Preliminary Measurements Supporting Reactor Vessel and Large Component Inspection Using X-Ray Backscatter Radiography by Selective Detection

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Abstract – *X-ray backscatter radiography by selective detection (RSD) is a field tested and innovative approach to non-destructive evaluation (NDE). RSD is an enhanced single-side x-ray Compton backscatter imaging (CBI) technique which selectively detects scatter components to improve image contrast and quality. Scatter component selection is accomplished through a set of specially designed detectors with fixed and movable collimators. Experimental results have shown that this NDE technique can be used to detect boric acid deposition on a metallic plate through steel foil reflective insulation commonly covering reactor pressure vessels. The current system is capable of detecting boric acid deposits with sub-millimeter resolution, through such insulating materials.*

Industrial systems have been built for Lockheed Martin Space Co. and NASA. Currently the x-ray backscatter RSD scanning systems developed by the University of Florida are being used to inspect the spray-on foam insulation (SOFI) used on the external tank of the space shuttle. RSD inspection techniques have found subsurface cracking in the SOFI thought to be responsible for the foam debris which separated from the external tank during the last shuttle launch.

These industrial scanning systems can be customized for many applications, and a smaller, lighter, more compact unit design is being developed. The smaller design is approximately four inches wide, three inches high, and about 12 inches in length. This smaller RSD system can be used for NDE of areas that cannot be reached with larger equipment.

X-ray backscatter RSD is a proven technology that has been tested on a wide variety of materials and applications. Currently the system has been used to inspect materials such as aluminum, plastics, honeycomb laminates, reinforced carbon composites, steel, and titanium. The focus of RSD is for one-sided detection for applications where conventional non-destructive examination methods either will not work or give poor results. Acquired images have clearly shown, for a variety of conditions, that proper selection of x-ray field scatter components leads to a significant improvement in image quality and contrast. Improvements are significant enough in some cases that objects not visible to conventional CBI or transmission radiography become readily discernable with RSD.

I. INTRODUCTION

Radiography by selective detection (RSD) is a new type of x-ray Compton backscatter imaging (CBI) where different components of the x-ray backscatter field are preferentially selected to enhance the contrast and detection of specific features. A variant of this technique, called lateral migration radiography (LMR), was first applied at the University of Florida (UF) to the detection of buried land mines[1-10]. The land mine results demonstrated the ability of this technique to detect voids, and air spaces. As a result, RSD was applied to the detection of subsurface features including: cracks, voids, delaminations and corrosion. A wide variety of materials have been imaged including: aluminum, plastics, honeycomb structures, laminates[11,12], steel, reinforced carbon-carbon composites (RCC), concrete, and titanium. Most recently, an RSD scanning system is being used by Lockheed Martin Space Systems Co. and NASA to detect defects in the spray-on foam insulation (SOFI) used on the external fuel tank of the space shuttle[13, 14].

The x-ray backscatter RSD approach is based on image contrast induced by varying electron densities along the photon path. Changing subsurface features cause photons to be scattered, absorbed or stream along their path to the detector. Each of these interactions results in changes in the detector response. These changes in detector response are collectively used to generate an image, where changes in field intensity (count rate or voltage) are visually represented as changes in image contrast. Backscatter RSD selectively detects x-rays that enhance the image signal-to-background ratio allowing for the detection of features, which may otherwise go undetected using conventional CBI or transmission radiography. Figure 1 illustrates how a combination first- and multiple- scatter events from various scan depths, can be used to image a variety features at different depths. Noise can be subtracted from the image using other detectors, or rejected through the use of collimators. Subsurface features can be anything of interest: boric acid deposits (Figure 1), cracks, corrosion, voids, delaminations, land mines, hidden objects, or improvised explosive devices (IEDs).

