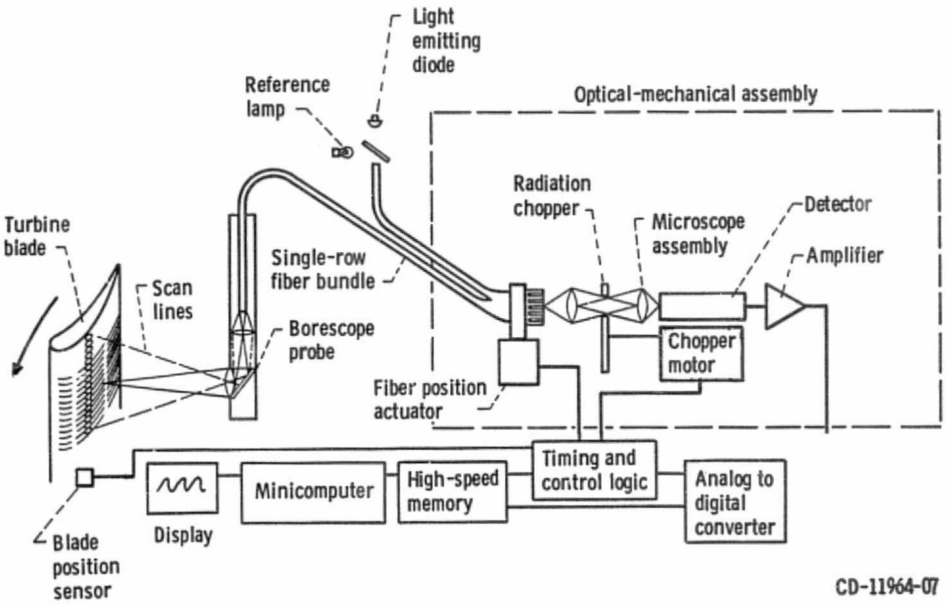

Figure 1. - Turbine-blade pyrometer.

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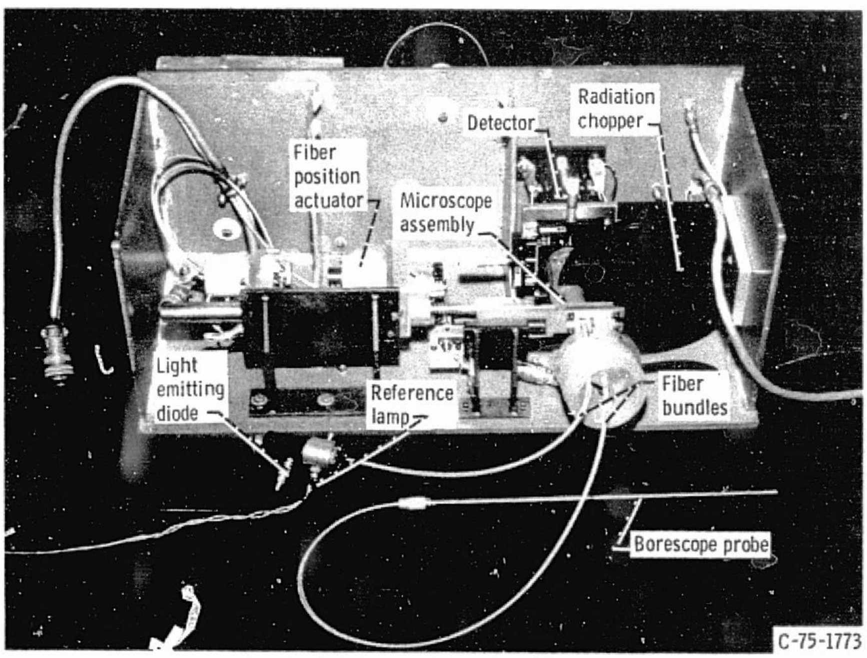

Figure 2. - Optical-mechanical assembly - prototype pyrometer.

