# Exploration of COTS Ultrasonic NDE Methods for ISS MMOD Impact Analysis

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**The high orbital speed of the International Space Station (ISS) has created a concern about Micro-Meteorite and Orbital Debris (MMOD). The possibility exists that such an impact could cause significant damage to the ISS pressure wall, and possibly lead to a pressure leak. This paper explores the potential of using commercial off-the-shelf (COTS) Ultrasonic Non-Destructive Evaluation (NDE) techniques in order to inspect and analyze MMOD impact damage if such an event would happen to occur. Different types of intra vehicular activity (IVA) Ultrasonic NDE equipment were evaluated, including the Olympus *Omniscan MX* and the General Electric *Phasor XS*. The equipment was tested by inspecting various aluminum standards and impact damage test plates in order to determine technological limitations of the equipment as well as the ease of use and availability of features. This study allowed for the design of scanning procedures in order to evaluate the extent of damage caused by an MMOD impact. Lastly, comparisons were drawn between the different pieces of COTS software and a recommendation is made based on each device's capability.**

## Nomenclature

| | | |
|---|---|---|
| *ISS* | = | International Space Station |
| *MMOD* | = | Micro-Meteorite and Orbital Debris |
| *NDE* | = | Non-Destructive Evaluation |
| *COTS* | = | Commercial Off-The-Shelf |
| *PAUT* | = | Phased Array Ultrasonic |
| *ECA* | = | Eddy Current Array |
| *IVA* | = | Inter-vehicular Activity |
| *EDM* | = | Electrical Discharge Machining |
| *FBH* | = | Flat-Bottomed Holes |
| *ASTM* | = | American Society for Testing and Materials |
| *AMS* | = | Alpha Magentic Spectrometer |
| *LW* | = | Longitudinal Wave |
| *SW* | = | Shear Wave |

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# I. Introduction

The ISS On-Orbit Leak Detection and Repair Panel was established in 2000. In 2001, the panel proposed a development plan so that in the event of a pressurized module leak aboard the ISS (Risk 4669), the crew would be trained and ready to perform a repair. Step 4 of the Risk 4669 mitigation plan calls for the development and use of COTS NDE equipment aboard the ISS in order to evaluate the extent of pressure wall damage. For this study of COTS NDE equipment, ultrasonic NDE techniques are evaluated for IVA action.

## A. Ultrasonic Testing

Ultrasonic NDE requires a pulser and receiver system (Fig. 1.) The pulser relies on a piezoelectric crystal that oscillates when an AC source is introduced. The pulser generates high-energy ultrasonic waves that propagate through a material when in direct contact. These ultrasonic waves are reflected by material boundaries, such as the front and back walls of the material, as well as any flaw that may be present within the material. When the ultrasonic waves reach the receiver, they are converted into an electrical signal and displayed on a screen. The strength of the signal versus the time from signal generation to echo are displayed in what is commonly called an A-scan (Fig 1.). The time from signal generation to echo can easily be converted from a time to a distance according to

$$f * \lambda = v \qquad v * t = d \tag{1}$$

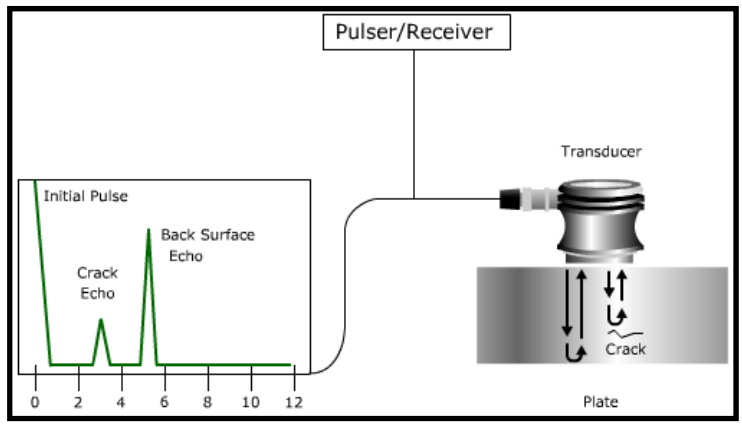


**Figure 1. Ultrasonic Testing Diagram.** *Depicts an ultrasonic transducer performing NDE on a flawed sample. The echo signal is displayed in the green A-scan, where the strength of the response (arb) is plotted against the ultrasonic pulse's time of flight (s).*

where $v$ is velocity, $t$ is time, $d$ is distance, f is frequency, and $w$ is wavelength. The pulser/receiver system is housed in what is called a transducer. While the most basic transducers consist of a single-element pulser/receiver, multi-element phased array transducers are more effective, and allow for beam steering and focusing for better flaw resolution. Phased arrays allow for the construction of more intuitive scans, such as the top-down view C-scan and the cross-sectional view S-scan.

Ultrasonic inspection has some limitations. Ultrasonic waves do not propagate in air, so the transducer must be in direct contact with the part undergoing inspection, and a couplant must be used. Also, any process that will affect the homogenization of the part, such as cold-worked hardening, will cause the ultrasonic pulse to travel at different speeds, potentially harming your results. Next, the ultrasonic wave will attenuate over time and lose strength at a rate of

$$A = A_0 e^{-az} \tag{2}$$

where $A$ is the amplitude, $A_o$ is the unattenuated amplitude of the ultrasonic wave, $a$ is the attenuation coefficient and $z$ is the traveled distance from the initial location. Lastly, there is a minimum flaw size that ultrasonic testing can not longer, based on the wavelength of the ultrasonic waves used. If the flaw is less than half of the ultrasonic wavelength, then no echo will occur, and the flaw will not be detected.

