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SPACE SHUTTLE MAIN ENGINE COMPUTED TOMOGRAPY APPLICATIONS*

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ABSTRACT

For the past 2 yr, the Rocketdyne Division of Rockwell International, with the support of the Marshall Space Flight Center, has been evaluating the potential applications of computed tomography to the fabrication and overhaul of the Space Shuttle Main Engines. Application tests were performed at various government and manufacturer facilities with equipment produced by four different manufacturers. The hardware scanned varied in size and complexity from a small temperature sensor and turbine blades to an assembled heat exchanger and main injector oxidizer inlet manifold. The evaluation of capabilities included the ability to identify and locate internal flaws, measure the depth of surface cracks, measure wall thickness, compare manifold design contours to actual part contours, perform automatic dimensional inspections, generate 3-D computer models of actual parts, and image the relationship of the details in a complex assembly. The capabilities evaluated, with the exception of measuring the depth of surface flaws, demonstrated the existing and potential ability to perform many beneficial Space Shuttle Main Engine applications.

INTRODUCTION

The Computed Tomography (CT) effort at Rocketdyne began in 1987 with a special 1-yr task assignment from National Aeronautics and Space Administration Marshall Space Flight Center (NASA-MSFC) to evaluate current state-of-the-art industrial CT and its potential as a nondestructive test method for Space Shuttle Main Engine (SSME) hardware. Due to the very promising results of the initial task, a follow-on 1-yr task was assigned to continue evaluating the application of CT to the SSME hardware and to better define the capabilities and limitations of CT. As various applications were evaluated, the results highlighted another potential application. As a result, CT has, potentially, a much greater use on SSME hardware than initially expected.

This report contains an overview and highlights of the CT SSME application evaluations since 1987.

APPLICATIONS

TURBINE BLADES

Turbine blades were the first actual SSME hardware scanned with CT. The purpose of the evaluation initially was to determine whether a single Digital Radiography (DR) mode scan could replace our current film radiography, which requires eight exposures to inspect the various thicknesses of the blade material. This effort was very successful. It was determined that the CT system was able to locate all of the casting flaws that were detectable by the conventional method. Additionally, CT could distinguish between actual flaws and grain solidification patterns and locate microshrinkage that was undetected previously. Figure 1 shows a CT image of turbine blade casting microshrinkage and a 50X photograph of a metallographic cross section at the same location.

To evaluate the modeling capability, a turbine blade was scanned in 152 CT slices. These raw CT data were transferred to Rocketdyne's CAD-Computer Vision system. Figure 2 shows the initial 3-D model of the turbine blade and Fig. 3 shows the transparent model of the fir tree area containing microshrinkage porosity.

Although not initially considered as an application, results appeared to indicate that the CT system could perform dimensional inspections of the turbine blades. The system was calibrated using blades with known dimensions. The blades to be measured were then scanned in both the CT mode and DR mode as required to image the area to be measured. The dimensions were then taken by manually placing the cursors at the dimension end points and the system then calculated the distances. Figures 4, 5, 6, 7, and 8 show the various images of a turbine blade and the dimensions taken. The dimensional accuracy was found to be within 50.8 µm (0.002 in.) of the conventional measurements. It is believed that, when the CT software to automate the internal flaw detection and dimensioning is completed, the turbine blade inspection time will be reduced from the current 4 h per blade to approximately 4 min.

The turbine blade CT scanning was accomplished on a General Electric XIM system located in the GE NDE Systems and Services facility in Cincinnati, Ohio.

*This work was performed under Contract NAS8-40000 with NASA-MSFC in Huntsville, Alabama.

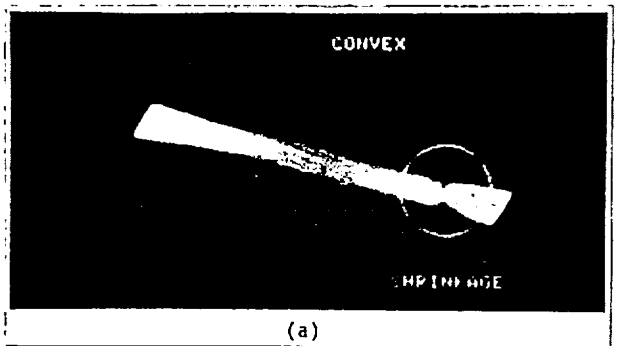

Figure 1a. CT Slice of Turbine Blade Showing Shrinkage and Metallographic Section at the Same Location

