PNNL-SA-113998

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Progress in the Development and Demonstration of a Phased Array Ultrasonic Probe for Under-Sodium Viewing

Work Package AT-15AN230102
Subtask: Under-Sodium Viewing

October 28-29, 2015

Mike Larche
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PNNL

DOE Advanced Sensors and Instrumentation Webinar: 2015 NE I&C Review – Advanced Reactor Technologies (ART) Program, Instrumentation, Control, and Human-Machine Interface (ICHMI) Research Program – Oct. 28-29, 2015

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Subtask: Under-Sodium Viewing

Topics of Discussion:

- Project Background and Overview
  - Project Relevance
  - Past Accomplishments and Lessons Learned
- FY15 Objectives and Scope
- FY15 Technical Progress
  - Technical Activities/Results
  - Conclusions
  - Accomplishments
- FY16 Next Steps
- Questions

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Subtask: Under-Sodium Viewing

Subtask Relevance & Technology Impact:

The need to re-establish domestic technology infrastructure to support the deployment of sodium-cooled fast reactor (SFR) technology has been identified

- **A key enabling nondestructive examination (NDE) technology is Ultrasonic Testing for Under Sodium Viewing to:**
  - Monitor operations in optically opaque sodium at high temperatures
  - Provide imaging technology and NDE sensors not commercially available
  - Provide nondestructive capability to inspect structures, systems, and components within the reactor
  - Complement SFR inservice inspection (ISI) requirements

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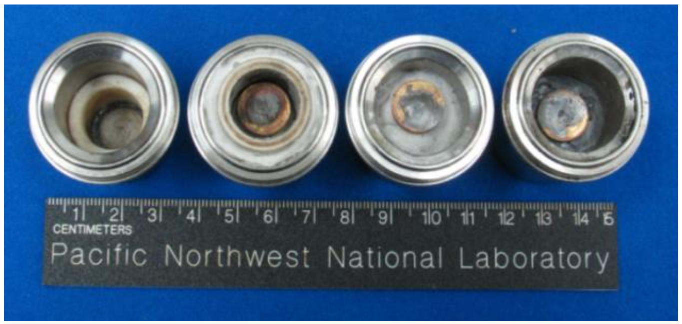
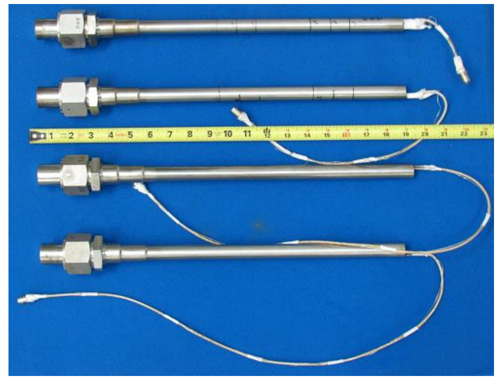
Past Accomplishments and Lessons Learned:

- **Better understanding of ultrasonic propagation in sodium via modeling, simulation and empirical laboratory measurements**
  - Physical and acoustic properties as a function of temperature
  - Signal-to-noise ratio (SNR), sensitivity, penetration and resolution requirements
  - Wetting issues and sodium quality (effects of impurities)
  - Thermal effects on probe structural integrity and performance

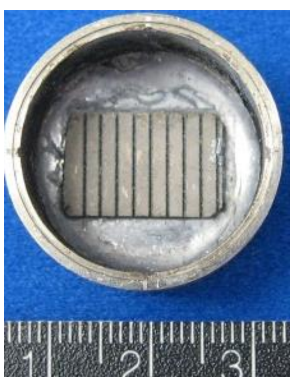
- **Identified effective materials/processes for fabricating and operating phased array ultrasonic testing (PA-UT) probes, for imaging in sodium**
  - Piezo-element, solder, cabling, housing materials, nickel faceplate, polishing the faceplate, filtering the sodium, etc.
  - Overcame issues with voids/de-bonds at the piezoelectric-to-nickel faceplate/solder-joint interface
  - Each probe iteration has improved upon the previous design and provided valuable data used to enhance robustness, imaging, detection and characterization capability for in-sodium ISI

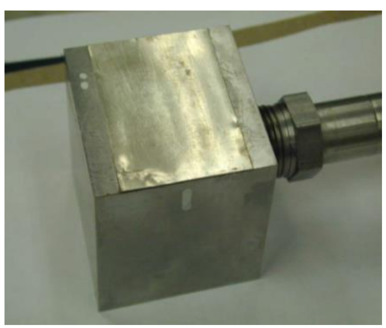
Project History: (Single Element Probes)

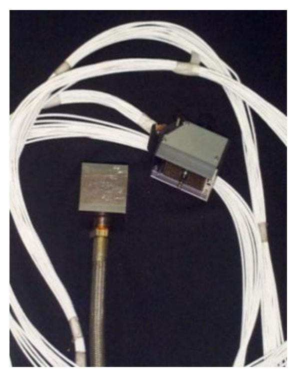


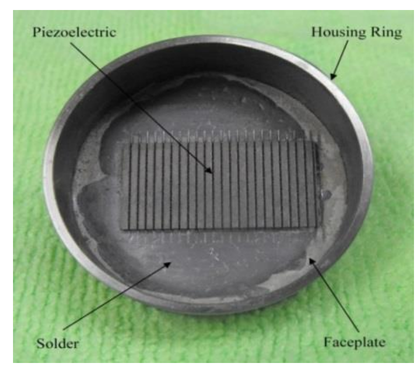


Project History: (Linear Array Probes)









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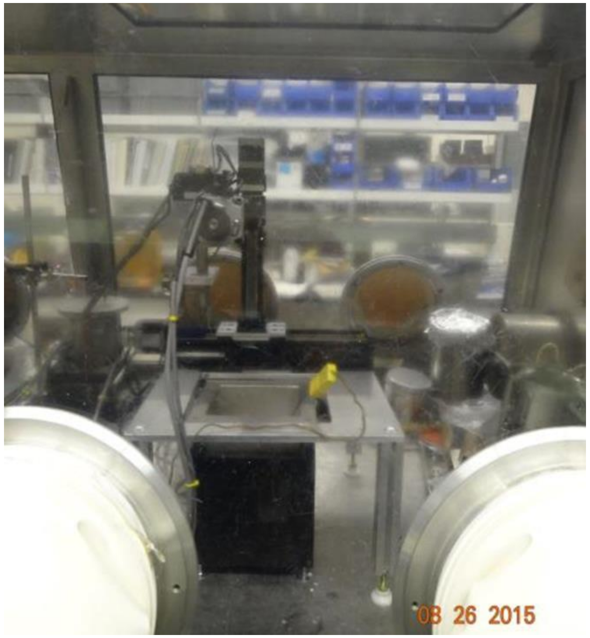
Drivers Behind FY15 Work Scope:

