ABSTRACT
With the cost of maintaining a fleet of gas turbine engines continuing to rise, there is a greater need to develop methods to diagnose engine deterioration and identify faulty engine components quickly and efficiently. The Structures, Materials and Propulsion Laboratory of the National Research Council of Canada (NRC) has established a program to develop and evaluate various diagnostic techniques. The effort is aimed at investigating the effects of typical in-service faults on engine performance characteristics. An important aspect of the engine test program is the evaluation of non-intrusive sensors to accurately measure gas turbine performance.

Using infrared thermography, the measurement of temperature is accomplished non-intrusively using the infrared radiation spectra. This instrumentation provides an indirect measurement of temperature and does not interfere with the flow field being measured. The temperature patterns can be used to determine engine health, and identify possible fault conditions within the hot section of the engine.

This paper describes the project objectives, the experimental installation, and the results of the performance evaluations. A description of the infrared thermography system, and the data reduction and analysis systems used to convert infrared light into temperature profile contours is given.

INTRODUCTION
The measurement of thermodynamic parameters within a gas turbine using conventional methods such as thermocouples is hampered by the fact that the probes are large and bulky, due to the harsh test environment. These relatively large rakes of thermocouples interfere with the measurement of gas temperature because the probe influences the flow field and therefore disrupts the temperature variations in the vicinity of the probe. This interference cannot be calculated out of the measured data, and is thus carried as some unknown bias error from the true temperature.

Generally speaking, the temperature measurements made in a gas turbine engine, such as the Allison T56, are made using single point thermocouples. In some locations within the engine, as many as 20 thermocouples are used to calculate an average gas temperature. However, the T56 engine has extremely high spatial temperature variations, as high as 120 °C. This makes it nearly impossible to measure a true average station temperature to any accuracy. Any particular thermocouple could be located in a hot or cold spot and give a misrepresentative value. Aside from placing 200 thermocouples in the engine at each desired location (which would interfere with the flow field as mentioned above), the most suitable solution is to use an infrared thermography system (Kaplan, 1989, 1990). Such a system is capable of indirectly measuring over 122,880 temperature measurements (1 per screen pixel), thus providing the capability to completely map the gas...
temperature variations in the exhaust plane (MacLeod, et al., 1993).

Using the infrared system to detect changes in the thermal patterns of the exhaust gas, a method to diagnose turbine faults can be established. Faulty fuel nozzles, turbine erosion and blade damage or any other fault which significantly affects the thermal pattern can be detected by comparison to a healthy pattern.

EXPERIMENTAL INSTALLATION

To properly assess the capabilities of an infrared imaging system to measure temperature in the exhaust of a gas turbine engine, a sophisticated test set-up, with specialized instrumentation was required. A description of the engine, and instrumentation used for this assessment is included to illustrate the installation used for this project.

Engine Description

The test vehicle for this thermal imaging study was an Allison T56-A14LFE single spool turboprop engine from a CP-140 Aurora patrol aircraft. The T56 engine has a fourteen stage compressor, with interstage bleed valves, a six can combustor, and a four stage turbine.

The single shaft is coupled to a reduction gearbox mounted forward of the compressor. For the NRC tests, power was transmitted through the gearbox to a flywheel and a Froude waterbrake dynamometer. A schematic diagram of the engine test configuration is shown in Figure 1.

Infrared Instrumentation

The infrared imaging system used in this project was the Hughes Model 7300 Thermal Video System, which consists of an imager, an image processor, a power supply and a monitor. The imager converts the infrared radiation into electronic signals. The electronic signals are interpreted by the image processor and the results are displayed on the monitor.

Thermal Imager

The thermal imager contains four parts, the optics, the scanning system, the infrared detector and the associated electronics. The optics transmit the infrared radiation to the scanning system, which reflects the radiation to the infrared detector. The electronics then transmit the electronic signals from the infrared detector to the image processor.

