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HIGH-RESOLUTION SURFACE TEMPERATURE MEASUREMENTS ON ROTATING TURBINE BLADES WITH AN INFRARED PYROMETER

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16. Abstract
A high-resolution pyrometer was developed and tested on a modified turbine engine. The pyrometer was used to obtain temperature profiles of the viewed surface of turbine blades in the engine at tip speeds up to 366 meters (1200 ft) per second. The combination of coherent fiber optics, a silicon avalanche detector, and high-speed electronics enabled surface resolution of a spot diameter of 0.05 centimeter (0.020 in.). The data, in the form of temperature profiles, were obtained in near real time as a hard copy output from a computer display terminal. Temperatures measured with the pyrometer and with thermocouples agreed within 2 percent at temperatures between 977 to 1144 K (1300° to 1600° F).

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HIGH-RESOLUTION SURFACE TEMPERATURE MEASUREMENTS ON ROTATING TURBINE BLADES WITH AN INFRARED PYROMETER

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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 on this engine at tip speeds up to 366 meters per second (1200 ft/sec). Temperatures measured with the pyrometer and with thermocouples agreed within 2 percent at temperatures between 977 to 1144 K (1300° to 1600° F).

The rotating blade is scanned by an optical system composed of 80 coherent fibers which are focused on the blade. The combination of coherent fiber optics with a silicon avalanche detector and high-speed electronics has enabled surface resolution of a spot diameter of 0.05 centimeter (0.020 in.). The radiant energy emitted by the blade is converted to an analog signal, which in turn is digitized at rates up to 2.0 megahertz for processing by a minicomputer. The processed information is presented as temperature profiles across the blades in near real time on a cathode ray tube display.

A blackbody oven was used to calibrate the system. Dynamic response tests using a light emitting diode as the source showed that the system reproduced the driving wave shape to within a fraction of a microsecond.

The pyrometer system can be used to monitor temperature on selected blades or all the blades, and it is capable of generating data so that a two-dimensional contour map of temperature distribution can be made with additional computer processing.

INTRODUCTION

Experimental data obtained from a high-resolution turbine-blade pyrometer system are described in this report. The system permits detailed surface temperature measurements on cooled rotating turbine blades without the mechanical and heat-transfer problems associated with the installation of thermocouples in the blades. The pyrometer system, which was designed at Lewis, is described in detail in reference 1. The performance of a jet engine improves with increased turbine-inlet temperature. The turbine blades must be cooled, however, so that they can survive in the higher temperature environment. Blade cooling schemes vary, but most pass air through internal passages and through surface perforations. The effectiveness of these cooling schemes can best be evaluated by studying the temperature distribution over the blade surface. For these studies knowledge of the temperature gradient over a distance less than 1 millimeter is desirable. Temperature changes over this distance can be readily detected using optical methods. The use of a large number of miniature thermocouples is impractical because of structural limitations.

Turbine-blade pyrometer systems have been investigated for many years. These systems are used to monitor blade temperature and also to serve as sensors in fuel control systems on operational engines. Relatively coarse spatial resolution of surface temperatures was permissable for these measurements. A review of pyrometer systems used for these applications can be found in references 2 to 7. The primary design consideration of this pyrometer was to obtain temperature distribution measurements with spatial resolution on the order of 0.05 centimeter (0.020 in.) on a single blade or a small group of test blades for heat-transfer studies in ground-based facilities.

The turbine-blade pyrometer system was tested on a modified J-75 engine with turbine-inlet-gas temperatures of 1644 K (2500° F), and blade tip speeds up to 366 meters per second (1200 ft/sec). Cooled test blades contained several surface thermocouples as well as a ceramic coating in the shape of a chevron on one blade. The thermocouples were used to compare temperature measurements with those determined by the pyrometer. The chevron pattern was used to investigate the spatial resolution obtainable on the blade surface. The results of these temperature measurements are discussed together with the calibration method and dynamic response testing. An overall description of the pyrometer system is also given.

TURBINE BLADE PYROMETER

System Design and Construction

The operating requirements which were established for the pyrometer system were as follows:

(1) Obtain temperature profiles of rotating turbine blades with tip speeds in the range from 300 to 400 meters per second (1000 to 1300 ft/sec).

(2) Achieve an optical resolution capable of resolving a spot diameter of 0.05 centimeter (0.020 in.) on the moving turbine blade.

(3) Provide near real time display of temperature profiles.

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

Figure 1 is a schematic representation of the pyrometer, which shows its major parts. A detailed description of the pyrometer system is given in reference 1. A brief description is included herein to aid the discussion which follows.