- **To increase image resolution in sodium and focus on key factors:**
  - Array design parameters
    - 1-D versus 2-D matrix array design (improved resolution/sensitivity, increased volume of examination, and improved SNR via isolation of T and R elements)
    - Ability to better control/steer the beam with a 2-D matrix array (in primary and secondary axes)
    - Ability to focus more energy and improve sound field focal dimensions will be enhanced with a 2-D matrix array
  - Eliminate scanning motion (x-, y-, z-axes) constraints posed by PNNL's older scanner platform and the current sodium containment glove-box, and provide raster scan capability



Work Package AT-15AN230102 (PNNL) Subtask: Under-Sodium Viewing

FY15 Objective

To design, fabricate and demonstrate an effective PA-UT probe for USV in support of technology readiness for implementation of advanced imaging NDE in sodium to address future SFR ISI requirements

FY15 Scope

- Fabricate, test and demonstrate two improved prototype phased array probes (SN3) with a 2-D matrix array design.
- Develop a performance demonstration (PD) protocol.
- Validate probe performance via PD.

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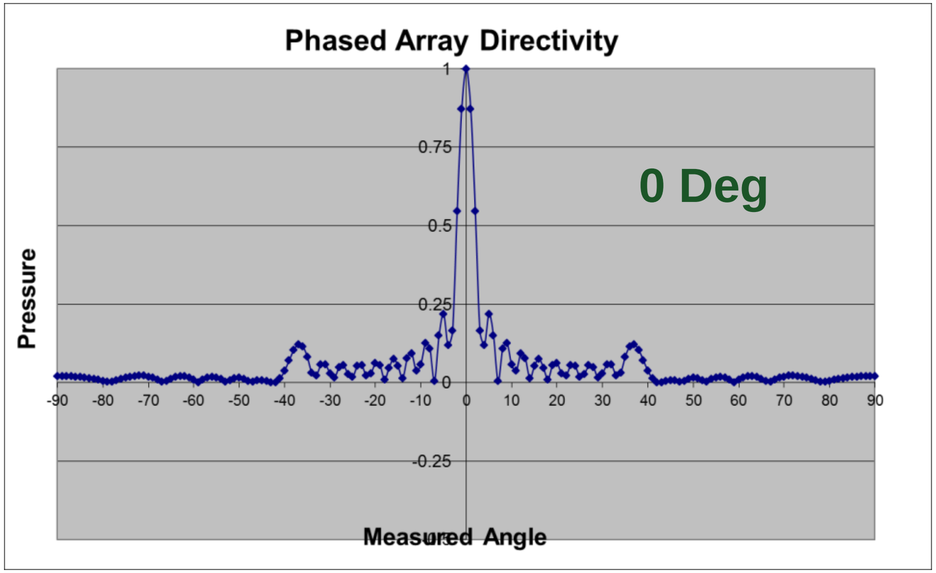
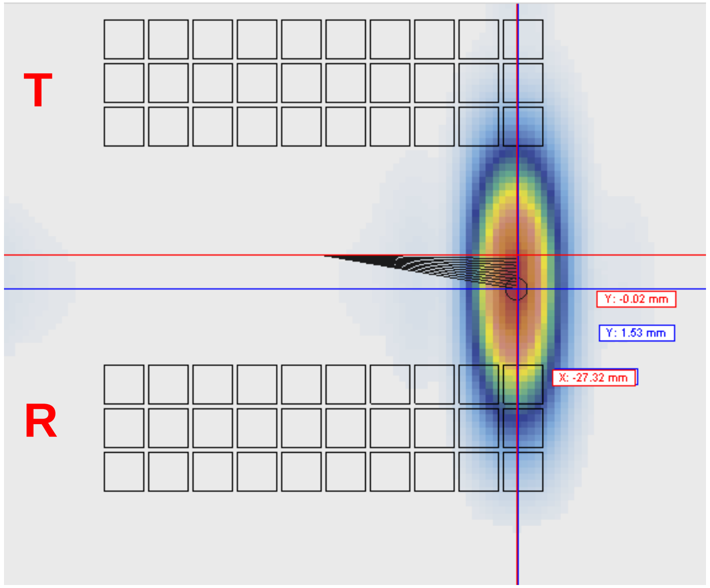
Technical Progress (FY15)

- Completed the design of the (10x3) x 2 element, transmit-receive-longitudinal (TRL) matrix-array PA-UT prototype probe (SN3)

