LA-UR-16-25431
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Title:	Feasibility Study of Non-Destructive Techniques to Measure Corrosion in SAVY Containers
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Intended for:	Report
Issued:	2016-07-22

Feasibility Study of Non-Destructive Techniques to Measure Corrosion in SAVY Containers

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ADPSM: Nuclear Process Infrastructure, NPI-2

July 15, 2016

INTRODUCTION

Stainless Steel SAVY containers are used to transport and store nuclear material. They are prone to interior corrosion in the presence of certain chemicals and a low-oxygen environment. SAVY containers also have relatively thin walls to reduce their weight, making their structural integrity more vulnerable to the effects of corrosion. A non-destructive evaluation system that finds and monitors corrosion within containers in use would improve safety conditions and preclude hazards such as the ones shown in figures 1 and 2.

Non-destructive testing can determine whether oxidation or corrosion is occurring inside the SAVY containers, and there are a variety of non-destructive testing methods that may be viable. The following feasibility study will objectively decide which method best fits the requirements of the facility and the problem. To improve efficiency, the containers cannot be opened during the non-destructive examination. The chosen technique should also be user-friendly and relatively quick to apply. It must also meet facility requirements regarding wireless technology and maintenance.

A feasibility study is an objective search for a new technology or product to solve a particular problem. First, the design, technical, and facility feasibility requirements are chosen and ranked in order of importance. Then each technology considered is given a score based upon a standard ranking system. The technology with the highest total score is deemed the best fit for a certain application.

Stainless steel alloys contain at least 10.5% chromium by mass. [1] The chromium present in the steel forms a layer of chromium oxide when exposed to the air, preventing oxygen from corroding the surface of the steel. The layer quickly reforms when the alloy's surface is scratched (passivation). [2] In low oxygen environments, the chromium oxide layer does not effectively regenerate, making the metal vulnerable to corrosion. Hydrogen gas released during radiolysis also increases the likelihood of corrosion.

There are several potential corrosion mechanisms in stainless steel under typical storage and transportation conditions. Pitting corrosion occurs in the presence of high concentrations of chloride compounds. Once the oxide layer is broken and a pit is formed, the pit will deepen as more non-corroded metal is exposed. General corrosion can form over a large are of a stainless steel surface in acidic environments. [3]