Starting in the early 1990s, the Bugey 3 nuclear power unit, a pressurized water reactor (PWR) in France, showed signs of leakage from a reactor pressure vessel head. In the United States this was followed by Oconee 3 in 2000, and the Davis Besse incident where large boric acid deposits and leaking resulted in the formation of a substantial cavity around a control rod drive mechanism. As a result of the Davis-Besse incident more than 29 nuclear power plants have either replaced, or are scheduled to replace, their reactor pressure vessel (RPV) heads.[15] More recently, in April of 2003, boric acid deposits, indicative of leaks were found around bottom mounted instrumentation (BMI) penetrations. South Texas Project (STP) observed 150 milligrams and 3 milligrams of boron deposit on BMI penetrations 1 (Figure 2) and 46 (Figure 3).[16] Since these incidents, the Nuclear Regulatory Commission (NRC) has required inspections of these location.

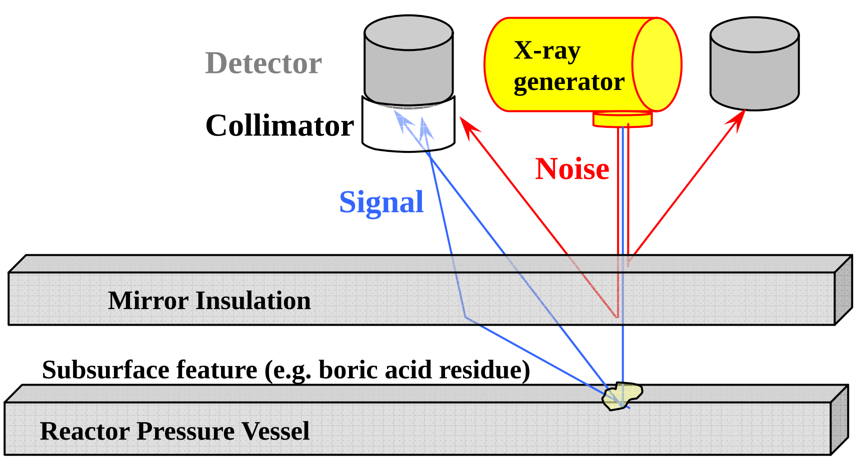

Figure 1 - Simplified Schematic of a RSD Subsurface-Feature Experimental Setup with a Collimated Detector

Inspection of these areas can be troublesome, especially if mirror insulation must be removed. Current RSD x-ray backscatter techniques can be used to inspect RPV penetrations without removing mirror insulation. Figure 4 shows an RSD x-ray backscatter device, developed at the University of Florida for inspecting the SOFI used by Lockheed Martin on the external tank of the space shuttle.[13,14] This device can be used to inspect BMI penetrations through RPV mirror insulation.

Figure 2 – STP BMI Penetration 1[16]

Figure 3 – STP BMI Penetration 46[16]

II. CURRENT SCANNING SYSTEM AND EQUIPMENT

In general, as shown in Figure 4**,** the current RSD scanning system consists of the x-ray generator, an array of detectors, scanning table, and a computer to control data acquisition, motion control, and image generation. The array of detectors is fixed to the x-ray generator and designated as the scanning head. A highly collimated x-ray beam illuminates a single pixel, and a selective backscatter field is measured by the array of detectors. Movable collimators allow each of the detectors to view a unique field. The measured signal of less-collimated, or uncollimated detectors is dominated by single-collision events and contains surface and near surface information. The collimated detector signals can respond to single- and multiple-scatter photons. These photons have greater depth penetration and carry information about sub-surface features as shown in Figure 1. This feature makes it possible to image the RPV or any surface beneath the TRANSCO insulation, shown beneath the RSD scanning system in Figure 4.

Figure 4 – Current RSD scanning system with TRANSCO mirror insulation

Two dimensional images are generated using a scanning pattern. For example, the scanning head will sweep from left to right, acquiring data and storing a line of pixels. The scanning head will then move to the next line and sweep in the opposite direction from right to left, obtaining the next line of data. This process is repeated one line at time until the entire image is completed.

