PHASED ARRAY ULTRASONIC EXAMINATION OF SPACE SHUTTLE MAIN ENGINE NOZZLE WELD

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Abstract. This paper describes a Phased Array Ultrasonic Examination that was developed for the examination of a limited access circumferential Inconel 718 fusion weld of a Space Shuttle Main Engine Nozzle - Cone. The paper discusses the selection and formation criteria used for the phased array focal laws, the reference standard that simulated hardware conditions, the examination concept, and results. Several unique constraints present during this examination included limited probe movement to a single axis and one-sided access to the weld.

INTRODUCTION

The Space Shuttle Main Engine, better known to NASA as the SSME, has proven to be the most reliable rocket engine ever built. Three of these remarkable machines power the space shuttle orbiter vehicle. Each one can be throttled.

A major component of the SSME engine is the nozzle, which controls the expansion of exiting combusted hydrogen gas. The nozzle is regeneratively fuel-cooled from hydrogen coming from a high pressure fuel turbo pump. After passing through a specialized valve this hydrogen splits into three coolant loops, one of which is the nozzle coolant loop. It is this function which requires a complicated and delicate process of brazing over 1000 individual tubes to the inside of a nozzle jacket. These tubes cool the nozzle inner wall when the hot combustion gases exit.

The nozzle jacket consists of many conical sections, hatband rings and stiffeners, which are all welded together by the Tungsten Inert Gas (TIG) method. The channel shaped stiffener is snapped onto the machined surface of the hatband rings and then welded there with a continuous automatic TIG weld on each side of the stiffener. [1] It is this type of joint that was the focus of this evaluation. These welds are considered critical and a flaw such as a crack inside the weld could propagate and cause a structural jacket failure, which could lead to leakage external to the nozzle and over pressurization of the aft compartment, thus causing engine failure and possible loss of vehicle and crew. So it became imperative that the nondestructive evaluation used to verify these welds be capable of finding the critical flaw size required.

The current method of finding cracks and other volumetric anomalies in these welds is the old reliable x-ray method. This inspection, though, can only be performed before the nozzle coolant tubes are placed on the inside of the nozzle. The backside is completely inaccessible after the subsequent assembly processes. On this particular nozzle, suspected anomalies were discovered on a subsequent x-ray interpretation after the tube stacking operation. With no access to visually inspect the backside, much less perform another

[1] Bryant, Melvin and Mitchell, William. "*Fabrication of the Space Shuttle Main Engine Nozzle*", May, 1992.

x-ray to confirm the anomalies, another method or approach would be needed. Ultrasonics has historically been an effective NDE method for single sided volumetric verification of many types of welds. The use of shear wave angles allows a maximum amplitude return from typical weld flaw orientations is a very effective quality tool. Phased array ultrasound, now finding wide acceptance in industrial applications, improves the sensitivity and resolution above similar conventional ultrasound approaches. Because of its proven ability in support of the Delta IV rocket and the Space Shuttle External Tank, the phased array method was considered. Detailed investigations determined it to be the most viable methodology to evaluate the suspected x-ray indications and then to assess their severity in the investigation.

ISSUE

Identify and implement an alternate Nondestructive Testing (NDT) method for verification of weld integrity in weld 1. Radiographic linear film indications estimated to be between .300" to 1.900", discovered during an audit, placed the weld under scrutiny. Since no defects were allowed, the area of the weld must be cleared of any suspicion. The nozzle, in its current stage of assembly prohibits a meaningful radiographic inspection. The Nozzle Integrated Product Team considered three options.

- Leave the assembly "As is" without performing any additional work/inspections. The disadvantage would be no depth quantification of the defect and thus the CEI requirements could not be insured.

- De-Stack the Nozzle and Re-perform the X-ray inspection. This option was estimated at over 1000 labor hours and contamination concerns to the assembly would be difficult to mitigate.

- Find an alternate inspection technique to validate the weld joint. The challenge to this option was that the nozzle assembly was three fold; one side accessibility, assembly could not be moved and rigid tooling was creating an obstacle in accessing the weld.

PLAN OF ACTION

To increase the solution possibilities, the Boeing NDT Process Action Team was alerted to the details of the situation. An over whelming response was to evaluate the feasibility of ultrasonics, then eddy current, and as a last resort Compton Backscatter.

To verify the ultrasonic inspection potential, a wave form propagation analysis of the structure at the weld joint was performed using modeling techniques by Boeing's Manufacturing Development and Research (MRD) Department (located in Renton, WA) and the Rockwell Science Center's Nondestructive Research Branch (located in Thousand Oaks, CA). The results of both analyses concluded that at approximately 60-degree shear wave the weld area in question could be interrogated.

