

NON-DESTRUCTIVE EXAMINATION (NDE) DEVELOPMENT FOR THE INSPECTION OF COPPER COATINGS ON USED FUEL CONTAINERS

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Abstract

In the Nuclear Waste Management Organization's (NWMO) concept of a deep geological repository for the storage of Canada's spent nuclear fuel, a major engineered component in the system is the Used Fuel Container (UFC). NWMO's design for the UFC incorporates an external copper coating bonded directly to the carbon steel structural core for corrosion protection. This paper reports current work being carried out in collaboration with Nucleom Inc. for Non-Destructive Examination (NDE) technique development used for the inspection of electrodeposited and cold spray copper coatings utilized in the UFC design. A combination of ultrasonic and eddy current methods are being investigated for the detection and sizing of volumetric, surface and dis-bond defects and verification of coating thickness. The results to date from inspection trials are presented herein.

1.0 Introduction

The Nuclear Waste Management Organization (NWMO) (Toronto, Canada) is responsible for the implementation of a deep geological repository for the storage of Canada's spent nuclear fuel. A major engineered component in this system is the Used Fuel Container (UFC). NWMO's UFC design has been optimized for CANDU fuel. It is a mid-sized capacity vessel (12 bundle/layer x 4 layers = 48 bundle) which incorporates a carbon steel core for structural strength and a 3 mm thick exterior copper coating for corrosion resistance.

The steel core consists of a cylindrical shell affixed to two hemi-spherical heads at either end. Two welds are applied in the assembly of the core; a "factory weld", joining the lower head to the shell (i.e., the lower assembly) and the "closure weld" applied after loading with fuel at the Used Fuel Packing Plant (UFPP). During manufacture, the exterior surface of the steel core "factory" components (lower assembly and upper head) will be pre-coated with 3 mm of electrodeposited copper prior to delivery to the UFPP. After the UFC is loaded with fuel, the vessel will be welded shut by laser-hybrid-arc-welding followed by the application of the required 3mm thickness of copper to the closure weld region by the cold spray coating process.

The NWMO is currently executing a multi-year Proof Test Program to validate the design of the UFC. Critical design characteristics of the copper corrosion barrier are the thickness, quality (absence of rejectable defect) and substrate bond (adhesion). The verification of these design characteristics will be conducted by non-destructive examination (NDE) methods. The copper

coating thickness is closely tied to the limit of NDE detectability for volumetric and surface flaws. The limit of NDE detectability will be used to further define the required copper coating thickness as the sum of:

1. the minimum corrosion allowance plus
2. the detectible defect size plus
3. the maximum allowable surface damage plus
4. a safety factor.

As part of NWMO's copper coating development program, preliminary NDE investigations [1] were performed in 2012 by the University of Windsor (UWindsor Institute for Diagnostic Imaging Research). Ultrasonic examination was utilized to inspect/characterize 3mm cold spray coatings applied to 38 mm thick UFC steel substrate samples. Several inspection methods were investigated: conventional pulse-echo ultrasonic, scanning acoustic microscope, phased array ultrasonic and matrix array ultrasonic systems. It was found that artificial reflectors (0.8 mm diameter flat bottom holes) representing volumetric defects, natural defects (inclusion clusters~1-2mm) as well as the copper-steel interface (i.e., bond) could be detected by ultrasonic test methods. This study did not utilize reflectors <0.8mm and no conclusions regarding defect detection beyond this level were established.

Following on from the preliminary investigations at UWindsor, it was decided that further development work was required to be able to implement an inspection system to be used during the manufacture of prototype UFCs. NWMO enlisted Nucleom Inc. (Quebec City, Canada) to aid in the development of techniques, equipment, and procedures for the inspection of the steel closure weld and copper coating of the UFC. The data presented herein details the initial copper coating inspection development work completed to date by Nucleom, Inc. using commercially available equipment. Subsequent development work would make use of custom equipment as required.

2.0 Non-Destructive Examination Technique Development

Within the framework of NWMO's UFC Development Program, Non Destructive Examination (NDE) procedures are required to ensure service performance for its intended safety function: containment and isolation of the used nuclear fuel for several thousand years. Phase 1 of the program involves selecting, developing, and qualifying NDE methods appropriate for the volumetric and surface examination of the UFC closure welds and external copper coating. Phase 2 of the program involves the design and specification of a NDE System (Inspection and Process Application Equipment) for the purposes of constructing a pilot scale inspection cell to be used in the inspection of UFC prototypes during the execution of the Proof Test Program. Phase 1, detailed in this paper, involved the following:

- Review codes and standards to determine acceptable techniques, equipment, and preliminary target flaw sizes.
- Develop representative samples to aid in NDE technique development.