Phased Array Directivity Calculator



Sound Beam Simulation



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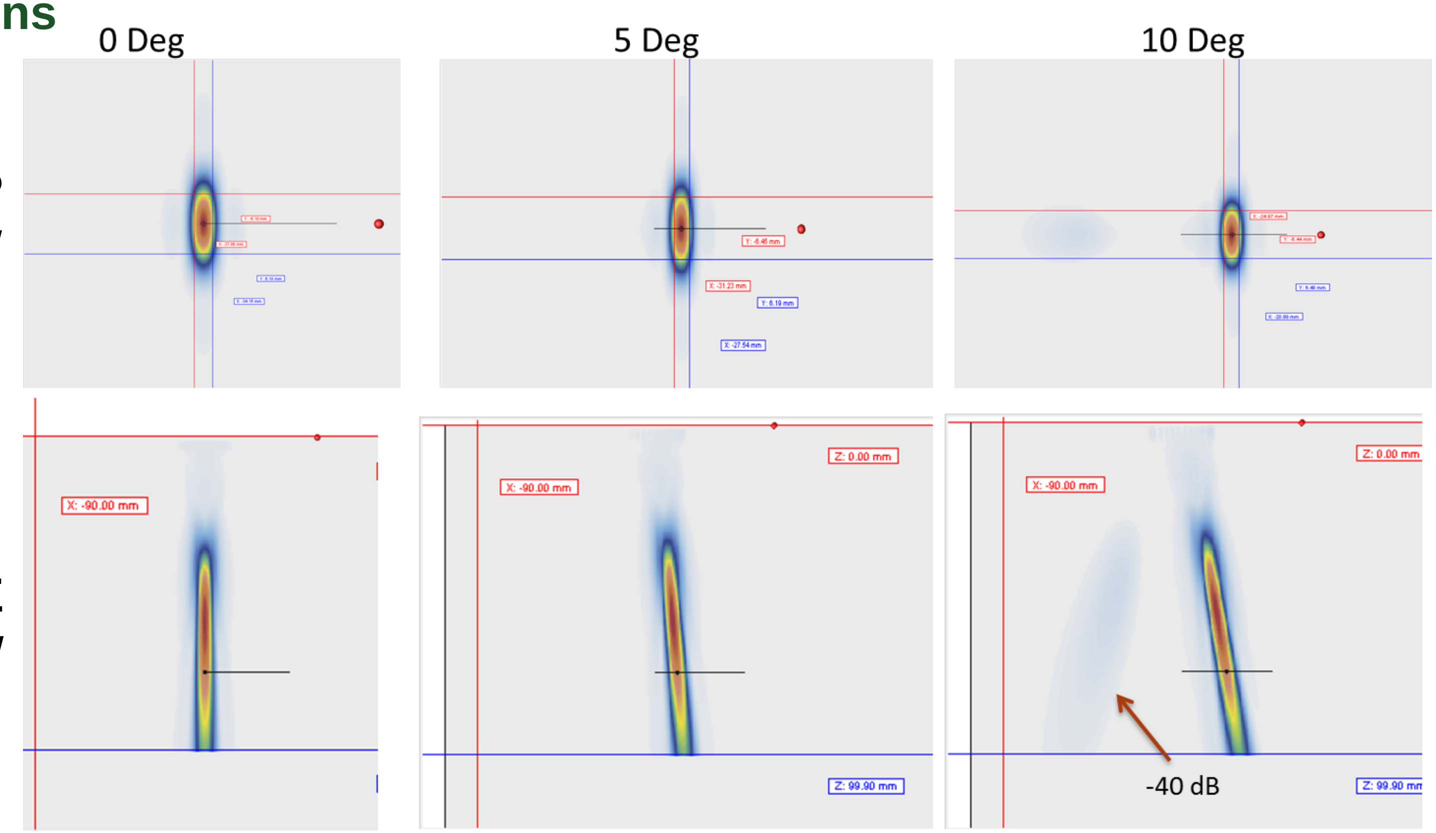
Technical Progress (FY15 - Continued)

- **Used modeling tools to simulate probe beam formation, steering and spot size dimensions**

(10x3)x2 array
75 mm focus
Primary Axis Steering

TOP VIEW

SIDE VIEW



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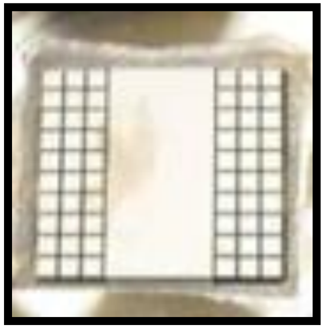
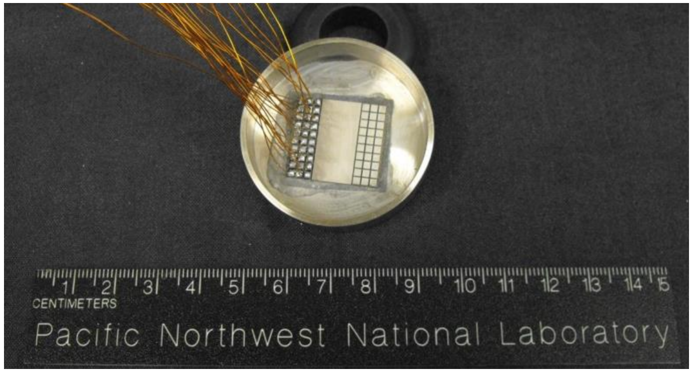
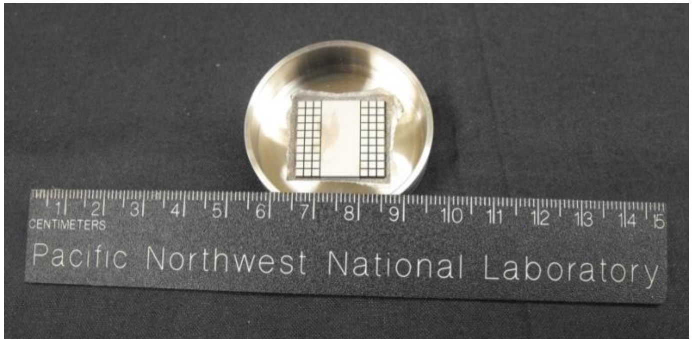
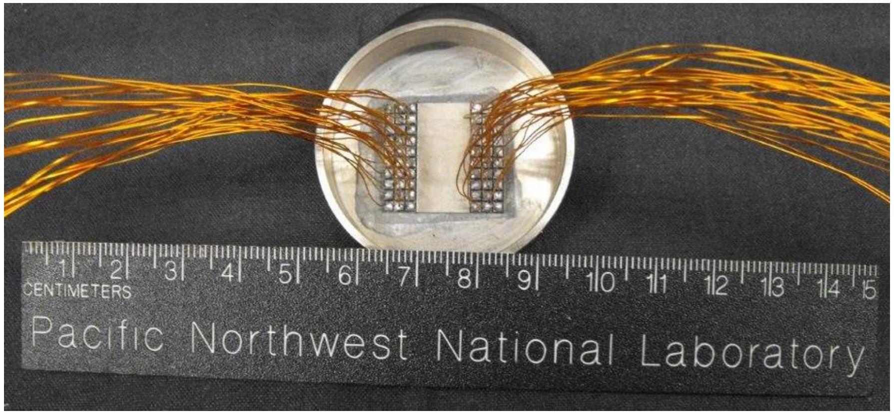
Technical Progress (FY15 - Continued)

