Dynamic Surface Temperature Measurement on the First Stage
Turbine Blades in a Turbofan Jet Engine Test Rig

by

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APPROVED:

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Turbine blade surface temperatures were studied during transient operation in a turbofan engine test rig. A single fiber radiation pyrometer was used to view the suction side of the blades from approximately 60 percent axial chord to the trailing edge at an average radial location of 70 percent blade height. A single ceramic-coated blade produced a once-per-revolution signal that allowed for the tracking of individual blades during the transients. The investigation concentrated on the light-off starting transient and the transients obtained during accelerating and decelerating between power settings. During starting and acceleration transients, the blade surface temperature gradient was observed to reverse. This phenomenon was most apparent during starting when the trailing edge was initially much hotter than the 60 percent chord location, resulting in large temperature gradients. In steady operation the trailing edge temperature was lower than the 60 percent chord location, and the gradients were less severe. During deceleration transients, the trailing edge cooled more rapidly than the 60 percent chord location. This resulted in larger temperature gradients than were seen in steady operation, but no profile inversion was observed. These temperature gradients and profile inversions represent a cycling of thermally-induced stresses which may contribute to low cycle fatigue damage. A simple one-dimensional heat transfer model is presented as a means of explaining the different heating rates observed during the transients.
I would especially like to thank my major professor, Dr. Walter F. O'Brien and our sponsor, Rosemount Aerospace Division for the opportunity to work on this project. Dr. O'Brien provided the guidance and experience needed to achieve our goal, but still allowed the freedom to incorporate original ideas. This has proven an excellent opportunity to become exposed to the many aspects of gas turbine research.

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<th>Description</th>
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<tr>
<td>N2</td>
<td>high pressure turbine speed</td>
</tr>
<tr>
<td>ITT</td>
<td>intermediate turbine temperature</td>
</tr>
<tr>
<td>EGT</td>
<td>exhaust gas temperature</td>
</tr>
<tr>
<td>T_{\infty}</td>
<td>free-stream temperature</td>
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<tr>
<td>\varepsilon</td>
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1.0 Introduction

Considerable improvements in turbine blade materials coupled with recent efforts in the development of air-cooled turbine blades have allowed higher turbine inlet gas temperatures. In the turbofan engine, thrust and specific impulse can be made to increase with turbine inlet temperature as a result of improved thermal efficiency [1]. The desire to utilize this improved performance has led gas turbine manufacturers to increase turbine inlet temperatures. However, achieving the highest possible turbine inlet temperature requires accurate knowledge of the turbine blade temperatures for control and for prolonging engine life. The need for such knowledge has prompted much research in developing various techniques for measuring blade temperatures.

The trade-off of these increased temperatures is the increased risk of experiencing a blade failure. Failure can be defined in many ways, but is most conveniently defined as any occurrence that requires removal of the blade from the engine. Under steady operation at elevated temperatures, problems arise in the form of blade creep and oxidation. The extent of damage resulting from both creep and oxidation is determined by the amount of time a blade is sustained at a given temperature. It follows that increasing gas temperatures would reduce the life of the blade. Cohen et. al. [2] demonstrate that the time required to exceed a 0.2 percent creep strain limit due to a steady stress of 200 MPa is reduced from about 5000 hours to 200 hours by increasing...
the blade temperature from 1020 degrees Kelvin to 1090 degrees Kelvin. This represents a great reduction in engine life due to only a 70 degree Kelvin increase in blade temperature.

Another possible mode of blade failure is pitting or cracking due to low cycle fatigue. For the Pratt and Whitney JT15D-1 engine used in this investigation, any observable cracks, or pits greater than 0.005 in. (0.127 mm) deep will require the blade to be repaired or replaced [3]. Majumdar [4] argues that low cycle fatigue is related to transient temperature gradients and rotor speed. During transient operation, overshoots in both temperature and rotor speed can result in low cycle fatigue damage. Halford [5] claims that most of the cyclic fatigue loading is due to severe thermal cycling associated with engine startup and shutdown. The large temperature gradients and high temperatures experienced during the start of the engine can lead to localized problems. The extent of the damage is dependent on the severity and duration of the transient.

Although the two previously-mentioned failure modes have different causes, their effects are not entirely separate. For example, creep strain can only cause rupture when resulting from tension, but compressive creep strains can also be encountered. The presence of compressive and tensile creep strains constitutes a cycling of stresses which can contribute to low cycle fatigue. Also, the failure mechanism for thermally-induced low cycle fatigue is assumed identical to that of creep. Therefore, the effects of both failure modes are additive when acting on the same location. Arvanitis et. al. [6] argue that the effects of cycling strains can be considered as an equivalent creep strain effect. Thus, cyclic fatigue effects can be translated into equivalent operating hours for engine life prediction and maintenance purposes. It is evident that knowledge of transient temperature distributions is valuable for the improved prediction of engine life.

Various methods of measuring blade temperatures exist, but the radiation pyrometer provides the fast response time needed to record transient data. Another measurement
technique involves embedding thermocouples in the blade itself. However, difficulties arise in transmitting signals, and in the inherent slow response time of thermocouples. Another disadvantage of thermocouples is the reduction of structural integrity by the mounting of the sensor in the blade. The non-contacting nature of the engine pyrometer makes it attractive for the turbine engine environment. Also, the measurements are direct rather than derived from a cycle analysis, as might be done from an intermediate turbine temperature measurement.

Benyon [7] points out that a major advantage of pyrometers is the inherent exponential response to target temperatures. This is especially beneficial for pyrometers used for engine control since the limiting high temperatures will result in a good signal-to-noise ratio. Increased digital signal processing speed has resulted in additional advantages which may be offered by pyrometers, including the ability to obtain temperature profiles at very high rotor speeds. This latter advantage involves the possibility of using a once-per-revolution signal from the pyrometer as an accurate real-time speed sensor.

Pyrometers, however, do have their disadvantages. Measurement errors are due mainly to spurious radiation and lens contamination [8]. Reflected radiation and transient interference from flames and glowing particles result in an additive or one-sided error which is always biased high. Conversely, errors due to lens contamination result in lower measured temperatures than actually exist. This latter problem is of major importance for engine control considerations due to the resulting fail-dangerous situation.

The choice of optical target spot size is of great importance, and is dependent on the intended specific function of the pyrometer. Small spot sizes will result in lower signal levels, but will provide more accurate blade profiling. The result of the lower signal is a limited effective temperature range of the pyrometer. However, at higher
temperatures, peak blade temperatures can be measured, which can allow for increased engine performance and improved diagnostic ability. Larger spot sizes will result in stronger signals, but much profile information is lost in the inherent averaging over the target spot. This design is most useful when obtaining average rotor temperatures.

The present investigation utilized a single fiber radiation pyrometer with a small focus spot to measure transient temperatures on the surface of the first stage turbine blades of the engine test rig. Blade temperature profiles were recorded throughout starting, acceleration and deceleration transients which allowed for comparison among the various transients.

A brief background of the ongoing pyrometer research program at VPI & SU is presented in Chapter 2, while the research engine and pyrometer system are described in Chapter 3. Starting, acceleration, and deceleration transients were studied and the results are presented in Chapter 4 followed by a discussion of these results in Chapter 5. A simplified, one-dimensional heat transfer model of the blades during a starting transient is presented in Chapter 5 as well. Some detailed aspects of the investigation are included in the Appendices.
2.0 Background

The experiments reported in this thesis were conducted in the Gas Turbine Research Facility of the Center for Turbomachinery and Propulsion Research located at Virginia Polytechnic Institute and State University. The Project was performed as part of phase III of the ongoing Pyrometer Research and Development Program at VPI, which is sponsored by Rosemount Aerospace Division. The research was performed using a modified Pratt & Whitney JT15D-1 turbofan, which is a small engine designed specifically for business aircraft. Modifications were made to the engine to accommodate pyrometers, and one of the turbine blades was coated to provide for identification of certain blades as well as for signal processing. The location of the pyrometer is such that the suction sides of the first stage high pressure turbine blades are viewed from approximately the 60 percent chord location to the trailing edge.