# II. ISS Ultrasonic NDE Procedure

The use of NDE technology on the ISS occurs when there is an impact. The astronauts on board the ISS will be made aware by a number of ways, including finding a visual dent in the pressure wall, hearing an impact, and through alarms that trigger if pressure starts to decrease inside a module. Their first goal is to find the damage, which is not always straightforward. The ISS is cluttered with scientific gear, computers, and equipment, and direct line of site to the pressure wall is not always available. The U.S. modules also contain racks and wall standoffs that can reduce the clearance one has to inspect an area of the pressure wall to as low as 1". On the Russian side of the

ISS, panels obscure the pressure wall and must be removed. The Russian modules also possess an isogrid that is attached on the interior of the pressure wall. Once they have located the impact, they must inspect it for damage and determine if it is leaking. This is usually done with the assistance of an ultrasonic leak detector kit, which has been developed and is currently aboard the ISS.

### A. No Leak – Technique 1

If there is an impact, but no leak occurs, the astronauts are in luck. In that case an instant repair is not always necessary and NDE can be applied. In this case, a paintbrush, or longitudinal wave (LW), probe would be used (Fig. 2). The paintbrush probe is preferable for several reasons. Using a paintbrush probe allows you to position the probe directly over the impact sight and perform a scan. The paintbrush probe allows for full damage mapping, and can evaluate remaining wall thickness. The data display is also very intuitive, and easy to follow. Throughout this report this scan type will be called, *Technique 1*.

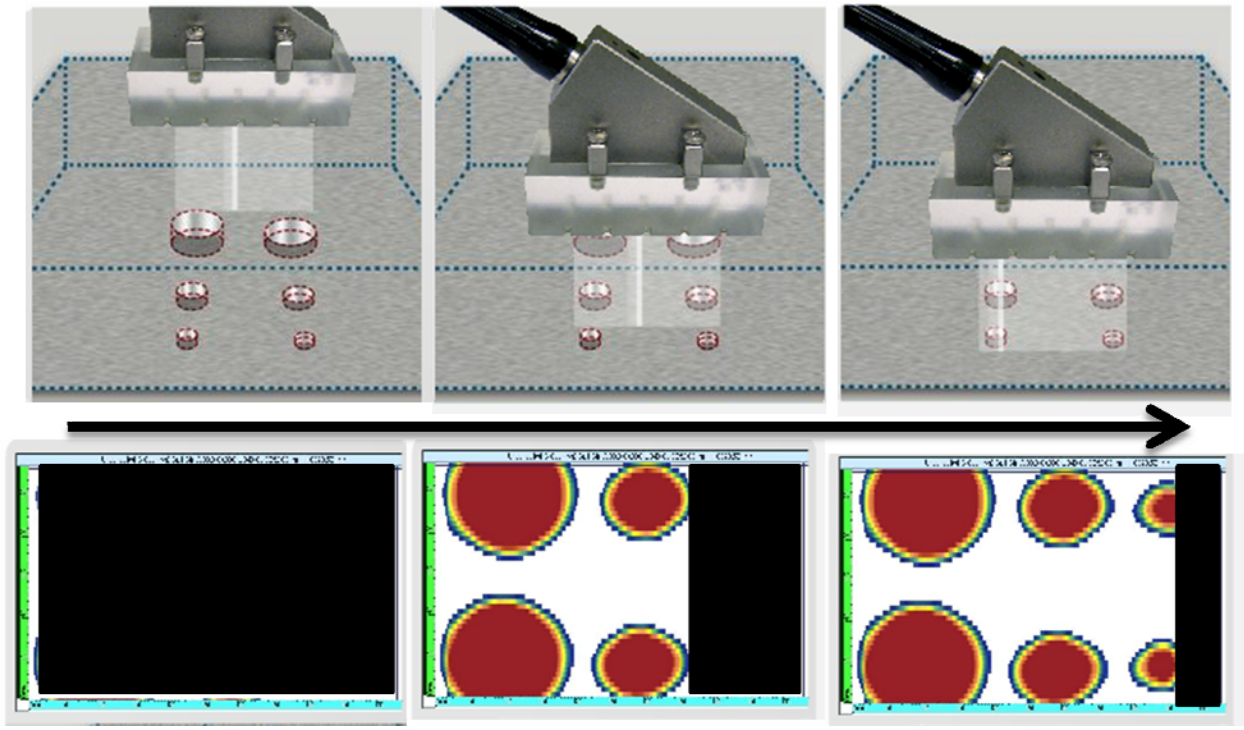

**Figure 2. Technique 1: Paintbrush LW Scan.** *This diagram portrays a simple ultrasonic scan of a sample with flaws on the far side of the piece. When the transducer is scanned directly over these flaws, a top-down image is created, called a C-scan.*

### B. Leak – Technique 2

In the case of a pressure leak, certain steps must be taken before the extent of the damage can be evaluated. The In the case of a pressure leak, certain steps must be taken before the extent of the damage can be evaluated. The leak must first be repaired. Two types of repair patches can currently be found aboard the ISS in the case of an MMOD impact. There is a rigid repair patch comprised of an elastomer o-ring and an aluminum disc that has a 5.0” x 5.0” footprint, and a flexible patch created by layering aluminum tape with a 3” diameter elastomer disc in the center that has a 7.0” x 7.0” footprint. Technique 1 can no longer be used because the patches do not allow a direct contact with the pressure wall. In this case, a linear angle shear wave (SW) transducer will be used (Fig. 3). This allows for the transducer to scan around and underneath the repair patch by taking advantage of angled waves. While this allows indirect flaw detection, little information is given beyond knowledge of the flaw’s existence. A thickness map cannot be created, and only the damage perimeter can be mapped. All other defects closer to the center of the patch will be blocked by flaws closer to the edge, and will be subjected to a much lower signal/noise (S/N) ratio.