The coherent bundle of optical fibers contains 80 tangent fibers oriented in a single vertical row so that the images are projected to the turbine blade in a vertical line as shown. The purpose of this orientation is to view 4.0 centimeters (1.6 in.) of the blade span with the borescope probe in a fixed location. Each 0.005-centimeter (0.002-in.) diameter fiber is focused on the blade at a magnification of 10. The motion of the turbine blade generates 80 scan lines running across the blade. The radiant energy emitted by the hot blade is transferred by all the fibers to a microscope assembly where they are individually focused onto a single silicon avalanche detector. Each fiber is focused onto the detector, one-by-one, in turn, as the fiber position actuator moves the coherent bundle across the microscope assembly.

The detector and amplifier converts 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. This aspect of the system is covered in more detail in reference 1.

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. (Its 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 ($1\frac{1}{2}$-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 25 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 such a table 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 -225 to 225, 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.

TURBINE BLADE PYROMETER TESTS

J-75 Turbine Engine

The turbine-blade pyrometer was extensively tested on a modified J-75 test engine. More than 100 hours of testing were completed over a period of 1 year. Test duration varied from 3 to 8 hours. Approximately 1000 temperature profile scans were recorded.

Figure 5 is a photograph of the turbine looking upstream at the trailing edge and suction surface of the blades. The turbine had 76 blades and a tip diameter of 81.3 centimeters (32 in.). The convection-cooled blades had a span of 10.2 centimeters (4 in.) and a midchord length of 4.0 centimeters (1.6 in.). During steady-state tests the engine was operated at a turbine-inlet-gas temperature of 1644 K (2500° F) while the maximum blade temperature was limited to 1200 K (1700° F) by adjusting the coolant airflow. The tip speed of the blades was approximately 366 meters per second (1200 ft/sec). The group of blades at the top of figure 5 were used as test blades.

An enlarged photograph of the six test blades is shown in figure 6. The photograph shows the direction from which the blades were viewed by the borescope probe and two of the scan line locations along which measurements were made. The test blades contained ceramic coatings and thermocouples. Only three of the blades had ceramic coatings applied to selected areas. Two of these three had coatings in the form of square patches and were used for identification purposes (blades 2 and 6); and one blade (4) had a coating in the form of a chevron. Temperature profile scans were made across the chevron to examine the spatial resolution of the system. Ten chromel-alumel sheathed thermocouples with sheath diameter of 0.05 centimeter (0.020 in.) were flush mounted on the surface of the test blades at the midspan. The thermocouples were tested and installed according to current NASA procedures as described in reference 8. Scans were made across these blades at midspan, and the thermocouple-measured temperatures were compared with the pyrometer-measured temperatures at the thermocouple locations.

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 experienced 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.

As can be seen in figure 6, only 2.8 centimeters (1.1 in.) of the blade chord or about 70 percent of the area of the suction surface is visible to the probe. The leading-edge region and the pressure surface could not be viewed from this borescope probe location.

After the engine reached a stable operating point, the borescope probe was positioned radially in the engine by the actuator. As a safety measure the pyrometer output was monitored with an oscilloscope to observe the temperature distribution across all the turbine blades. This real-time presentation was observed periodically during the entire testing program. In this manner overtemperature blades could be detected when the blade cooling air was adjusted.

Before initiating a measurement scan, four selections were made: (1) The starting point of the scan 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 measurements was set by selecting a digitizing frequency; (3) the optical fiber to be used was positioned in front of the detector; and (4) the number of scans 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 numbers 10 and 20, etc. The ordinate is a temperature scale for cursory examination of the profile scan. The scan was made with the boresope 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 in 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 digitizing frequencies of 0.5, 1.0, and 2.0 megahertz (shown in figs. 7(b) to (d)). The higher measuring rates results in increased spatial resolution over shorter path lengths that represent 4, 2, and 1 blade, respectively. The higher digitizing frequencies are used when features on the blades are small like film cooling holes or slots, and detailed heat-transfer studies are involved.

Measured Temperatures

Ten thermocouples were flush mounted to the six test blades along the midspan region as shown in figure 6. Several temperature profile scans at various ampling frequencies were made across the test blades at the midspan location. The temperature profiles were similar in appearance to those in figure 7. The locations of the thermocouples were accurately determined on the temperature profiles.

The data of table I are a comparison of thermocouple measured temperatures and temperatures measured with the turbine blade pyrometer 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^{o} to 15^{o} 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^{o} to 1600^{o} F) because of engine operating safety considerations.

Isometric Display of Temperature Profiles

A useful mode available from the system is an isometric display on the CRT of temperature profiles. The isometric display is a grouping of temperature profile scans with the origin progressively offset with each scan. Figure 8 is such a plot made across the four blades sketched at the top of the figure. In this example, as with all other data presented, a single fiber was used to generate the profiles. The borescope probe was repositioned along the blade span in increments of 0.5 centimeter (0.2 in.) to generate the seven scans. An alternative way to generate this display is to keep the probe location fixed and use different fibers within the optical probe.