- Using the codes and standards as a basis, develop the NDE techniques, using appropriate methods, equipment, and probes for the detection and sizing of flaws in the copper coating.
- Perform a Probability of Detection (PoD) analysis to finalize target flaw sizes; this work to be reported at a later date.

2.1 Review of Codes and Standards

The codes and standards contain mandatory requirements and non-mandatory guidance for NDE for a wide variety of applications. Deviations based on engineering judgement are allowed as long as they are consistent with code philosophy and do not overrule mandatory requirements or specific prohibitions of the code. Most requirements or recommendations found in the codes & standards are common practices of the NDE industry.

Review of ASME Section III (Division 3) along with any referenced sections and code cases led to the selection of phased array ultrasonic testing (PAUT), time-of-flight diffraction (TOFD)(not discussed in this work) and eddy current testing (ET) as the examination methods to be used for inspection of the copper coating in order to achieve full volumetric coverage. Review of the codes also led to a preliminary target flaw size (TFS), as shown in Tables 1 and 2, to be used for design of the development, calibration and PoD samples. The preliminary TFS are based on code guidance and NWMO's requirements.

Table 1: Target Flaw Size (TFS) for copper coating volumetric ultrasonic inspection. [2]

Ultrasonic Acceptance Criteria (WC-5330)	Calibration Block Requirements (T-434.4.1 & T-434.4.2)		Preliminary Target Flaw Size		
	Reflector Type		Reflector Type		
	SDH	FBH	SDH		FBH
Length	Diameter	Diameter	Length	Diameter	Diameter
0.25in. (6mm)	0.0625in. (1.5mm)	0.125in. (3mm)	0.125in. (3mm)	0.0394in. (1mm)	0.0394in. (1mm)

SDH = Side drilled hole
FBH = Flat bottom hole

Table 2: Target Flaw Size (TFS) for copper coating surface eddy current inspection. [2]

Eddy Current Acceptance Criteria (Code Case N-748)	Calibration Block Requirements (III-860 & VI-832)		Preliminary Target Flaw Size		
	Notch				
			Reflector Type		
			Linear	Rounded	
Rounded indication Diameter	Length	Depth Extent	Length	Depth Extent	Diameter
0.188in. (5mm)	0.25in. (6mm)	0.020in. (0.5mm)	0.125in. (3mm)	0.0125in. (0.3mm)	0.0787in. (2mm)

SDH = Side drilled hole
FBH = Flat bottom hole

2.2 Representative Samples for Technique Development

In order to assist in NDE technique development, representative samples containing manufactured flaws were required. The flaw types identified as being most common were:

- Lack of bonding between the carbon steel substrate and the copper coating;
- Linear and rounded surface connected indications (open on the copper coating surface);
- In-volume voids embedded in the copper coating layer;
- Variation in copper coating thickness.

Based on the code review and operational experience provided by the coating provider, technique development blocks containing combinations of side-drilled holes (SDHs), flat-bottom holes (FBHs), and notches were manufactured. These representative samples allow the effectiveness of a particular NDE method to be tested against a flaw that may be encountered in a UFC.

2.3 NDE Technique Development

2.3.1 NDE Modelling

The NDE techniques and equipment to be used should be chosen to meet the following criteria:

- Detect and size defects in various orientations.
- Ensure coverage of the area in question.
- Ensure the probe/wedge assembly can fit in the available surface area.

For each selected NDE technique, modelling (ray tracing, acoustic beam simulation or theoretical calculation of penetration depth) was performed to assess volumetric coverage, suitable equipment, and preliminary capabilities with regards to specific types of flaws and issues. These simulations were used to define a baseline set of equipment and parameters rather than having to resort to trial-and-error methods, which can be costly and time-consuming.

2.3.2 Acoustic Ray Tracing

Acoustic ray tracing simulation (Figure 1) computes and displays ultrasound rays propagating in a specimen. The ray paths can undergo reflection and transmission, including mode conversions, within simple or complex geometries.