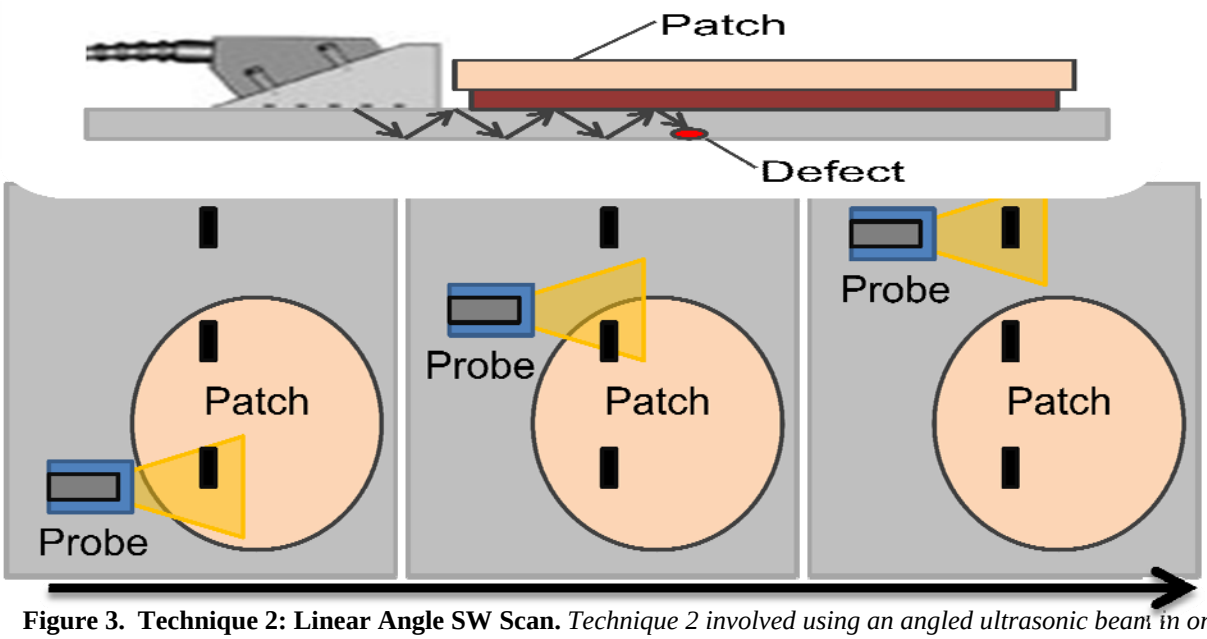


**Figure 3. Technique 2: Linear Angle SW Scan.** *Technique 2 involved using an angled ultrasonic beam in order to peer under a patch (top). When scanning for flaws, one moves the probe alongside the patch in a straight line (bottom). This is because an encoder will only measure distance in a straight line, and not radially.*

## III. MMOD Impact Characteristics and Analogues

During an impact, three types of flaws occur. These include pitting, cracks, and erosion damage, all of which can be seen in Fig 4. When an MMOD collides with the ISS, it first has to pass through an external MMOD barrier, which causes the object to break apart before the collision with the pressure wall. The MMOD can impact deeply into the pressure wall causing pits, and radiating cracks. Erosion is the general reduction in thickness of the area due to the collision and abrasion.

Before NDE was performed on MMOD impact test plates, it was first tested using similar analogues in order to design the procedural use of the equipment. Two standards were used, including the ASTM 30 flat-bottomed hole (FBH) block, and the AMS plate. The ASTM standard is a 1.5" thick plate with 30 FBH of three different sizes and ten different depths. The AMS standard is a 0.25" thick plate (close to the ISS's 3/16" and 1/16"), that contains rows and clusters of FBH as well as two rows of EDM notches. The flat-bottomed holes located on these plates were comparatively similar to the pits that would be found in the impact sample. Next, the AMS sample also had EDM notches that are comparable to cracks found in an MMOD impact sample. Dimensions can be seen in Fig. 5.

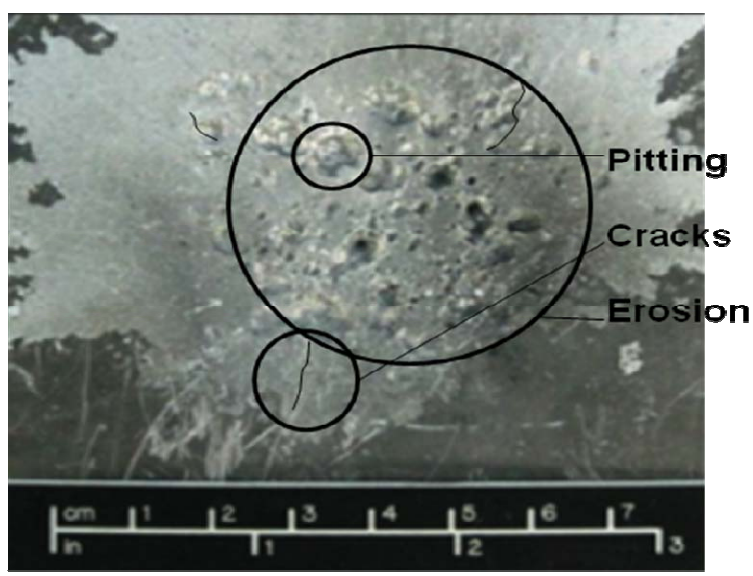


**Figure 4. Impact Damage Types.** *Shows examples of pitting, cracks, and erosion*

Lastly, an MMOD impact test plate was acquired for testing. X-ray tomography was utilized to get a clear picture of the extent of the damage (Fig. 6). Technique 1 was first used to scan along certain portions of the panel