The infrared detector consists of 30 elements is constructed of mercury cadmium telluride (HgCdTe), and thus responds to infrared radiation in the 3.2 to 5.6 micron spectrum. The detector changes resistance when irradiated. This effect is used to create a voltage variation across a bias resistor that is proportional to the intensity of the radiation. The detector is cooled to 200 K by a solid state "Peltier effect" refrigerator, to improve the signal-to-noise ratio.

An internal silicon lens triplet, 4x telephoto lens and an optical window make up the optics of the system. The silicon lens triplet focuses the infrared radiation on the detector, thus setting the focal distance of the imager. The telephoto lens gives the imager a smaller field of view, enabling it to image an object that is further away than would be possible without the lens. The optical silicon window protects the imager from the exhaust of the engine. Absorption of infrared light in the 3-5 micron band is approximately 1% for the silicon window.

The scanning system consists of an eight-sided reflective surface "scan wheel". The rotation of the "wheel" scans the image from left to right. Each side of the "wheel" is tilted differently, which allows the thirty elements in the detector to give 240 lines of discrete infrared data. The "scan wheel" rotates 30 times per second, to produce 30 images per second. Between each image the radiation from a reference surface internal to the imager is reflected to the detector elements, which restores the image data to near-ambient temperature. The temperature of this surface is measured with an internal thermocouple and is sent to the processor to aid in interpreting the signals from the detector elements.

The 30-element detector array is biased and ac-coupled into three separate 10-channel hybrid amplifiers. Each of these amplifiers consists of 10 low noise variable gain pre-amplifiers, 10 dc restore switches and 10 variable gain post-amplifiers followed by a 10-channel analog.
multiplexer. The three multiplexers are connected serially, which multiplexes all 30 channels into one high speed channel. This signal is then buffered through a high speed opamp/driver and transmitted to the processor. The gain and dc-restore level for the amplifier are used by the processor to locate the desired temperature range of observed radiation within the active voltage range of the analog to digital converter (ADC) in the processor.

Image Processor
The image processor contains four parts, the imager interface, the scan conversion memory, the video output module and the central processing unit.

The thermal imager interface buffers, amplifies and quantifies the data from the imager into digital data. The quantifier is a high speed, 8-bit analog-to-digital converter operating at 12.4 MHz. The digital data is processed through a set of input look-up tables which correct for differences in detector responsivity and convert the digital data into temperature data for a given temperature display range.

The video output module is synchronized with the scan conversion memory transfers so that TV output does not interfere with the transfers. The module combines the image from the scan conversion memory with overlays created by the central processing unit such as a colour bar and various messages such as the temperature at a certain point or area, the date and time and the emissivity value that the imaging unit is using to calculate temperatures. The video output unit uses output look-up tables to assign a different colour or grey scale to each intensity value. It then outputs the video in three formats, RS-170 black and white, analog RGB, and NTSC colour. The black and white channel was connected to the VHS VCR, the RGB channel was connected to the video monitor, and the NTSC colour channel was unused.

VCR and Frame Grabber Boards
The images created by the Hughes Thermal Video System were recorded by a VHS video recorder (VCR) connected to the black and white outputs during the engine run. The images could then be played back at a later time to be analyzed. A VHS VCR was used because of ease of use and the availability of compatible hardware and software components. An IBM compatible computer using the 386 processor and a math coprocessor was used to analyze the thermal images. The complete component configuration is shown in Figure 2.

![Figure 2: Component Configuration](image)

Image Processing
The process of reducing the infrared image data gathered by the camera and recorded by the VCR (some 122,000 points at 30 frames per second) and reducing it to a manageable and understandable form is a multi-step process.

In the first step, the images are averaged. Averaging is done on a pixel by pixel basis for the entire image. During the averaging process, statistical information on standard deviation is gathered for each pixel, to determine image repeatabilities as a function of time. One hundred frames are averaged to give one image (Figure 3). Three of these averaged images are acquired for each power setting during the run from 300 independent frames. The repeatability or tolerance of the images as a function of power setting is determined from comparison of the three individual images. Irrelevant data such as probes, struts, the wall of the exhaust duct and the inner exhaust cone are masked out of the image. The resulting image then contains only the image data from the plane of interest itself (Figure 4).