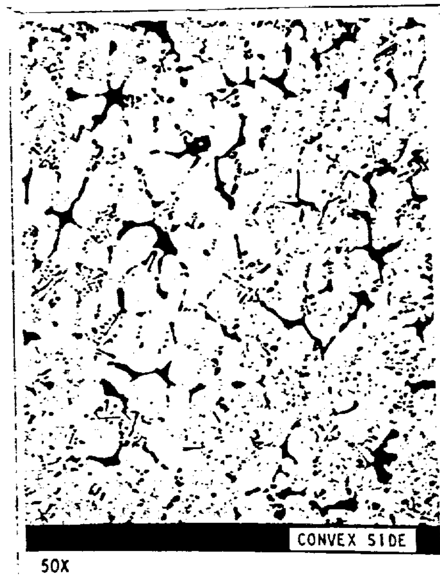

Figure 1b. CT Slice of Turbine Blade Showing Shrinkage and Metallographic Section at the Same Location

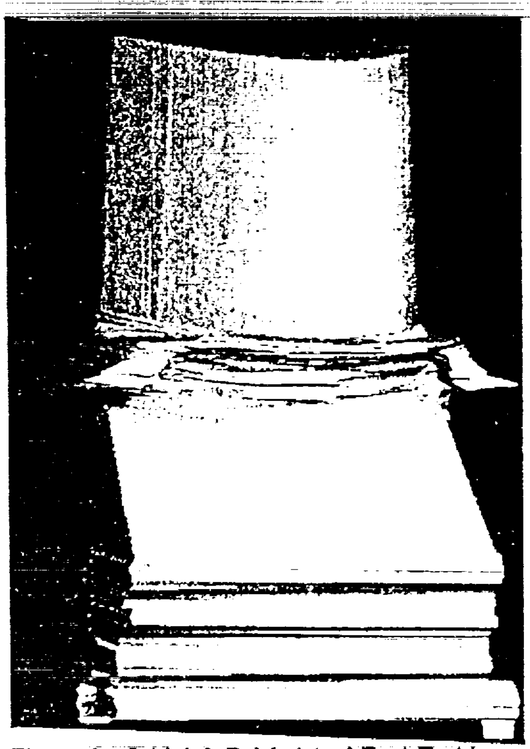

Figure 2. Initial 3-D Model of Fuel Turbine Blade on CAD/CAM System

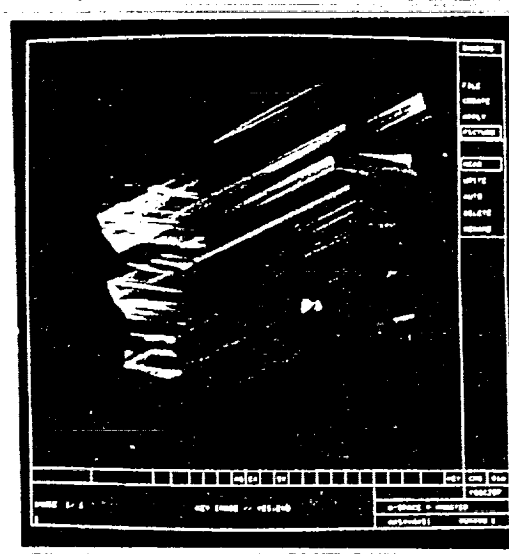

Figure 3. 3-D Model of the Fir Tree Area Containing Microshrinkage Porosity on CAD/CAM System