Two ultrasonic techniques were selected:

"Phased Array (PA) is a NDT technique by which a multi-element probe is pulsed using applied delays to form and shape the resulting ultrasonic beam. Software controls are used to define the "Focal Lays" which create the phase shifts that are used to steer and focus the beam as desired." Jim Engel "Phased Array Ultrasonic Inspection of Friction Stir Welds" 5th Annual Boeing-wide Friction Stir welding Conference August 16, 2000.

This technology provides three permanent methods to evaluate and review the ultrasonic output; "A" scan of the oscilloscope, "B" scan a cross section of the material thickness and "C" scan a planned view looking down on the material.

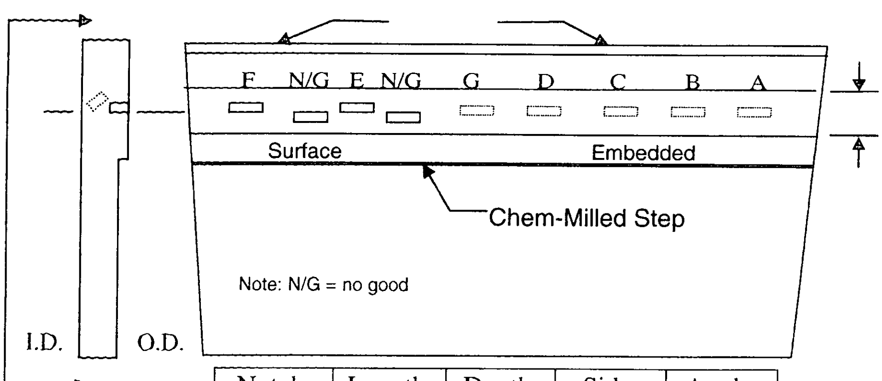
Conventional "A" scanning is a NDT technique using specifically designed acrylic "shoes" to provide a pre-determined shear wave angle into the test material. The ultrasonic responses are viewed and evaluated in real time on the system's oscilloscope by the person conducting the evaluation. Permanent records are not produced by the system for later review.

Reference Standard

Ultrasonic techniques commonly utilize a reference standard for equipment standardization prior to inspection. To accurately simulate the Weld 1 joint configuration under evaluation, a portion of an existing "scrapped" Weld 1 was provided by the SSME Program. To match the configuration of the in process nozzle which has not completed the final braze cycle, the fuel tubes were removed from the inside diameter of the provided portion by Rocketdyne's Electro Discharge Machining (EDM) department.

The nozzle under evaluation was unique in the fact that nickel alloy had been plated to the back surface (inside diameter) in the area to be evaluated. Measurements of the nozzle's wall thickness were taken from the outside and subtracting the minimum drawing requirement for the jacket area from the overall wall reading allowed the nickel plating thickness to be estimated which would be applied to the standard after EDM notches were machined.

To determine the appropriate "flaw" sizes (EDM Notches) a team was formed. The team consisted of; Boeing NDT and Customer NDT subject matter experts (SME) and Main Combustion Chamber (MCC) & Nozzle Product Team Stress Engineers. This team designed the reference standard including defining the EDM notch sizes, orientations, and locations. These notches would assist in the quantification and ultimate acceptance or rejection of any ultrasonic indications resulting from either ultrasonic examination. (see sketch below).



Notch	Length	Depth	Side	Angle
A	.300	.012	I.D.	30°
B	.300	.018	I.D.	30°
C	.300	.024	I.D.	30°
D	.300	.036	I.D.	30°
E	.300	.012	O.D.	Normal
F	.300	.036	O.D.	Normal
G	.300	.030	I.D.	30°

Figure 1 - Sketch of Reference Standard – looking at the entry surface

Technique Development

Phased Array - The standard was used during the development of the technique at Boeing Huntington Beach's facility (see figure 3). A comprehensive explanation of Phased Array beam forming methods are available in the ASNT NDT Handbook - Volume 7, pp. 284 - 292 Final system parameters were co-developed by SME representatives of Boeing Huntington Beach, Boeing Canoga Park and NASA MSFC.

<u>Final set-up specifics</u>

- Linear Array Probe 10 Mhz 64 elements – element size 0.5mm x5mm – 64 total elements in probe
- R/D Tech 128 pulser/receiver Focus System w/Rover Scanner
- Focal law = 16 elements, 48 laws per angle (indexed forward @ each focal law, i.e. Law 1 = Elements 1-16, Law 2 = Elements 2-17, Law 3 = Elements 3-18, etc.)
- Focal laws created to focus the beam @ a depth of 0.2"
- Coupling "localized immersion" bath custom fit to hardware profile
- Fixed angle of shoe 19 degrees.