Various types of pyrometers have been tested in previous program phases and the results have revealed that a probe utilizing an Indium Gallium Arsenide (InGaAs) detector gave the best performance over the temperature range produced by this engine. Previous results also revealed interesting phenomena suggesting further investigation. It was discovered that the chordwise first stage turbine blade temperature profile was considerably different during transient operation than under steady operating conditions. During steady operation, the trailing edge appeared to be the coolest spot on the blade.
However, under certain transient operating conditions, the opposite was observed, with the trailing edge being the hottest part of the blade. There was also a very large temperature gradient experienced during the starting transient. Although these different situations were observed, little was known about the transients since only a small portion of the transients had ever been recorded. Therefore, extended transient data records were required in order to better understand the dynamic characteristics of the transients.

It was necessary to determine which part of the recorded waveform was actual temperature data and which part was the transition from one blade to another. The pyrometer inherently averages temperatures over the target spot size which has the effect of smoothing the temperature profiles in the transition between blades, rather than producing the instantaneous step that actually occurs. The coated blade was intended to provide a once-per-revolution signal that would aid in distinguishing the transition region of the waveform. This also allowed for a given blade to be tracked through entire transients, and the identification of any “hot blades”.

Background
3.0 Experimental Arrangement

The following chapter contains an overview of the experimental set-up. The research engine rig, test cell configuration and engine monitoring systems are described. A discussion of the pyrometer system and high speed data acquisition system is also presented. Finally, a description of the calibration technique used in this investigation is discussed.

3.1 Research Rig

The rig used for the research program is a modified Pratt and Whitney JT15D-1 turbofan which is shown schematically in Figure 1. The JT15D-1 is a small twin spool turbofan engine that produces approximately 2000 pounds thrust using a bypass ratio of about three. The single stage centrifugal compressor produces a maximum pressure ratio of approximately ten. The turbine consists of a single stage high pressure turbine followed by a dual stage low pressure turbine. All stages of the turbine are uncooled.

The low pressure turbine stator support assembly (commonly referred to as the wishbone section) was modified in order to accommodate three research pyrometers. A schematic of the modified wishbone section showing a typical pyrometer penetration is presented in Figure 2. The modifications consisted of installing in the wishbone section
Figure 1. Schematic of Pratt & Whitney JT15D-1
Figure 2. Modified Wishbone Section Showing Pyrometer Configuration
sight tubes to support and align the pyrometer probes, and purge lines to carry purge air to cleanse the pyrometer lens. Situated at an angle to the flow, the sight tube passes between the low pressure turbine casing and the combustor liner. This close proximity to the combustor subjects the pyrometer to high temperatures. However, this problem is partially alleviated by the cooling effect provided by the purge air. The purge system has the capability of using shop air from a separate compressor, or using compressor bleed air from the engine itself. Thin static pressure tap lines were also installed in the penetration both upstream and downstream of the pyrometer to provide a means of measuring the pressure differential across the pyrometer. This allowed for direct calculation of the purge air flow rate.

The high pressure turbine disk was also modified. A single blade was removed from the disk and the suction side of the blade was coated with a ceramic coating. The coating used was Rockide H, which characteristically has a lower emissivity than the Nickel alloy blades. The coating technology [9] was developed by Pratt and Whitney Government Engine Business, and the coating procedure was performed by them for this investigation. The synchronizing signal produced by this blade allowed for the identification of given blades as well as signal processing. This will be further discussed in later sections. A picture of the high pressure turbine disk showing the coated blade as it is installed in the engine is presented in Figure 3. Since the seventy-one blade disk can reach speeds of about 31000 RPM, re-balancing of the disk after installation of the coated blade was necessary to minimize any unbalanced forces.
Figure 3. High Turbine Disk Showing Coated Blade
3.2 Test Cell Configuration

Safety was a primary consideration in the test cell design. The engine is mounted in the test cell which is equipped with a noise-reducing inlet section as well as a blast deflector positioned at the rear of the engine to reduce the hazards associated with the high velocity exhaust jet. Figure 4 shows the research engine as it is mounted in the test cell. A steel reinforced solid concrete wall separates the control room from the test cell with a section of impact-resistant glass to allow for visual observation of the engine during operation.

The control room is equipped with an instrument panel from which the operator runs the engine. Analog gages on this panel provide a means for monitoring engine operation parameters. For this investigation, engine operation parameters were used for monitoring purposes only, and thus, are not reported in detail. In addition to the analog gages, an IBM PC-XT computer is used to digitally monitor engine operation parameters. This computer contains a Data Translation DT-2801 analog to digital converter (ADC) which is driven by a data acquisition program developed in-house. The parameters recorded by the computer include N1 and N2 spool speeds, compressor pressure and temperature, oil pressure and temperature, EGT, ITT, fuel flow, and ambient conditions. The calibrations of all transducers are incorporated into the data acquisition software.

The purge air parameters are monitored using an IBM PC-AT located next to the control room. This computer is equipped with a Data Translation DT-2805 ADC card. The usual parameters recorded with this computer include the differential pressures in the purge flow across the pyrometers and the static pressure and temperature of the purge flow. Using these data, the purge air flow rates for each penetration can be
Experimental Arrangement

Figure 4. Research Engine Mounted in Test Cell
calculated and monitored during operation. Flow calibrations are incorporated in the data acquisition software. The importance of the purge flow will be discussed in the following section.

3.3 Pyrometer System

The main components of the pyrometer temperature measurement system are illustrated in Figure 5. A pyrometer probe is used to monitor and channel radiation from the suction side of the blades onto a photovoltaic cell located in the photodetector. A 45 foot single strand fiber optic cable is used to transport the radiation to the electronics housing that contains an InGaAs photodetector and a pre-amp. A voltage output from the pre-amp is transmitted to the pyrometer processor box. This processor performs both amplification and signal processing on the signal, resulting in a voltage that is digitized by the high speed data acquisition system. This digitized data is then written to disk on the IBM PC-AT.

The probe used in the experiments can be seen in Figure 6. The pyrometer uses a single color scheme which integrates radiant energy over the wavelength range of the detector. The fiber optics and the lens are rigidly housed in the tip of the probe, while purge air is forced along the outer circumference. The lens is recessed into the probe a few millimeters and the pyrometer is prevented from bending by the supports at the end and mid-length of the probe. There is a single strand fiber optic connector at the top of the probe, which mates with a similar connector on the 45 foot long fiber optic cable, which carries the radiant energy to the photodiode and the pre-amp. These connections are very sensitive to alignment and can produce a significant error, but this is of little consequence to profile observation. However, this does lead to significant error for
Figure 5. Main Components of Pyrometer System
Figure 6. Rosemount Single Fiber Probe and Turbine Blade
absolute temperature determination. This topic will be discussed further in a later section.

The geometry of the pyrometer penetration requires the pyrometer to view the blade at an angle looking radially inward. Figure 7 shows a schematic of the pyrometer configuration and viewing path. The geometry of the blade itself is such that the trailing edge is closer to the lens than the 60 percent chord location. Because of this, the pyrometer does not trace a constant radius path across the blade. The pyrometer views the 60 percent chord location at about 61 percent blade height. The path traced is such that the radial location of the target spot on the blade increases to about 80 percent blade height at the trailing edge. This is shown in Figure 8 which is taken from the Computer Aided Design work done by Williams [10]. The focusing envelope depicted in this figure is a two-dimensional representation of the actual three-dimensional focusing envelop, which is conical in shape. Since the distance from the lens to blade surface is different at each axial location on the blade, the distance from the focal plane to the blade is continually changing. This also causes a variation in target spot size as the pyrometer tracks across the blade. The result is a varying degree of "out of focus" of the pyrometer. Kirby [8] addresses this matter in detail and concludes that the error due to the pyrometer being out of focus is small relative to other possible errors and can usually be ignored.