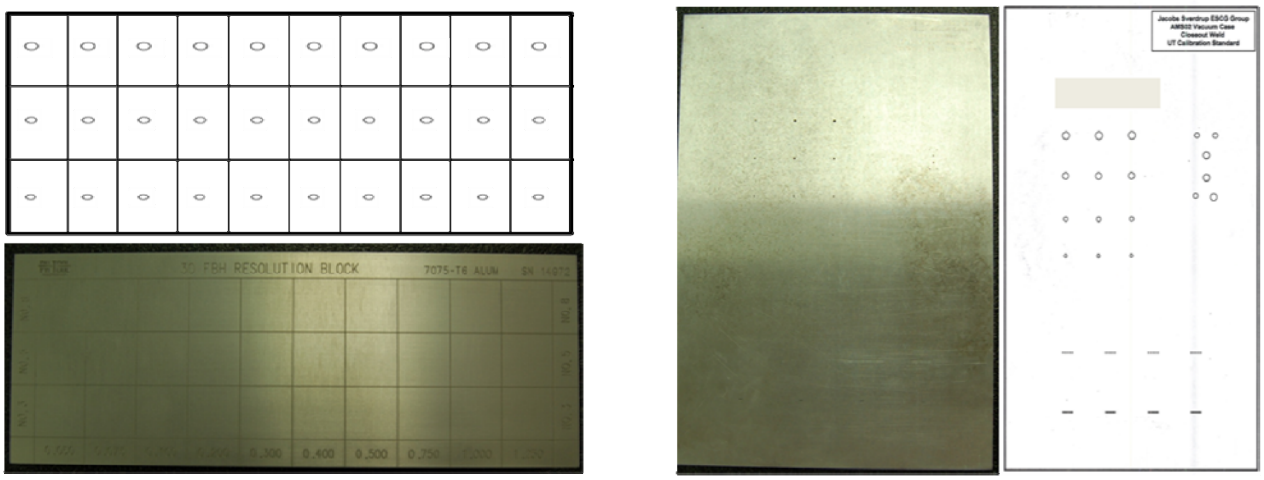


**Figure 5. Impact Damage Analogues.** *ASTM FBH Plate (left) and AMS Plate (right). The ASTM block is 1.5" thick while the AMS block is 0.25"thick. Both physical images and diagrams of the analogues are show, with the circles representing FBHs and the lines representing EDM notches*

and determine the visibility of some pitting damage. Next, an aluminum tape patch analog was applied to the impact plate, and technique 2 was performed along one edge. An encoder was utilized so once data was collected, it was possible to analyze the data for the exact locations of the flaw identifications. This analysis was done by hand and writing down flaw locations, before being input into the MATLAB program to create a surface map.

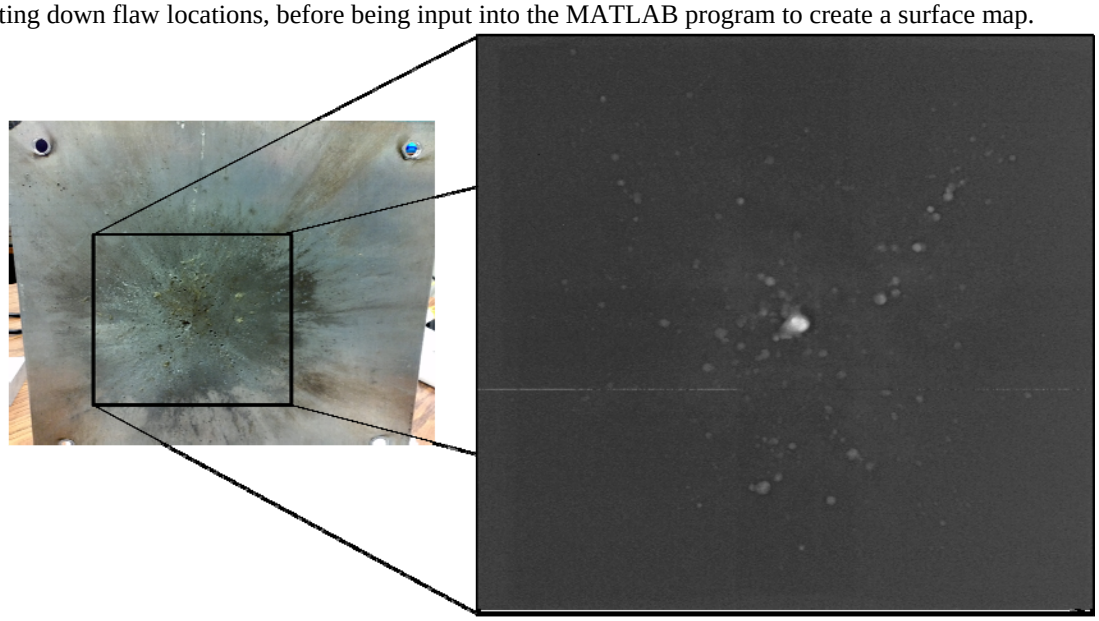

**Figure 6. Impact Plate Sample.** *Picture of impact plate damage with x-ray tomography image of eroded area.*

## IV. Results

First the impact plate analogs were analyzed. Technique 1 was performed on all FBH and EDM notches using both the Omniscan MX as well as the Phasor XS. Thickness map C-scans were created by each device for each standard. Both pieces of equipment identified the smallest, shallowest FBH at .025" deep and a .025" diameter, and had a high enough resolution to make out the separate FBH in the small FBH cluster, .150" apart. However, when using the paintbrush transducers to analyze the EDM notches, both pieces of equipment failed to detect the smallest notch at a depth of 0.010" and 0.005" – 0.007" wide. The rest of the notches also had a small profile due to their shape—only a small portion of the flaw impedes ultrasonic waves traveling straight down through the material.

Images of the C-scans for the AMS clustered FBH and the ASTM FBH can be seen in Fig. 7. The AMS EDM notches are shown in Fig. 8.