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 on blade 4. Figure 9 is an isometric display made across blade 4 with the maximum sampling frequency of 2.0 megahertz. The eight temperature profiles shown cover a span height of 2.5 centimeters (1 in.).

CONCLUDING REMARKS

The turbine-blade pyrometer described in this report can generate temperature profiles with spatial resolution on the blade surface of the order of 0.05 centimeter (0.020 in.). These profiles can be made using any or all of the 80 optical fibers. The first pyrometer was designed to have 80 fibers in the bundle. The purpose of the 80 vertically tangent fibers was to view 4.0 centimeters (1.6 in.) of the blade span with the probe in a fixed location. Under computer control, each fiber could be interrogated in turn, and the 200-temperature-spot measurements placed in storage. After all 80 fibers are interrogated, the 16 000 (80×200) measured temperatures could be plotted in the form of a two-dimensional temperature distribution map. In the testing program described in this report, the fiber position actuator often failed to position accurately the individual fibers at the microscope assembly. This difficulty necessitated using a single fiber and radially actuating the borescope probe to obtain scans at various radii. The position actuator is being replaced with a compact commercial model that will give a fivefold increase in fiber position accuracy and allow all 80 fibers to be used as intended. Other changes that are being made include using larger diameter fibers, to effect a trade-off between resolution and improved S/N, and replacing the bulky rotating chopper with a small oscillating mirror scanner. The basic criterion for incorporating these improvements was to increase reliability and decrease size without sacrificing any of the original design features.

SUMMARY OF RESULTS

The turbine-blade pyrometer was extensively tested on a modified J-75 test engine with turbine-inlet-gas temperatures up to 1644 K (2500° F) and tip speeds up to 366 meters (1200 ft) per second. More than 100 hours of testing was completed over a period of 1 year. Approximately 1000 temperature profiles and isometric plots were made.

Some of the important results of these tests are as follows:

1. Temperatures measured with the pyrometer and with thermocouples agreed within 2 percent at temperatures between 977 to 1144 K (1300° to 1600° F).

2. The pyrometer was capable of providing a spatial resolution of 0.05 centimeter (0.020 in.) which was adequate to define small surface features on the blades when high sampling rates were used.

3. The system permits much data to be taken and processed rapidly. A scan line of 200 spot measurements repeated 25 times for signal enhancement took only 7 seconds. The cathode ray tube display of temperature profiles (from which hard copies were made) were available within a few seconds, providing near real time operation.

4. The isometric display of temperature profiles proved to be useful in studying surface features.

5. The calibration technique (which used a blackbody oven as a stable temperature source) gave reliable measurements.

6. The blade position sensor supplied a precisely repetitive trigger pulse, which was necessary to obtain improved measurement accuracy at low temperatures by averaging repeated measurements.

7. The housing which contained the borescope end of the fiber optics probe gave excellent protection during long-term engine tests.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 6, 1976,
505-04.

REFERENCES

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

2. Mossey, P. W.: Experimental Pyrometer for Turbine Blade Temperature Measurement. SAE Paper 690431, April 1969.

3. Barber, R.: A Radiation Pyrometer Designed for In-Flight Measurement of Turbine Blade Temperature. SAE Paper 690431, April 1969.

4. Duffy, Thomas E.; and Compton, W. A.: Radiation Pyrometer for Gas Turbine Buckets. RDR-1647-2, Solar Division of International Harvester (AD-872174; AFFDL-TR-70-75), 1970.

5. Rohy, D. A.; Duffy, T. E.; and Compton, W. A.: Radiation Pyrometer for Gas Turbine Engines. SAE Paper 720159, Jan. 1972.

6. Katz, Herbert: Experiences in the Design and Application of Turbine Blade Pyrometers. Progress in Astronautics and Aeronautics, vol. 34, Mass. Inst. Tech. Press, 1974, pp. 409-418.

7. Curwen, K. R.: Turbine Blade Pyrometer System in the Control of the Concorde Engine. Progress in Astronautics and Aeronautics, vol. 34, Mass. Inst. Tech. Press, 1974, pp. 399-407.

8. Crowl, Robert J.; and Gladden, Herbert J.: Methods and Procedures for Evaluating, Forming, and Installing Small Diameter Sheathed Thermocouple Wire and Sheathed Thermocouples. NASA TM X-2377, 1971.