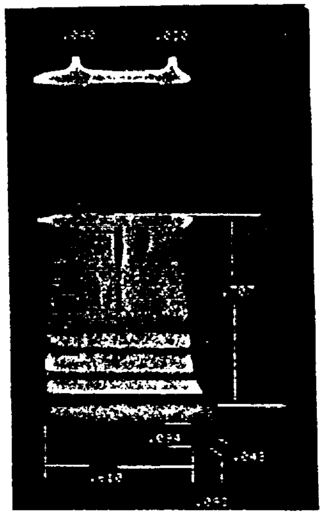

Figure 4. Digital Radiograph of Turbine Blade Used for Dimensional Measurements

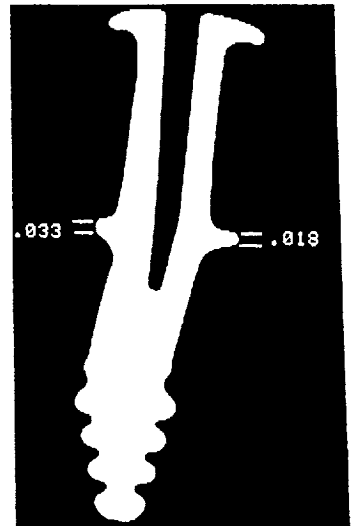

Figure 5. Tomograph Through Blade Vertical Axis With Platform Measurements

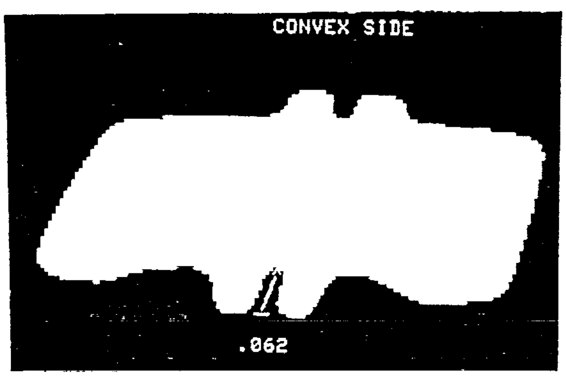

Figure 6. Tomograph Through Blade Shank Showing Damper Pocket Depth

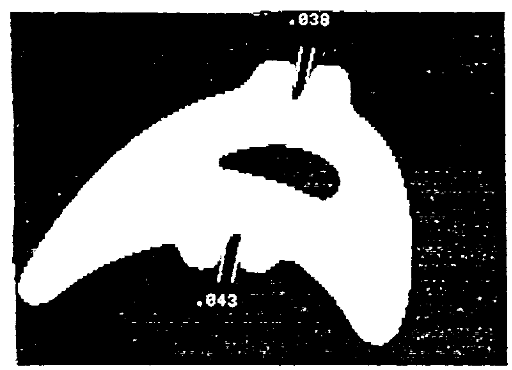

Figure 7. Tomograph Through Shank Showing Damper Pocket Widths

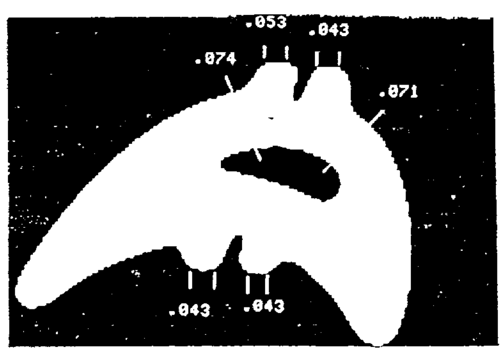

Figure 8. Tomograph Through Shank Showing Wall Thicknesses and Damper Pocket Sidewall Thicknesses

TEMPERATURE SENSOR

A sketch of the SSME hot gas temperature sensor is shown in Fig. 9. The active part of the sensor is the element, which consists of a 17.78-µm- (0.0007-in.-) dia platinum (Pt) wire wound around an aluminum oxide covered Pt tube and then covered with a Pt tubular cover. The spacing between the windings of the element is nominally 63.50 µm (0.0025 in.). The element is 1.52 mm (0.060 in.) dia and is installed in the sensor body, which is approximately 6.35 mm (0.250 in.) dia with a 1.27-mm (0.050-in.) wall. The sensor body is machined from Inconel 625 high nickel alloy.

One sensor developed an intermittent shorting condition during an engine test. Engineering believed that the failure might be caused by the element winding spacing being less than required, which allowed adjacent windings to touch. An attempt was made to identify a nondestructive test method to measure the element spacing prior to any disassembly of the part. Conventional radiographic and microfocus methods were unable to penetrate the element's Pt enclosure.