Various statistics are calculated from these images, eg. average temperature and the centroid of the image. These statistical values were found to be stable with time, and repeatable over the power range of the engine, and thus...
were investigated as useful tools in the detection of implanted faults.

Figure 3: Original Averaged Image

Figure 4: Masked Averaged Image

For example, the centroid of the image was found to be very repeatable. The horizontal position of the centroid showed a standard deviation of no more than 0.15 pixels out of 512 for the same power setting, for 12 test runs. The vertical position of the centroid had a standard deviation of approximately 2 pixels. Although this centroid analysis can detect unusual hot or cold spots with as low as a 10°C average temperature change, the results may be ambiguous. This single statistic cannot determine the location of the unusual spot, as a cold spot on one side of the vertical centre line would have the same effect as a hot spot on the other. The mean temperature would change. This simple approach will not address multiple spots, which may keep the image "in balance" and not change the position of the centroid at all. Other methods were investigated to improve the detection of unusual patterns.

To reduce the size of the data set and remove the empty space at the centre of the image due to the inner exhaust cone, the image is "unwound." After masking, all that remains in the image is the turbine flow annulus. This annulus is transformed to create a rectangular block of data. An example of the unwound image is shown in Figure 5.

Figure 5: Unwound Masked Averaged Image

To visualize this transformation, imagine a line extending from the centre of the ring to the outside edge. The line is swept from 0 to 360 degrees in one degree increments. At each angle the pixels that the line crosses are recorded as a column of data in the rectangular image. Only the pixels from the inside edge of the ring to the outside edge are recorded. The resulting rectangular image has 360 columns each representing a different degree of rotation. These unwound images are not only much smaller in size than the original, but polar coordinates are easily obtained from these images, as the x axis represents circumferential location and the y axis represents the radius.
Figure 6: Image Processing Steps
The image processing steps are illustrated in Figure 6. Each of the averaged images is unwound and all available unwound images from the same power setting are then processed to determine an average image and a standard deviation image. The average and standard deviation are calculated on a pixel by pixel basis, which creates images which represent the average and standard deviation of each pixel. From these two images maximum and minimum tolerance images are created. Two standard deviations are used, as 95% of all pixels should then be between the two tolerance images.

The two tolerance images are used to determine any unusual pixel values in a test image. The maximum tolerance image is subtracted from the test image. This operation leaves the pixel values that are greater than the maximum tolerance. The test image is subtracted from the minimum tolerance image. Any pixel values below the minimum tolerance will be left by this operation. Two additional images are then created. One contains any unusual hot spots and the other contains any unusual cold spots. A program was written to detect these spots in an image by threshold edge detection. First the image is scanned circumferentially for spots. Every second line in the image is scanned for pixel values above zero. The centres of "groups", of three or more consecutive values above zero, are stored in an array. The resulting array is then scanned for vertical groupings. Two groups are considered as on spot, if their centres are within ten degrees of each other. The resulting group centres from this operation are the centres of the spots in the image and are reported in polar coordinates. Sample results corresponding to the grouping in Figure 6, numbered from left to right, are shown in Table 1 (distances are measured from the top of image down).

Table 1: Hot/Cold Detection Results

<table>
<thead>
<tr>
<th>No.</th>
<th>Dist.</th>
<th>Angle</th>
<th>No.</th>
<th>Dist.</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66</td>
<td>105°</td>
<td>1</td>
<td>90</td>
<td>44°</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>201°</td>
<td>2</td>
<td>60</td>
<td>135°</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>287°</td>
<td>3</td>
<td>68</td>
<td>242°</td>
</tr>
<tr>
<td>4</td>
<td>66</td>
<td>297°</td>
<td>4</td>
<td>32</td>
<td>347°</td>
</tr>
</tbody>
</table>

The three dimensional representation of the data (Figure 6), is most useful, with the two dimensional distance dimensions and the third dimension being temperature.