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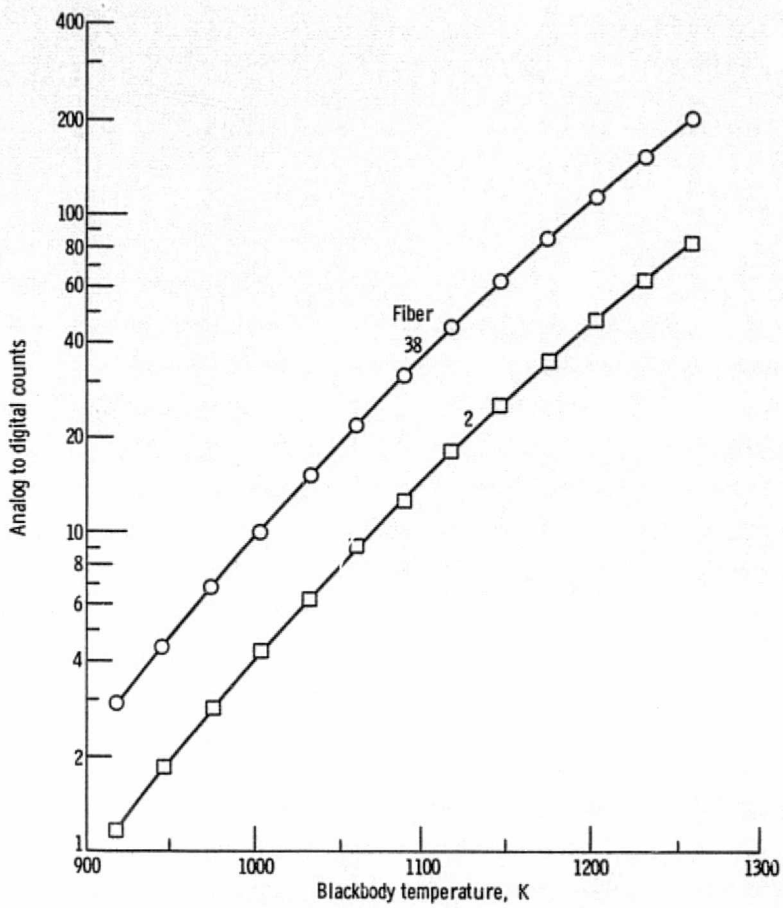
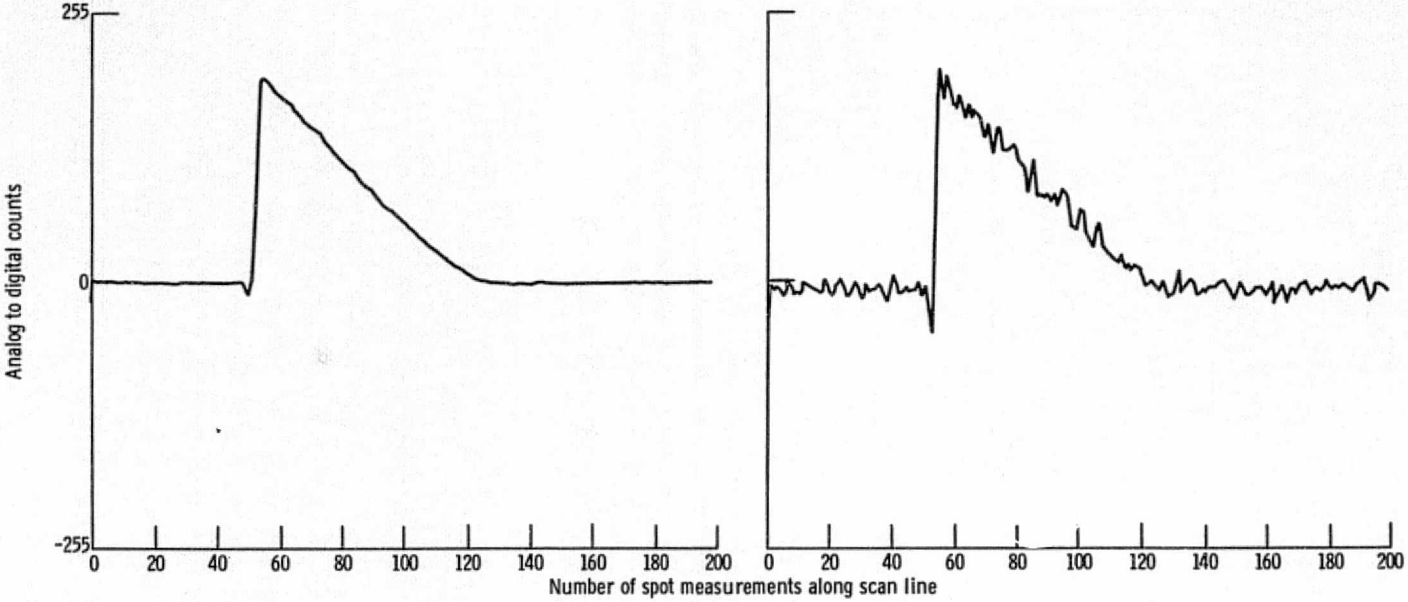


Figure 3. - Fiber calibrations for turbine-blade pyrometer.