Inspection using CT was then attempted. The sensor was inspected by Scientific Measurement Systems, Inc., using their Model 101B CT scanner located in their Austin, Texas, facility. A 420-kV source was used to operate the system in the DR mode. Various columnator arrangements were tried until a combination was found to produce a spatial resolution of 12.20 µm (0.0005 in.), necessary to image the windings. Figure 10 shows the high-resolution DR image of the element windings. The spacing between the windings was then measured by making an opacity (density) trace through the windings, as shown in Fig. 11. The individual peaks in the trace correspond to the element wires. The results of the dimensional analysis of the wire spacing is shown in Table I. The accuracy of the measurements is ±2.54 µm (0.0001 in.). Spacings between the windings were found to be correct and, therefore, probably eliminate winding shorts as the source of the problem.

WELDED MANIFOLD PROFILE MEASUREMENT

The Rocketdyne Robotic Welding Development Group requested that CT be applied to measure the weld mismatch and profile on the sample assembly being used to qualify robotic welding for use on the SSME main injector oxidizer inlet manifold. Figure 12 shows a sketch of the assembly. The stress department was also concerned about the amount of distortion to the manifold shape that may have occurred as a result of the welding. The assembly was scanned in the CT laboratory at NASA-Kennedy Space Center. A CT scan was performed through the vertical centerline of the inlet flange. Figure 13 shows the CT image, and Fig. 14 shows

