THERMOGRAPHIC NONDESTRUCTIVE EVALUATION OF THE SPACE SHUTTLE MAIN ENGINE NOZZLE

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ABSTRACT

The methods and results presented in this summary address the thermographic identification of interstitial leaks in the Space Shuttle Main Engine nozzles. A highly sensitive digital infrared camera is used to record the minute cooling effects associated with a leak source, such as a crack or pinhole, hidden within the nozzle wall by observing the inner "hot wall" surface as the nozzle is pressurized. These images are enhanced by digitally subtracting a thermal reference image taken before pressurization, greatly diminishing background noise. The method provides a nonintrusive way of localizing the tube that is leaking and the exact leak source position to within a very small axial distance. Many of the factors that influence the inspectability of the nozzle are addressed; including pressure rate, peak pressure, gas type, ambient temperature and surface preparation.

INTRODUCTION

The nozzles of the Space Shuttle Main Engines (SSME) consist of over one thousand tapered Inconel coolant tubes brazed to a stainless steel structural jacket (Figure 1). Liquid hydrogen flows through the tubing under high pressure, from the aft to forward end of the nozzle, to maintain a thermal balance between the rocket exhaust and the nozzle wall. Three potential problems occur within the SSME nozzle coolant tubes as a result of manufacturing anomalies and the highly volatile service environment. These problems include poor or incomplete bonding of the tubes to the structural jacket, leaks into the interstices between the tubes and jacket, and leaks into the inner "hot wall" or "flame" side of the nozzle. Identification of hot wall leaks can be accomplished with the application of a liquid leak check solution to the inner surface of the nozzle while it is pressurized with helium gas. X-ray techniques are utilized for characterizing the condition of the braze line. The identification of interstitial leaks between the tubing and structural jacket is not as well defined and has historically been the most problematic.

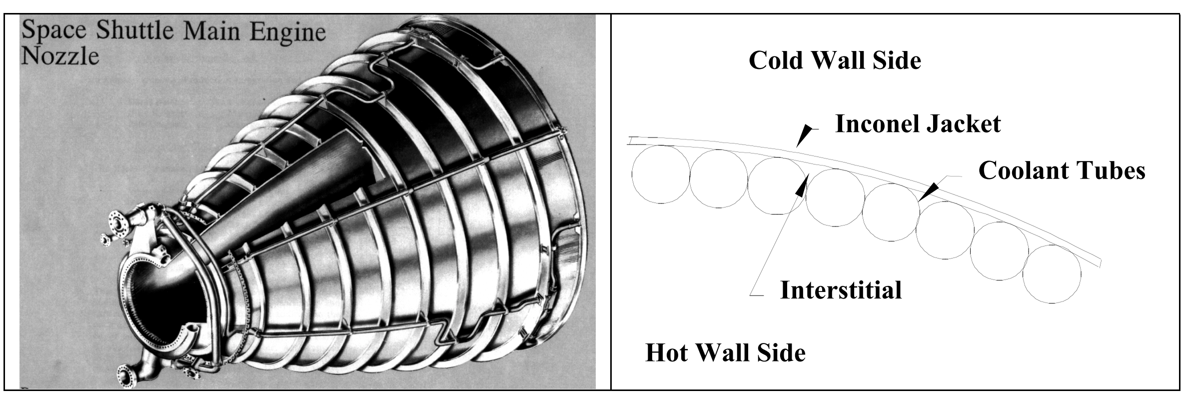


Figure 1. SSME Nozzle.

If a small leak occurs between the tubing and structural jacket the gas flows down the interstices and vents harmlessly out the aft end of the nozzle. As the leak grows though the potential exists for the nozzle to fail by pushing a section of tubing into the hot exhaust path which in turn can cause them to rupture. If the rupture is severe enough the engine will be starved of hydrogen, and thus become oxygen rich. This at best reduces the thrust of the engine and in the worst case can endanger the launch vehicle.