3.4 Pyrometer Electronics

The pyrometer electronics consist of a pre-amp, a processor box, a LeCroy high speed data acquisition system and a host computer as shown in Figure 5. The pre-amp used is the limiting component in terms of frequency response with a usable bandwidth.
Figure 7. Schematic of Pyrometer Viewing Turbine Blade

Experimental Arrangement
Figure 8. Path of Pyrometer Target Spot Across Turbine Blade (from ref. 9)
up to approximately 200 KHz. There are two more stages of amplification in the processor box. This processor box supplies three different output signals with frequency response at 200 KHz, which are attenuated for three db down at frequencies from 10 to 250 KHz based on user selection, and a mean signal that is three db down at about 10 Hz. For this investigation, the 200 KHz output signal was mainly used in order to obtain as much profile information as possible.

The pyrometer data is recorded using a LeCroy high speed data acquisition system with an IBM PC-AT as the controller. The LeCroy system used in the experiments consisted of two 6810 waveform recorders, an 8901A GPIB interface, and a 8013A housing. Each 6810 module is a 12 bit instrument which has the capability of sampling at a maximum frequency of 5 MHz with a storage capacity of 512 K words. Since the memory of each 6810 is divided among the channels being used, only one channel of data was taken during the recording of long transients.

The two waveform recorders were triggered alternately using a square wave. The first recorder triggered off the rising edge of the signal while the second triggered off the falling edge. Figure 9 shows a typical triggering and data collection series. Region A represents the time between successive triggers, while region B depicts the time required to collect the data for a given trigger. The values of the parameters shown in Figure 9 that were used for the various tests performed will be discussed in a later section. At the start of each recording, the first trigger was initiated manually just prior to applying fuel to the combustor. Each subsequent trigger was controlled by the period of the square wave. Although the square wave was input into channel two of each recorder, no memory was used in sampling those channels. The period of the square wave could be adjusted to most effectively capture the transient depending on the duration of the transient. Typically, each 6810 was triggered 64 times taking 8 K words of data on each trigger. This resulted in 128 triggers and a total of 1024 K words of data. The
Figure 9. Schematic of Square Wave Timing Series and Data Collection Periods
arrangement permitted very high data rate samples of the relatively long duration engine transients. The pyrometer signals were coupled using negative DC coupling in order to invert the negative signal output by the processor. Ultimately, the host computer was used to store the digitized data on disk.

3.5 Calibration

One limitation of the pyrometer system used in this investigation was the lack of an easily-applied calibration scheme. The effectiveness of the fiber optic couplings and the sooting of the lens are not constant from test-to-test, and thus, render any overall calibration inaccurate. However, data taken from previous test programs does provide a means of comparison. That is, previous results have yielded a curve relating average blade surface temperature to rotor speed. Data used to generate this curve were obtained using multi-spectrum pyrometry to obtain radiance data directly from the engine, from which the true blade temperatures were determined. For each start of this investigation, data were recorded at various speeds under steady operating conditions. Using the once-per-revolution signal, it was possible to relate average pyrometer output at these steady conditions to rotor speed. This information was used with the previous test results to relate pyrometer data obtained during this investigation to surface temperature at given rotor speeds. Knowing that pyrometer output increases exponentially with temperature, an exponential curve was fit to the data at these given rotor speeds. This curve was then used to relate all pyrometer output for a given test to temperatures. To ensure the best accuracy, a separate curve was generated for each start. Appendix A contains the equations used to map pyrometer voltages into surface temperatures for all the starts as well as the data used to generate these equations. It
should be noted that, in this investigation, the fiber optic couplings were not disturbed once testing had begun. Thus, differences in the measured temperature-pyrometer output relationships of Appendix A were due to lens sooting and other effects. The curve relating mean blade temperatures to rotor speed is also shown in Appendix A.

There is some error associated with the above calibration, but it is the best approximation of surface temperatures available. The accuracy of the temperatures depends on the accuracy of the previous test results used in the generation of the temperature versus rotor speed curve and the repeatability of the engine operation. The error associated with the absolute mean blade temperatures used in this calibration should be within ± ten degrees Kelvin [11]. However, the errors associated with the measurement of temperature differences will be less. This is because forming temperature differences eliminates the constant temperature offset produced by the calibration described in Appendix A. The intent of this investigation was to focus on recording temperature profiles and trends occurring during transients.
4.0 The Investigation

The goal of the experiments was to learn more about the thermal behavior of the turbine blades under transient operating conditions. The experimental plan included investigations into the duration and severity of the starting transients as well as comparisons among starting, acceleration, and deceleration transients. Initially, data were recorded under steady operating conditions at various operating speeds to serve as baseline data for comparison purposes. Once these data were obtained, starting transients were captured.

Because of the desire to limit starting transients of the engine, an attempt was made to keep the number of starts to a minimum. However, enough starting transients needed to be recorded to establish the repeatability of the data taken on any given start. Each time the engine was started, a starting transient was recorded as well as acceleration and deceleration transients. The transients between power settings were more difficult to record due to their short duration. Information gained from each previous start was used to more effectively capture data on future starts.
4.1 Results

The suction sides of the turbine blades were studied at an average radial location of 70 percent blade height. Temperature profiles were obtained for steady operation and for several transient operating conditions. The data collection parameters, including sampling rate and triggering period, are summarized in Table 1 for the various transient recordings. All sampling rates were selected such that approximately 30 or more data points per blade were recorded. Regions A and B of this table are identified in Figure 9. The results of these investigations are presented in the following sections.

4.1.1 Coated Blade

The coated blade has a surface treatment of Rockide H ceramic coating that is approximately 9 mm wide. However, the entire surface seen by the pyrometer is not covered by the coating. The pyrometer sees exposed blade surfaces at both the 60 percent chord and trailing edge sides of the strip. Because of this, the coated blade produces pyrometer signals which are considerably different during steady operation and starting transients. The coated blade signal as it appears during steady operation is presented in Figure 10. Since the emissivity of the coating is different from that of the blade material, the temperatures presented for the coated blade are not valid. However, this blade was used exclusively for identification purposes and no attempt was made to predict the effect of the coating on the temperature of that blade. Also shown in Figure 10 are the few blades immediately preceding and following the coated blade. The data of Figure 10 are steady state, and were not recorded using the triggering method presented in Figure 9. All subsequent data in this section were transient data, and were captured using the sequential square-wave triggering method of Figure 9. These data
Table 1. Data Collection Parameters

<table>
<thead>
<tr>
<th>Transient Recorded</th>
<th>Region A Time (sec)</th>
<th>Region B Time (msec)</th>
<th>Sampling Rate KHz</th>
<th>Samples Recorded In Region B K Words</th>
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<tr>
<td>Start #1</td>
<td>0.25</td>
<td>16.384</td>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>Start #2</td>
<td>0.25</td>
<td>16.384</td>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>Start #3</td>
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<td>16.384</td>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>Acceleration</td>
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<td>4.096</td>
<td>2000</td>
<td>8</td>
</tr>
<tr>
<td>Deceleration</td>
<td>0.10</td>
<td>4.096</td>
<td>2000</td>
<td>8</td>
</tr>
</tbody>
</table>

The Investigation
STEADY OPERATION TEMPERATURE PROFILE
N2 = 27800 RPM

Figure 10. Coated Blade Profile During Steady Operation
were taken at a constant 85 percent N2 speed and sampled at a frequency of 1 MHz. This resulted in approximately 30 data points per blade. From these signals, it is seen that under steady conditions the trailing edge is the coolest part of the blade, while the 60 percent chord location is the hottest spot. This accounts for the initial increase in measured temperature level of the coated blade, followed by a sharp decrease as the coating is encountered.

The thermal characteristics of the coating are such that the coated blade appears to thermally lag the other blades during the process of starting the engine. This can be seen in the plot of the coated blade under transient conditions presented in Figure 11. These data were taken approximately four seconds into a starting transient. The large increase in temperature level seen at the trailing edge of the coated blade reflects the fact that the trailing edge is the hottest part of the blade during this portion of the starting transient, and the fact that the coating does not quite cover the entire blade surface.

4.1.2 Starting Transient

All of the starting transients presented in this section were recorded in identical fashion. For each start recorded, 128 segments of data were taken each with a triggering period of 0.25 seconds. This amounted to a total of about 32 seconds of the transient. This proved to be sufficient time to capture the entire transient. The results presented concentrate on data obtained during three starts.