The image in figure 2 shows the .012" deep notch (fabricated at 30 degrees from back surface) with a signal to noise ratio of 3:1.

<u>Optimum Angle and Focal Law Viewing of Weld 1*</u>
50 degrees at focal laws 33 through 44
55 degrees at focal laws 31 through 40
60 degrees at focal laws 26 through 35
65 degrees at focal laws 31 through 34

*Determined at time of evaluation.

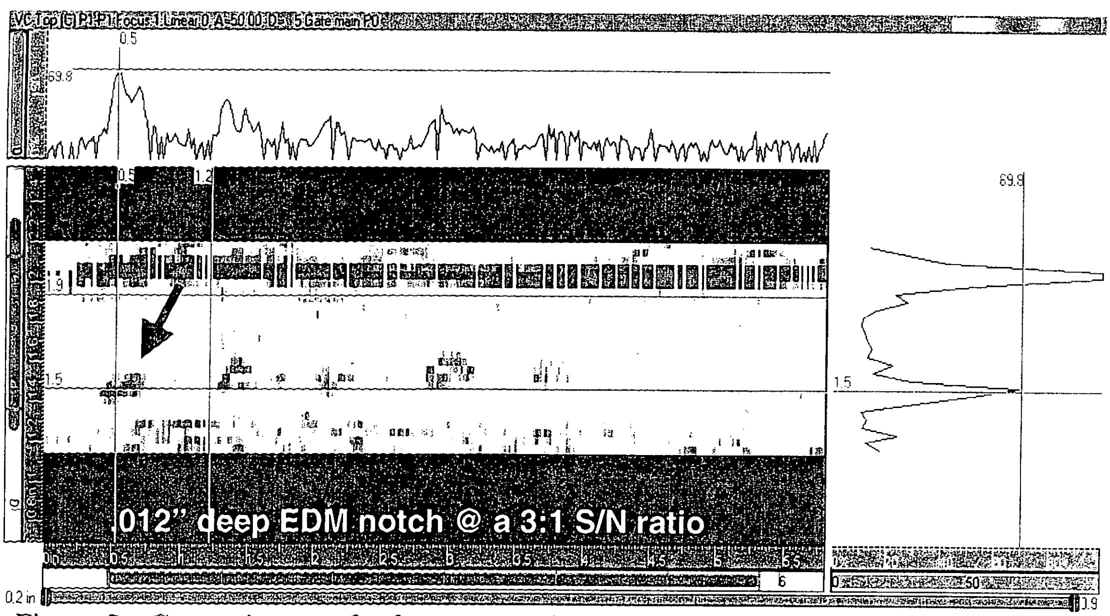


Figure 2 - C-scan image of reference standard @ above described technique (55 degree)

Conventional "A" Scan – The standard was used during the development of the technique at Boeing Canoga Park' facility prior to evaluation of Weld 1 areas. Final system parameters were co-developed by SME representatives of Boeing Canoga Park, Defense Contractors Management Agency (DCMA) Canoga Park, and NASA MSFC.

EXAMINATION

A large team of individuals participated in the actual setup, scanning and evaluation of the Weld 1 areas. The Nozzle Team provided assistance including blending the chem-milled radius and bending the tool skirt for proper couplant and alignment of the phased array probe. The NDT department provided assistance in wall thickness measurements and ideas for best probe fit up to Weld 1. The Main Combustion Chamber and Nozzle Product Team provided photo support and resources to complete the examination in as timely a manner as possible. The DCMA representatives supported throughout the evaluation in both expertise and hands on participation. The NASA representative provided both expertise in phased array and conventional "A" scan ultrasonics as well as hands on setup and scanning of the weld 1 areas.

RESULTS

All areas that required evaluation were evaluated using both techniques. The A scan technique revealed no indications. The phased array technique revealed only two ultrasonic responses in Weld 1 radiographic view 3 to 4. The responses were ultrasonically characterized jointly by the team of experts; Boeing Huntington Beach, Boeing Canoga Park, DCMC Canoga Park and NASA MSFC. These ultrasonic findings were reported to the MCC and Nozzle Product Team Leader and Stress Engineers.

CONCLUSIONS

The examination results were analyzed by Stress Engineering and they recommended the ultrasonic responses be considered acceptable. The responses were considerably smaller than the calculated critical initial flaw (CIF). Upon program and customer review of these recommendations and a detailed presentation of the phased array examination technology the nozzle was found acceptable.

Lessons Learned

The Boeing NDT PAT Network provided timely and useable information. This network brought the NDT resources of the Boeing Company to the disposal of the Canoga Park location. It should be noted the high priority that Huntington Beach rendered, in providing their equipment and personnel for assisting Canoga Park in resolving this issue as quickly as possible.