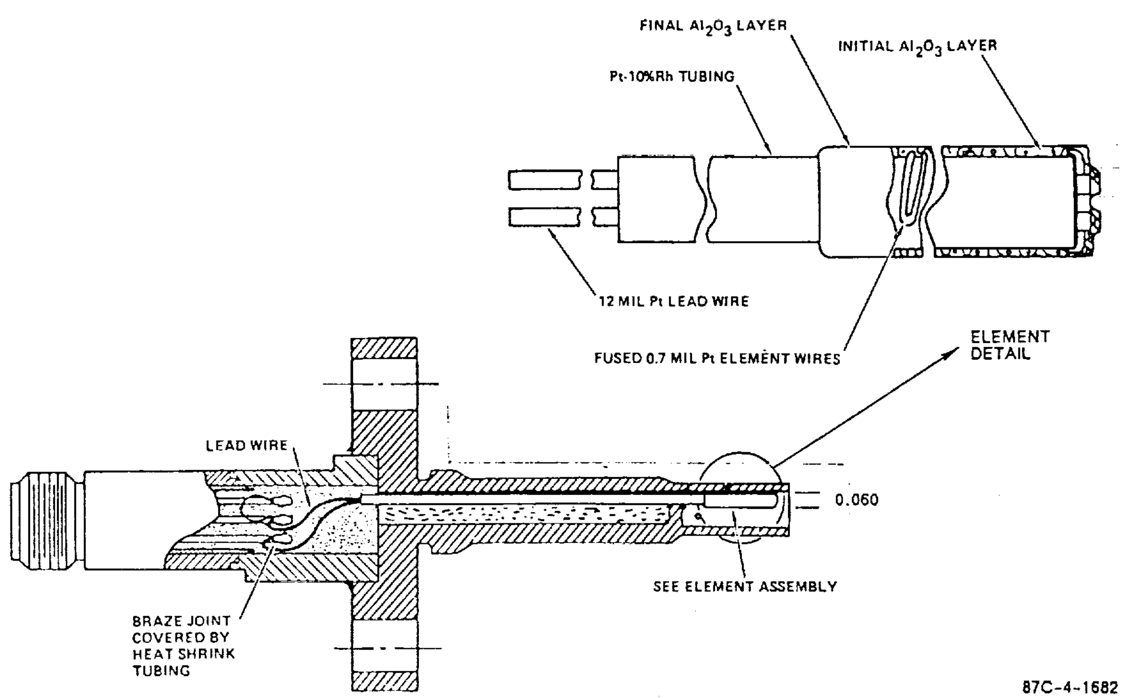

Figure 9. Temperature Sensor Sketch and Element Details

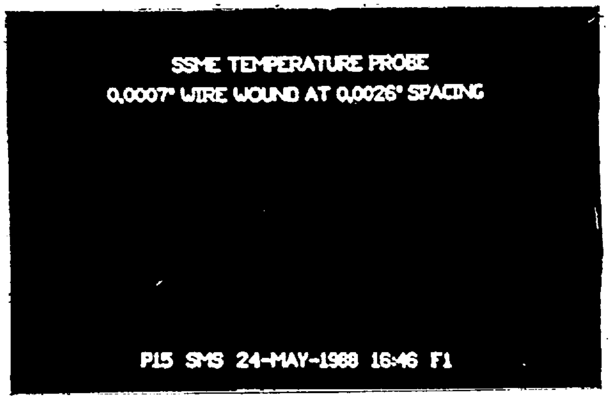

Figure 10. High Resolution DR Image of Element Showing Windings

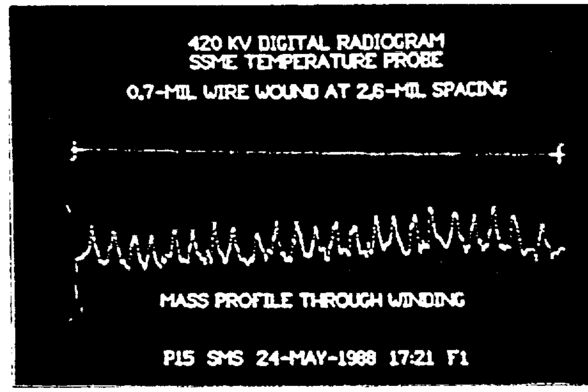

Figure 11. Opacity Scan Through Windings Used to Measure Spacing

Table I. Spacings Between Windings

Interval	Spacing	Interval	Spacing
1	77.978 µm = 0.00307 in.	12	69.342 µm = 0.00273 in.
2	72.644 µm = 0.00286 in.	13	72.644 µm = 0.00286 in.
3	63.754 µm = 0.00251 in.	14	74.168 µm = 0.00292 in.
4	81.280 µm = 0.00320 in.	15	66.294 µm = 0.00261 in.
5	63.500 µm = 0.00250 in.	16	70.612 µm = 0.00278 in.
6	77.470 µm = 0.00305 in.	17	57.150 µm = 0.00225 in.
7	65.278 µm = 0.00257 in.	18	87.376 µm = 0.00344 in.
8	86.614 µm = 0.00341 in.	19	70.612 µm = 0.00278 in.
9	69.088 µm = 0.00272 in.	20	67.310 µm = 0.00265 in.
10	70.612 µm = 0.00278 in.	21	70.104 µm = 0.00276 in.
11	68.072 µm = 0.00268 in.	22	101.600µm = 0.00400 in.

the enlarged detail of one of the two weld joints. Figure 15 shows the cross section reduced to a profile outline. It was determined that this CT-generated profile could be overlaid on the CAD profile data and used by the stress engineers to evaluate the presence and extent of any distortion of the manifold.

HEAT EXCHANGER ASSEMBLY

A heat exchanger assembly removed from an SSME was chosen to evaluate the capability of CT to image and measure details within a complicated assembly. Figure 16 shows a sketch of the heat exchanger assembly. The outer bowl is an Inconel 718 forging with an average thickness of 19.05 mm (0.750 in.). The liner is Inconel 903-formed sheet material 2.29 mm (0.090 in.) thick. The primary tube is 4.83 mm (0.190 in.) dia 316 CRES with 317.5 µm (0.0125 in.) wall, and the secondary tubes are 9.53 mm (0.375 in.) dia 316 CRES with 0.71 mm (0.028 in.) walls. The scans shown were made on an ARACOR system during its acceptance testing at Hill Air Force Base. The scans were made using a 2-MeV source and a scan time of 135 s. Figure 17 shows a CT slice through the assembly, including the threaded studs that mount one of the engines turbopumps. Figure 18 shows a CT section through the most critical area of the heat exchanger; i.e., primary tube weld RS008812 3 (see Fig. 16). This heat exchanger had been removed and scrapped due to known thinning of the tube wall in this weld area. Microfocus radiography had been used to locate and estimate the thinning. It was believed that the 317.5 µm (0.0125 in.) nominal wall thickness had been reduced to 152.4 µm (0.006 in.) on one side of the tube. A series of eight scans was made along the cursor line shown in Fig. 18 with the first and last scan through the opposite tube walls and the remaining scans spaced equally across the tube diameter; approximate scan spacing was 0.635 mm (0.025 in.) (see Fig. 19).