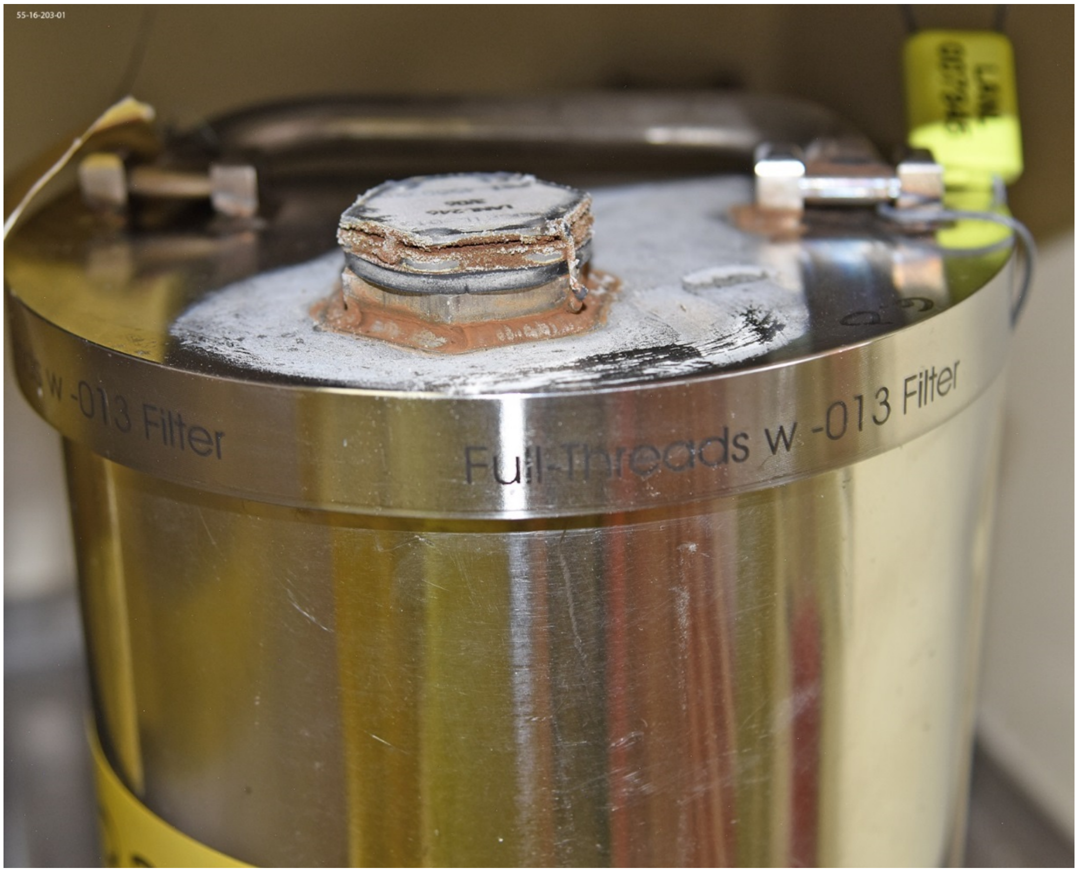

Fig. 1: Hagan canister with unacceptable corrosion levels.

Fig. 2: SAVY container with interior corrosion.

REQUIREMENTS

Design Requirements:

These requirements are non-negotiable, with possible scores being either pass or fail. If a technology fails here, it will not be considered further.

1. Container cannot be opened. [0/1]
2. Method applied cannot exceed certain criticality risk limits. [0/1]
3. System cannot use wireless communications. [0/1]
4. Soft cost cap of $250,000 [0/1]
5. Must be applicable to stainless steel (304L or 316L). [0/1]
6. It must be possible to detect corrosion with the system [0/1]

Scoring Guidelines:

Technical and Feasibility Requirements each have a relative importance score given in brackets. Each technique is assigned a compliance grade from 1-10 for each requirement based upon the following rubric.

Table 1: Feasibility Requirement Score Rubric

Score	Scoring Guideline	
	Requirement Importance	Technique Score
1	Negligible Importance	Poor performance, requirement conditions barely met
2	Negligible Importance	Poor performance, requirement conditions barely met
3	Useful but not important	Below average performance, essential requirement conditions met
4	Useful but not important	Below average performance, essential requirement conditions met
5	Important but not critical	Average performance, All requirement conditions met
6	Important but not critical	Average performance, All requirement conditions met
7	Important but not critical	Above average performance, Requirement conditions exceeded
8	Critical, Determines project's success	Above average performance, Requirement conditions exceeded
9	Critical, Determines project's success	Excellent performance Requirement drastically exceeded.
10	Critical, Determines project's success	Excellent performance Requirement drastically exceeded.

Technical:

Technical requirements are used to assess how well the technology matches the measurement or performance necessary for the specific application. These are more important than feasibility requirements.

1. Accuracy
    - *Systematic error*
    - *System sensitivity*
    - *Propagation of error through the analysis process*
2. Precision
    - *Repeatability*
    - *Potential for human error*
3. Detection Limit
    - *Lowest limit of corrosion detection.*
    - *Limit of Blank – highest apparent corrosion in a blank control sample*
4. Geometry and Surface Compatibility
    - *How much surface area is required to make a measurement?*
    - *Can the technique be applied to all the surfaces of the can?*
    - *How does the technique perform on thin walls?*
5. Surface Information
    - *Can the system discern between different surface corrosion phenomena?*
    - *How much information can the system provide about these phenomena?*

Feasibility:

Feasibility requirements assess how compliant a technology is with facility-specific safety, size, and cost considerations. These are more flexible than technical requirements.