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

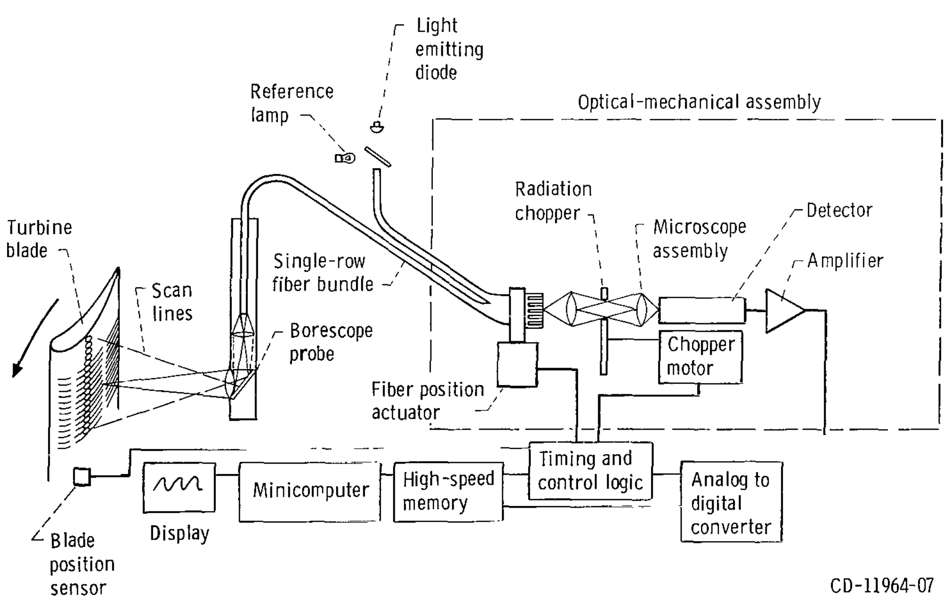


Figure 1. - Turbine-blade pyrometer.

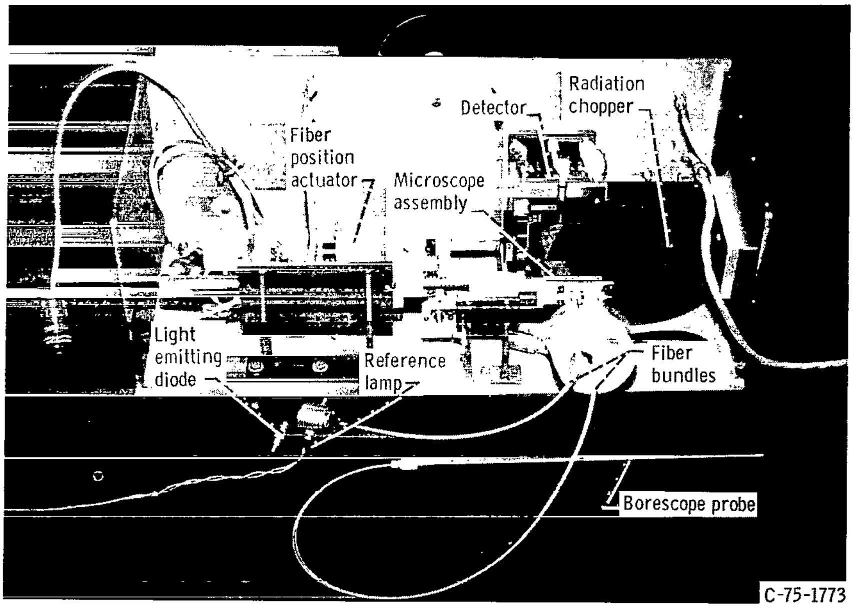


Figure 2. - Optical-mechanical assembly - prototype pyrometer.