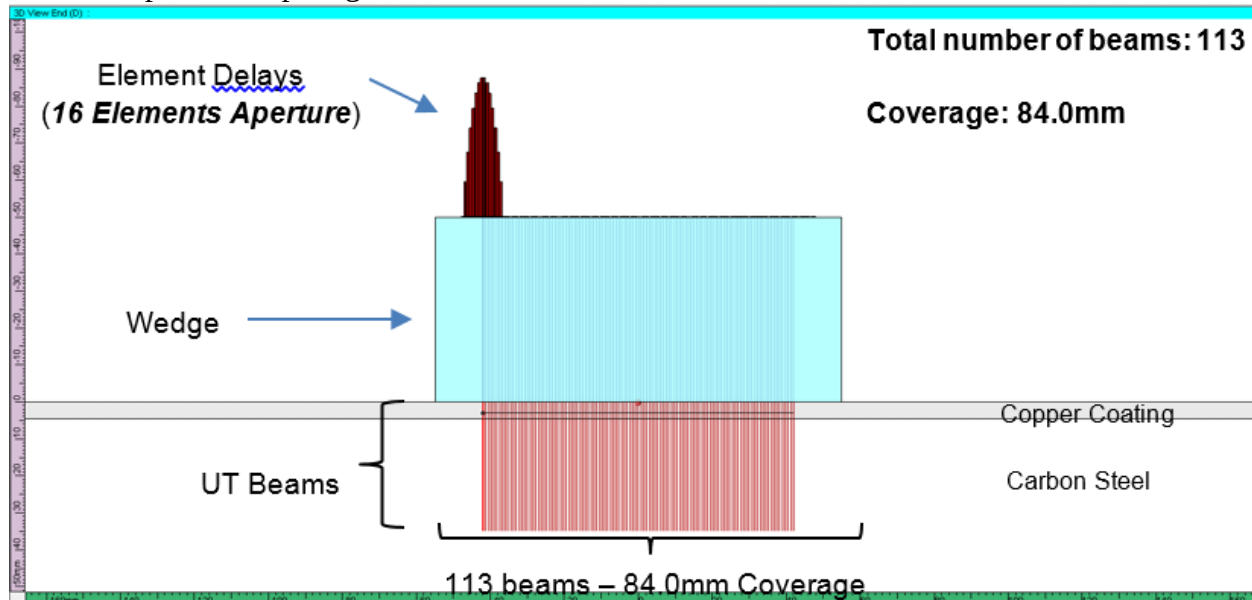


Figure 1: Acoustic ray tracing of 0-degree PAUT scan. [3]

For the 0-degree simulation, it was found that:

- This configuration is appropriate for detection and sizing of planar and void-like defects.
- The ray tracing shows proper coverage of the entire copper coating thickness (not taking into account the “wedge/specimen” interface echo).

2.3.3 Acoustic Beam Simulation

Acoustic beam simulation (Figure 2) presents the ultrasound beam shape in the material to evaluate the beam profile and focal zone at -6dB. This information allows to further define transducer capabilities and coverage.