- Completed fabrication of two submersible, SN3 PA-UT probes









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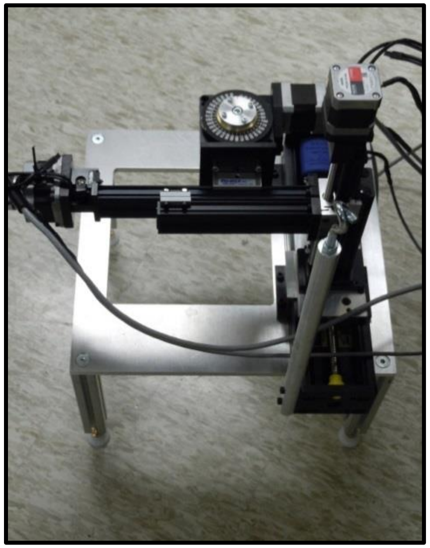
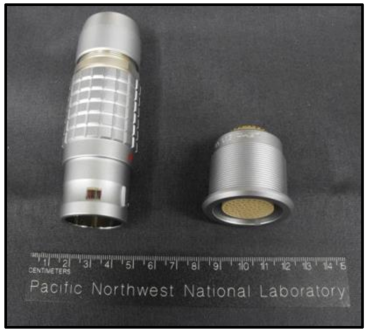
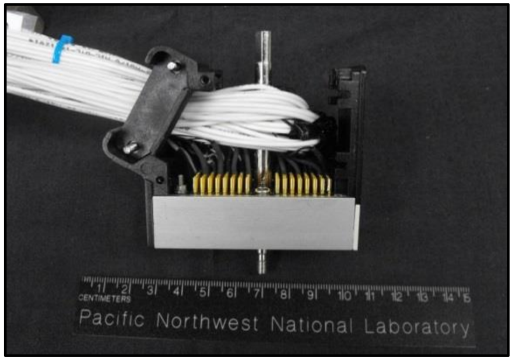
Technical Progress (FY15 - Continued)

- Completed fabrication of the upgraded USV scanner and controller platform for raster scanning of the PA-UT probes in sodium



- Reduced cabling footprint, improved scanning/control software and sodium containment and thermal control systems, for improved functionality during data acquisition





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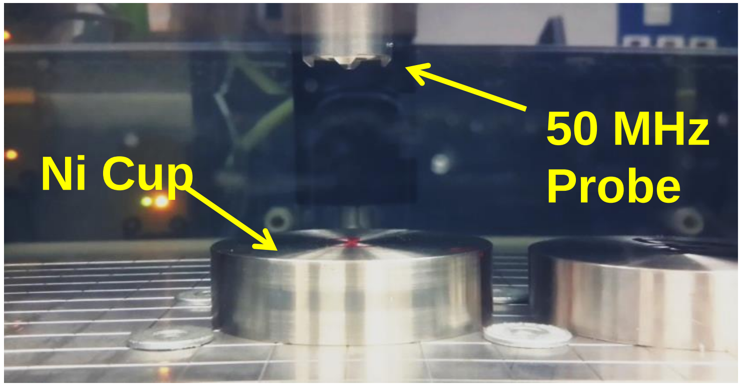
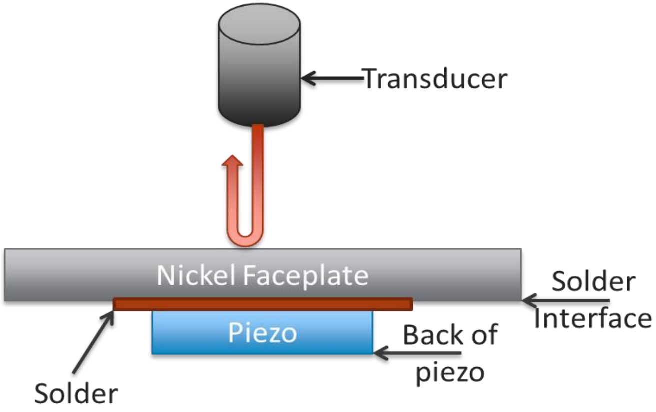
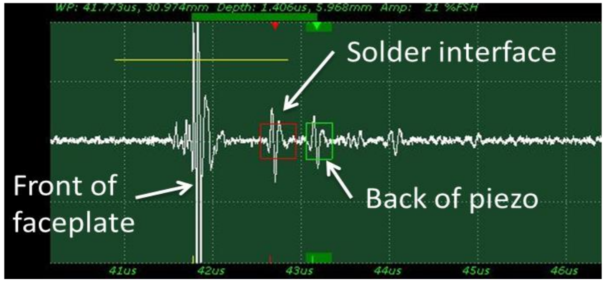
Technical Progress (FY15 - Continued)

- Employed acoustic microscopy to validate piezo-element to nickel faceplate coupling
- 50 MHz immersion transducer used to assess solder bond
- Pulse-echo configuration
- 50x50 µm scan resolution
- Software gates were used to collect data (C-scan images) at the piezo-solder interface and the back of the piezo







Technical Progress (FY15 - Continued)

Image of Solder-Nickel Interface (cup #3)