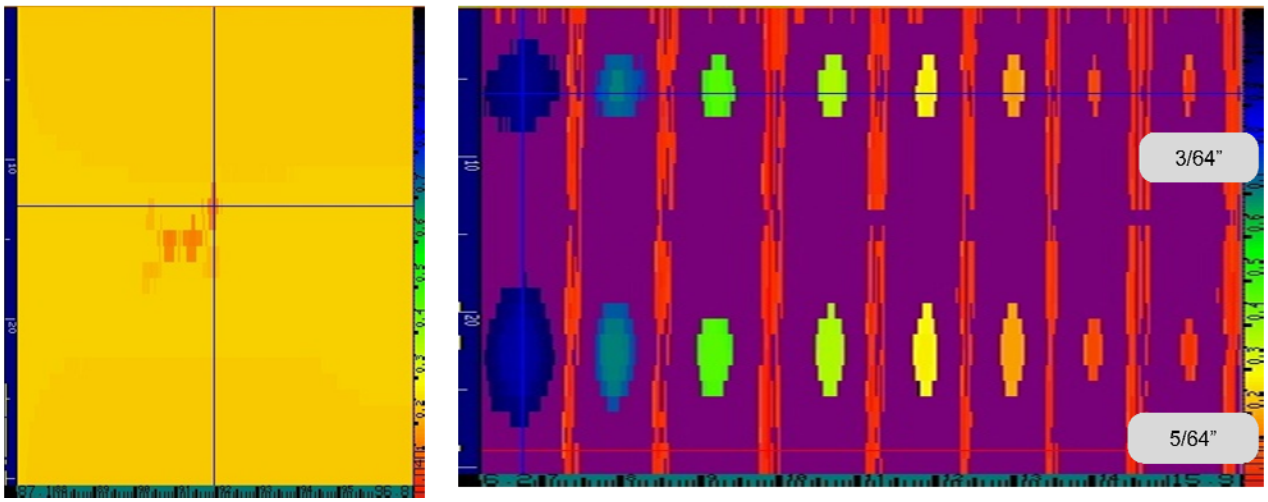


**Figure 7. Technique 1 FBH Scans.** *This figure depicts C-scans from the Phasor XS of a FBH cluster (left) as well as rows of FBHs with different depths from the ASTM standard (right). Both of these scans are thickness maps, and the colors correspond to the depth. Dark blue is a flaw that only shallowly penetrated the sample, while the red flaws are very close to penetrating all the way through. The lines depicted in the right scan are called scribe lines and are located on the surface of the ASTM standard.*

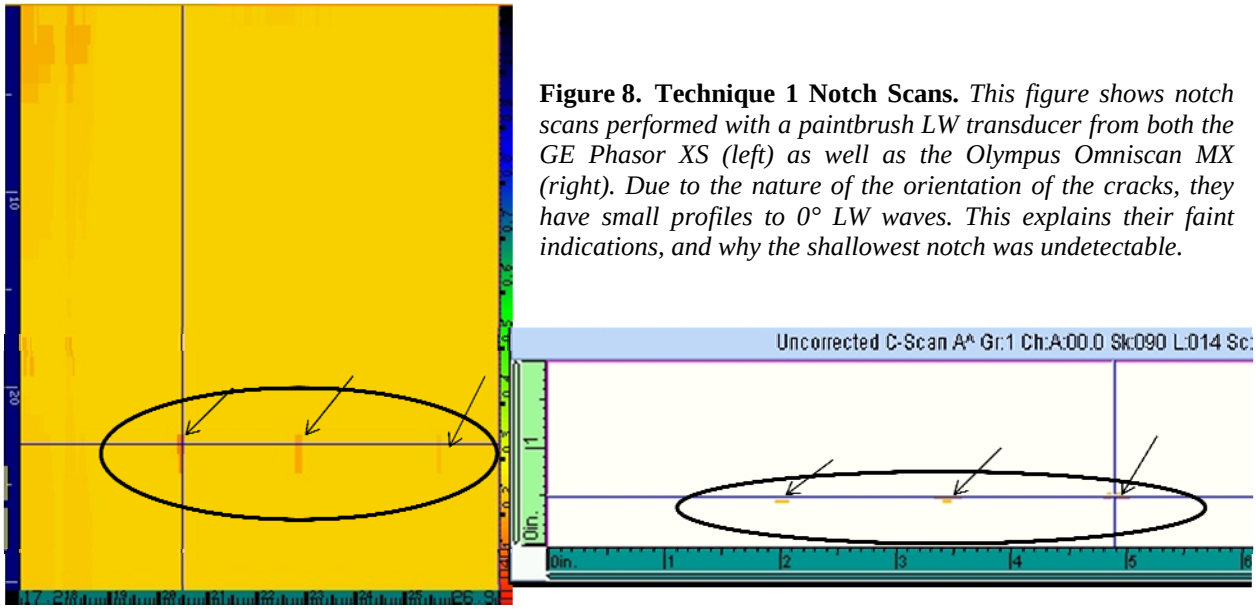


**Figure 8. Technique 1 Notch Scans.** *This figure shows notch scans performed with a paintbrush LW transducer from both the GE Phasor XS (left) as well as the Olympus Omniscan MX (right). Due to the nature of the orientation of the cracks, they have small profiles to 0° LW waves. This explains their faint indications, and why the shallowest notch was undetectable.*

Next, technique 2 was performed using an Omniscan MX 45° linear angle SW transducer from both 2.5” away from the flaw and 3.5” away from the flaw, representing the distance from the center of the two separate repair patches to their edge in case of a worse-case analysis scenario where the damage lies in the middle of the patch. The testing was performed on the AMS standard EDM notches. It was determined that at 2.5” away, the transducer had sufficient resolution to resolve even the smallest crack at 0.005 - 0.007” wide, 0.10” long and 0.10” deep. However, once tape was applied, the S/N ratio decreased dramatically and the 0.025” and 0.010” deep notches could no longer be detected. From 3.5” away, the transducer could identify all EDM notches except for the 0.010” deep notch. However, once tape was applied, only the deepest notch at 0.100” deep could be detected (Fig. 9). A chart detailing all known holes and notches tested and whether they were detected can be found in Fig 10.