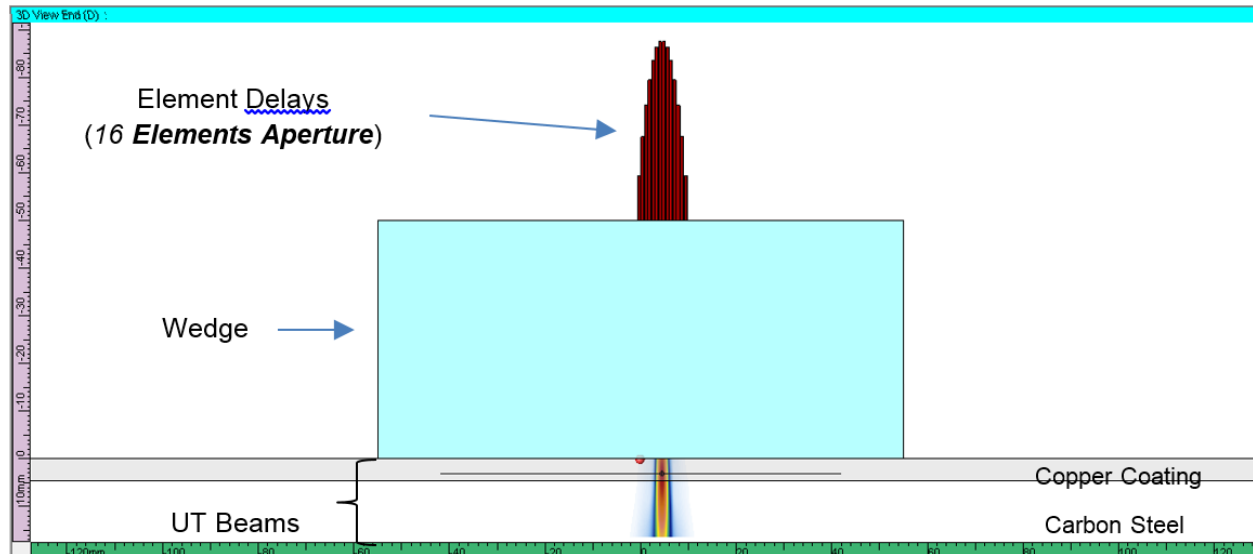


Figure 2: Acoustic beam simulation of 0-degree scan. [3]

For the 0-degree beam simulation, it was found that:

- The focal zone length is sufficient to cover the 4.52mm of copper coating.
- At 5MHz, the theoretical minimum detectable defect size is 0.47mm (i.e. half of the wavelength). In theory, the smallest manufactured defects (0.5mm) should be detectable.

2.3.4 Eddy Current Depth of Penetration

Eddy current examination was chosen for surface or near surface flaw detection in the copper coating. Eddy current density, which varies through the depth of the material, is based on various material properties and may be calculated as follows:

Equation 1 – Eddy Current Depth of Penetration [6]

$$\delta(mm) = 50 \sqrt{\frac{\rho}{f \times \mu_r}}$$

Where:

ρ = Material Resistivity (Ohms-mm)

f = Inspection Frequency (Hertz)

μ_r = Relative Magnetic Permeability

Equation 1 describes the standard depth of penetration, at which eddy current density decreases to 1/e (natural logarithm number). At three standard depths of penetration (3δ), the eddy current density is reduced to approximately 5% and beyond this value, is too small to generate a readable signal. Calculation showed that with frequencies between 600 and 900 kHz, which are necessary to detect small indications, the penetration of the eddy current generated fields is 2.7mm, beyond which the strength of the signal is insufficient for flaw detection.

3.0 NDE Experimental Equipment and Method

NDE experimental scanning was carried out using the following equipment:

- Zetec ZIRCON[®] phased array system with 32/128PR configuration. Zetec 5MHz phased array transducer (LL-5MHz) with 0-degree longitudinal wave wedge (UT-Probe1).
- Eddyfi Ectane[®] eddy current test instrument, with a 64 channel configuration. Eddyfi ECA-PDD-056-250-032-N03S padded ECA probe (ET-Probe1).

NDE data acquisition and analysis was performed by a Canadian General Standards Board (CGSB) certified Level 2 or Level 3 NDE technician in the specified method.

The representative samples used for analysis were made of a carbon steel substrate (300mm x 150mm x 38mm for Dev-1, and 150mm x 150mm x 38mm for Dev-3 and Dev-4) with a copper coating approximately 4.5mm in thickness. The flaws embedded were as follows:

- Sample Dev-1 → electrodeposited copper coating with 16 FBHs and 8 SDHs
- Sample Dev-3 → electrodeposited copper coating with 16 FBHs and 13 electrical discharge machining (EDM) notches
- Sample Dev-4 → cold-spray copper coating with 16 FBHs and 13 EDM notches

4.0 Experimental Results

4.1 Ultrasonic Scanning

Block Dev-1 contains 16 FBHs and 8 SDHs of varying sizes and depths in the coating thickness (CT). A representative ultrasonic top-down (C-scan) image of block Dev-1 is shown in Figure 3, for visualization of flaw characteristics and locations.