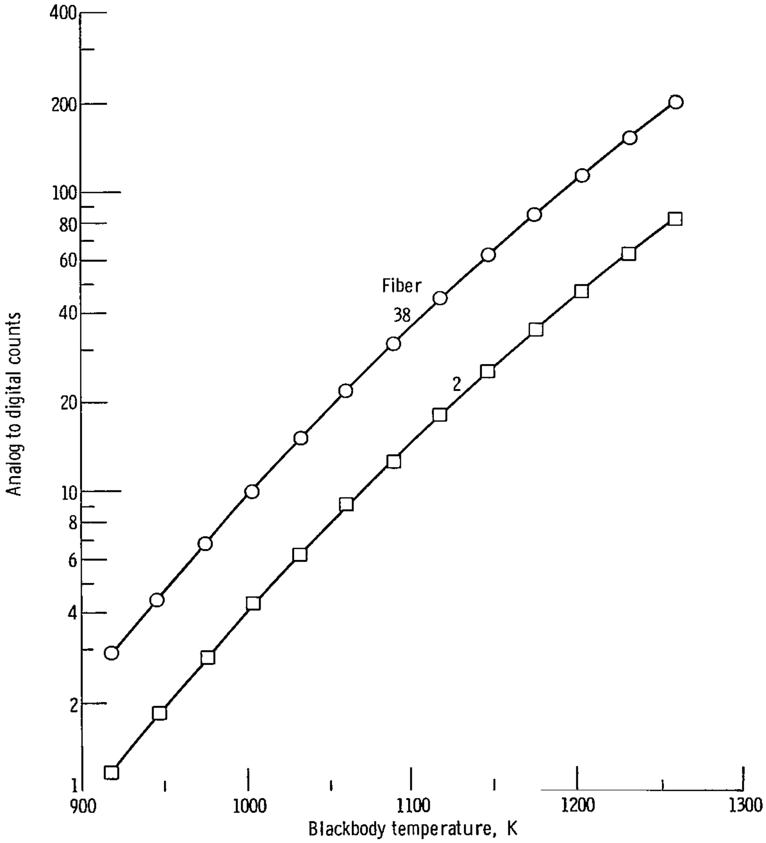
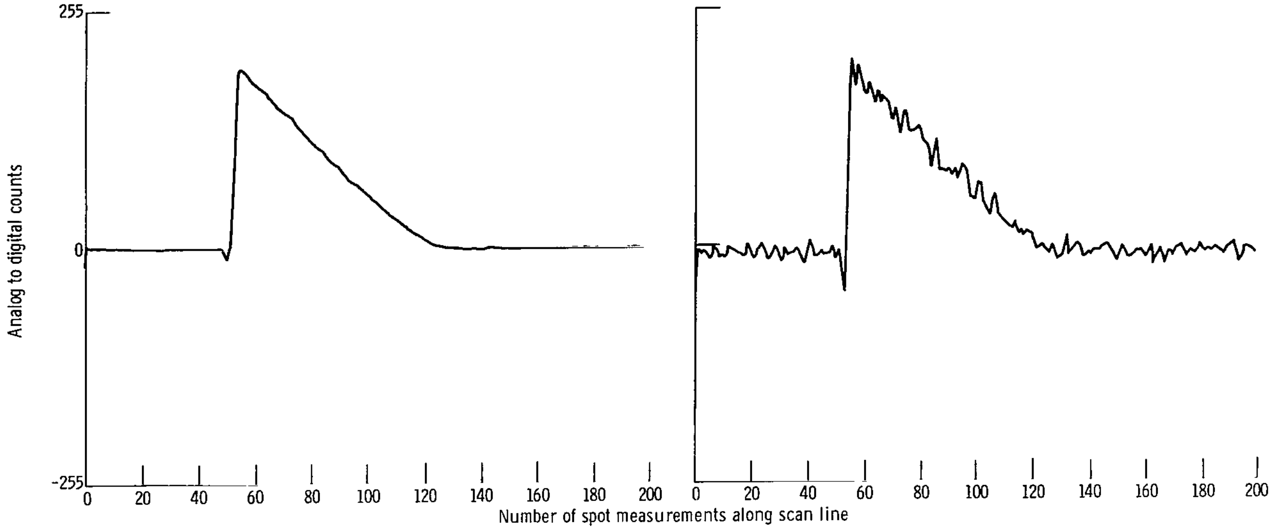


Figure 3. - Fiber calibrations for turbine-blade pyrometer.



(a) Average of 99 scans.

(b) Single scan.

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

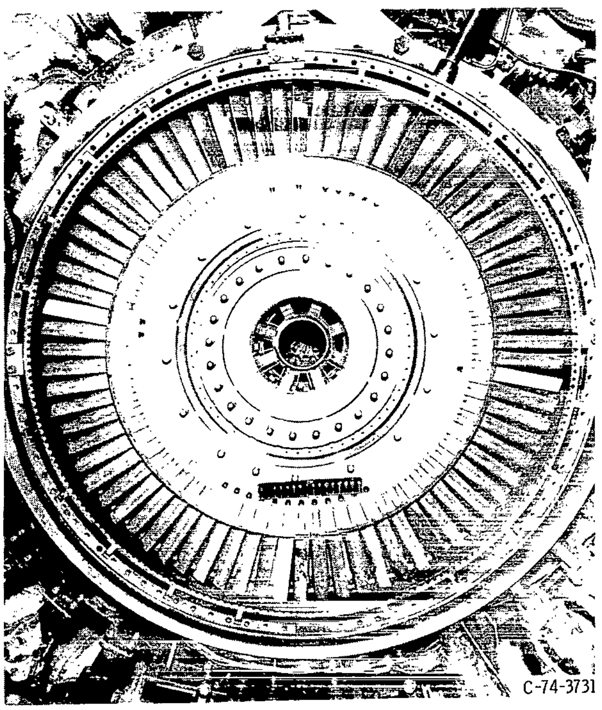


Figure 5. - Test blades in J-75 engine.