TECPLOT™ was used to produce these figures, which allows for variation of the angle of view, or perspective. Either a mesh representation or a shaded surface can be produced. The light source location in the surface representation can be specified and a pseudo colour image of the original can be overlaid on the surface or mesh. The viewpoint can be changed. The results are readily imported into other applications or printed out.

FAULT DETECTION METHODS

The techniques developed to scan and process the images can be used to detect differences from one image to another, when one image represents a healthy engine, and the second image represents an engine with a particular fault. The two fault detection methods described here are the movement of centroids, and hot/cold spot relocation detection. To date, these techniques have only been tested using simulated faults. Verification of these methods, with real implanted engine faults is the next phase of the program, and is scheduled to begin in early 1994.

Centroids

The centroids of the images have been found to vary very little within the same power setting over different runs. The horizontal position varies by only ±0.15 pixels out of 512 for the same power setting, while the vertical position varies ±2 pixels out of 480.

Sample faults were randomly implanted in the image at small areas, changing the average temperature of the location by ±12°C. In one case, the fault was a cold spot centred half way down the turbine blade at an angle of 314°. It represented an average temperature change in the spot of 11°C, which would simulate a faulty combustor fuel nozzle. This fault varied the horizontal position of the centroid by 1 pixel.

Hot and Cold Spot Relocation Detection

The second fault detection method involves detecting the relocation of hot and cold spots between the healthy and faulted images.

Figure 7 is an example of this process used to find hot and cold spots in a sample "fault" image. The average image was calculated from four different runs of the engine with the engine producing the same amount of torque. Three hundred images were averaged from each run and the resulting images from each run were then averaged.
The standard deviation image was determined using this average image and three sets of one hundred images averaged from each run, giving twelve sets of data. Table 2 illustrates the locations of the faulted image, corresponding to Figure 7:

Table 2: Faulted Image Locations

<table>
<thead>
<tr>
<th>Hot Spots</th>
<th>Cold Spots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>Angle</td>
</tr>
<tr>
<td>54</td>
<td>15°</td>
</tr>
<tr>
<td>62</td>
<td>61°</td>
</tr>
<tr>
<td>58</td>
<td>164°</td>
</tr>
<tr>
<td>60</td>
<td>208°</td>
</tr>
<tr>
<td>48</td>
<td>255°</td>
</tr>
<tr>
<td>56</td>
<td>322°</td>
</tr>
</tbody>
</table>

These are the positions of the implanted hot and cold spots. A comparison of the new positions of the hot and cold spots relative to their normal locations in the healthy image (Table 1), was then used to verify that a relocation has taken place thus indicating that a fault had been detected. A generated library of actual fault versus hot/cold spot relocation is then used to identify the actual fault. The generation of such a library for a particular engine type, can take a considerable amount of time to generate, especially if multiple faults are considered. In particular, certain combinations of faults may cancel each other out in terms of relocation of the hot/cold spots.

SUMMARY AND CONCLUSIONS

An infrared imaging system to be used to measure temperatures in a gas turbine engine has been assembled and tested. Software was developed to process, analyze, store and print out the thermal images. Using infrared thermography, the measurement of temperature is accomplished non-intrusively using the infrared radiation spectra. This instrumentation provides an accurate measurement of temperature and does not interfere with the flow field being measured. Such a system is capable of measuring temperature at over 120,000 locations simultaneously, thus providing the capability to completely map the temperature profiles in the exhaust plane.

Methods to detect the location and movement of hot/cold spots within the thermal image of the engine exhaust plane can be used to ultimately detect, non-intrusively, the health
of the engine hot section, and diagnose faulty components at a relatively early stage in deterioration.

RECOMMENDATIONS
It is recommended to proceed with efforts to expand the capabilities of the infrared imaging techniques to measure temperature in the exhaust plane of a gas turbine. More specifically, the proceed with the installation of cooled, flush mounted infrared probes to measure temperatures inside the turbine and combustor components should be investigated to provide additional information on upstream components.

REFERENCES