(a) Average of 99 scans.

(b) Single scan.

Figure 4. - Pyrometer output using light emitting diode source input.

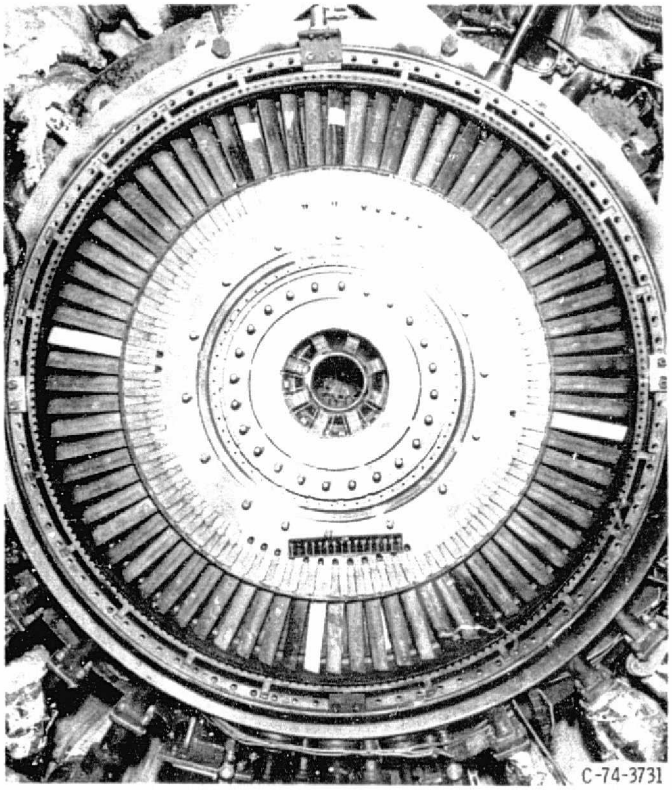


Figure 5. - Test blades in J-75 engi:ne.

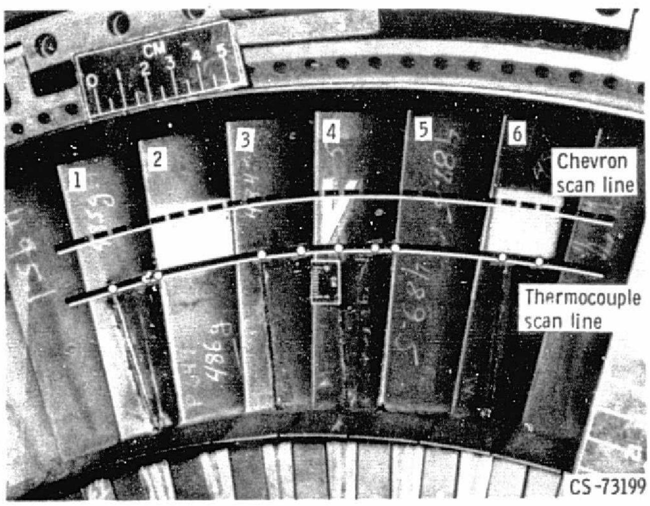
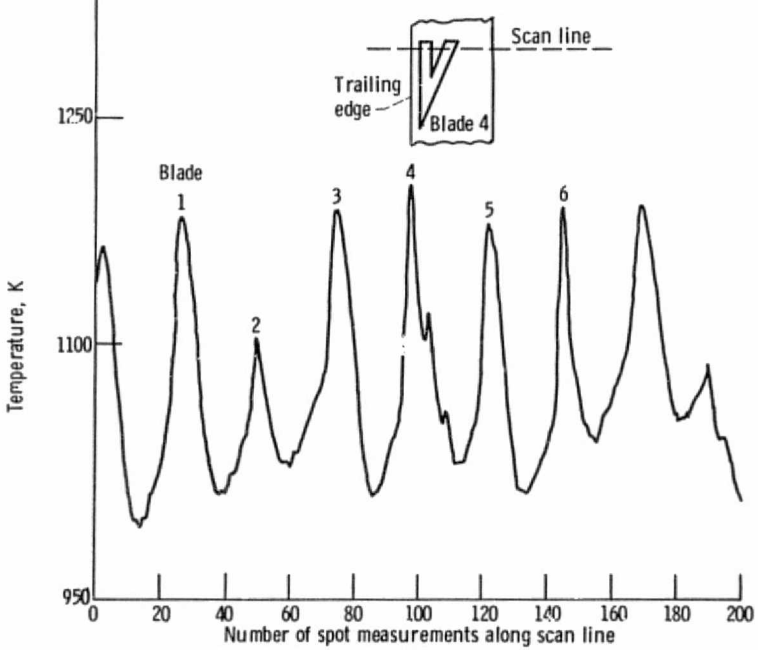