Interstitial leaks are often found by first identifying which tubes are leaking by the application of a liquid leak check solution where the interstices vent at the aft end of the nozzle. Then, through a trial and error approach, tubes are cut open and an angioplasty device inserted to block off a specific region of the tube. A boroscope is then used to look at the inside of suspect tubes but leak source identification is difficult due to their typically microscopic size. With the suspect tube blocked from the pressure circuit, pressure is reapplied and the interstices leak checked again. This process is repeated until the source is located or all suspect tubes are tested. If the leak is severe enough and it cannot be found, then the nozzle must be pulled from service. Identification of which tube is leaking is difficult due to manifolding between interstices through braze line voids, resulting in the opening and inspection of many tubes that were previously undamaged. Also, when the leak originates from multiple sources it is difficult to tell if the angioplasty device has isolated a leaking tube.

BACKGROUND AND THEORY

Leaks in pressurized systems can be some of the simplest and easiest defects to identify, or they can be extremely challenging to locate. A low pressure leak check using a liquid bubble solution applied to the vessel with a brush or bottle is usually adequate if the vessel is geometrically simple and has unrestricted in access. With this method, not only can the leak be located, the leak rate can often be determined by observing the bubble formations produced in the leak check solution. Frequently though, applications exist where the leak source is inaccessible due to structural complexity. In these situations it may be possible to measure the effects of the leak on the physical condition of the structure. For example the leak may produce an audible, or ultrasonic, "hiss". For practical leak rates the magnitude of the "hiss" from the leak source may be very small making it difficult to identify over the interference from background noises. Another alternative is to record the temperature change associated with the expansion of a gas though the leak source. Here, even if the vessel has a complicated geometry, restricted assess, chemical sensitivity, or a large area, an infrared video camera may be useful for identifying, locating, and characterizing leaks. The temperature change due to a hidden leak may be observed on the outer surface of the structure provided a direct heat path is present and the structural material has an appropriate thermal conductivity. Also, infrared video cameras can inspect large areas very rapidly and with out contacting the component.

In real systems, with hidden leaks, the leak geometry is usually unknown and unpredictable making it difficult to uniquely define the physical phenomena active at the leak. The leak may act like a throttle valve, a nozzle, or a combination of both. Also, transient effects may be present including the pressurization of the gas already in the vessel, causing work on the trapped gas. For the detection of a leak, these effects do not usually need resolution or understanding. A local temperature change is simply detected. However, an understanding, or as a substitute empirical data, may be needed to locate and approximate leak rate. A discussion of some of these effects, some competing, follows.

The Joule-Thompson effect is classically exhibited in flow through a throttling restriction or valve. The flow through the restriction causes no work to be done and is considered adiabatic. For real gasses the temperature can either increase or decrease depending on the type of gas, temperature, and pressure. For each given gas there is an inversion temperature at which no temperature change occurs for the throttling process. This inversion temperature is a weak function of temperature. Below the inversion temperature the gas heats and above the gas cools upon throttling. This critical temperature is below standard conditions for hydrogen (202 K) and helium (25 K) and above standard conditions for nitrogen (621 K), air (603 K), argon (723 K), and CO_2 (1500 K).

A leak may occur in a region that has a flow cross-section that geometrically resembles a converging-diverging nozzle. An example of this is a cooling tube that has a crack, or small hole, that opens into another confined region. For the converging-diverging nozzle and compressible gasses, supersonic flow is possible if the internal pressure of the contained gas is (for air) greater than 1.893 times the absolute outside pressure[1]. Under normal atmospheric conditions this is a tank pressure of about 90 kPa (13 psig). If the flow at the opening of the pressure vessel is sonic then for air the temperature drop may be as low as -29 °C for a tank temperature of 20 °C. If the geometry acts as a converging-diverging nozzle the temperature drop away from the leak will be even larger if the flow is supersonic and will be a major factor in the detected temperature change.

The Joule-Thompson and compressible gas nozzle effects previously mentioned are usually predicated upon steady-state flow. There may be good reasons not to use a steady state condition during inspection. An example of a transient inspection will be presented later. For complex geometries during rapid pressurization, gasses contained in confined regions of the vessel may be compressed by the pressure increase. Work is then done on this confined slug of gas by the incoming gas. This causes a decrease of volume of the slug and a corresponding temperature increase.