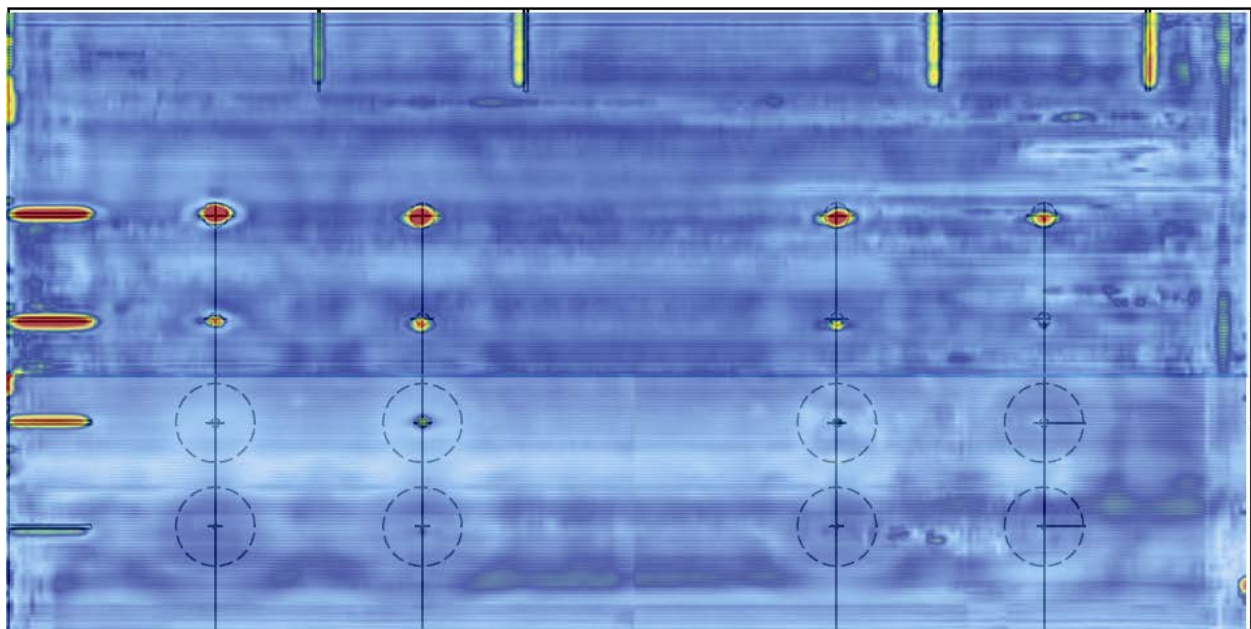


Figure 3: Ultrasonic C-scan data from 5MHz, 0-degree probe of block Dev-1. [3]

The following table presents a summary of the detection results for the FBHs with signal amplitude information normalized to the 1.5mm diameter FBH at 80% Full Screen Height (FSH) using UT-Probe1.

Table 3: Sub-Surface FBH Detection – UT-Probe1 [3]

Diameter	FBH @ 0xCT		FBH @ 1/4xCT		FBH @ 1/2xCT		FBH @ 3/4xCT	
	Status	%FSH	Status	%FSH	Status	%FSH	Status	%FSH
0.5mm	ND	--	D	17.9%	ND	--	ND	--
1.0mm	D	27.4%	D	33.6%	D	28.5%	D	38.9
1.5mm	D	81.6%	D	82.8%	D	79.9%	D	78.5%
3.0mm	D	>100%	D	>100%	D	>100%	D	>100%

CT: Coating Thickness

D: Detected

ND: Not Detected

The following observations were made for detection of the FBHs:

- The 0.5mm FBHs were not detected which could be a consequence of the size of the ultrasonic beam being much larger than those FBHs (seen from beam simulation), and the surrounding reflections at the carbon steel/copper interface or the wedge/copper interface.
- All FBHs with diameter of 1.0mm and higher are detected.
- For sizing, most FBHs are smaller than the ultrasonic beam. The 0.5mm to 1.5mm FBHs are sized readily at 2mm while the 3mm FBHs are more easily estimated to 3mm.

The following table presents a summary of detection results for the SDHs with signal amplitude information normalized to the 1mm diameter SDH, located at 1/2xCT, at ~80%FSH using UT-Probe1.

Table 4: Sub-Surface SDH Detection (Diameter 1mm, varying depth) – UT-Probe1 [3]

Diameter	SDH @ 0xCT		SDH @ 1/4xCT		SDH @ 1/2xCT		SDH @ 3/4xCT	
	Status	%FSH	Status	%FSH	Status	%FSH	Status	%FSH
1.0mm	D	>100%	D	>100%	D	80.3%	D	48.3%

CT: Coating Thickness

D: Detected

The following observations were made for detection of the SDHs at various coating depths:

- 4 out of 4 SDHs were detected.
- For depth location measurement, the SDHs were located within 0.3mm of the nominal location in the copper coating.