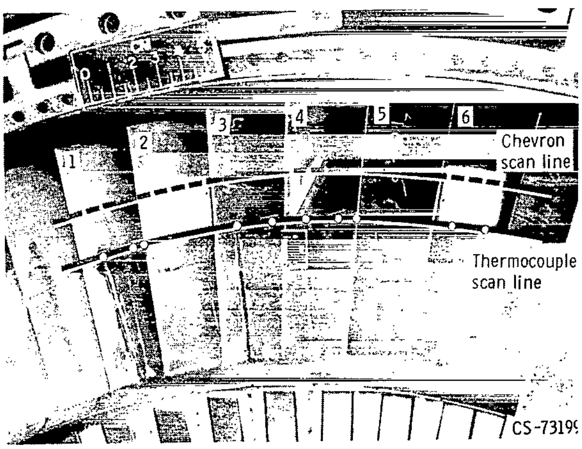
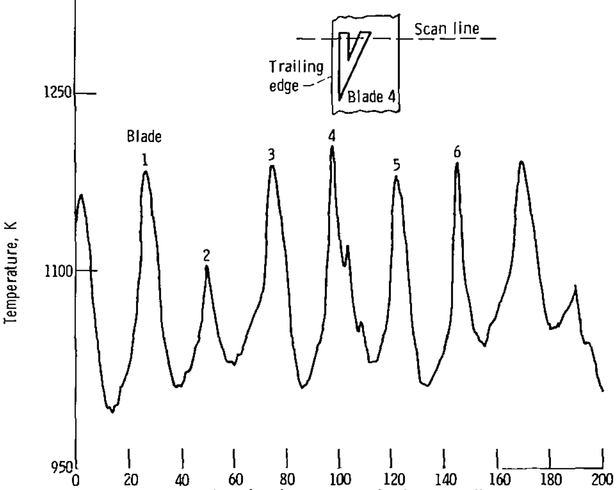


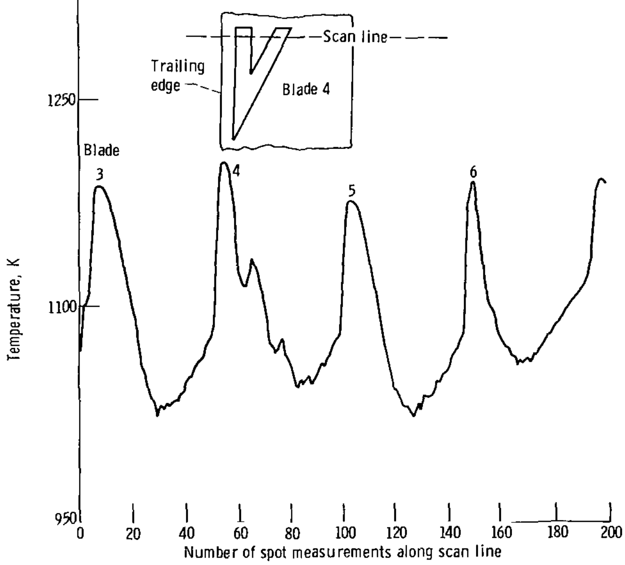
Figure 6. - Trailing-edge view of test blades.

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.

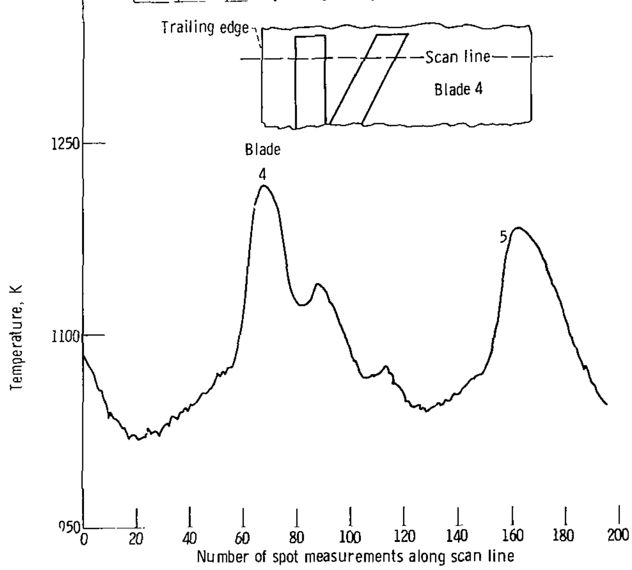
Temperature, K									
1075	1075	1070	1065	1060	1053	1049	1048	1041	1039
1029	1033	1028	1026	1025	1020	1020	1013	1014	1015
1016	1013	1013	1013	1013	1020	1016	1018	1019	1017
1021	1023	1025	1023	1030	1030	1028	1033	1033	1035
1034	1039	1038	1040	1043	1046	1048	1047	1051	1052
1056	1063	1061	1064	1063	1068	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.