As an illustration of how leaks behave thermally, a series of tests were performed on a single 5.08 mm (0.20 inch) diameter tube with a 0.127 mm (0.005 inch) hole. The tube was painted flat black, giving it an emissivity of approximately 0.85 and imaged with a high resolution (256 x 256 pixel) high sensitivity (0.025 °C per A/D output bit value) infrared camera. The tube was capped on one end and connected to a K-bottle containing the test gas. Four gasses in all were tested including nitrogen, argon, helium and carbon dioxide. The pressure regulator on the K-bottle was set to deliver 40 psig and was valved to provide that pressure to the tube in less than 2 seconds. The tube was purged with each test gas prior to pressurization to ensure that the tube contained only that test gas. The infrared imager was set to acquire one unpressurized reference image then one frame every 1/60 of a second for 10 seconds.

The images shown in Figure 2 demonstrate the thermal behavior of each gas as it escapes through the hole in the side of the tube. Two images are given for each gas type, the source peak temperature frame and the end frame. A time-temperature plot is also given depicting the transient thermal behavior of each gas. By referring to the time-temperature plot one can easily see how each gas has its own unique thermal response. First, and most obvious, note that when the nitrogen, argon and carbon dioxide were used an increase in temperature occurs when pressure is first applied as opposed to when the helium was used which begins to cool immediately. Secondly, notice that the nitrogen, argon and helium pressurized tubes all showed some cooling after the pressure had been applied for a long period of time, whereas the carbon dioxide pressurized tube returned to room temperature.

BUBBLE LEAK CHECK APPLICATION TO THE SSME NOZZLE

The circumferential location of interstitial leaking can be identified by the application of a liquid leak check solution in the openings where the interstices vent out the aft end of the nozzle, while the tubes are pressurized. The nozzle is pressurized with helium gas to 25 psig and the liquid solution is squirted into the interstitial vent. When the leak solution bubbles at the nozzle aft end, the leak is classified as described in Table 1, and if it is severe enough actions are taken to fix the leak. Due to cross linking of the interstices many interstitial vents may bubble when only one tube is actually leaking, making it difficult to not only locate which tube or tubes are leaking but also to determine the magnitude of the leak. If the leak is seen to manifold across several tubes it is impossible to tell if all the tubes are leaking at the degree seen at the bottom of the nozzle or if the leak is cross-linking from a single source with sufficient flow to create all the indications.

Table 1. Flow rate

Class	Flow rate (scim)	Description
1	> 2	Foaming
2	2 to 50	Bubbling
3	50 to 100	Strong bubbling that burst and re-form
4	> 100	Blowing (Bubbles cant persist)

scim = Standard cubic inch per minute

One method for isolating the defect tube and determining where along its length the leak source is located is to cut open the suspect tubes one at a time, insert an angioplasty device to close off a portion of the tube, and then repressurizing the system. In theory by using this method the leak can be isolated to a given tube by moving the angioplasty device along the length of the nozzle. Although this method requires no specialized equipment (other than the angioplasty device) many inspection induced repairs must be made to cover all the holes cut into the tubes for the angioplasty device. Also, due to the additional heating required by the hot wall repair, new cold wall "interstitial" leaks may be produced in the process of trying to find one leak.

Another method is to boroscope the inside of the tubes and to visually locate the leak. Since the boroscope can only cover a finite tube length and since it is impossible to identify which tube (to the right or left of the identified interstitial) is leaking, many extra and undesired repairs must be made to fix just one leak. Also, due to the small size of the fracture required to generate a critical leak, the defect may not be detectable through the boroscope.