Figure 12 shows a sequence of chordwise temperature profiles of start number one at various times during the engine start-up, while the entire transient temperature behavior of two points on the surface of a single blade is summarized in Figure 13. The latter plot represents a temperature history of the 60 percent chord location as compared to that of the trailing edge. The data presented in all of the temperature histories shown
Starting Transient Temperature Profile

Time = 4.25 sec  \( N2 = 20.7 \pi \)

Figure 11. Coated Blade Profile During Starting Transient
Figure 12. Chordwise Temperature Profiles During Starting Transient #1
Figure 13. Starting Transient #1 Temperature History
in this section are taken from the blade immediately preceding the coated blade. From Figure 13, it can be seen that the trailing edge is heated considerably faster than the 60 percent chord location, and both temperatures overshoot the steady operation (idle) temperature. Results from previous test programs have revealed steady idle temperatures to be approximately 810 degrees Kelvin. This rapid heating of the trailing edge leads to large temperature gradients early in the transient. After the peak temperatures of both locations have been reached, the trailing edge begins to be cooled at a faster rate than the 60 percent chord location. This eventually leads to an inversion of the temperature profile, represented graphically by the intersection of the two lines in Figure 13. After this time, the trailing edge remains the coolest part of the blade and the blade temperature distribution eventually settles into a steady condition. This steady state condition at idle has a very small peak-to-peak temperature variation on the order of 2 to 4 degrees Kelvin [12].

There are three distinct phases of each starting transient. Referring to Figure 13, Region I is the early part of the transient in which the trailing edge is hottest. Typical blade temperature profiles during this period were presented in Figure 11. Characteristics of this phase are a hotter trailing edge and very large temperature gradients. The second distinct phase (Region II) is that in which the blade surface temperature profile passes through a point of no slope. That is, there is no chordwise temperature gradient on the blade surface. A typical temperature profile from this part of the transient is presented in Figure 14. The last part of the transient (Region III) is characterized by having a cooler trailing edge than 60 percent chord location. Typical temperature profiles from this portion of the transient are presented in Figure 15. These profiles closely represent those of steady operation, having much smaller temperature gradients than during the first part of the transient. Note also that the coated blade now has a small spike at the 60 percent chord location, which is characteristic of steady
STARTING TRANSIENT TEMPERATURE PROFILE
TIME = 10.0 SEC.  N2 = 30.6 %

Figure 14. Detail of Typical Temperature Profiles In Region II of Start #1
Figure 15. Detail of Typical Temperature Profiles In Region III of Start #1
operation. The three detailed temperature profile plots presented were all taken from starting transient number one.

It can be seen from the detailed profile plots that individual blades can be identified. This allows temperature data for a single blade to be isolated for curve-fitting purposes. It was determined that a third order polynomial fit the temperature data very well, giving a maximum curve-fit error of less than one-half percent. A least squares curve-fit procedure was employed and examples of typical results are presented in Appendix B. The resulting cubic equation is easily differentiated yielding continuous chordwise temperature gradients at the given time during the transient. Figure 16 shows one such plot of temperature gradients versus percent chord. The gradients are presented from about 65 percent chord to 95 percent chord due to the effects of the transition region limiting the determination of accurate temperature data over this portion of the blade. The temperature data used for the curve-fit and differentiation performed to obtain Figure 16 were previously presented in Figure 11. This procedure of curve-fitting the temperature data of single blades and differentiating to obtain gradients was performed on data taken at several times during the start. The results are presented in Figure 17, which shows a time history of the maximum chordwise gradients observed during the start. The figure presents data for times beyond three seconds into the start, so that only data from the effective temperature range of the pyrometer are presented.

Temperature histories similar to those presented in Figure 13 are presented in Figures 18 and 19 for the other starting transients recorded. Figures 18 and 19 correspond to starting transients number two and three respectively. All transients were recorded on different occasions but under similar conditions. The intent of these plots is to establish the repeatability of all starting transient data. It can be seen that the trends of each start are the same, but the settling time and time of profile inversion vary. This is evidence that the engine operator, starter operation, and other factors play a role.
Figure 16. Chordwise Temperature Gradient of Single Blade During Start
Figure 17. Starting Transient #1 Maximum Temperature Gradient History
STARTING TRANSIENT TEMPERATURE HISTORY

START # 2

Figure 18. Starting Transient #2 Temperature History
STARTING TRANSIENT TEMPERATURE HISTORY

START #3

Figure 19. Starting Transient #3 Temperature History
in the temperature transients, and therefore, the severity of the thermal gradients for a given start.

4.1.3 Acceleration Transient

Acceleration transients were recorded as the engine was accelerated between power settings by way of a quick throttle change. These transients differ from starts in that acceleration transients start and end with steady profiles and are typically much less severe. Figure 20 shows chordwise temperature profiles at various times of the transient. Figure 21 shows a temperature history of both the 60 percent location and the trailing edge of the blade immediately preceding the coated blade. The transient was from 84 percent N2 to 88 percent N2.

From Figure 21, it can be seen that even during this small range acceleration, two distinct temperature profile inversions were experienced. The acceleration transient also had three distinct regions, however, these regions were quite different than those depicted during the start. The first part of the transient, denoted region A, is characterized as being similar to the steady operation. Typical temperature profiles during this period are presented in Figure 22. This period represents the transition from steady operation into a transient operating condition. It can be seen that the temperature profile is fairly flat over a good portion of the blade and makes a fairly sharp drop near the trailing edge. This results in a large gradient at the trailing edge but not a very large temperature difference. Because of this small temperature difference, not much time is required for the trailing edge temperature to exceed that of the 60 percent chord location when higher temperature gasses are present during acceleration.

The period after this first inversion is the second distinct region in the transient, denoted region B. Typical temperature profiles from this period are presented in Figure
Figure 20. Chordwise Temperature Profiles During Acceleration Transient
ACCELERATION TRANSIENT TEMPERATURE HISTORY
84% - 88% N2

Figure 21. Acceleration Transient Temperature History
TEMPERATURE PROFILE DURING ACCELERATION

84% - 88% N2  TIME = 0.0 SEC.  N2 = 84.5%

Figure 22. Detail of Typical Temperature Profiles in Region A of Acceleration
23. It should be noted that although the trailing edge is hotter than the 60 percent location, neither of the two locations are the hot spot of the blade. This occurs somewhere near the 90 percent chord location, creating an almost parabolic temperature profile. Toward the end of this period of the transient, the profiles began trending toward those for steady operation. Once again, a temperature gradient inversion was experienced and the trailing edge became the coolest spot of the blade.

This second inversion marks the start of the third distinct region of the transient. This period, region C in Figure 21, is characterized as having temperature profiles similar to those for the final steady operating conditions. Typical temperature profiles during this period can be seen in Figure 24. This plot reveals a slightly parabolic temperature profile as seen in the previous region. However, distinct characteristics of steady operation are evident. These include a cooler trailing edge as well as a coated blade profile that resembles that of steady operation as previously discussed. The previous three plots along with twelve others were used to develop the data used to generate the temperature history presented in Figure 21.

Once again, individual blades can be identified and the data from these blades can be fitted to a curve. A third order polynomial was used to describe the temperature data and differentiated to obtain temperature gradients as described in Appendix B. Figure 25 shows a plot of chordwise temperature gradients versus percent chord during the acceleration transient. Again, the effects of the transition region limit usable data to the region between approximately 65 percent chord and 95 percent chord. The data used for the curve-fit is that of the blade preceding the coated blade presented in Figure 22. The point of zero gradient in Figure 25 corresponds to the point of maximum surface temperature of the parabolic-shaped profiles seen in Figure 22. Temperature gradient plots, similar to that of Figure 25, were produced for various times during the
Figure 23. Detail of Typical Temperature Profiles in Region B of Acceleration
TEMPERATURE PROFILE DURING ACCELERATION

84% - 88% N2  TIME = 7.0 SEC.  N2 = 86.7%

Figure 24. Detail of Typical Temperature Profiles in Region C of Acceleration
INSTANTANEOUS CHORDWISE TEMPERATURE GRADIENTS

GRADIENT VERSUS PERCENT CHORD  TIME = 1.5 SEC.