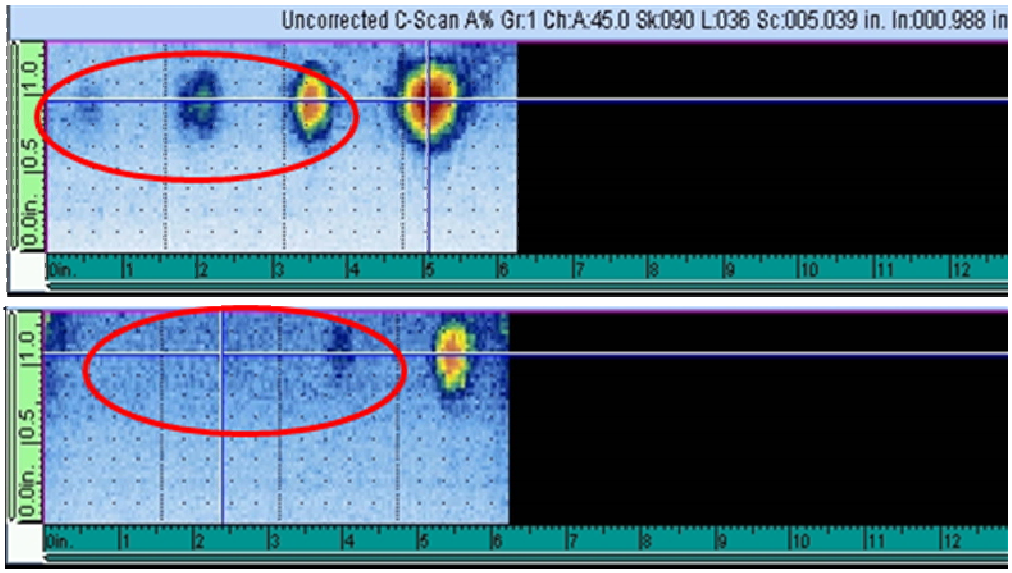


**Figure 9. Technique 2 Notch.** *This figure depicts C-scans from the Olympus Omniscan MX preformed by a 45 degree linear angle SW transducer. Both scans were taken 3.5" away from the flaw. The top scan was performed without tape and only the smallest flaw is below the required S/N ratio. Once the aluminum tape patch analog was added however (bottom), only the deepest of the EDM notches is significant.*

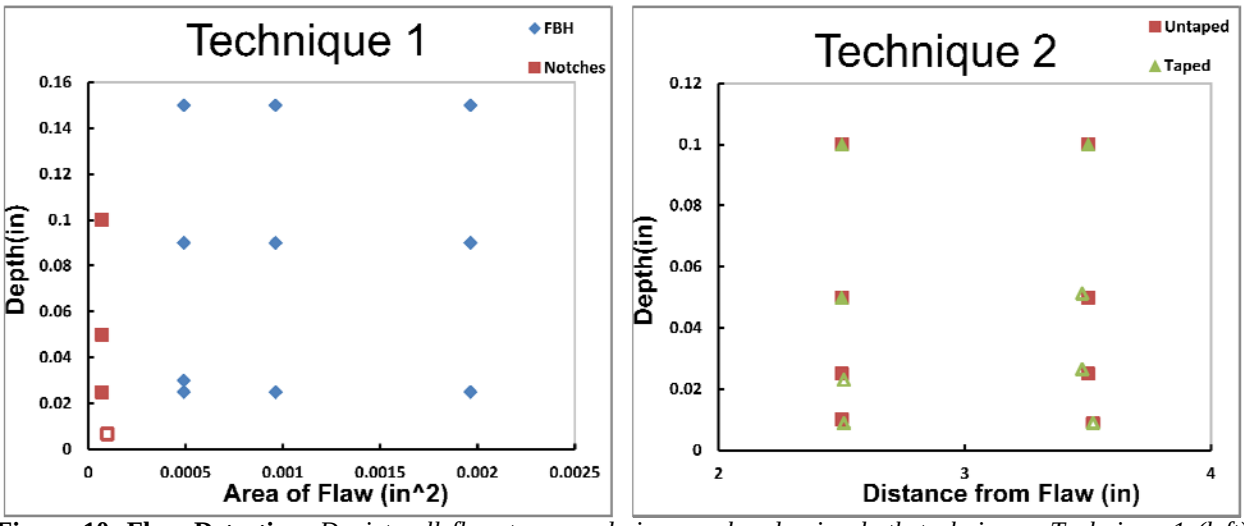


**Figure 10. Flaw Detection.** *Depicts all flaw types and sizes analyzed using both techniques. Technique 1 (left) utilized both FBH (blue) and notches (red). Technique 2 (left) was performed both with (green) and without (red) a patch analog. The empty shapes represent flaws that did not have a high enough S/N ratio to be confirmed as flaws. All notches were .005-.007" wide and 0.10" long.*

Finally, the MMOD impact plate was analyzed using the techniques developed on the impact analog samples. First, the MMOD plate was treated as if no leak occurred, and technique 1 was applied (Fig. 11).Tape was applied to the plate to allow the transducers to stay along a given path. Of the two paths analyzed, two separate clusters of holes where detected (Fig. 12 and Fig. 13), and the C-scans of the paintbrush transducer are compared with the areas under inspection in order to determine their accuracy. It was determined that the paintbrush probe C-scan data matches very closely with the impact plate damage. Next, a patch was applied to the MMOD

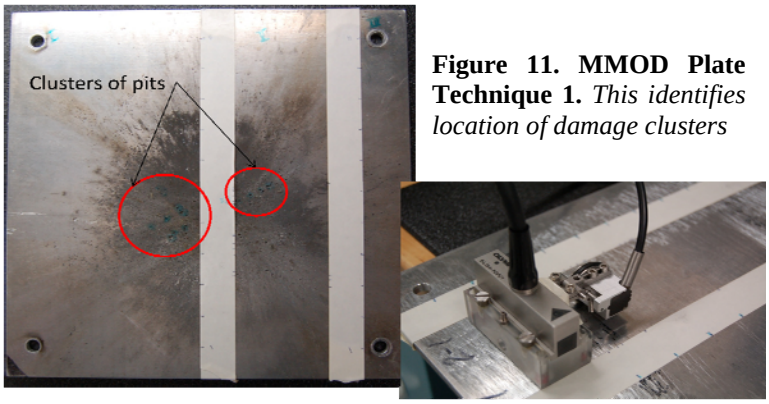


**Figure 11. MMOD Plate Technique 1.** *This identifies location of damage clusters*

plate and a 45 degree linear angle transducer was used to evaluate the perimeter of the damage. A MATLAB figure was created and can be found in Fig. 14. It was found that the perimeter of the damage, while not matching the impact plate perfectly, does show similar perimeter characteristics, which are marked by white lines.