The scanning system in Figure 4 was used to determine if it is feasible to find boric acid deposits and defects in steel structure through reactor pressure vessel insulation. The yellow cylinder is an Yxlon MXR-160/22 x-ray generator. This is a liquid-cooled x-ray generator with a maximum tube voltage of 160 kV. The scans used to detected boric acid through TRANSCO insulation were performed at 100 kVp and 45 mA with a 5.5 mm electron beam focal spot. The four silver cylinders in Figure 4 are the detector assemblies. Each detector assembly includes a 50 mm diameter by 50 mm long NaI scintillator crystal, a photomultiplier tube and a specially-designed, high speed, ultra low-noise pre-amplifier from Inspirion LLC. The collimator assembly at the end of the detector includes an array of lead collimators and the design allows for independent adjustment of the assembly in different directions. This includes in-and-out movement of the outer, circular (sleeve) collimator; in-and-out and rotational movement of the inner collimator (collimator component with the lead fins); and in-and-out movement of the entire assembly. The collimator design provides the ability to "focus" the image by the selection of the desired scatter components. Each of the detectors generates a separate image and a cross-correlated image can also be generated from any combination of detector images. The x-ray illumination beam spot size used for these experiments was 1.5 mm for large deposits and 1 mm for finding very small deposits. The beam spot can be either round or square or customized for any application. The shape of the illumination beam is controlled by a lead insert (aperture) in the bottom of the brass, lead-lined source collimator tube that extends in a direction normal to the end of the x-ray tube and which is centered between the four detectors. The fastest linear scan rate for this system is about 50 mm per second. For 2 mm pixels, this translates into scanning rate of approximately 15 minutes per 0.093 m^2 (1 ft^2). A LabVIEW-based program is used to control the scanner motion, data acquisition and image generation.

III. RESULTS AND DISCUSSION

In order to determine the feasibility of using an x-ray backscatter RSD system, a series of experiments were performed with varying quantities of boric acid (starting with about 2 grams) and drilled holes in a steel plate. Later experiments make a first attempt to quantify the minimum detectable amount of boric acid.

III.A. Large Boric Acid Deposit and Drilled Holes

An initial experiment was performed using a small piece of plate steel and a sample of TRANSCO insulation, constructed from a stainless shell with internal metallic foils which serve as heat reflective insulation on RPVs. The insulation shown in Figure 4 is about 7.62 cm thick with an average density of about 3 g/cm^3. Figure 5 shows a steel plate with different size holes drilled in the plate. The holes decrease in size from 12.7 mm to 3.175 mm and are about 0.7938 mm deep with a slightly deeper (~1.5875 mm) locating hole, an artifact of the drill bits used.

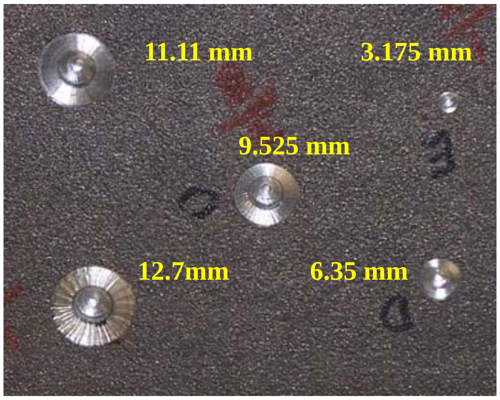

Figure 5 – 12.7 mm to 3.175 mm holes 0.7938 mm deep in steel plate

This piece of steel plate was located 7.62 cm behind the TRANSCO insulation and imaged using the RSD scanning system shown in Figure 4. The RSD x-ray backscatter image shown in Figure 6 was acquired at 100 kVp, 45 mA, and using 1.0 mm pixels. It took about 20 minutes to complete the scan. The steel plate is in the same orientation as shown in Figure 5 with 2 grams of boric acid deposit on the right side. Each of the five drilled holes is visible on the left of the image, and appears as a dark area of contrast. The boric acid residue appears as a large bright spot to the right of the drilled holes centered at position (x = 140, y = 45 mm). Boric acid is bright, because the absorption cross section for boric acid is lower than the absorption cross section of steel. To the right side of the boric acid residue is a vertical lighter contrast line at x = 192 mm. This is the edge of the steel plate.