Figure 25. Chordwise Temperature Gradient of Single Blade During Acceleration
acceleration. Figure 26 shows a time history of the maximum surface temperature gradient encountered during the acceleration transient.

4.1.4 Deceleration Transient

Several deceleration transients between power settings were recorded. The decelerations were generated by a quick throttle change between power settings. A sequence of chordwise temperature profiles of one deceleration is presented in Figure 27. A temperature history of this deceleration transient is presented in Figure 28. Once again, this plot was developed using data from the blade immediately preceding the coated blade. The transient was a deceleration from approximately 85 percent N2 to 75 percent N2.

The temperature history reveals characteristics considerably different from those of the starting and acceleration transients. The major difference is that no temperature inversion is experienced. During the initial steady operation, the trailing edge has the lowest surface temperature of the viewable portion of the blade. As the gas temperature is decreased, the trailing edge is cooled at a faster rate than the 60 percent chord location, which initially causes large temperature gradients. However, the 60 percent chord location is quickly cooled and the surface temperatures trend toward those for steady operation.

As with previous transients, temperature data were fitted to a third order curve. The derivative of this temperature profile represents the continuous chordwise temperature gradient. Figure 29 shows one such plot of temperature gradient versus percent chord. Similar gradient curves were generated at various times during the deceleration, and Figure 30 shows a time history of the maximum gradients observed during the transient.
Figure 26. Acceleration Transient Maximum Temperature Gradient History
Figure 27. Chordwise Temperature Profiles During Deceleration
DECELERATION TRANSIENT TEMPERATURE HISTORY
85% - 75% N2

Figure 28. Deceleration Transient Temperature History
Figure 29. Chordwise temperature Gradient of Single Blade During Deceleration
DECELERATION TRANSIENT TEMPERATURE GRADIENTS
MAXIMUM CHORDWISE GRADIENTS

Figure 30. Deceleration Transient Maximum Temperature Gradient History
4.2 Summary

In summary, blade surface temperature data for three different transient operating conditions have been presented. The starting transient, which was presented first, produced the largest temperature excursions. This transient was characterized by high mean temperatures along with large temperature gradients. A profile inversion was experienced as surface temperatures trended toward those for steady operations. The second transient was an acceleration transient which was characterized as having two profile inversions. Although the transition region between the inversions displayed an almost parabolic temperature profile, the temperature gradients were small compared to those for the start. The final transient was a deceleration transient in which the temperature gradients increased considerably for a brief time but soon settled to steady operation with no profile inversion. Results for each of these operating conditions will be discussed in further detail in the following Chapter.
5.0 Discussion of Results

Much of the experimental data presented in the previous Chapter requires interpretation in order to reach conclusions. The following sections will discuss the results in relation to how the data were interpreted. Possible sources of errors will be discussed along with the presentation of a simplified heat transfer model as a possible means of explaining the occurrences observed in the previous Chapter.

5.1 Measurement Error Sources

There are two categories of errors that can arise in using radiation pyrometers to measure turbine blade temperatures. The first includes errors induced by the harsh environment which exists in the turbine, while the second involves errors of the pyrometer system itself.

In dealing with the turbine environment, there are five major sources of radiation that can affect a pyrometer reading: the target blade, flames, neighboring blades, the combustor wall, and stator vanes. Kirby [8] argues that the temperature of the latter three are close enough to that of the target as to not cause appreciable errors in pyrometer readings. He also suggests that the degree of error encountered due to the combustion flame is a strong function of combustor geometry. In the present
experiment, there are two advantages specific to the combustor and pyrometer geometry that can minimize the error due to flames. The first advantage is the wrap-around geometry of the combustor employed by the JT15D-1. This allows a longer residence time in the combustor which in turn decreases the number of glowing particles passing through the turbine rotor. The combustor geometry also prevents most flame radiation from being reflected downstream to the pyrometer. The second advantage is inherent to the geometry of the pyrometer installation. Since the pyrometer views the suction sides of the blades from a downstream position, the chance of glowing particles passing through the line of sight is low.

The final environmental error considered is the surface emissivity of the target blade. As stated earlier, the surrounding surfaces in the hot section of a turbine engine are at temperature levels that should not significantly affect the pyrometer's reception of radiation. The turbine blade is considered to reside in an environment that is referred to, in optical terminology, as a "black body".

The surface condition of the blades and the angle of the surface with respect to the viewing axis are factors that do affect the transmission of radiation from the blade to the pyrometer. The net transmission or emissivity factor is generally greater than 80 percent. The emissivity of the blade surfaces must be determined by engine analysts to obtain absolute blade temperatures when using single-color pyrometers. However, multi-color pyrometers with corrective signal processing algorithms provide absolute temperatures directly.

The other major sources of pyrometer errors rest within the pyrometer system. Fiber optic connections, lens contamination, and pyrometer defocus all can introduce error into the pyrometer system. Fiber optic connectors are very sensitive to alignment. These connectors can be responsible for up to a 20 to 30 percent variation of output signal depending on the effectiveness of the coupling [13]. Because of this, all of the data
reported in this investigation was taken without disturbing the fiber optic connections. Thus, any error due to coupling of the fiber optics should remain constant throughout all the tests. Therefore, variations in the measured temperature-pyrometer output relationship were due to sooting and other effects.

Another source of possible error is lens contamination. The effectiveness of the pyrometer depends strongly on having a clean lens through which the blade can be viewed. If no cleansing scheme is employed, the lens will quickly accumulate combustion by-products, blocking the radiation path. As discussed in Chapter 3, the tactic used on this particular engine is to expand purge air over the lens prohibiting any sooting of the lens. The purge air used for this investigation was filtered air from a remote air compressor. The importance of the two types of errors previously discussed is that they both will result in temperature readings lower than the true temperature. This is an especially dangerous situation if the system is used for engine control.

Pyrometer defocus is the last type of pyrometer error considered. Defocus has the effect of increasing or decreasing the target spot size on the blade. This effect is dependent on the position of the blade relative to the focal plane of the pyrometer. Kirby [8] addresses this problem in detail and concludes that the defocus of the pyrometer has little effect on the spatial sensitivity of the pyrometer. This is because defocus tends to weight the spatial sensitivity toward the viewing axis, thus, tending to offset the effects associated with target spot size.

5.2 Data Interpretation Errors

One of the goals of this investigation was to use the once-per-revolution signal as a reference point to better interpret the data. That is, to better distinguish the blade
temperature profile from the region of transition between blades. This transition zone is the direct result of a finite spot size and a finite bandwidth. The pyrometer collects radiation from over the entire target spot and essentially area-averages to produce a resulting signal which is interpreted as temperature. The transition region begins when the first part of the target spot sees the next blade. The transition ends when the target spot completely leaves the previous blade. The shape of the waveform during this transition depends on the relative temperatures and temperature gradients of the trailing edge of one blade and the 60 percent chord location of the next blade. Clearly some of the blade profile detail is hidden in this transition region. An example of this effect is given in Figure 31. The assumed true profile is seen as the sawtooth wave, while the sampled profile appears much smoother. The most serious effect of this occurrence is the underestimation of the peak temperatures at the transition between blades [7].

For most of the data presented, there has been little problem distinguishing the transition region from the blade profile. However, the transition region is not immediately evident in the data presented for Region B of the acceleration transient of Figure 21. Detailed profile data from region B were presented in Figure 23. The transition profile appears cubic in nature. This is because of the parabolic-shaped temperature profile and the fact that the trailing edge and the 60 percent chord location are very close in temperature. It is very difficult to determine exactly where the transition region exists. Since inspection of the waveforms did not immediately reveal the temperature data, an alternate method was required to determine the location of the temperature profile on the blade.