1. Ease of use
   - *Necessary training to operate the system*
   - *How objectively interpretable is the data?*
   - *Has this technique been used to perform a similar task before?*
   - *Vendor support*
2. Processing Time
   - *How much time is required to process a can?*
   - *How frequently will the system require maintenance?*
3. Financial Feasibility
   - *Overall price of system*
   - *Useable life of the instrument*
   - *Maintenance cost/frequency, warranties*
   - *Power/resource/personnel requirements*
4. Criticality Risk
   - *How does the technique affect the nuclear material inside the can?*
   - *Does the system tend to reflect neutrons?*
   - *Are there components that increase criticality risks?*
5. Portability
   - *Weight*
   - *Size*

- *Is the system especially fragile?*
- *Does the system have special movement/storage requirements?*

6. User safety
   - *Hazardous elements*

   Ergonomics

TECHNOLOGIES

Table 2: NDT Techniques Considered

NDT Technique	Status	Notes
Eddy Current	Viable	
Ultrasonic	Viable	
Dye Penetrant	Non-Viable	Requires access to interior surface [4]
Magnetic Particle	Non-Viable	Only useable on ferromagnetic materials [4]
Radiographic	Non-Viable	Unacceptable criticality risk [4]
Acoustic Emission	Non-Viable	Only detects stress changes under loading
Infrared/Thermal	Non-Viable	Temperature gradient not high enough
Remote Field	Non-Viable	Most applicable to ferromagnetic materials
Laser Shearography	Non-Viable	May require access to the interior [5]

Eddy Current Testing (ECT)

Eddy current testing uses electromagnetic induction to analyze a part for flaws. Probes use alternating current and coiled wire to create electromagnets. If the probe's magnetic field are near a conductive material, a circular flow of electrons known as an eddy current will develop. That eddy current will then generate its own magnetic field, which interacts with the probe and its field through mutual inductance. [6]

Deviations in metal thickness or defects like cracks and pitting alter the amplitude and pattern of the eddy current in turn its magnetic field. The probe detects these phenomena through changes in its impedance. The attached data processing instrument plots the impedance amplitude and phase angle, which can be used to identify changes in the test piece. [7]

Resolution is determined by probe type, while the potential detection capability is determined by material and equipment characteristics. Instruments must be calibrated with reference standards, and data must be compared with a control. Eddy Current Array (ECA) testing uses an array of ECT probes to increase resolution, inspection speed, and 2D imaging capabilities.

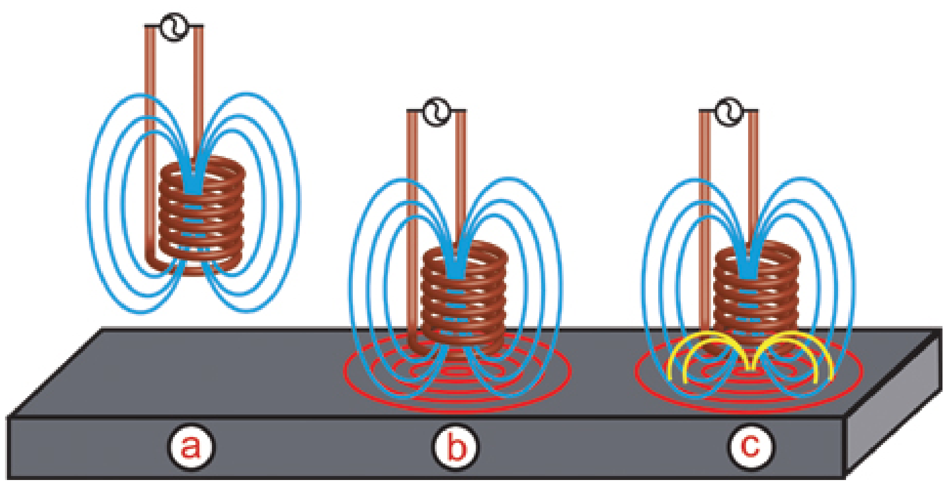

Fig 3. Blue lines and yellow lines are induced magnetic fields. The red lines are eddy currents. [8]