Table 5: Sub-Surface SDH Detection (Depth 1/2xCT, varying diameter) – UT-Probe1 [3]

Depth	$\phi = 0.5\text{mm}$		$\phi = 0.8\text{mm}$		$\phi = 1.5\text{mm}$		$\phi = 3.0\text{mm}$	
	Status	%FSH	Status	%FSH	Status	%FSH	Status	%FSH
1/2xCT	D	57.2%	D	72.7%	D	78.8%	D	93.5%

CT: Coating Thickness

D: Detected

The following observations can be made for detection of the SDHs of varying sizes at $\frac{1}{2}$ CT:

- All SDH at $\frac{1}{2}$ xCT are detected.
- For depth location, the SDH are located within 0.4mm of nominal locations in the copper coating.

4.2 Eddy Current Scanning

The Dev-3 and Dev-4 samples are designed for evaluation of surface flaws such as surface connected notches and holes. The main detection and sizing tool for such defects is eddy current testing. The Dev-3 and Dev-4 samples were examined using ET-Probe1 and was used to estimate the depth extent of flaws. A representative ultrasonic top-down (C-scan) image of block Dev-3 is shown in Figure 4 for reference only, for visualization of flaw characteristics and locations.

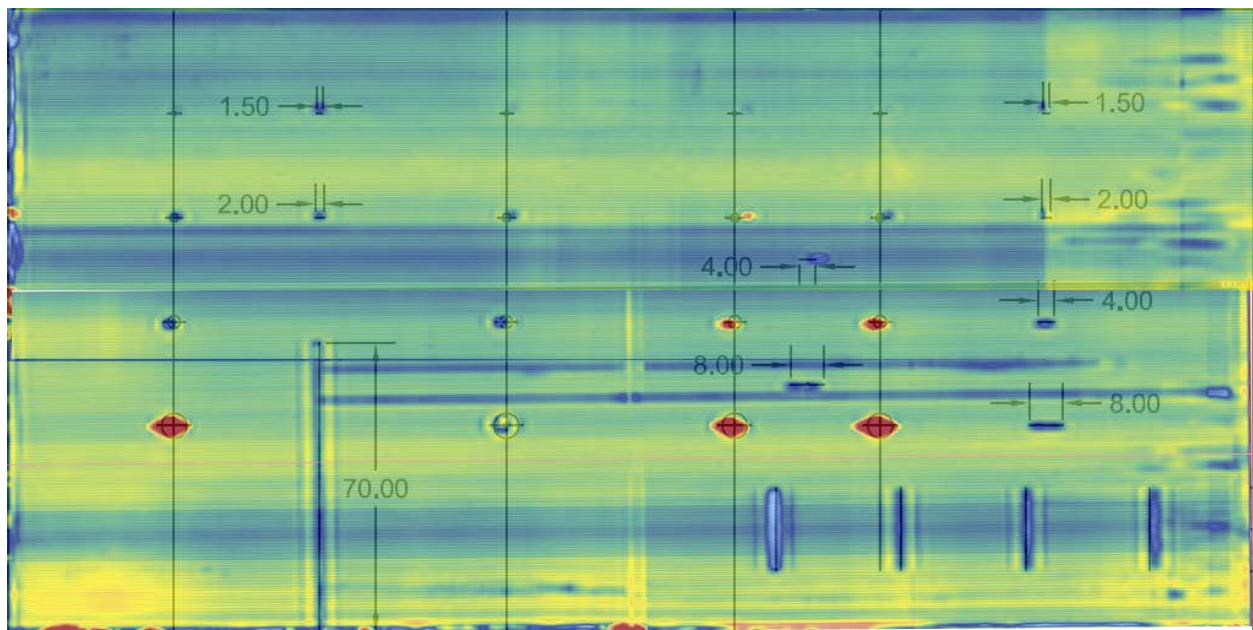


Figure 4: Ultrasonic C-scan data from 5MHz, 0-degree probe of block Dev-3. [3]

The following table presents a summary of the detection results of the FBHs on the Dev-3 and Dev-4 samples.