The method used essentially involved counting back from a reference point on the coated blade by a given number of data points. The coated blade provided a very accurate speed reading which lead directly to a knowledge of the number of data points per blade. Knowing the approximate size of the target spot revealed the number of data
Figure 31. Effect of Finite Spot Size and Bandwidth
points contained in the transition. The target spot size was taken to be 20 percent of the viewable blade width. Using a reference point on the coated blade and the number of data points per blade and per transition region, a better estimate of the transition region was obtained. It is reasonable to expect errors of a plus or minus a few data points when using this method to locate the transition region. It is assumed to be these errors that cause the apparent oscillations of temperature history and maximum temperature gradient history in Figures 21 and 26 respectively. A more reasonable approach may very well be to construct a smooth curve through the lines.

5.3 Steady Operation Characteristics

This research has been focused on the recording and analyzing of various transient operating conditions. However, before conclusions can be reached or any comparisons made, something must be said about the thermal characteristics during steady operation. As mentioned previously, the initial stage of the investigation included recording steady state data at various power settings. Analysis of this data has revealed that the characteristics of the temperature profiles under steady operation are independent of power setting. The temperature differences were greater at higher power settings, but the 60 percent chord location was always hottest with the trailing edge always being coolest.

There are certain signal processing techniques made possible by the once-per-revolution signal that pertain only to steady state data. Two such techniques are ensemble averaging and minimum picking. Ensemble averaging will attempt to eliminate the random error associated with the data by tending to average the noise present in the signal to zero. A series of consecutive revolutions of steady state data
recorded at 85 percent N2 were averaged at each individual blade location. Each of the revolutions displayed little variation from the resulting averaged revolution, indicating minimal random error was present in the signal.

Since most spurious radiation produces erroneously high temperatures, minimum picking will tend to eliminate the bias error in the data. No large instantaneous spikes in the data were observed, so no minimum picking technique needed to be applied to the data. Comparison of the results of the two techniques will determine how much variation there is in the data taken. Any large variations in data can be attributed to glowing particles or spurious flames since these are the only instantaneous type errors. Since no significant variations in data were observed, errors due to flames and glowing particles were indeed minimal.

5.4 Analytical Model

Once the starting transient results were analyzed, a simplified model was developed in an attempt to analytically reproduce these results. It should be stated at the onset that the model presented is offered as only one possible explanation of the phenomena observed. The blade geometry is simplified and assumptions are made. For this reason, it is not intended to predict exact temperatures or temperature profiles but merely to show trends of the predicted transient for comparison purposes.

Since the blade is much longer than it is thick in the region of interest, conduction in the axial direction is ignored in the model to be presented. Only conduction from the centerline out to the exposed surface is considered. Therefore, the geometry of the blade is reduced to simply the thickness of the blade at a given axial location. A symmetrical boundary condition is imposed on the centerline of the blade. In practice, this will not
occur exactly at the centerline, but is a reasonable assumption given the intent of the model. The blade surface is subjected to convection from the gas flow as well as radiation to the surroundings. Blade geometry is such that the 60 percent suction side chord location radiates mainly to the pressure side of the neighboring blade. However, the trailing edge radiates to surfaces downstream of the high pressure turbine. For this reason, the surrounding temperature seen by the trailing edge was taken to be a certain percentage of that seen by the 60 percent chord location. In the case presented, 75 percent was used. This value was used because the temperature of the gas entering the low pressure turbine is approximately 75 percent of the gas temperature entering the high pressure turbine [3]. Appendix C contains a schematic of the model used as well as derivations of the energy equations used at each boundary.

A time history of the turbine inlet temperature was also needed. Knowing the trends of the ITT and the related maximum gas temperature, a reasonable profile was assumed. The profile used for this study is presented in Figure 32. Since the gas temperature is not known exactly, no accuracy would be gained by varying the film coefficient with temperature. Because of this, a film coefficient was assumed and was held constant throughout the transient. An average thermal conductivity of the blade was used and considered constant also.

A finite difference model employing the above conditions was solved numerically. Appendix D contains a listing of the code used. As with the starting transients obtained experimentally, only the 60 percent chord location and the trailing edge temperature histories are presented. Various cases were run to check the effect of varying some of the parameters that were assumed constant. As expected, all cases exhibited the same trends but the temperatures and lag times differed somewhat. The results of a typical case is shown in Figure 33. Values for the film coefficient and the thermal conductivity used in this case were 3000 W/m²K and 12 W/mK respectively. The thermal conductivity
Figure 32. Assumed Turbine Inlet Gas Temperature History
STARTING TRANSIENT TEMPERATURE HISTORY
APPROXIMATE FINITE DIFFERENCE SOLUTION

Figure 33. Approximate Finite Difference Solution of Starting Transient
value is the average value for the Inconel 100 blades over the expected temperature range. The plot shows the same trends as seen in the experimental results of the starting transients. The small temperature difference occurring as the transient approaches steady state is evidence that the effects of radiation are small. Though the effect will be somewhat greater during the transient than at steady state, this supports the conclusion that radiation is not the dominant mode of heat transfer during the transient. The effects of radiation should be most evident at steady operation as the blade approaches the free-stream temperature.

5.5 Temperature Gradients

The analytical model presented has indicated that the transient temperature profiles are dominated mainly by convection to the blade and the thermal capacity of the blade. The more massive 60 percent chord location increases temperature at a slower rate than the trailing edge when subjected to the same gas temperature. The overshoot in turbine gas inlet temperature causes high temperatures at the trailing edge resulting in large gradients. This overshoot in temperature is related to the inefficient operation of the compressor during the start phase, and the slow response time of the fuel control system. As the gas temperature is cooled to its steady value, the trailing edge is cooled at a faster rate than does the 60 percent chord location. This "reluctance" of the 60 percent chord location to release its stored energy results in an eventual temperature profile inversion. As the transient ends and steady operation occurs, the effects of the thermal mass become small. The effects of the radiation are likely at least partly responsible for the lower measured surface temperature of the trailing edge of the blade.
Each of the transients presented were seen to cause an increase in surface temperature gradients during the transient, followed by a decrease in the gradient as the engine approached steady operation. This represents a cycle in the thermally-induced stresses exerted on the blade. This thermal cycling results in low cycle fatigue effects that have been observed to add to the effects of creep strain. Since the low cycle thermal fatigue effects are related to temperature gradients during transients, accurate knowledge of transient temperature distributions is essential to determine effects of the transient on engine life.

The results indicate that starting transients cause the most severe gradients being on the order of 15.5°K/mm with very large gradients near the trailing edge of the blade. The gradients experienced during the deceleration transient were also large being on the order of 5.5°K/mm. These large gradients would likely result in large thermally-induced stress on the turbine blade. The least severe test in terms of temperature gradients was the acceleration transient. However, the acceleration presented was fairly "gentle", and thus, the gradients should not be severe. In contrast, wide range accelerations might produce more severe temperature gradients.

Since fatigue effects combine with those of creep strain, accurate knowledge of transient temperature distributions may lead to an improved prediction of engine life for a given engine mission. It is most convenient to calculate engine life and maintenance intervals in hours of operation. Therefore, it is desirable to relate the fatigue effects to equivalent operating hours under steady conditions that would result in similar damage due to creep. The ability of the pyrometer to detect temperature gradients under transient conditions represents a technology which can be used to more accurately analyze the factors and effects of thermally-induced low cycle fatigue on engine life.
6.0 Conclusions

The thermal dynamics of the suction sides of the first stage turbine blades of a JT15D-1 research gas turbine under transient conditions were investigated. Using a single strand InGaAs radiation pyrometer, the blades were viewed from approximately 60 percent chord to the trailing edge. Included in the study were starting, acceleration, and deceleration transients.

The starting transients were found to be the most severe in terms of both peak temperature and temperature gradients. The experiments revealed that a reversal in the chordwise temperature gradient was occurring during the starting transient. Initially, the trailing edge was heated quicker than was the more massive 60 percent chord location. This resulted in high temperatures at the trailing edge as well as large gradients. As the turbine inlet temperature and rotor speed approached their steady state value, the trailing edge became cooler than the 60 percent chord location. The observed transient temperature changes appeared to be the result of thermal response lag of the blade material, based on the results of the simple analytical model.