Advantages:

- Eddy current instruments are often used to detect and quantify corrosion on the inside of thin metal such as aluminum aircraft skin.
- Large surface areas can be quickly tested using ECT
- No post-inspection analysis, immediate results
- No liquid contact interface or chemicals/consumables required
- Sensitive to small cracks and other defects
- Equipment is portable
- Equipment can be used for many other NDT applications
- Minimum part preparation is required

Disadvantages:

- Lower, more penetrative test frequencies reduce resolution
- More conductive materials correspond to lower ECT penetration
- Highly user dependent (ECA much less so)
- Extensive skill and training is required depending on how ECT is applied
- Limited depth of penetration
- Slow inspections

Ultrasonic Testing (UT)

While here are several different types of ultrasonic testing probes, the basic mechanism remains the same. The general principle of ultrasonic testing (UT) is to generate sound waves travelling within the testing medium. When these sound waves encounter flaws, part of their energy will be reflected back to the transducer and displayed on the screen. The sound waves can either travel straight to the back wall of the material in a direct path, or they can travel in shear, diagonal path. Shear probes are used for flaw detection and direct, and axial probes are used for thickness measurements. [4]

To take thickness measurements, the transducers (probes) essentially act like stopwatches. First, they emit a pulse of sound and start counting. Once the echo bounces off of the back wall and is detected by the transducer, the total time is recorded. The wall thickness is then calculated using a calibrated measurement for the speed of sound in the test piece material. [9] Ultrasonic thickness gauges can be accurate down to the tens of thousands of an inch with the right transducer and proper calibration. [10]