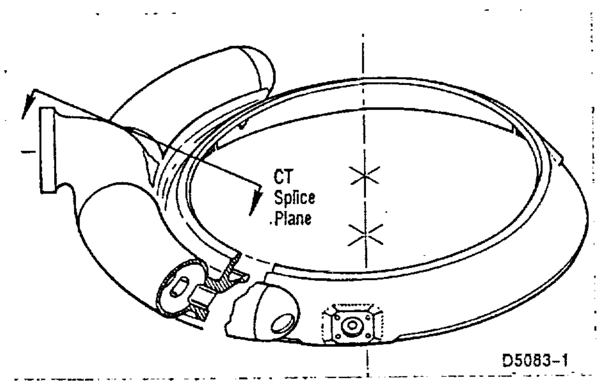

Figure 12. SSME Main Injector Manifold Assembly

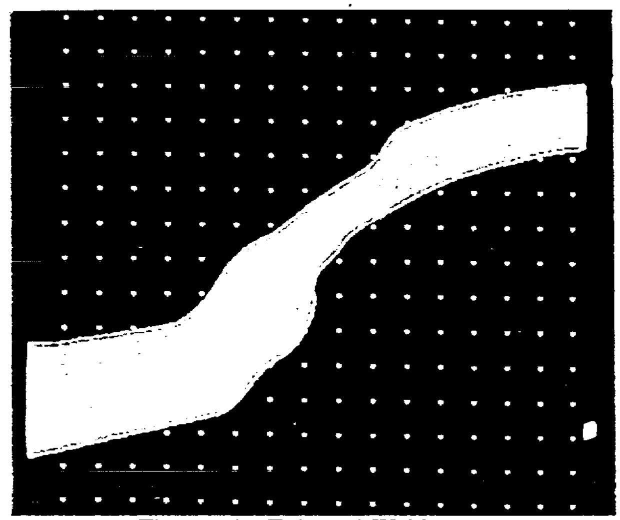
Figure 14. Enlarged Weld Area

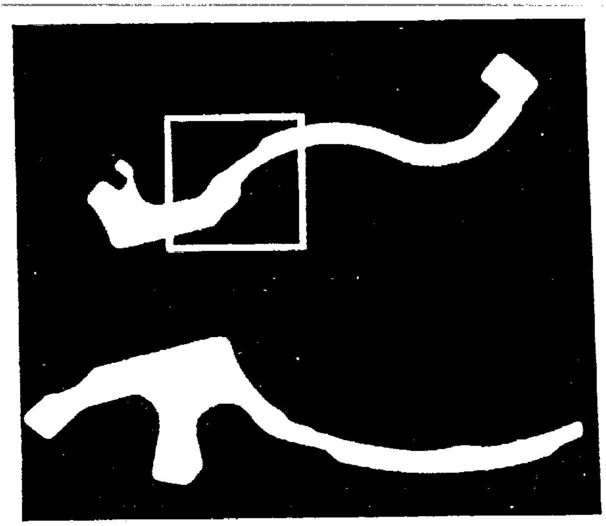
Figure 13. CT Image Through Flange Centerline

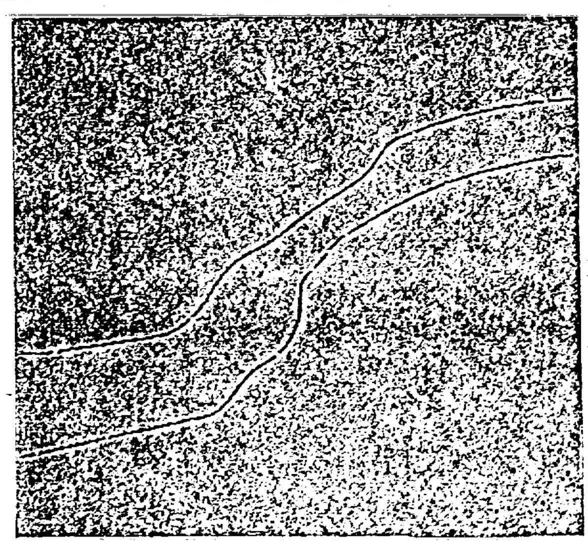
Figure 15. Image Reduced to Profile Outline