The gradients experienced during the deceleration transients were less severe than those for the start, but no temperature gradient inversions were observed. During acceleration transients, the gradients became only slightly larger than at steady operation, but two temperature profile inversions were observed.
It has been argued that both overshoots in temperature and large temperature gradients are contributing factors to low cycle fatigue. The results presented show that large temperature gradients are observed during the starting transients which would be associated with the most severe thermally-induced stresses. Other transients would contribute to the damage, but were observed to be less severe in this investigation. The demonstrated ability of the pyrometer to record transient temperature distributions appears to be a valuable addition to low cycle fatigue analysis and study.
7.0 Future Recommendations

Although some questions have been answered by this investigation, much work remains to be done. The first step could be to create a radiation model of the hot section of this engine. This would greatly aid in the substantiation of pyrometer output signals, which was the focus of a previous study.

The next area to be addressed is that of signal processing of the digitized data. Some work needs to be done to accurately correct spot averaging during the transition region of the waveform. That is, it may be possible to digitally determine realistic temperatures for the blade surfaces at the junction of adjacent waveforms. Also, dedicated signal processing circuits might be developed to provide real-time display of thermal gradient information. Applications of this type of circuit might include engine control and diagnostics.

Another area to be investigated might be that of modifying the simple analytical model presented. A more sophisticated heat transfer model could be developed to describe the acceleration and deceleration transients.

Finally, a finite element model of uncooled turbine blades, which incorporates the measured transient temperature distributions as boundary conditions, might be developed to analyze the thermally-induced stresses and related strains.
References


Appendix A. Calibration data

The rotor speeds and mean voltages presented in this appendix come from measurements taken during this investigation. The temperatures presented are taken from previous Rosemount tests which are summarized in a plot relating temperature as a function of speed. This plot is presented at the end of this appendix. An exponential curve is fit to these data using a least squares technique.

Start Number 1

The data used for this start are as follows:

<table>
<thead>
<tr>
<th>Rotor Speed (% N2)</th>
<th>Voltage</th>
<th>Temperature (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.8</td>
<td>0.065</td>
<td>822</td>
</tr>
<tr>
<td>87.6</td>
<td>2.562</td>
<td>1125</td>
</tr>
</tbody>
</table>

A curve fit of these data results in the following equation to map output voltages into surface temperatures in degrees Kelvin.

\[ T = 82.41 \ln (V) + 1047.29 \]
Start Number 2 and Deceleration Transient

The data used for this start are as follows:

<table>
<thead>
<tr>
<th>Rotor Speed (% N2)</th>
<th>Voltage</th>
<th>Temperature (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.2</td>
<td>0.080</td>
<td>811</td>
</tr>
<tr>
<td>74.6</td>
<td>0.564</td>
<td>955</td>
</tr>
<tr>
<td>81.6</td>
<td>1.360</td>
<td>1044</td>
</tr>
<tr>
<td>87.4</td>
<td>2.322</td>
<td>1122</td>
</tr>
</tbody>
</table>

A curve fit of these data results in the following equation to map output voltages into surface temperatures in degrees Kelvin.

\[ T = 91.12 \ln (V) + 1027.54 \]

The deceleration transient presented was taken during this run and thus, uses the same temperature function.

Start Number 3 and Acceleration Transient

The data used for this start are as follows:

<table>
<thead>
<tr>
<th>Rotor Speed (% N2)</th>
<th>Voltage</th>
<th>Temperature (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44.5</td>
<td>0.057</td>
<td>828</td>
</tr>
<tr>
<td>74.3</td>
<td>0.467</td>
<td>955</td>
</tr>
<tr>
<td>84.5</td>
<td>1.641</td>
<td>1083</td>
</tr>
</tbody>
</table>

A curve fit of these data results in the following equation to map output voltages into surface temperatures in degrees Kelvin.

Appendix A. Calibration data
\[ T = 76.06 \ln (V) + 1034.74 \] 

The first acceleration transient was captured during this run and thus, uses the same temperature function.
Figure A1. Calibration Curve For Mean Blade Temperature Versus Rotor Speed

Appendix A. Calibration data
Appendix B. Curve-fit Procedure

A least squares approximation curve-fit technique was employed using a Lotus spreadsheet for data manipulation. Temperature data from approximately the 65 percent chord to the 95 percent chord location of a single blade were isolated. The region utilized is smaller than the viewable portion of the blade, and reflects the fact that data from the transition region are not considered accurate. These data were then entered into the least squares program that returned the coefficients of the polynomial that best described the data. It was determined that a third order polynomial described the temperature data very well. The temperature data used to generate Figure 16 was used in the following example. The approximate analytical temperature, in degrees Kelvin, as a function of the chordwise location on the blade was determined to be:

\[ T \approx 964.08 + (7.844)X + (1.467)X^2 - (0.1276)X^3 \]

where \( X \) is the chordwise distance in mm from approximately the 65 percent chord location. A comparison of the actual temperature data and approximate temperature function are presented in Figure B1. Figure B2 shows the percent error of the curve-fit as a function of percent chord.
COMPARISON OF CURVE–FIT AND EXPERIMENTAL DATA

Figure B1. Comparison of Curve-fit Results and Temperature Data
VARIATION BETWEEN CURVE–FIT AND EXPERIMENTAL DATA

\[
\frac{\text{CURVE–FIT} - \text{EXPERIMENTAL}}{\text{EXPERIMENTAL}} \times 100
\]

Figure B2. Percent Difference Between Curve-fit and Temperature Data
Appendix C. Finite Difference Equations

A simplified one-dimensional finite difference model was presented to analytically predict the surface temperature trends of the starting transients. This appendix presents the details of the finite difference model. A schematic of the heat transfer model is presented. From this schematic, it is seen that there are three different types of nodes used in the model. These are the centerline node, the interior nodes, and the outer surface node. Derivations of the governing energy equation and the related finite difference equations for each type of node are also presented. A listing of the code used to solve the finite difference equations is presented in the following appendix.
Appendix C. Finite Difference Equations
The finite difference approximation is:

\[ \frac{\partial T}{\partial t} \approx \frac{\left( T_{n+1}^p - T_n^p \right)}{\Delta t} \]

\[ \frac{\partial T}{\partial x} \approx \frac{\left( T_{n+1}^p - T_{n-1}^p \right)}{\Delta x} \]

\[ \frac{k}{\Delta x} \left( T_1^p - T_0^p \right) \approx \frac{\rho C_p \Delta x}{2\Delta t} \left( T_{n+1}^p - T_n^p \right) \]

\[ T_{0+1}^p \approx T_0^p + \frac{2k\Delta t}{\rho C_p (\Delta x)^2} \left( T_{n+1}^p - T_n^p \right) \]

Define the Fourier Number as:

\[ \frac{2k\Delta t}{\rho C_p (\Delta x)^2} = \frac{\alpha \Delta t}{(\Delta x)^2} = F_o \]

The resulting equation is:

\[ T_{0+1}^p \approx 2F_o T_1^p + (1 - 2F_o) T_n^p \]
INTERIOR NODES

\[ m=n+1 \]

\[ \Delta X \]

\[ m=n \]

\[ m=n-1 \]

One-Dimensional Heat Transfer Equation:

\[
\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\]

The finite difference approximation is:

\[
\frac{\partial^2 T}{\partial x^2} \approx \frac{(T_{n+1}^p + T_{n-1}^p - 2T_n^p)}{(\Delta x)^2}
\]

\[
\frac{\partial T}{\partial t} \approx \frac{(T_{n+1}^p - T_n^p)}{\Delta t}
\]

\[
\frac{1}{\alpha} \frac{(T_{n+1}^p - T_n^p)}{\Delta t} \approx \frac{(T_{n+1}^p + T_{n-1}^p - 2T_n^p)}{(\Delta x)^2}
\]

The resulting equation is:

\[
T_{n+1}^p = T_n^p + \frac{\alpha \Delta t}{(\Delta x)^2} (T_{n+1}^p + T_{n-1}^p - 2T_n^p)
\]
The finite difference approximation is:

$$-kA \frac{\partial T}{\partial x} + hA (T_\infty - T_N) + \varepsilon \sigma A (T_{\text{sur}}^4 - T_N^4) = \rho C_p V \left( \frac{\partial T}{\partial t} \right)$$