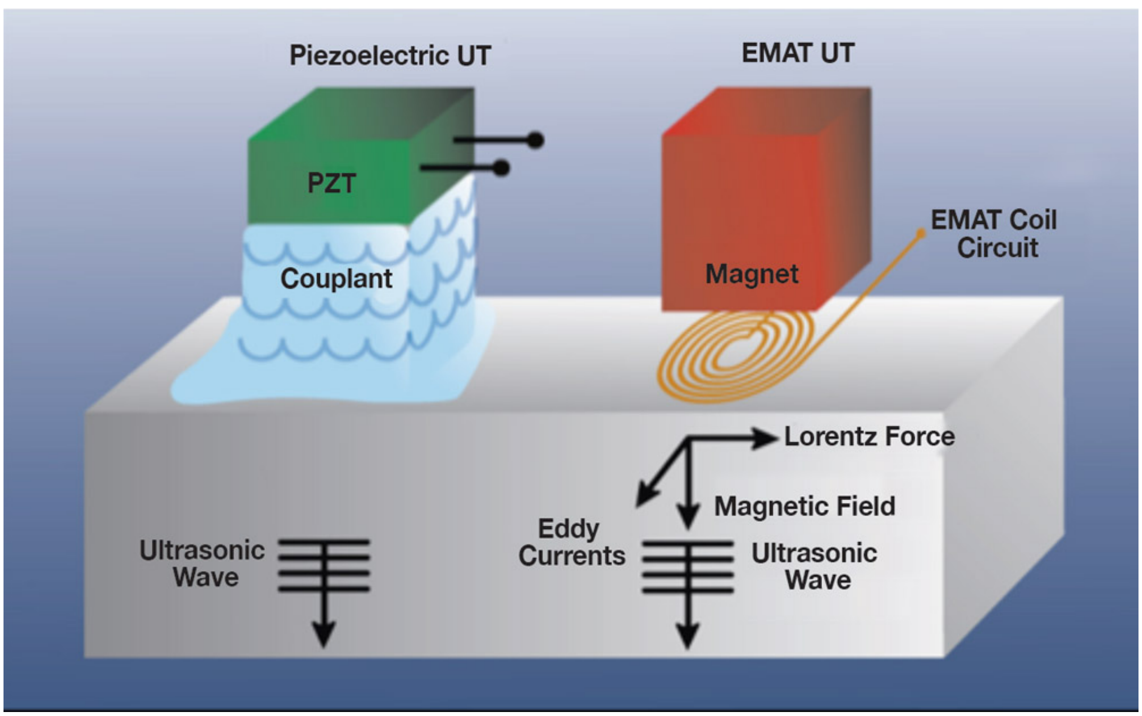

Fig. 4. Two different types of ultrasonic transducers: piezoelectric and electromagnetic acoustic transducers [4]

Piezoelectric Transducers (PT)

- Advantages:
  - Extremely portable
  - Probes can be custom-made for a particular application
  - Higher accuracy for wall-thickness measurements than other transducers
- Disadvantages:
  - Requires contact with a fluid intermediary couplant between the part and the transducer.
  - High frequency ultrasound not feasible due to piezoelectric material limitations.

Electromagnetic Acoustic Transducers (EMAT)

- Advantages:
  - No couplant or contact with test piece required
  - Can generate complex frequency patterns
  - Good flaw detection capabilities
- Disadvantages:
  - Requires large magnetic fields and high currents
  - Ultrasonic signals generated are relatively weak
  - A limited number of basic frequencies can be used
  - Relatively inaccurate for thin test pieces.