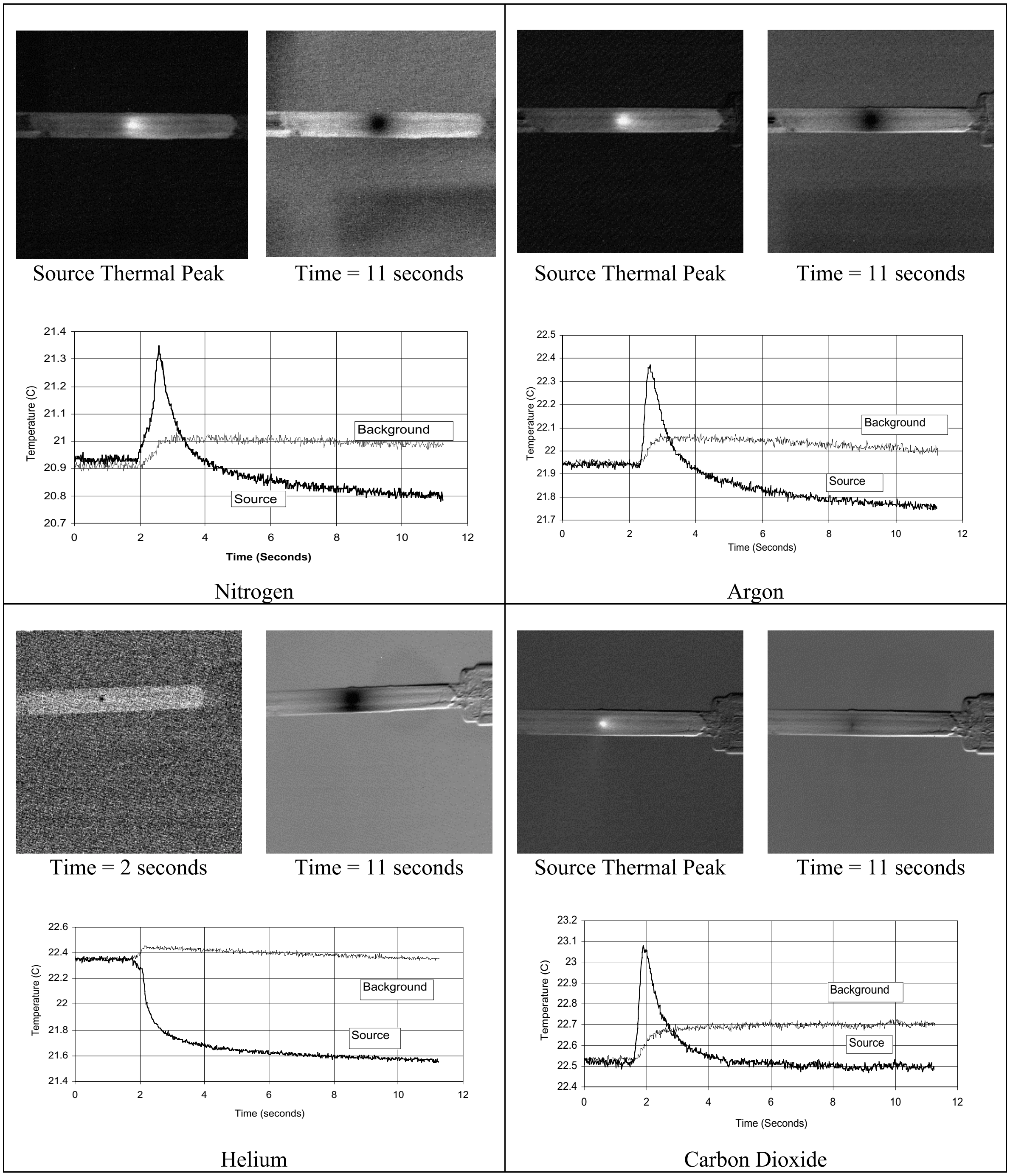
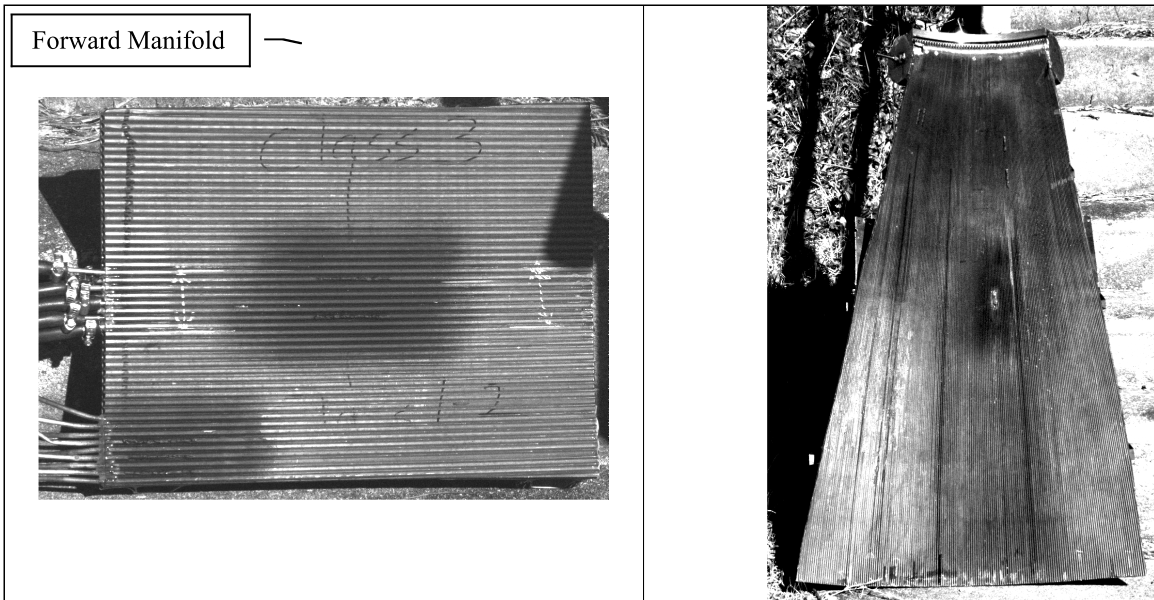