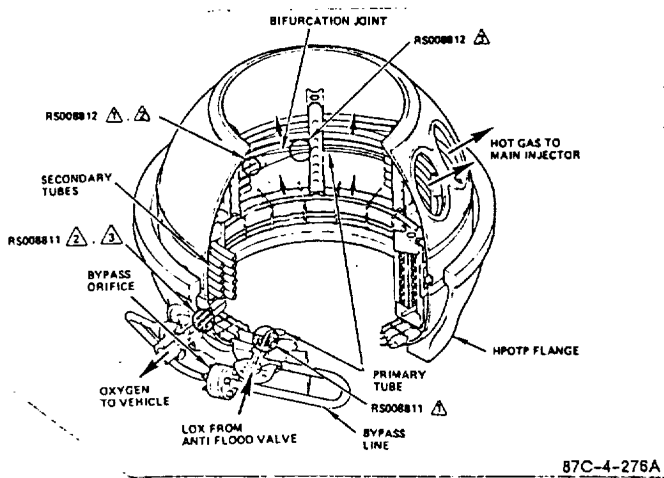

Figure 16. Sketch of Heat Exchanger Assembly

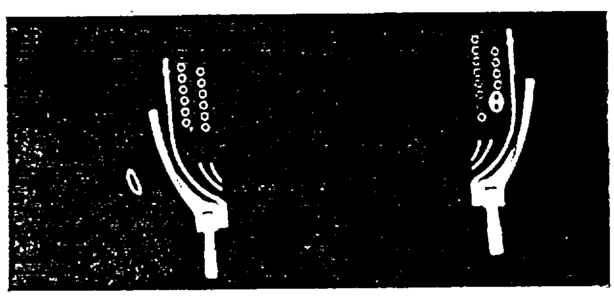

Figure 17. CT Slice Through SSME Heat Exchanger Assembly

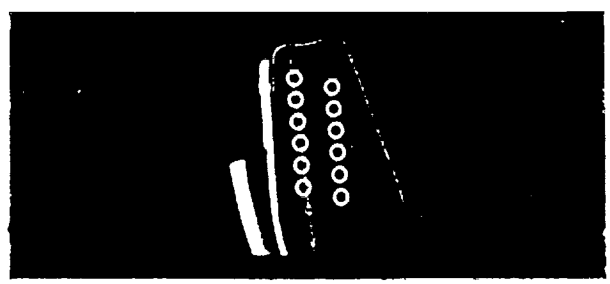

Figure 18. Enlarged Image of CT Scan Through Critical Weld Joint Area

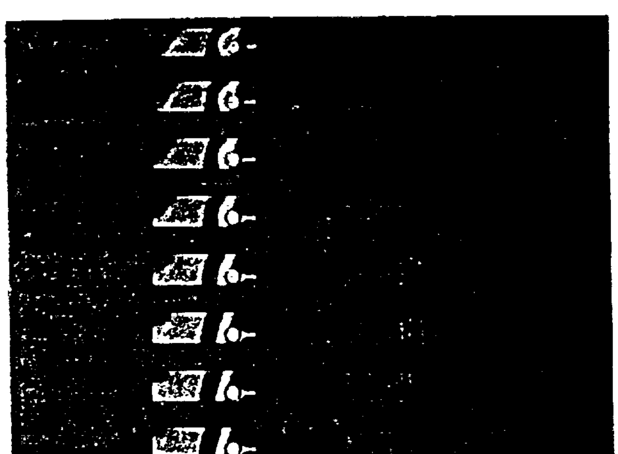

Figure 19. Series of CT Images at 0.635 μm (0.025 in.) Intervals Through Critical Weld Joint Showing Tube Wall Thinning

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Note the tube wall thinning apparent in the small tube toward the middle of the images. An analysis of the reconstructed images revealed the remaining tube wall to be 144.8 μm (0.0057 in.) at its thinnest point. Subsequent metallographic sectioning and measurements of the thinned tube determined the actual thickness to be 139.7 μm (0.0055 in.).

CONCLUSION

The 2-yr study of CT applications on the SSME hardware demonstrated the potential of CT as a very powerful diagnostic and inspection tool. The uses of the equipment seem to be limited only by the user's imagination and rapport with the CT equipment manufacturer. The relationship with the equipment manufacturer is vital, since many of the innovative applications require a software or hardware modification most effectively accomplished by working with the developer-supplier of the CT equipment. One of the most unexpected results of this study was the tremendous increase in value to the SSME program that evolved. Whereas CT was initially being evaluated as only an advanced flaw detector, its other capabilities to image, measure, and evaluate hardware characteristics that currently cannot be inspected by nondestructive means are of tremendous import to the SSME program.