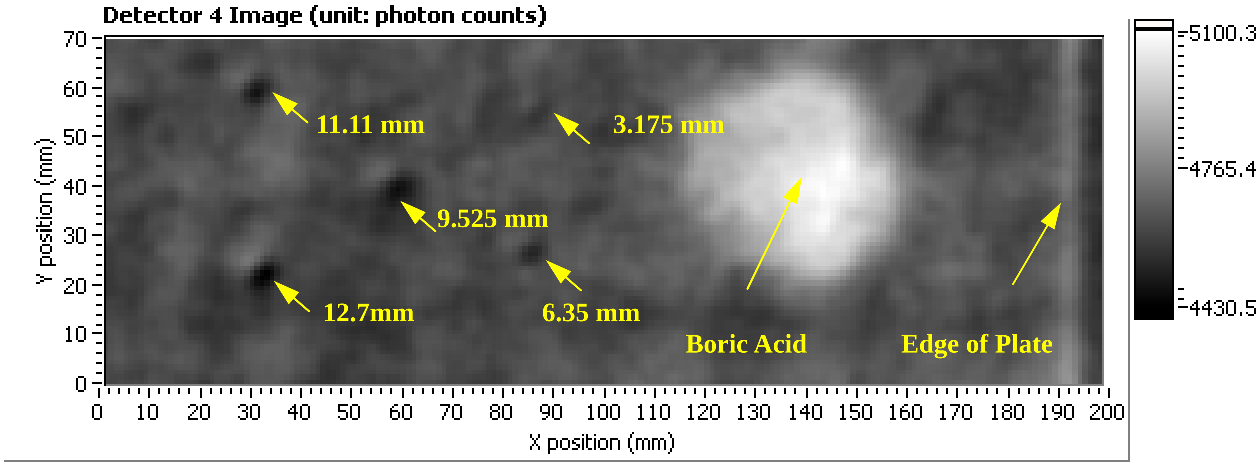

Figure 6 – RSD scan of steel plate with 5 holes and boric acid through TRANSCO insulation with a 7.62 cm air gap

III.B. Estimating Detectable Level of Boric Acid Deposit

After easily locating the boric acid deposit and holes, a second set of experiments was performed to begin to determine detectable concentration levels of boric acid. One, two, three and four grams of boric acid were dissolved in water and spread over a 5 cm diameter circle on a piece of steel. This resulted in concentrations of boric acid with 51 mg/cm^2 (left), 101 mg/cm^2, 153 mg/cm^2, and 204 mg/cm^2 (right) as shown in Figure 7. Visually detectable concentrations are estimated to be between 50 and 100 mg/cm^2 based on the average size of crystals as boric residue solidifies.

Figure 7 – From left to right, 51, 101, 153, and 204 mg/cm^2 of boric acid in 5 cm diameter circles

The steel plate was then placed beneath the TRANSCO insulation with a 7.67 cm air gap as shown in Figure 8. Figure 9 is the RSD image which was acquired at 100 kVp, 45 mA, and using 1.0 mm pixels. All four boric acid deposits are easily visible. The top image is a correlation composite from all four detectors in the scanning system, while the bottom image is from unprocessed data from detector 3. Current image processing allows for the images to be viewed in either color or grey scale. Image processing not only allows for cross correlation between image data from multiple detectors, but image filtering, and contrast adjustments. Raw data is also stored in ASCII text format for easy processing with software.