Figure 2. Thermal behavior of leaks.

For the work described herein an Amber Radiance 1 camera with 25 mm lens controlled by Thermal Wave Imaging software was utilized. Inspections and tests were performed on sections cut from the forward and aft end of a scrap nozzle (Figure 3). The aft end section was fitted with a pressure manifold which permitted eight tubes to be pressurized simultaneously. The forward nozzle section, with its existing manifold intact was plumbed so that all the tubes were pressurized simultaneously. These sections were initially inspected using both a standard liquid leak check at the vented interstices and thermographically and determined to be free of any leaks. Artificial leaks were then manufactured in each nozzle segment to represent both class II and class III leaks. These artificial defects were fabricated by cutting open the tubing on the hot wall side of the nozzle, then puncturing the tube into the interstitial region and finally resealing the tube hot wall through a typical welding repair operation. During the reweld operation the hot wall surface of the tubes had to be cleaned with a wire brush which left the surface shiny, greatly limiting the thermographic inspection capability. Many methods were investigated to dull the surface of the nozzle, increasing the local emissivity to 0.8 or greater, without damaging the fragile nickel coating of the tubes. A water washable plat black spray paint was found to work well thermographically, but due to traces of sulfur, was deemed not acceptable from a chemical compatibility standpoint. Additional work is ongoing to find a paint that will be acceptable thermographically and chemically.



Aft End Segment **Forward End Segment**

Figure 3. Nozzle segments.

The artificially damaged panels were then thermographically inspected with various flow rates, peak pressure levels, ambient temperatures, gas temperatures and with a range of gasses to bound the detection capability. The pressurization rate was found to have a strong influence on the ability to detect the leak with higher pressurization rates yielding the best thermal response for most gasses (Figure 4). When the pressurization rate is too slow the thermal signature is lost due to the highly diffusive nature of the tubing material. In general it was found that a pressure transient less than 8 seconds (>5 psi/sec) was required for adequate thermal contrast of the defect to the background. The exception to the rule was found for carbon dioxide which was unaffected by pressurization rate and could be performed with ramp times in excess of 40 seconds. The only factor limiting the ramp time for carbon dioxide being the in-plane conductivity of the nozzle itself.

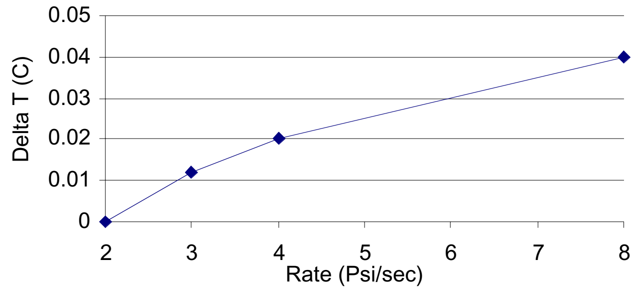


Figure 4. Thermal response as a function of pressurization rate for nitrogen.