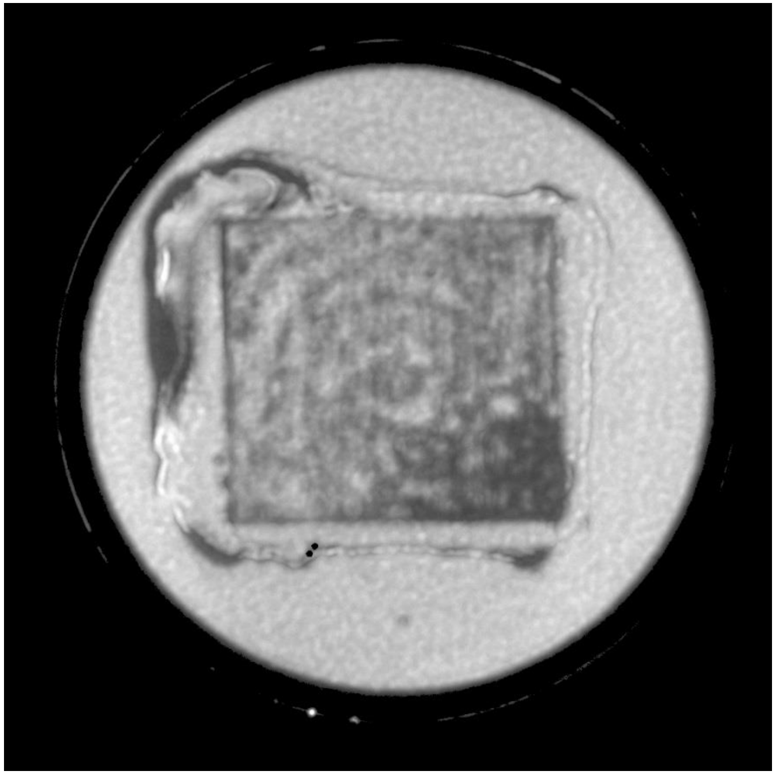
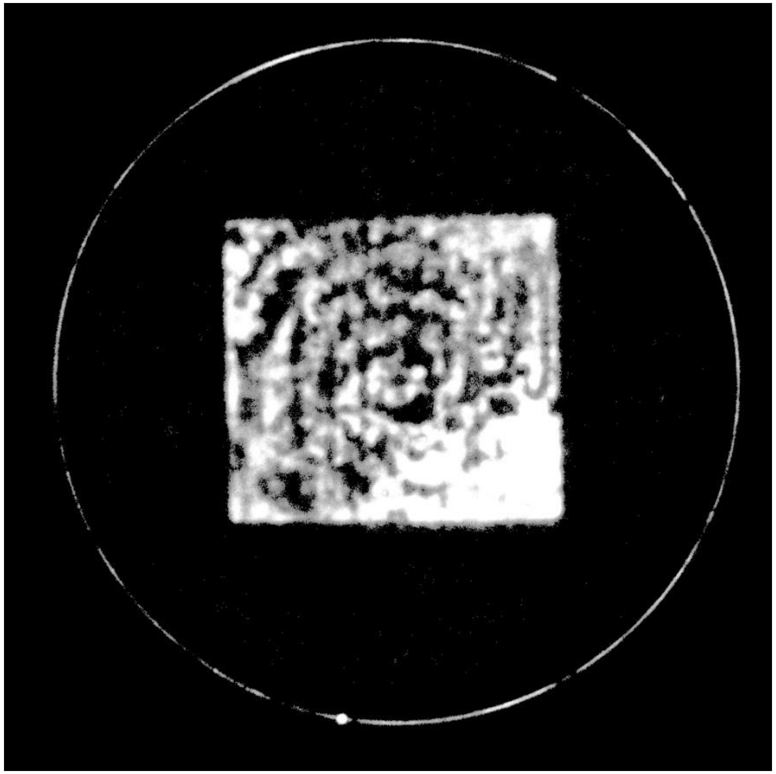
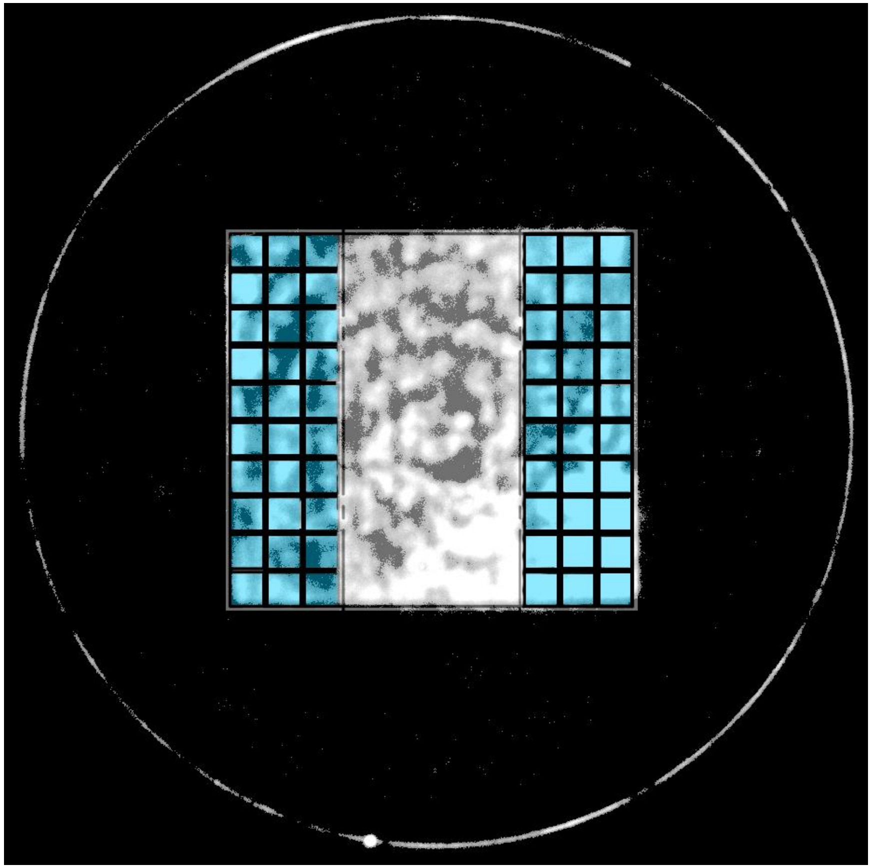


Image of Back of Piezo (cup #3)



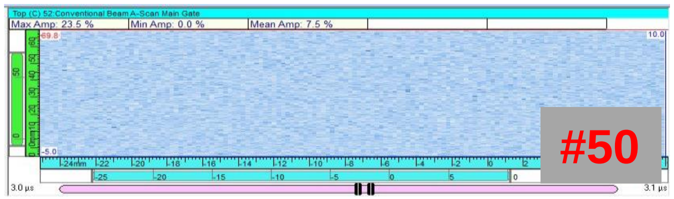
Technical Progress (FY15 - Continued)



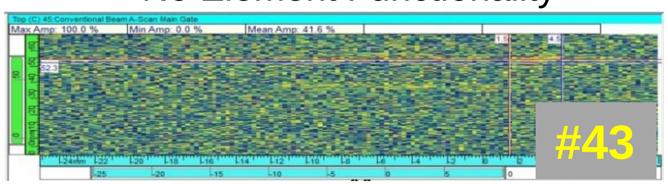
Overlaid 2D array of sliced piezo-elements on image of bonded PZT-5A element. Cup #3.