RESULTS

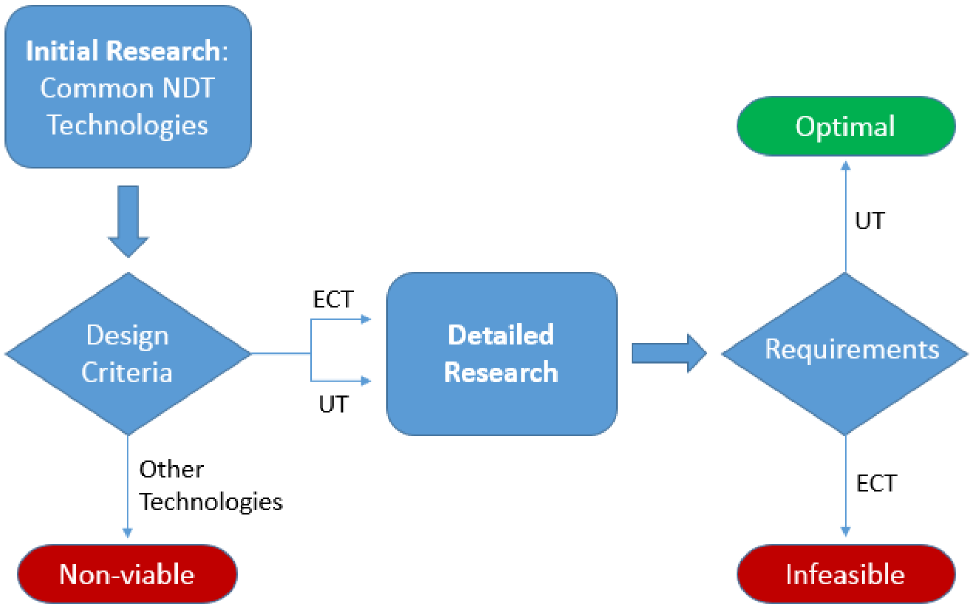

Fig. 5. Flowchart of feasibility study process

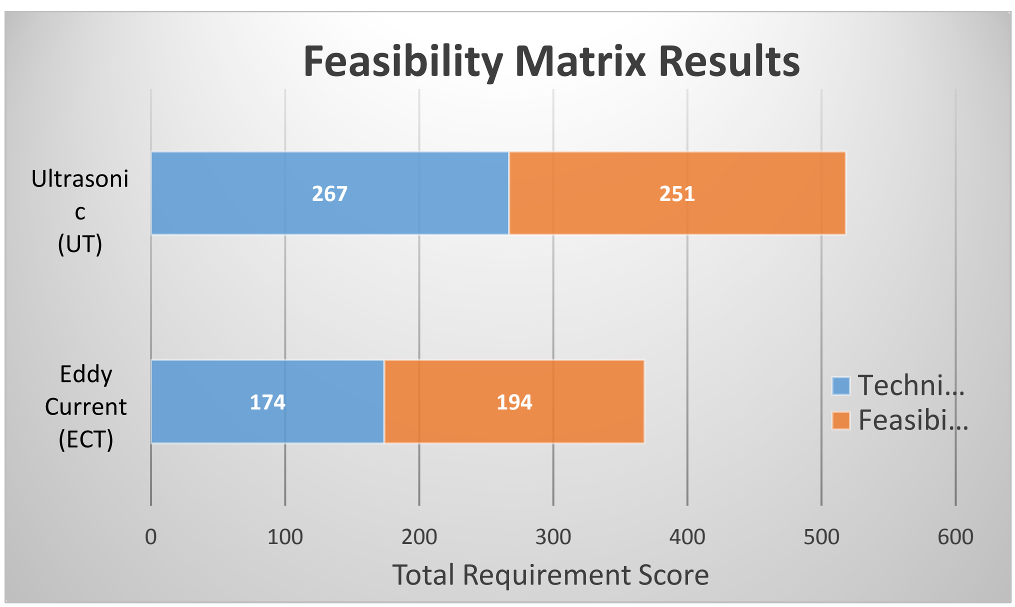

Fig. 6: Feasibility Matrix Results.

The orange bars correspond to the facility feasibility score.

Eddy Current Testing (ECT) and Ultrasonic Testing (UT) were the only two NDT technologies that passed the design requirements. An overview of the feasibility study process is shown in figure 5. Each one was scored for its performance in each technical and feasibility requirement. The importance of each requirement is shown in Table 3 as a “weight.” The total score for each technology was calculated by summing the product of each score with that particular requirement’s importance. A perfect total score was also calculated for comparison.

A summary of each techniques performance is shown in Figure 6. The maximum possible total score was 730. ECT performed poorly in comparison with the maximum and ultrasonic testing. It scored poorly on technical requirements because of its poor sensitivity and accuracy on thin walled containers. Though ECT faired better on facility feasibility requirements, it was still distinctly not user-friendly and was relatively expensive.

UT was clearly the more optimal between the two. Its total score was 71% of the maximum score, with 50% being an average score. It faired particularly well in accuracy and ease of use. It gives little information about the interior corroded surface other than the depth of corrosion, but this drawback wasn’t particularly impactful to the project. Because of its exceptional performance, a sixteen channel Olympus Focus PX coupled with sixteen delay-line 15 MHz ultrasonic transducers was ordered in July 2016. Testing will commence in the fall of 2016 and construction of a mechanical rastering system is slated for summer 2017.

Table 3: Quantitative Feasibility Study Scores

Feasibility Study Matrix								
	Requirements			Technique Score				
				1	2	ID		
	ID	Weight	Description	Eddy Current Testing (ECT)	Ultrasonic Testing (UT)	Description		
Technical	1	10	Accuracy	5	8			
	2	8	Precision	3	7			
	3	9	Detection Limit	4	7			
	4	7	Surface Compatibility	4	8			
	5	4	Interior Surface Info	9	3			
				174	267	*Technical Total*		
Feasibility	1	8	Ease of Use	5	9			
	2	5	Processing Time	6	7			
	3	4	Financial Feasibility	6	8			
	4	6	Criticality Risk	5	5			
	5	5	Portability	7	8			
	6	7	User Safety	5	6			
				194	251	*Feasibility Total*		
				368	518	*Total Score*		
				Comparison to Maximum			Max Score	10
				45.79%	70.26%	*Technical*	Max Technical	380
				55.43%	71.71%	*Feasibility*	Max Feasibility	350
				50.41%	70.96%	*Total*	Max Total	730

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