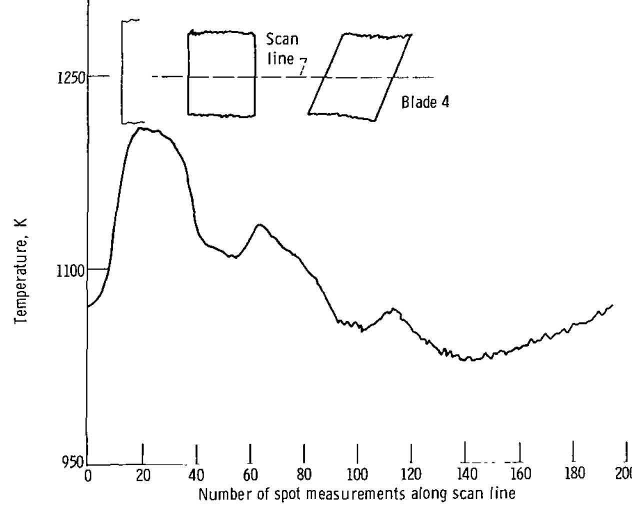
Figure 7. - Temperature profiles.

Temperature, K									
1073	1092	1094	1104	1149	1181	1188	1188	1187	1184
1178	1173	1164	1154	1144	1133	1125	1110	1099	1088
1076	1064	1055	1042	1036	1025	1019	1017	1008	1014
1015	1012	1016	1014	1017	1019	1019	1023	1025	1030
1035	1038	1043	1047	1048	1052	1061	1063	1068	1075
1104	1171	1203	1206	1206	1201	1192	1171	1136	1116
1112	1107	1107	1120	1130	1124	1117	1110	1100	1089
1072	1064	1061	1056	1059	1065	1066	1055	1049	1040
1037	1030	1029	1034	1031	1034	1037	1031	1035	1038
1044	1048	1046	1051	1054	1061	1065	1068	1075	1113
1160	1174	1176	1175	1173	1167	1161	1153	1143	1129
1119	1107	1093	1080	1071	1063	1053	1043	1032	1028
1024	1019	1014	1013	1013	1008	1006	1010	1015	1012
1021	1020	1020	1021	1025	1033	1032	1038	1039	1040
996	1051	1055	1058	1066	1071	1115	1173	1188	1189
1183	1164	1127	1109	1098	1092	1089	1084	1074	1068
1066	1061	1062	1055	1051	1051	1046	1049	1048	1049
1051	1048	1055	1054	1058	1060	1065	1069	1069	1075
1076	1080	1081	1086	1089	1093	1094	1099	1101	1105
1108	1111	1118	1134	1166	1184	1189	1190	1188	



(c) Sampling rate, 1.0 megahertz.

Temperature, K									
1046	1074	1075	1077	1081	1081	1089	1095	1104	1121
1134	1153	1168	1180	1191	1199	1205	1207	1209	1211
1210	1209	1210	1209	1208	1207	1206	1208	1205	1203
1202	1202	1199	1195	1191	1184	1178	1171	1162	1152
1140	1132	1127	1124	1121	1121	1121	1119	1118	1118
1117	1113	1112	1112	1113	1111	1110	1112	1116	1120
1123	1129	1131	1135	1136	1137	1136	1134	1130	1128
1127	1125	1124	1121	1118	1116	1117	1115	1114	1109
1108	1105	1103	1100	1098	1094	1096	1092	1086	1083
1078	1075	1071	1068	1066	1062	1064	1062	1062	1062
1060	1058	1062	1059	1058	1056	1058	1060	1060	1061
1064	1064	1066	1068	1070	1068	1072	1070	1067	1066
1063	1062	1059	1056	1054	1055	1051	1049	1048	1044
1048	1045	1044	1041	1039	1036	1039	1036	1039	1035
1035	1036	1031	1032	1032	1035	1035	1031	1033	1033
1034	1038	1036	1036	1035	1038	1037	1039	1039	1036
1039	1038	1040	1043	1042	1044	1046	1045	1046	1046
1045	1048	1048	1050	1053	1051	1048	1050	1053	1053
1055	1055	1052	1056	1058	1058	1061	1059	1058	1064
1060	1061	1064	1069	1066	1066	1071	1071	1074	



(d) Sampling rate, 2 megahertz.

Figure 7. - Concluded.