Technical Progress (FY15 - Continued)

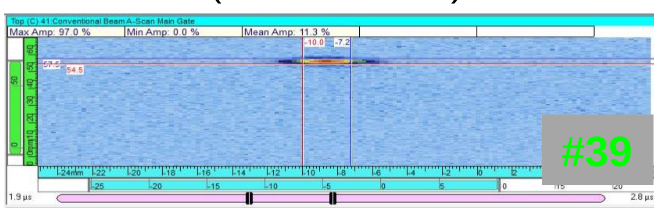
➢ Probe Functionality Testing Results:



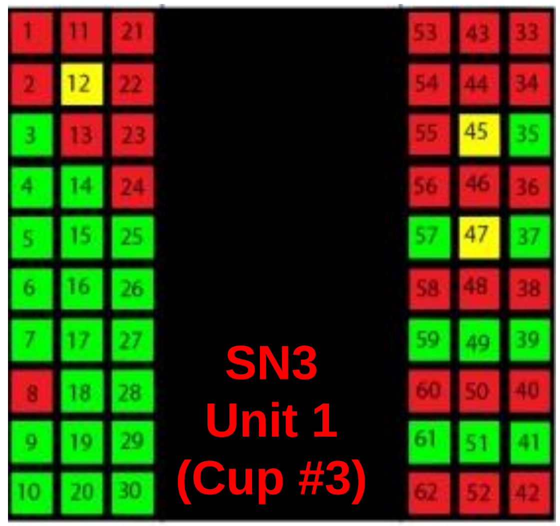
No Element Functionality



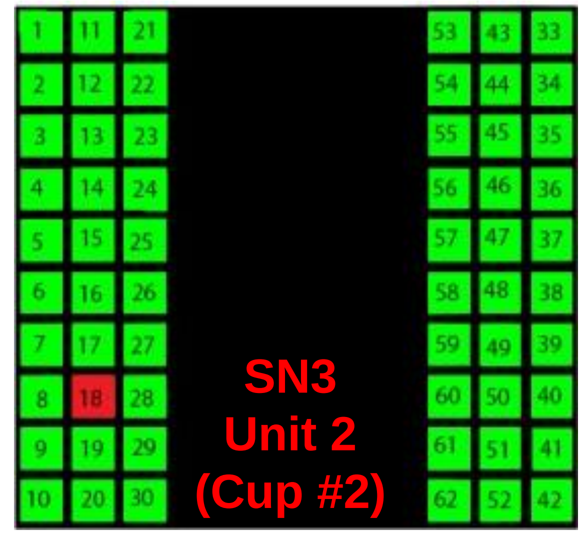
Poor Element Functionality
(SNR = 8.1 dB)



Excellent Element Functionality
(SNR= 23 dB)



- **Red**: Not Functional
  - 28 elements
- **Yellow**: Poor SNR (<10dB)
  - 3 elements
- **Green**: Acceptable SNR (>10dB)
  - 29 elements



- **Red**: Not Functional
  - 1 element
- **Green**: Acceptable SNR (>10dB)
  - 59 elements

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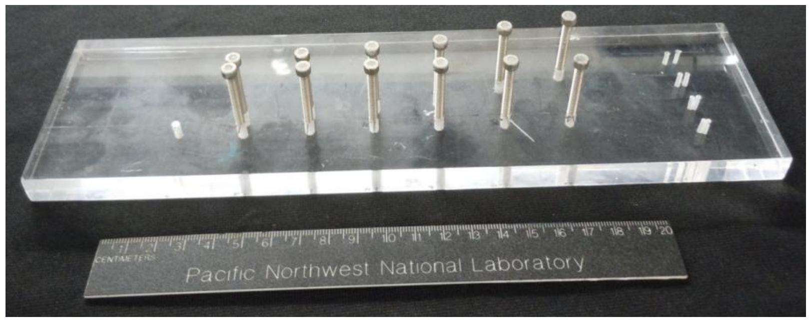
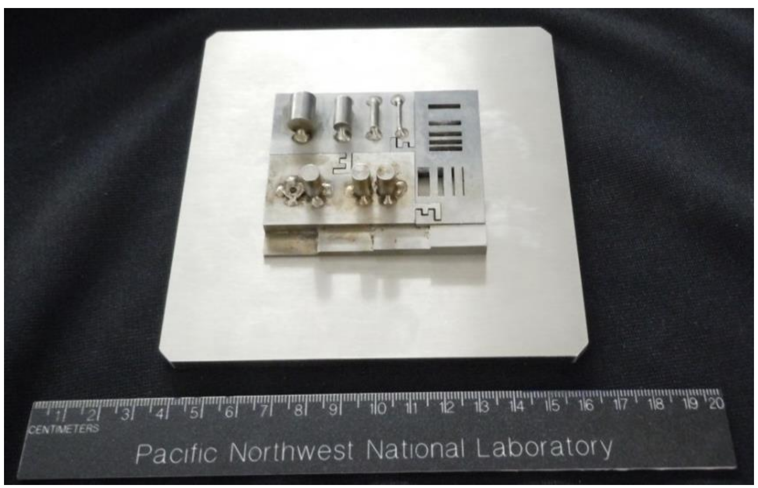
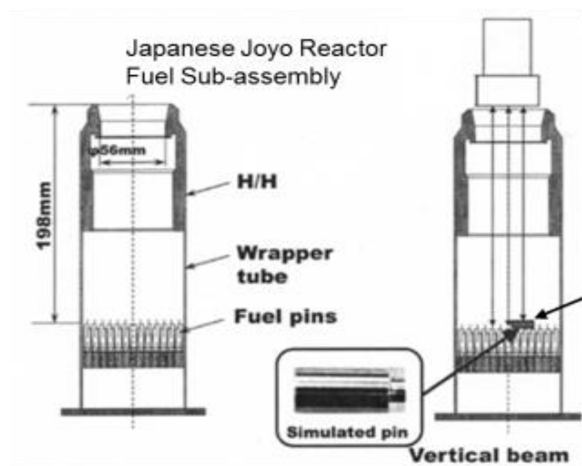
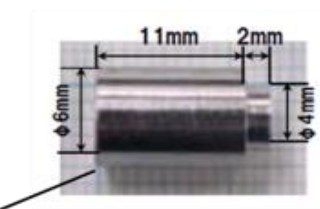
Technical Progress (FY15 - Continued)