Figure 8 – Steel plate with boric acid deposits positioned 7.62 cm beneath 7.62 cm of TRANSCO insulation

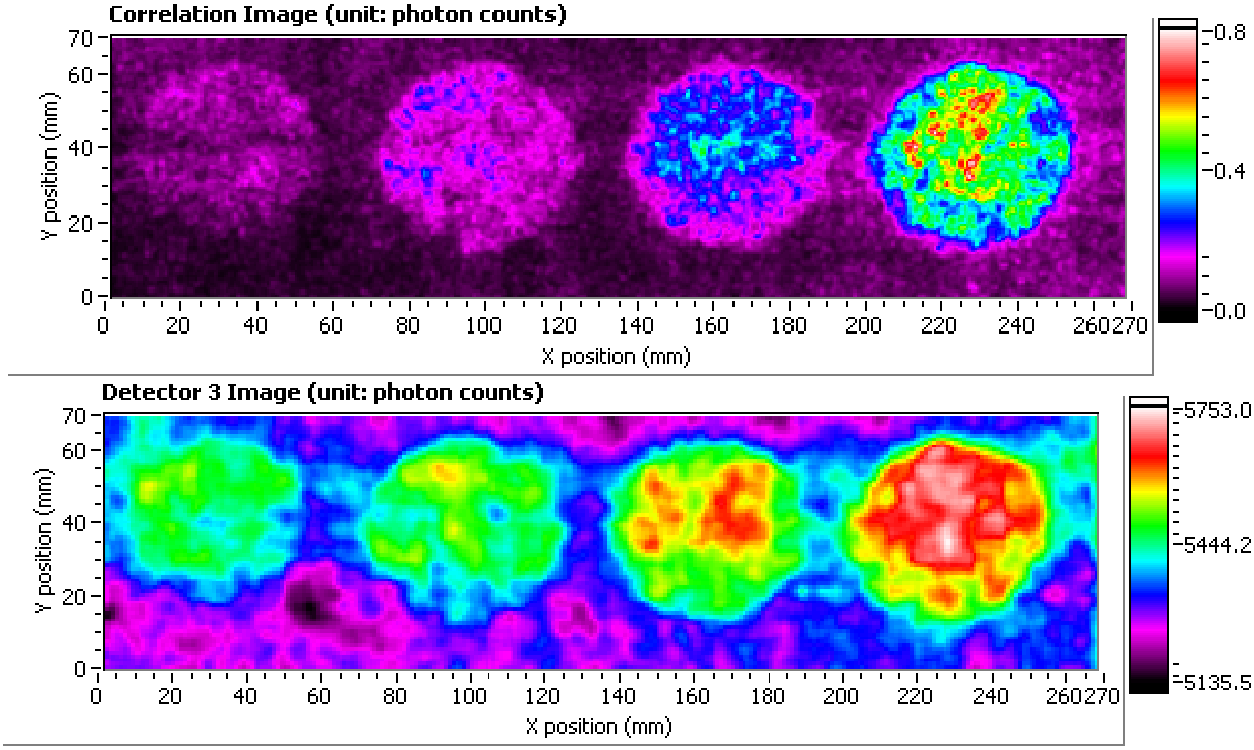

Figure 9 – RSD correlated (top) and detector 3 (bottom) images through TRANSCO insulation with deposits of boric acid in concentrations of 51, 101, 153, and 204 mg/cm^2 (from left to right) in 5 cm diameter circles

To demonstrate some of the features of the image processing, Figure 10 is a cropped image with the entire contrast range over the lowest concentration deposit (51 mg/cm^2). These results indicate that concentrations down to about 50 mg/cm^2 can easily be detected with an x-ray backscatter RSD scan without removing the RPV insulation. The darker lower contrast area is a result of crack that formed in the boric acid deposit as the steel plate was being handled.