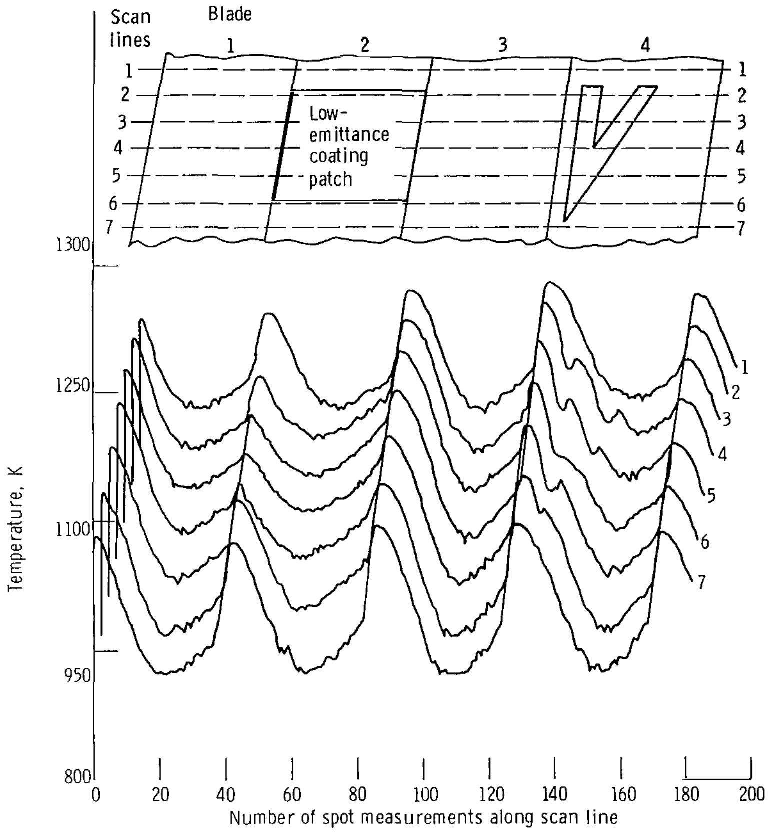


Figure 8. - Isometric display of blade temperature profile. Sampling rate, 0.5 megahertz.

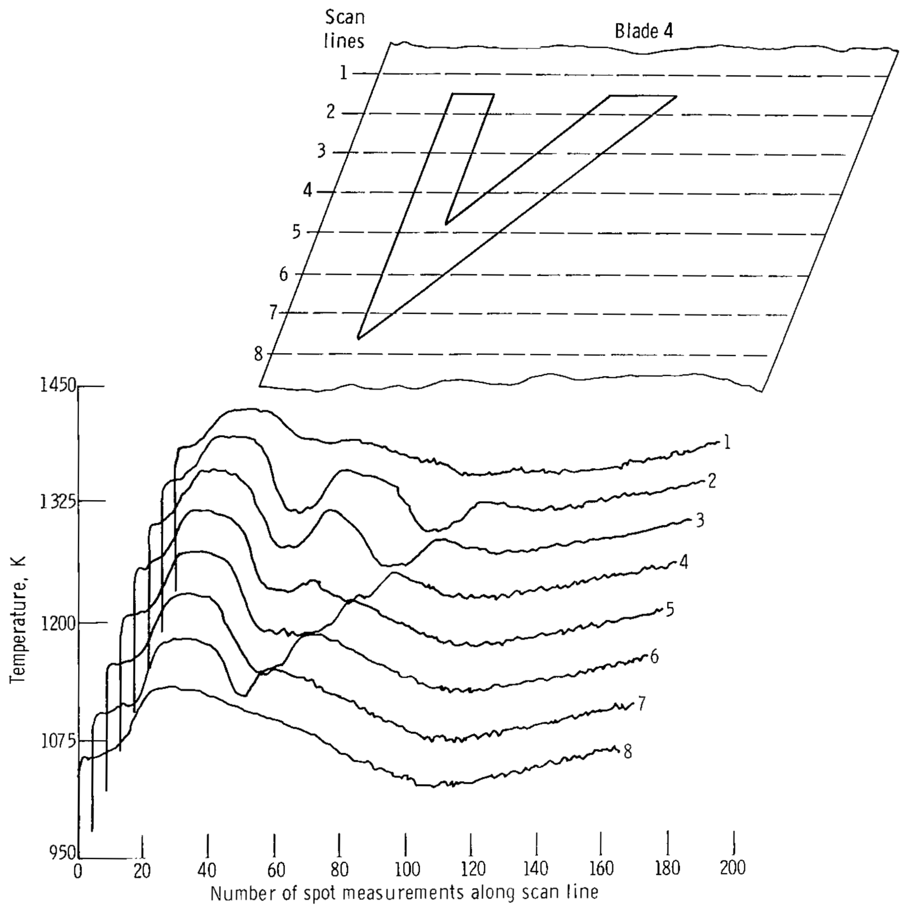


Figure 9. - Isometric display of blade temperature profiles of chevron. Sampling rate, 2 megahertz.

NASA-Langley, 1976 E-8613

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