- **Targets Used for Performance Characterization:**









MARICO-2
Test Sub-assembly

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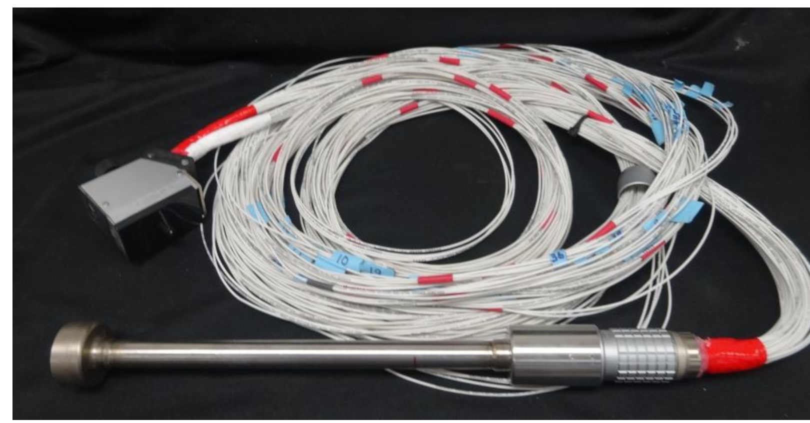
Subtask: Under-Sodium Viewing

Technical Progress (FY15 - Continued)

SN3 Unit 1

SN3 Unit 2



FY15 SN3 matrix-array engineering test units (ETUs), showing the probe housings, connectors and cabling

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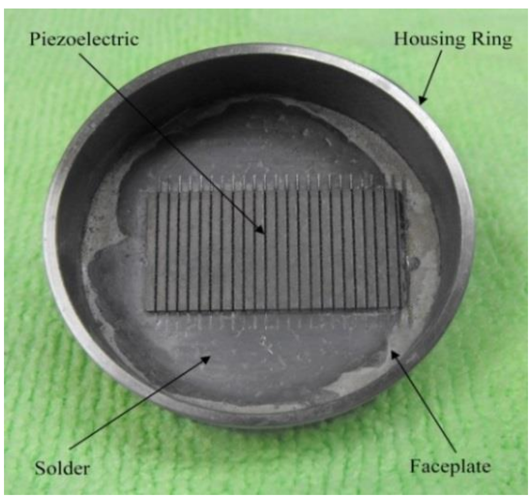
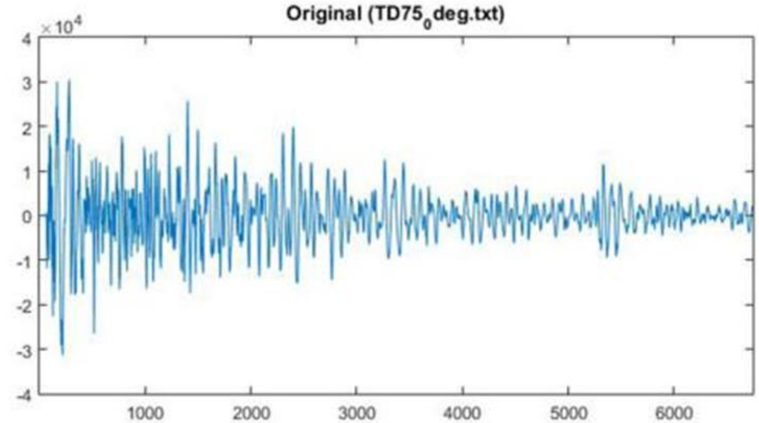
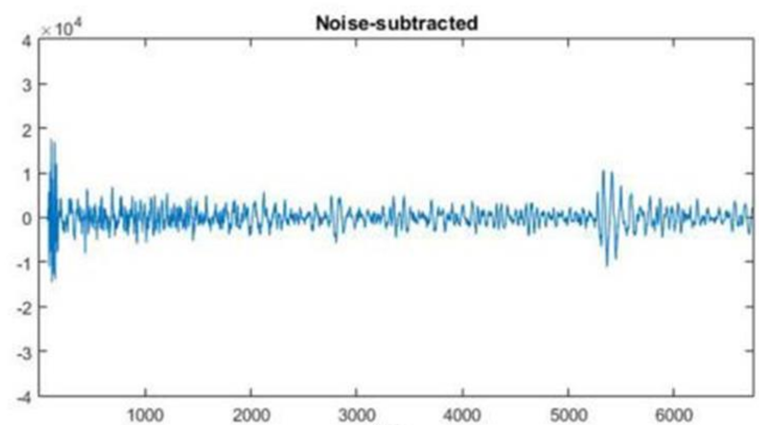
Technical Progress (FY15 - Continued)

The 22-element 1D linear array (SN2) was employed for in-sodium tests. PNNL employed a simple A-scan noise subtraction algorithm to filter the images and reduce noise bands from various sources. For the waveforms on the right, (a) shows the unprocessed A-scan, and (b) shows the processed A-scan, illustrating the improvements obtained from using the algorithm.





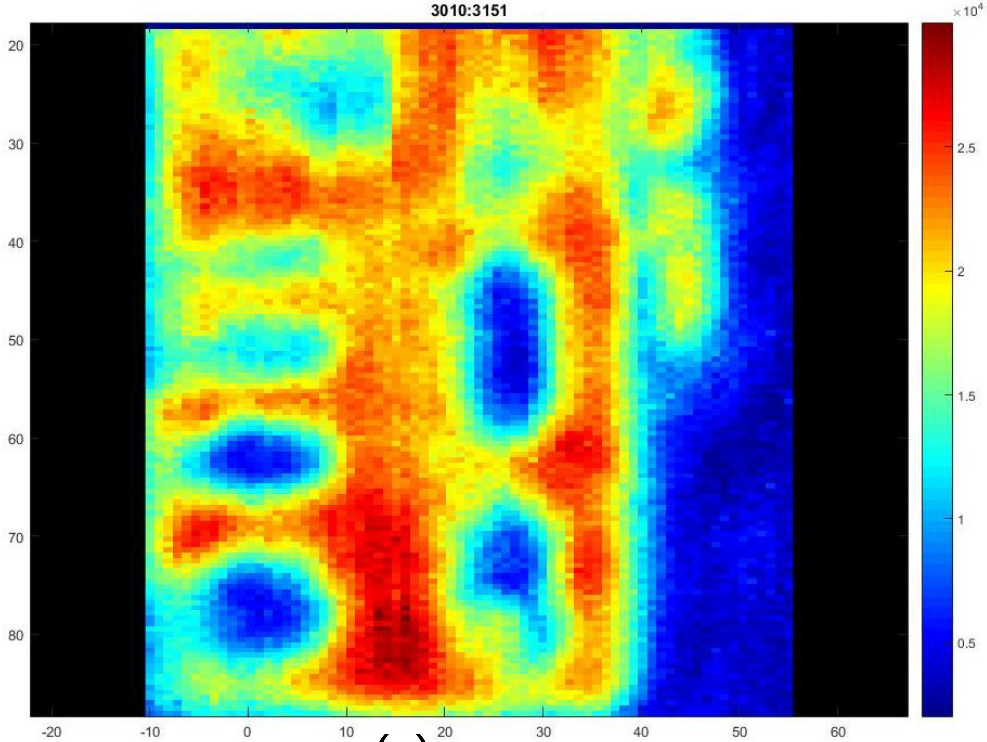
(a)