The maximum pressure was found to have a large effect on thermal detectability of the leak. For example, as shown in Figure 5 the thermal response, as determined by computing the maximum difference between the IR camera values in the defect region and acreage region, increases nearly linearly with increasing pressure. The thermograms in Figure 6 clearly demonstrate the need for higher pressures to be able to uniquely identify the leak source. In the figure, the Class 3 leak appears as a large cool (dark) region just above the upper repair patch. The Class 2 leak is not visible at 172 kPa (25 psig) yet is clearly visible above the lower repair patch at 310 kPa (45 psig). The limiting factor for the magnitude of the pressure used was controlled by safety related issues.

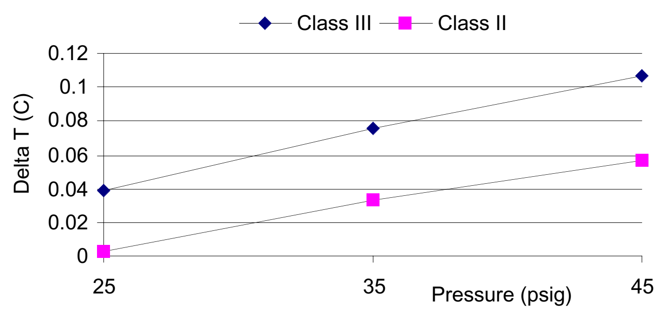


Figure 5. Thermal response at three pressures.

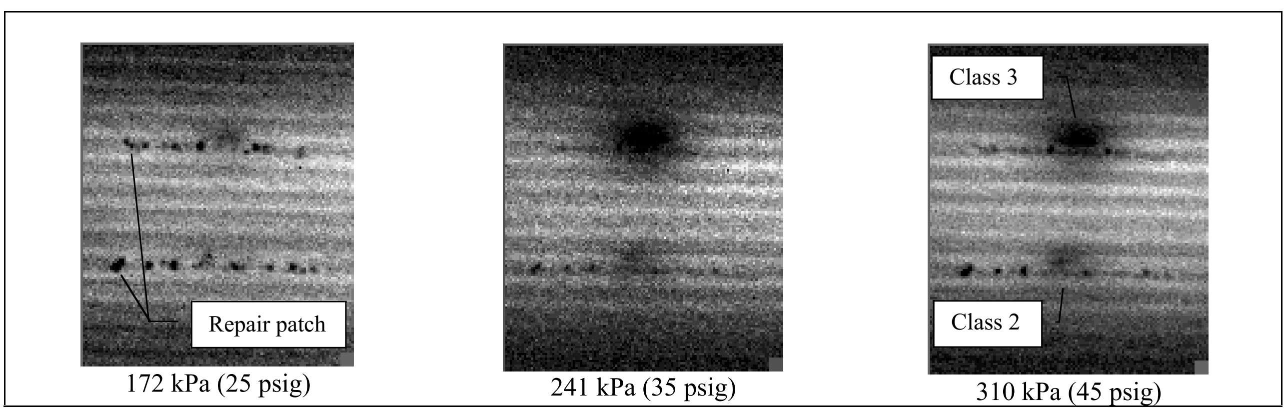


Figure 6. Thermograms at three pressure levels.

When the leaks were inspected using different pressurizing gas types it was found that the thermal response not only varied with gas type but also with the location of the leak along the nozzle length. For example, when helium was used to pressurize the aft nozzle segment no indication was present yet on the forward end of the nozzle it gave the best response (Figure 7).

Tests were also conducted to determine if the blockage associated with a repair could produce a false call for a leak. Calculations showed that the largest flow rate expected for a nozzle leak check would be below 12.2 meters/sec (40 feet per second). Two weld repair restrictions were fabricated by opening the tubing, applying braze to the bottom of the hole and then welding the tubes closed. Nitrogen gas was flowed through the tubes and its velocity measured with a hot wire anemometer at a distance of 3.175 mm (1/8 inch) from the tube opening. The tests demonstrated (Figure 8) that the flow rate threshold for thermal detection of a 50% area restriction is above 12.2 meters/sec. That is, below 12.2 meters/sec the signature of the restriction is to small for repeatable detection. Based upon these findings it is highly unlikely that a restriction alone would create a false positive signature during a thermal inspection of the nozzle.