Table 6: Surface FBH Detection. [3]

Nominal Diameter	1/4xCT	1/2xCT	3/4xCT	0xCT
	Status			
0.5mm	D	D	D	D
1.0mm	D	D	D	D
1.5mm	D	D	D	D
3.0mm	D	D	D	D

CT: Coating Thickness

D: Detected

The following observations can be made for detection of FBHs:

- 16 out of 16 FBHs are detected in Dev-3.
- 16 out of 16 FBHs are detected in Dev-4.
- With a frequency of 100kHz, all FBHs of the same diameter but at different depths show the same signal (phase and amplitude).
- With a frequency of 500kHz, FBHs of the same diameter but different depth extent have signals of different amplitude values.
- Diameter measurement accuracy is limited by the scanning resolutions on the index- and scan-axis as well as the size of the ECA probe coils.
- Depth measurement of the FBHs is challenging. A transmit-receive configuration (used for all probes) is influenced by the exact “location” of the FBH on the array. Manual scans could be repeated on the same features but if the coil assembly crosses the FBH right in the middle or on the edges, the signal signature will be different and depth evaluation would change accordingly.

The following table presents a summary of the detection results of the EDM notches on the Dev-3 and Dev-4 samples.

Table 7: Surface EDM Notches Detection [3]

Nominal Depth Extent	Set 1	Set 2	Set 3	Set 4
	Status			
0.3mm	D	D	D	D
0.5mm	D	D	D	
1.0mm	D	D	D	
2.0mm	D	D	D	

D: Detected

The following observations can be made for detection of the EDM notches:

- 13 out of 13 EDM notches were detected in Dev-3.
- 13 out of 13 EDM notches were detected in Dev-4.
- A depth sizing curve can be generated to estimate the depth extent of the EDM notches.

5.0 Conclusions

The NDE examination technique trials conducted for the development of the copper coating inspection provided detection and sizing capabilities for each defect type. Based on empirical evidence, the following conclusions can be made:

- For 0°LW examination of the copper coating, a pitch-&-catch 5MHz phased array transducer offers good performance for the copper coating evaluation (presence of in-volume flaws).
- Eddy current has proven to be an efficient detection and sizing tool for surface breaking flaws as well as a confirmation tool for sub-surface flaws.

- A combination of ultrasonic technique (0°LW PAUT) and eddy current (padded ECA probe) has shown to provide increased detection and sizing capabilities. Using two independent methods adds confidence in the results when flaws are detected with both techniques especially for near surface indications.
- The selected NDE techniques can achieve 100% coverage of the copper coating.
- For the definition of the preliminary TFS, the values presented in Tables 1 and 2 are considered achievable and will serve as the starting point of the PoD study.

6.0 Recommendations & Future Work

The following are recommendations for subsequent project activities:

- For PoD determination (scan of PoD samples), the following sensors will be simulated:
 - ET-Probe1 which provided some of the best results and whose implementation requires little work.
 - 5MHz PAUT transducers whose frequency is as recommended by codes and standard and that gave the best results in terms of detection and sizing.
- Length and height sizing tolerances should be reviewed based on the PoD data evaluations.
- To improve flaw characterizations and the sizing tolerance for the in-situ inspection, it is recommended to use dedicated transducers and wedges as well as dedicated eddy current probes.
- For a PAUT pitch-&-catch configuration, the use of 2D matrix probe should be considered in order to optimize beam cross-over depth. This would likely improve the flaw characterizations and sizing.

7.0 References

[1] R. Maev, S. Titov, “DEVELOPMENT OF NON DESTRUCTIVE EXAMINATION METHODS FOR COPPER COATING OF USED FUEL CONTAINERS”, Technical Report for Nuclear Waste Management Organization. Toronto, Canada. January 2013

[2] Nucleom Inc., “C14-NWM-01_TR 12-B_Coating Codes Standards and Preliminary TFS Report_Nucleom”. Technical Report for Nuclear Waste Management Organization. Quebec, Canada. March 2015.

[3] Nucleom Inc., "C14-NWM-01_TR.13-Draft01_Copper Coating Inspection Techniques Report (13M) - NDE Technique Evaluation_Nucleom,". Technical Report for Nuclear Waste Management Organization. Quebec, Canada. April 2015.