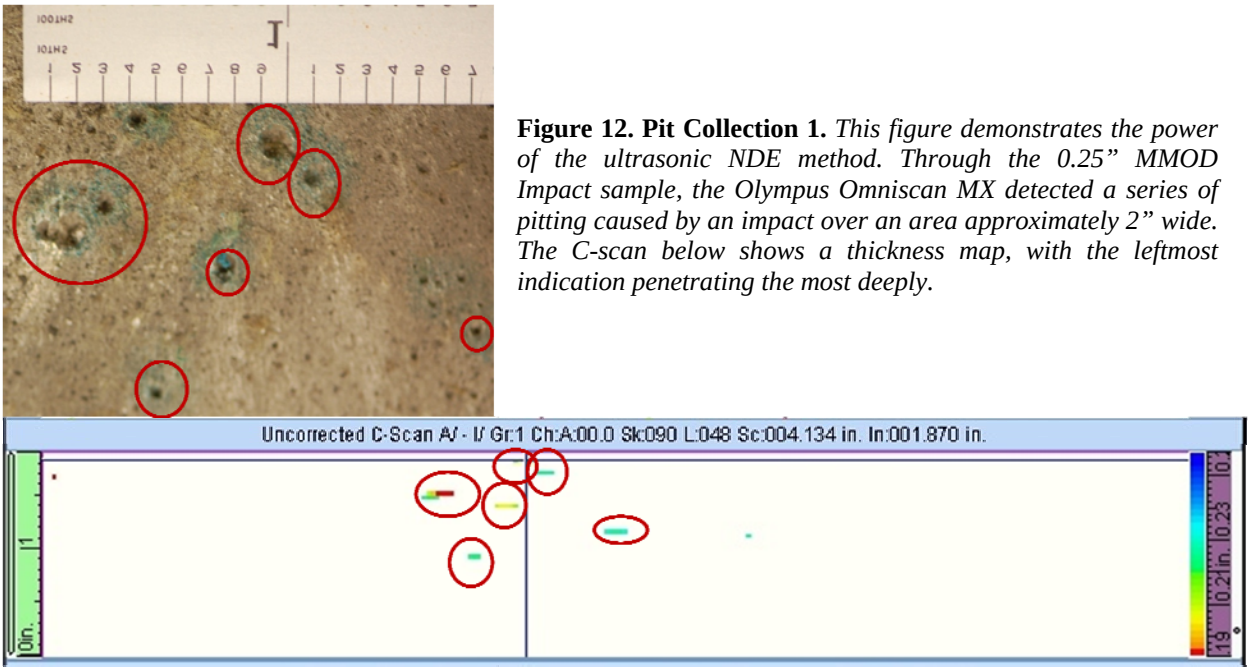


**Figure 12. Pit Collection 1.** *This figure demonstrates the power of the ultrasonic NDE method. Through the 0.25" MMOD Impact sample, the Olympus Omniscan MX detected a series of pitting caused by an impact over an area approximately 2" wide. The C-scan below shows a thickness map, with the leftmost indication penetrating the most deeply.*

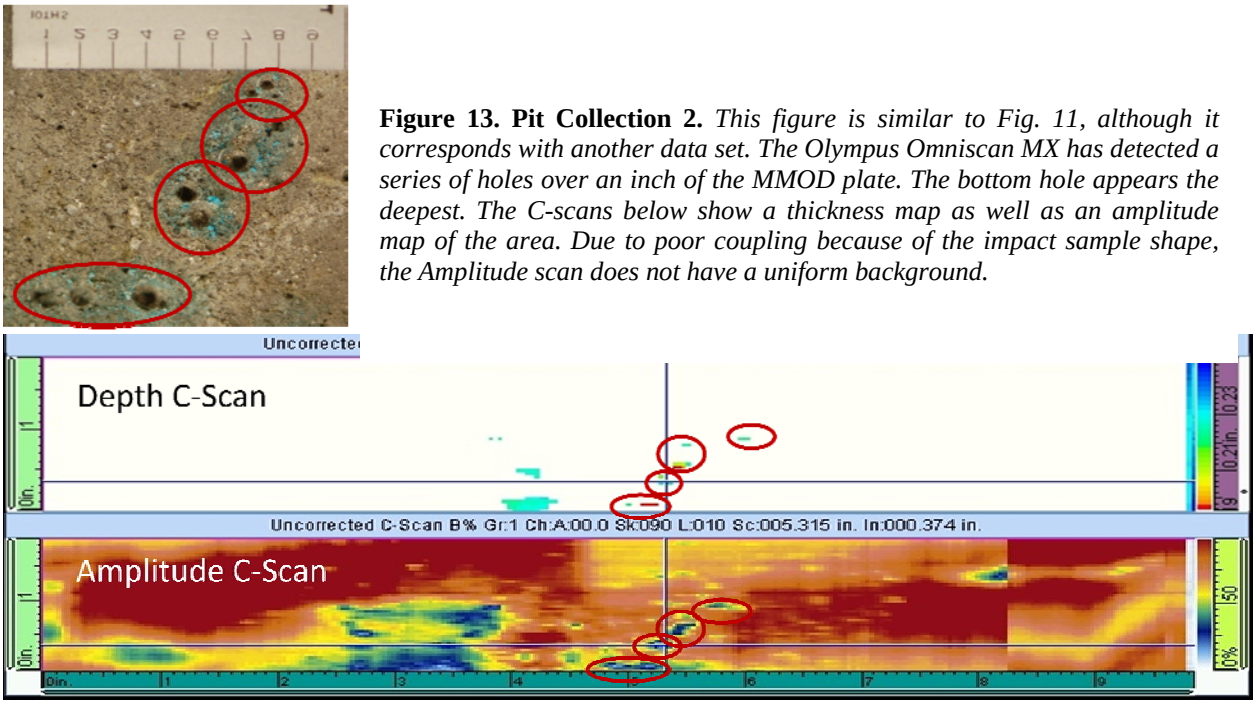


**Figure 13. Pit Collection 2.** *This figure is similar to Fig. 11, although it corresponds with another data set. The Olympus Omniscan MX has detected a series of holes over an inch of the MMOD plate. The bottom hole appears the deepest. The C-scans below show a thickness map as well as an amplitude map of the area. Due to poor coupling because of the impact sample shape, the Amplitude scan does not have a uniform background.*