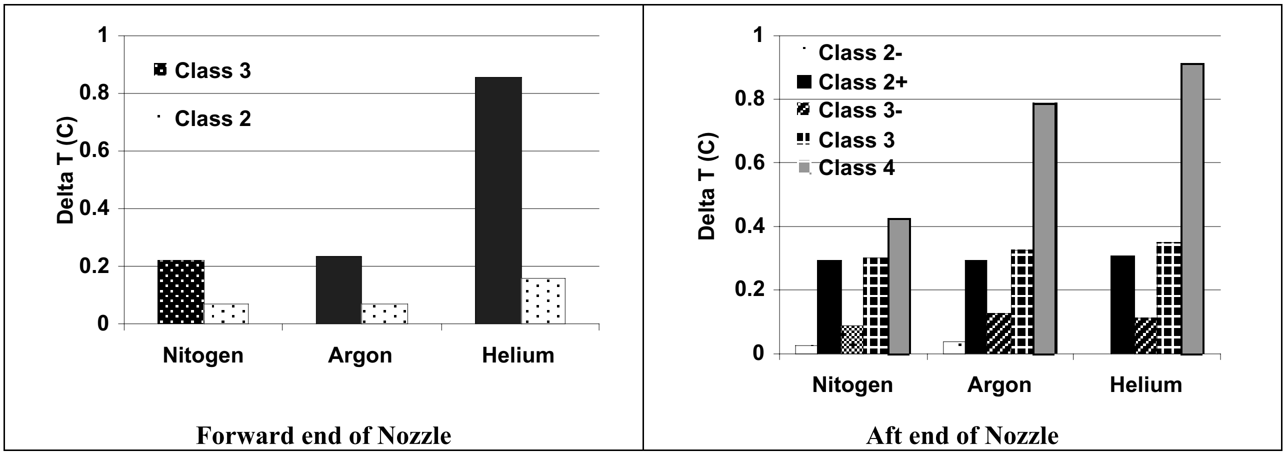


Figure 7. Effect of gas types on thermal leak signature.

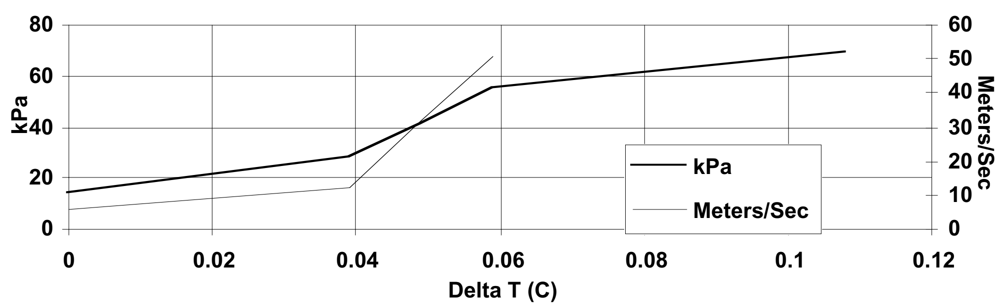


Figure 8. Flow Blockage Analysis.

APPLICATION POTENTIAL TO A FULL NOZZLE

The logistics of performing a thermographic inspection on a full nozzle were also investigated. Safety of the inspection crew and the hardware was the primary factor driving the development of the inspection procedures. To that end it was desired to limit the amount of time spent by the inspecting personnel inside the nozzle, minimize the number of pressure cycles and restrict the movement of the nozzle.

As shown in Figure 9 the nozzle is positioned vertically on three stands which support it approximately three feet off of the shop floor and a small personnel lift is placed under the nozzle cone. An initial liquid leak check is performed on the aft end of the nozzle and any leaking interstices identified. A band of tubes extending 20 tubes to either side of the leak zone is then marked at the aft end of the nozzle and reference foil markers are temporarily attached to the outermost tubes of the suspect region on six inch intervals along the length of the nozzle. A foil number is then placed next to every other marker to permit identification of camera position. Regions in the inspection area are visually inspected for hot wall leaks and prior repair work. Hot wall leaks are first repaired. Then all repairs are sprayed with an flat black paint.

The thermography camera is mounted to a pan and tilt unit on a tripod and an external focus unit is attached to the cameras lens. Starting at either end, each marked region of the nozzle is then thermographically monitored as the pressure inside the tubing is ramped and then vented. Any leak signature is marked with a foil tape and classified based upon its thermal intensity. Once the entire length of the nozzle has been inspected measures are taken to repair the defective tube and the inspection is repeated.