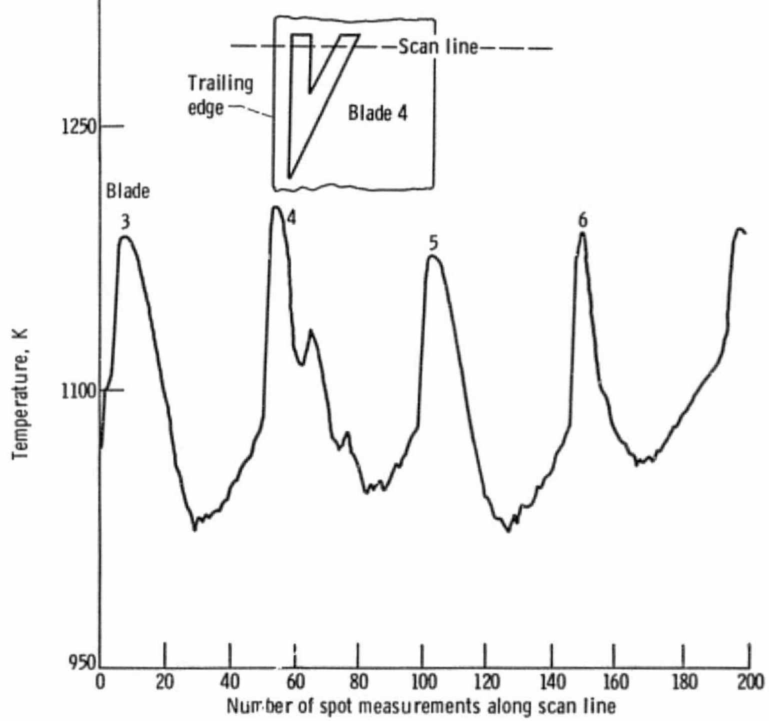
Figure 6. - Trailing-edge view of test blades.

Temperature, K									
1121	1161	1163	1151	1134	1109	1083	1061	1036	1023
1005	994	994	989	996	996	1010	1010	1019	1023
1035	1043	1058	1071	1152	1179	1178	1169	1152	1131
1090	1080	1063	1044	1029	1019	1011	1010	1011	1011
1015	1023	1023	1031	1041	1044	1049	1069	1107	1108
1086	1070	1064	1056	1044	1039	1030	1030	1031	1027
1036	1034	1039	1046	1050	1057	1064	1069	1073	1081
1079	1096	1161	1184	1183	1173	1159	1134	1117	1094
1072	1050	1031	1019	1009	1010	1011	1015	1019	1028
1038	1043	1047	1057	1069	1127	1196	1202	1187	1133
1108	1111	1124	1115	1095	1068	1057	1057	1063	1051
1035	1029	1030	1030	1030	1038	1045	1050	1061	1082
1160	1174	1166	1157	1136	1114	1089	1067	1048	1033
1015	1013	1012	1011	1013	1018	1021	1028	1031	1036
1047	1053	1064	1135	1184	1176	1124	1095	1084	1073
1061	1055	1051	1046	1042	1044	1049	1060	1060	1067
1075	1079	1085	1094	1100	1106	1118	1167	1186	1185
1178	1163	1149	1130	1118	1100	1084	1075	1063	1069
1054	1057	1055	1060	1066	1071	1072	1076	1081	1085
1073	1050	1044	1044	1039	1034	1020	1011	1008	



(a) Sampling rate, 0.25 megahertz.