Usage comparisons were also made between the Olympus Omniscan MX and the Phasor XS. The Omniscan requires a Compact Flash card to run, while the Phasor XS uses an SD card, but doesn't require it to run. The Phasor possesses a 6.4" display while the Omniscan uses an 8.4" display. The Omniscan's larger display also allows it to show multiple scans, such as side-view scans and C-scans, rather than just one at a time on the Phasor. The Omniscan also has the added functionality of possessing USB ports for the use of external keyboards and computer mice. However, the Omniscan is much more expensive than the Phasor. The Phasor also appears easier to use for those who have little experience with NDE, and can lock settings so they aren't accidently changed. Both units also

have a few perks in common, such as the ability to attach an external computer screen via VGA, and to easily pause data collection. Both machines possess the ability to create pre-set setting files that can be loaded on start-up and makes it easier for someone less experienced to do the job. Lastly, and most importantly, both pieces of equipment possess similar technical capabilities. The transducer is responsible for the majority of the technical capabilities and should be chosen carefully as a result. Therefore, it is important to take the user accessibility of each system into account.

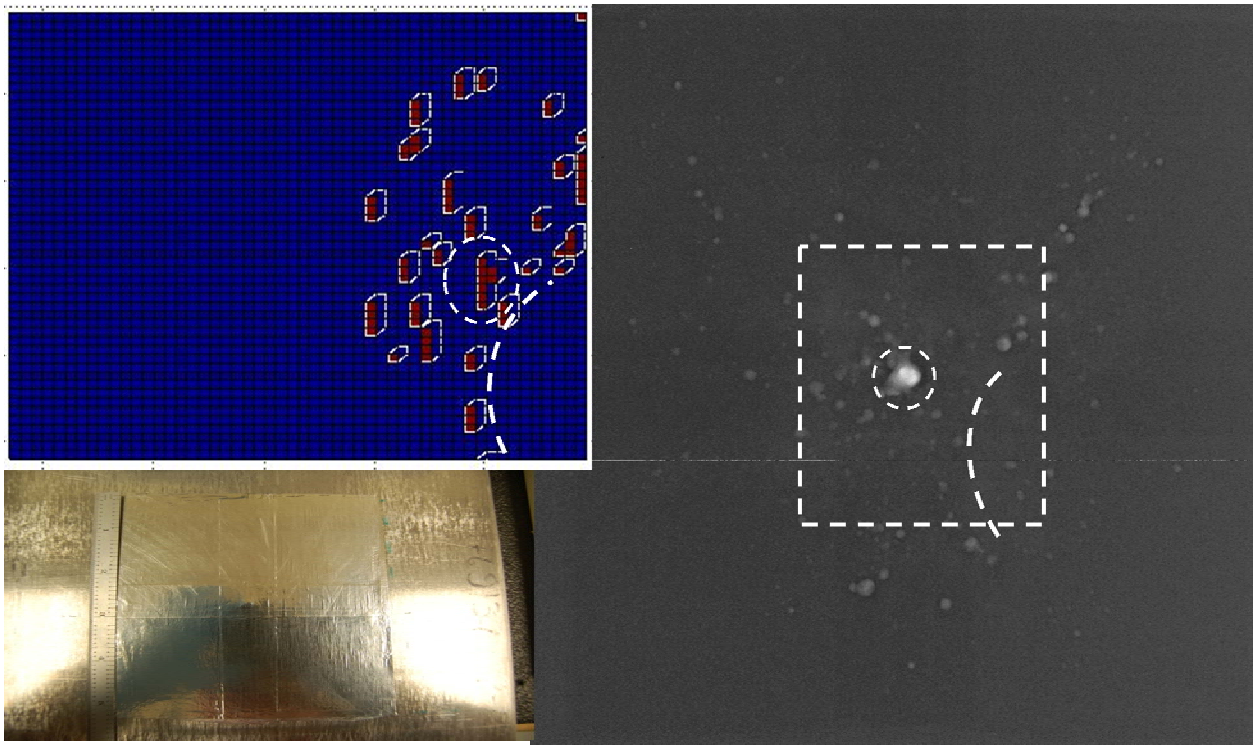

**Figure 14. MMOD Technique 2.** *This figure depicts a MATLAB surface plot (left) of data collected from a technique 2 scan preformed using the Olympus Omniscan MX. This figure includes a picture of the back side of the MMOD plate with an analog patch (bottom left), as well as an x-ray tomography scan of the damage (right).The white marks how the two sets compare.*

## V. Conclusion

This study has served its main goal to study the possibilities of Ultrasonic NDE for use aboard the ISS to analyze MMOD impact damage. Multiple pieces of COTS equipment were tested and compared, and two techniques were developed in order to gain the most knowledge possible about a damaged pressure wall area. Technique 1 was developed for use in a situation where no leak was present, while Technique 2 is ideal for cases where a pressure leak occurs. These techniques were tested on analog samples that helped to develop a preliminary understand of the limitations of the equipment. It was discovered that technique 1 is ineffective for finding and identifying cracks or notches, and that the procedure could be modified to include linear angled SW scans in order to increase the probability of crack detection. It was also learned that technique 2 quickly loses detection capabilities over large distances due to the applied patch. More information about the operation of the COTS devices was also acquired, and the ease of use of both pieces of equipment was analyzed. While the Phasor may have been more straightforward to use, the Omniscan possessed qualities, such as the ability to display multiple scans, that made it more effective at locating small flaws. General Electric however, recently developed a high-end ultrasonic tool called the Vision with capabilities similar to the Omniscan, and could be a contender in the future.

Many more steps must be taken before this project enters phase A. Better patch analogues must be developed, because both patches are more complex than simple aluminum tape, which may decrease the probability of detection

even further. More experimental standards are currently in development, and are 3/16" as well as 1/16" thick. These standards will give a clearer indication of the capabilities of the ultrasonic equipment, and will include many EDM notch and FBH sizes and depths that will assist in determining the limitations of the equipment, as well as to further develop the procedure. Input should also be acquired from the JSC Astronaut Office due to their ultimate involvement in the project. Coordination with the Astronaut Office will allow for a better evaluation of the ease of use of the two pieces of equipment.

## Acknowledgments

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