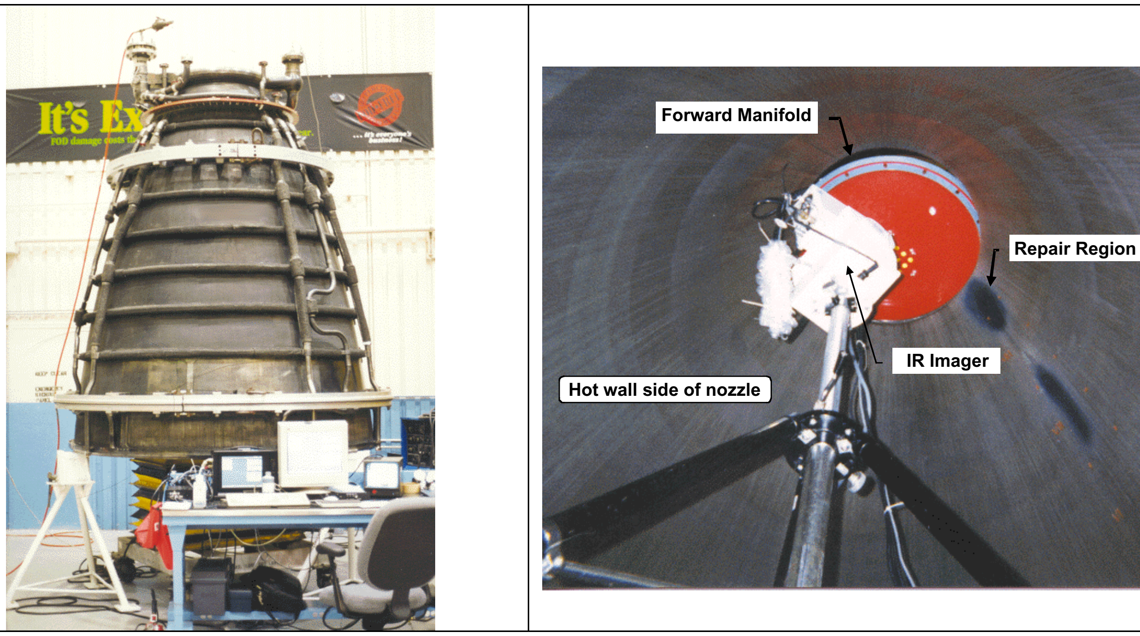


Figure 9. Thermal imager inside Nozzle.

CONCLUSIONS

The limitations and requirements for thermographic identification of interstitial leaking of the Space Shuttle Main Engine Nozzle have been addressed. With a standard thermographic test procedure established for the nozzle it should be possible to reliably locate and quantify the nature of interstitial leaking in the SSME nozzle. From these results it has been determined that the following conditions must be met to ensure adequate confidence that all critical level class II leaks are detected. First, the flow rate of gas into the nozzle must be sufficiently high to permit the transient thermal signature of the leak to be detected before it is lost to thermal conduction. Rise times to peak pressure less than 8 seconds greatly inhibit defect resolution. Next, the greater the maximum pressure reached during the pressurization the better the ability to detect a leak. Although the liquid leak check is performed at 25 psig it was found that for the best thermal response pressures of at least 40 psig were required. Carbon dioxide gas was found to give the best thermal indications of a class II or greater leak throughout the nozzle. At the forward end of the nozzle Helium was found to also work well, while at the aft end of the nozzle, either Argon or Nitrogen was found to work satisfactorily. A gas temperature slightly below ambient was required to get the desired thermal gradient and an ambient temperature between 70 °F to 90 °F was required. Optically, it was determined that the spatial resolution of the camera system must be able to uniquely identify individual tubes and the infrared imager needed to have a thermal resolution of at least 0.025 °C/Level. Finally, a surface emissivity of 0.8 or greater was required to allow measurement of the thermal gradient produced by the leak.

ACKNOWLEDGMENTS

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REFERENCES

1. Mechanical Engineering Reference Manual, Eighth Edition, Michael Lindeburg.