Reference Standards cannot be under estimated for the significance in the quality and validity of the evaluation results. The ability for this evaluation to measure responses just slightly above the noise level as well as identify key geometric reflectors provided the NDT SME's the confidence and physical evidence needed to make such a critical evaluation.

The participation of the required SME's (those responsible for the hardware) during the technique development and at the time and location of the evaluation is absolute. When using "advanced or new" techniques or methods the SME's possess the general knowledge base but require familiarization of the system, which in this case would be learned during technique development. This also builds the knowledge to agree with the results of the inspection (which is not the time to be asking a lot of questions about what has just occurred).

Review all items brought from the providing location for compatibility to local hardware requirements. For instance, it is shop practice to use "Red Tape" at Huntington Beach but this tape had not been approved for application on Canoga Park hardware.

Be prepared for the need of tooling expertise when introducing inspection systems to a situation for the first time. The Nozzle Department prepared the area around the evaluation zones as well as could be anticipated based on configuration and equipment still last minute adjustments were required.

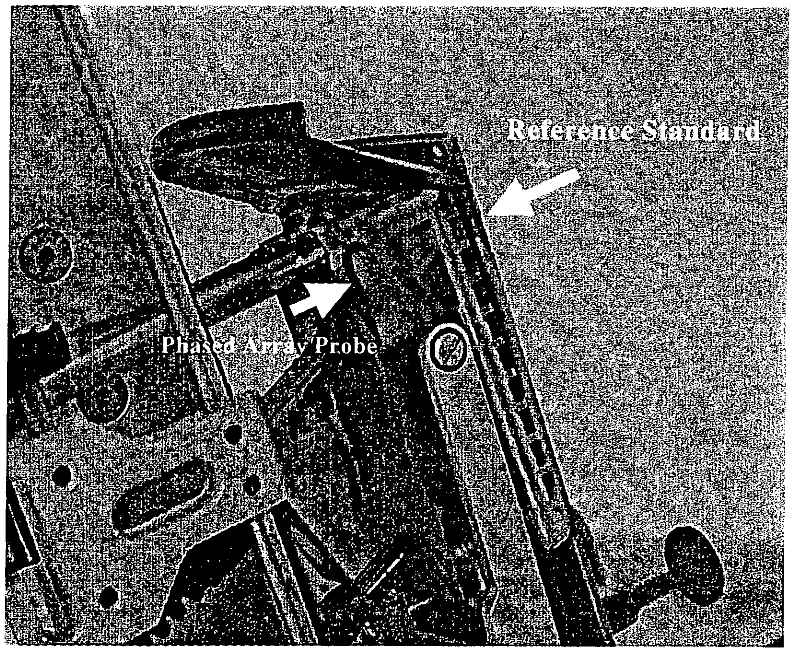
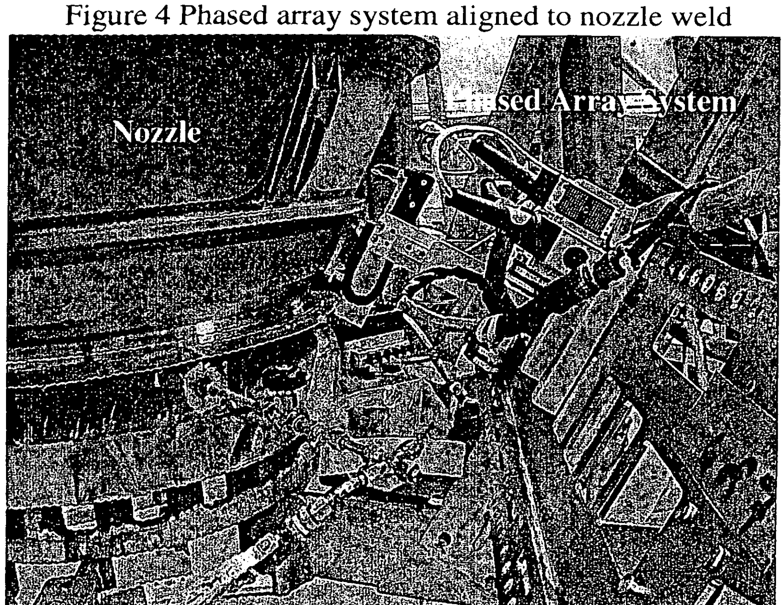


Figure 3 Phased array system with reference standard
(Experimental Laboratory Set-up conducted to validate the procedure prior to hardware evaluation)

Figure 4 Phased array system aligned to nozzle weld



(data points were taken @ 0.020" intervals along the X axis (length of weld))