The finite difference approximation is:

$$\frac{-k}{\Delta x} (T_N^p - T_{N-1}^p) + \varepsilon \sigma (T_{\text{sur}}^4 - T_N^4) + h (T_\infty^p - T_N^p) \approx \frac{\rho C_p \Delta x}{2\Delta t} (T_{N+1}^p - T_N^p)$$

The Biot number is defined as:

$$\text{Bi} = \frac{h \Delta x}{k}$$

The resulting equation is:

$$T_{N+1}^p \approx (1 - 2F_o - 2\text{Bi}F_o) T_n^p + \frac{2\varepsilon \sigma \Delta t}{\rho C_p \Delta x} (T_{\text{sur}}^4 - T_N^4) + 2F_o (\text{Bi} T_\infty^p + T_{N-1}^p)$$
STABILITY CRITERION

The stability criterion imposed on the numerical solution is one that requires the coefficient of $T_n$ to be greater than or equal to zero. The equation associated with the outer surface will result in the most stringent criterion and thus will be used in the determination of the time step. The equation was seen to be:

$$T_{n+1}^p \approx (1 - 2F_o - 2BiF_o) T_n^p + \frac{2\varepsilon_\sigma \Delta t}{\rho C_p \Delta x} \left( (T_{sur}^p)^4 - (T_n^p)^4 \right) + 2F_o (BiT_{\infty}^p + T_{N-1}^p)$$

Rearranging terms in the equation will result in the following coefficient for $T_n$:

$$\left( 1 - 2F_o - 2BiF_o - \frac{2\varepsilon_\sigma \Delta t}{\rho C_p \Delta x} T_n^3 \right)$$

Substituting for the Biot and Fourier numbers leads to the following equation for the maximum allowable time step.

$$\Delta t \leq \frac{1}{\left( \frac{2\alpha}{(\Delta x)^2} + \frac{2h_\alpha}{k \Delta x} + \frac{2\varepsilon_\sigma \alpha}{k \Delta x} \right)}$$

It is evident that the time constant is dependent on the surface temperature. To avoid problems in this analysis, a maximum temperature of 1250 degrees Kelvin was assumed and a time step calculated according to this temperature.
Appendix D. Finite Difference Program

THIS PROGRAM WILL SOLVE FOR THE SURFACE TEMPERATURE AT THE 60 PERCENT CHORD LOCATION AND TRAILING EDGE OF THE BLADE AS MODELED BY THE FINITE DIFFERENCE APPROXIMATION

REAL T(2,100), TEMP(50,2)
INTEGER NODES

DECLARE ALL VARIABLES

WIDTH = 0.0022

WIDTH IS DISTANCE FROM CENTERLINE TO BLADE SURFACE

ALPHA = 5.0E-6
K = 6.74
H = 3000.0
SIGMA = 5.67E-8

ASSUME AN EMISSIVITY OF 85 PERCENT
EPS = 0.85

INPUT NODAL INFORMATION

WRITE (5,*) , ENTER THE NUMBER OF NODES TO BE USED'
READ (5,*) NODES
DELX = WIDTH / (FLOAT(NODES) - 1.0)

CALCULATE MAXIMUM TIME STEP FOR STABILITY CRITERION

BIOT = H * DELX / K
FO = 0.5 /(1.0 + BIOT)
DELTAT = 1.0/((2.0*ALPHA/DELX/DELX) + (2.0*H*ALPHA/K/DELX) + & (2.0*SIGMA*EPS*ALPHA/K/DELX*1.9777E9))

WRITE(5,10) DELTAT
10 FORMAT(//5X,THE MAXIMUM TIME STEP IS ',F8.6)

ENTER NEW TIME STEP AND CALCULATE NEW FO

WRITE(5,*) , ENTER THE TIME STEP DESIRED'
READ(5,*) DELT
IF (DELT.GT.DELTAT) THEN
WRITE(5,*) 'TIME STEP TOO LARGE -- ENTER A NEW VALUE'
GO TO 5
BEGIN LOOP TO CALCULATE AT TWO LOCATIONS

DO 1000 ICNT = 1,2
   FO = ALPHA * DELT / (DELX * DELX)

ENDIF

BEGIN LOOP TO CALCULATE AT TWO LOCATIONS

DO 1000 ICNT = 1,2
   FO = ALPHA * DELT / (DELX * DELX)

ITIM = INT(1.0 / DELT)
DO 20 N = 1, NODES
   T(1, N) = 300.0
   TEMP(1, ICNT) = T(1, NODES)
20 CONTINUE

CALL INITIALIZE TEMPERATURE ARRAYS

CALL TEMPERATURES AT NEXT TIME STEP

DO 100 JJ = 1, 30
   DO 40 J = 1, ITIM
      CALL CALCULATE FREE STREAM TEMPERATURE
      TIME = FLOAT(JJ) - 1.0 + FLOAT(J) * DELT
      IF (TIME.GE.0.0.AND.TIME.LE.6.0) THEN
         TINF = 300.0 + 384.42 * TIME - 38.431 * TIME * TIME
      ENDIF
      IF (TIME.GT.6.0.AND.TIME.LE.20.0) THEN
         TINF = 1642.324 - 82.439 * TIME + 2.0807 * TIME * TIME
      ENDIF
      IF (TIME.GT.20.0) THEN
         TINF = 855.5828 - 1.4885 * TIME
      ENDIF
      TSUR = 1.0 * TEMP(JJ, ICNT)
      IF (ICNT.EQ.2) TSUR = 0.75 * TEMP(JJ, ICNT)
      CALL CALCULATE AT INSULATED BOUNDARY
      T(2, 1) = (1.0 - 2.0 * FO) * T(I, I) + 2.0 * FO * T(1, 2)
      CALL CALCULATE TEMPERATURES AT INTERIOR NODES
      DO 30 L = 2, NODES - 1
         T(2, L) = FO * (T(L, L - 1) + T(1, L + 1)) + (1.0 - 2.0 * FO) * T(1, L)
30 CONTINUE
      CALL CALCULATE TEMPERATURES AT FREE SURFACE
      CONST = 2.0 * DELT * SIGMA * EPS * ALPHA / K / DELX
      DUM = CONST * ((TSUR**4) - (T(I, NODES)**4))
      T(2, NODES) = DUM + (1.0 - 2.0 * FO - 2.0 * BIOT * FO) * T(1, NODES)
      & + (2.0 * FO * (BIOT * TINF + T(I, NODES - 1))
      DO 35 LL = 1, NODES
         T(L, LL) = T(2, LL)
35 CONTINUE
      CALL PRINT OUT SURFACE TEMPERATURES
      (2, NODES)
   40 CONTINUE
100 CONTINUE
1000 CONTINUE

CALL PRINT OUT SURFACE TEMPERATURES

Appendix D. Finite Difference Program
DO 60 M = 1,31
   TIME = FLOAT(M)-1.0
   WRITE(5,50) TIME,TEMP(M,1),TEMP(M,2)
50 FORMAT(10X,3F20.6)
60 CONTINUE

C WRITE VALUES TO SAS FILE

C
DO 80 ICNT = 1,2
   DO 80 M = 1,31
      TIME = FLOAT(M)-1.0
      WRITE(9,70) TIME,TEMP(M,ICNT),ICNT
70 FORMAT(1X,2F20.6,5X,I3)
80 CONTINUE
END
Vita

The author was born on February 20, 1964, in Baltimore, Maryland, where he resided until completion of High School. He graduated from Mount Saint Joseph's High School in June of 1982 and began undergraduate studies at Virginia Polytechnic Institute and State University the following September.

He obtained his Bachelor of Science degree in Mechanical Engineering, Cum Laude, in June 1987 at VPI & SU in Blacksburg, Virginia. Graduate studies began in July 1987, and he has recently accepted a position with Pratt and Whitney Government Engine Business in West Palm Beach, Florida.

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