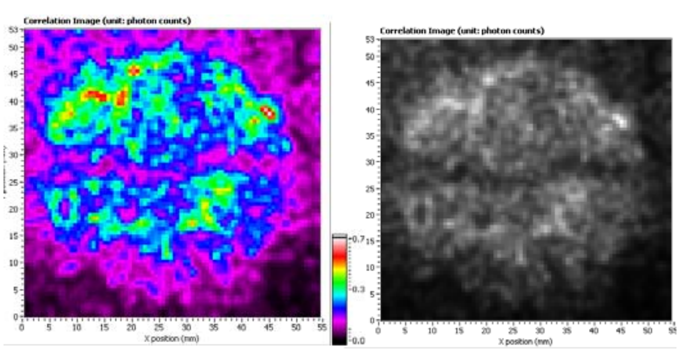

Figure 10 – RSD color (left) and grayscale (right) images through TRANSCO insulation of boric acid 51 mg/cm^2 in 5 cm diameter circle

Once it was determined that small concentrations (~50 mg/cm^2) could be detected, it was time to test for very small amounts that may be present or seen during a visual inspection. Boric acid deposits are not typically in perfect geometric circles. Figure 11 shows 50 mg (left) and 100 mg (right) deposits of irregularly shaped boric acid on a steel plate. A United State dime is shown in the figure for perspective. The steel plate was placed behind the TRANSCO insulation with a 7.62 cm air gap between the insulation and the steel plate as shown in Figure 8, and scanned with an x-ray backscatter RSD system. Initially the boric acid deposits were difficult to detect. The illumination beam aperture was decreased in diameter from 1.5 mm to 1 mm and increased in thickness from 1.65 mm to 3.00 mm. The aperture changed increased the beam resolution and a scan was done at 100 kVp and 45 mA. This inspection took about 5 minutes and both the 50 mg and 100 mg boric acid deposits are clearly visible in the image, Figure 12. It is important to note that the boric acid deposits are still visible even with the dime taking a portion of the image contrast.

Figure 11 – 50 mg (left) and 100 mg (right) of boric acid residue on steel

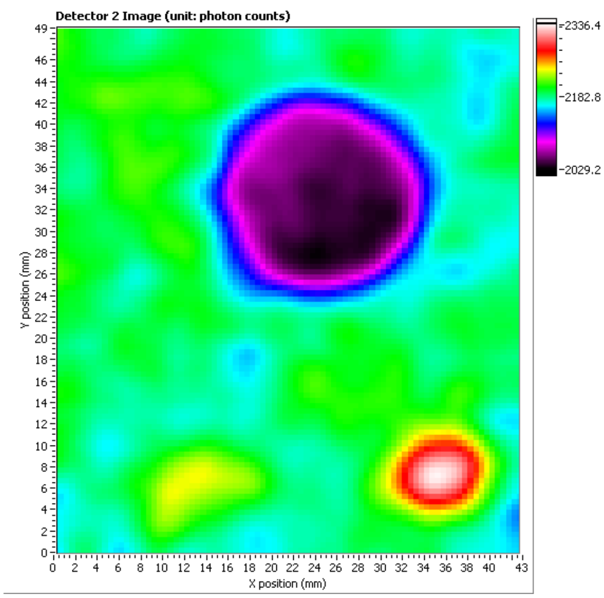

Figure 12 – RSD image of a dime (top), 50 mg (left), and 100 mg (right) of boric acid residue on steel through TRANSCO insulation

III.C. Current State of Technology

The Radiography by Selective Detection (RSD) x-ray backscatter scanning system is currently being used in industrial application by Lockheed Martin Space Systems Co. for the detection of flaws and defects in the Spray-on-Foam insulation used on the external tank of the space shuttle. Six systems, like the one shown in Figure 4, have been built and are in use today. Although the current system is a little bit large for maneuvering around RPV drives and instrumentation, x-ray generator tubes, and detectors are available for building a much smaller, more compact, and lighter scanning head. A conceptual design for a compact scanning system is shown in Figure 13. This design features an off-the-shelf, 100 kVp, industrial quality x-ray generator, and a tested detector configuration, which results in an RSD scanning system weighing around 9.1 kg and sizing in at about 13.3 x 10.8 x 27.8 cm. This system can be built with either a fixed or rastering illumination beam.