Temperature, K									
1075	1075	1070	1065	1060	1053	1049	1048	1041	1039
1029	1033	1028	1026	1025	1020	1020	1013	1014	1015
1016	1013	1013	1013	1013	1020	1016	1018	1019	1017
1021	1023	1025	1023	1030	1030	1028	1033	1033	1035
1034	1039	1038	1040	1043	1046	1048	1047	1051	1052
1056	1063	1061	1064	1063	1068	1067	1071	1078	1089
1102	1116	1142	1166	1184	1197	1204	1207	1208	1207
1204	1203	1199	1193	1185	1177	1162	1147	1132	1124
1120	1116	1115	1115	1115	1114	1118	1122	1129	1131
1131	1129	1126	1123	1118	1115	1109	1105	1100	1097
1091	1086	1080	1073	1072	1064	1063	1059	1059	1059
1062	1061	1062	1068	1066	1069	1067	1062	1062	1055
1053	1050	1048	1041	1041	1038	1037	1036	1037	1034
1037	1034	1035	1037	1038	1040	1038	1039	1042	1040
1043	1045	1049	1045	1049	1051	1053	1057	1058	1058
1060	1061	1061	1064	1068	1073	1080	1088	1099	1116
1135	1153	1163	1171	1174	1175	1175	1174	1174	1169
1168	1164	1163	1159	1155	1149	1146	1140	1134	1130
1122	1119	1113	1105	1099	1093	1086	1078	1078	1071
1065	1067	1059	1055	1051	1045	1043	1038	1036	



(b) Sampling rate, 0.50 megahertz.

Figure 7. - Temperature profiles.

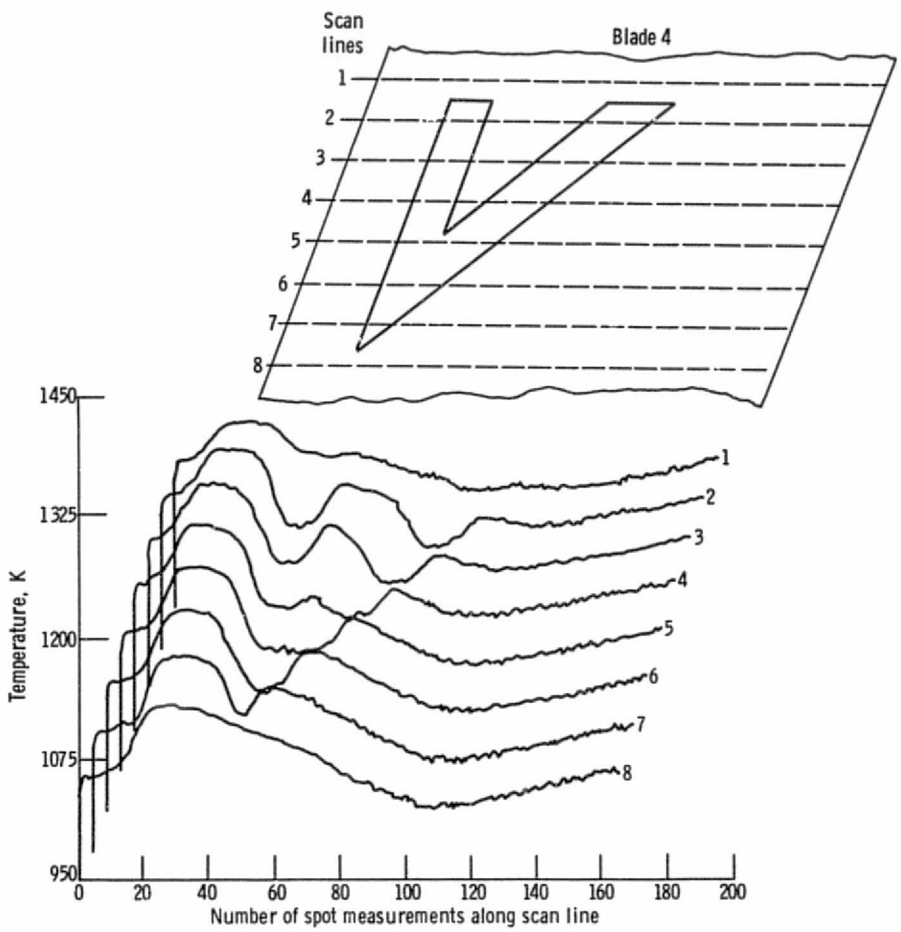


Figure 8. - Isometric display of blade temperature profiles of chevron. Sampling rate, 2 megahertz.