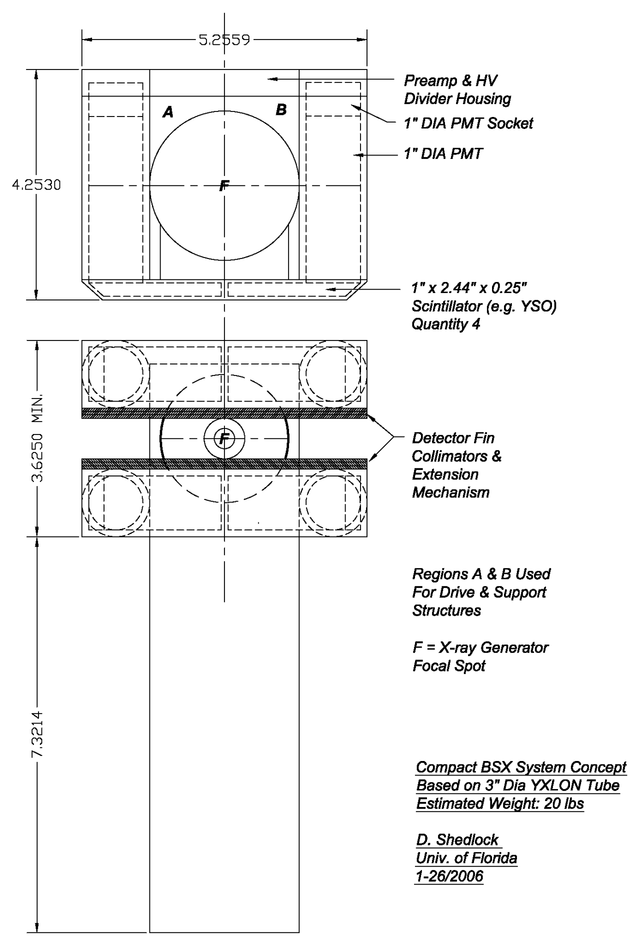

Figure 13 – RSD System Concept

IV. CONCLUSIONS

Radiography by selective detection (RSD) preferentially selects x-ray backscatter field components to enhance the contrast and detection of specific features. Acquired images have clearly shown, for a variety of conditions, that proper selection of x-ray field scatter components leads to a significant improvement in image quality and contrast, so much so that in some cases objects or features that are not visible in conventional CBI become readily discernable. The system has been used to detect cracks, voids, delaminations and corrosion in a wide variety of material including: aluminum, plastics, honeycomb structures, laminates, steel, reinforced carbon-carbon composites (RCC), concrete, and titanium. More recently, RSD scanning systems are being used by Lockheed Martin Space Systems Co. and NASA to detect defects in the spray on foam insulation (SOFI) used on the external fuel tank of the space shuttle.

This paper demonstrates that a system is currently available that could allow for reactor pressure vessel penetration inspection without having to remove the mirror insulation. Relatively quick scans have found 50 and 100 mg deposits of boric on steel through 7.62 cm of TRANSCO insulation with a 7.62 cm gap between the insulation and the steel plate. A customizable system**,** specific to a particular application**,** can be built based on the existing technology. The current RSD scanning head can be reduced in size and weight to allow scanning access to reactor pressure vessel penetrations.

V. FUTURE WORK

The RSD scans performed for this preliminary evaluation work were done using equipment that has been optimized for performing NDE work on Lockheed Martin's SOFI, used on the external tank of the space shuttle. The x-ray tube is limited to 100 kVp and the detector locations are relatively fixed. Additional work should include optimization specifically for inspecting RPVs through mirror insulation. Some of this work would include; simulation coupled to experimental work in order to determine optimum scanning energy, detector placement and configuration, and construction and testing of a compact scanning head to meet the space requirements based on optimization.

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