(b)

Technical Progress (FY15 - Continued)

Ultrasonic image (C-scan view) showing the shadowing effect, or lack-of-backwall echo response (a) corresponding to the various features on the target (b) in sodium, at 260°C.



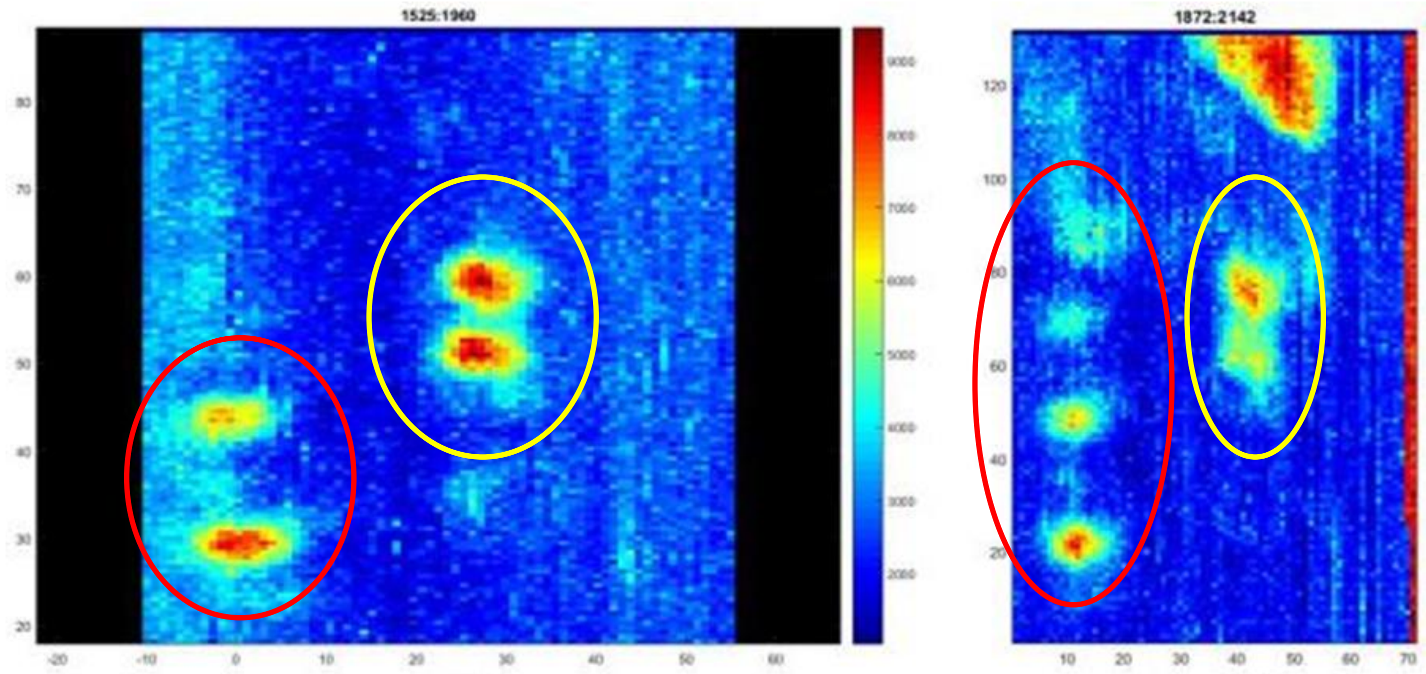
(a)

(b)

Technical Progress (FY15 - Continued)

(a) C-scan view showing the specular reflected energy from two vertical (yellow circle) and two horizontal pins (red circle);

(b) C-scan view showing signal responses from both vertical pins (yellow circle) and all four horizontal pins (red circle)



(a) (b)

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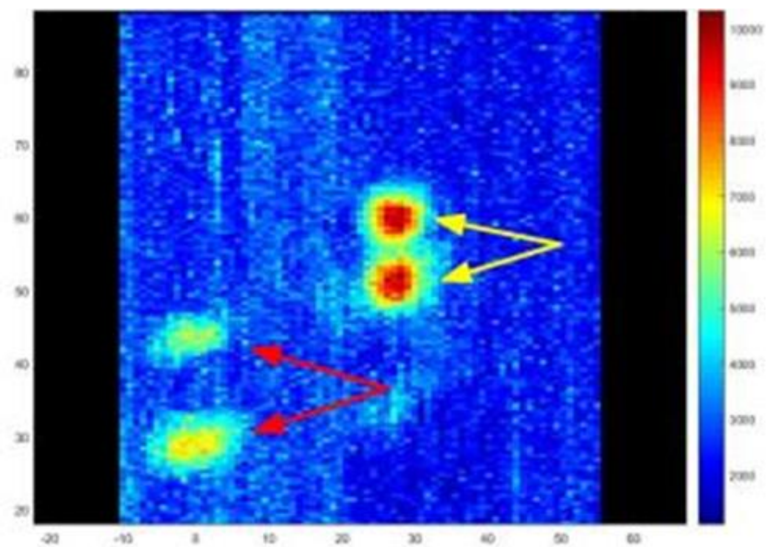
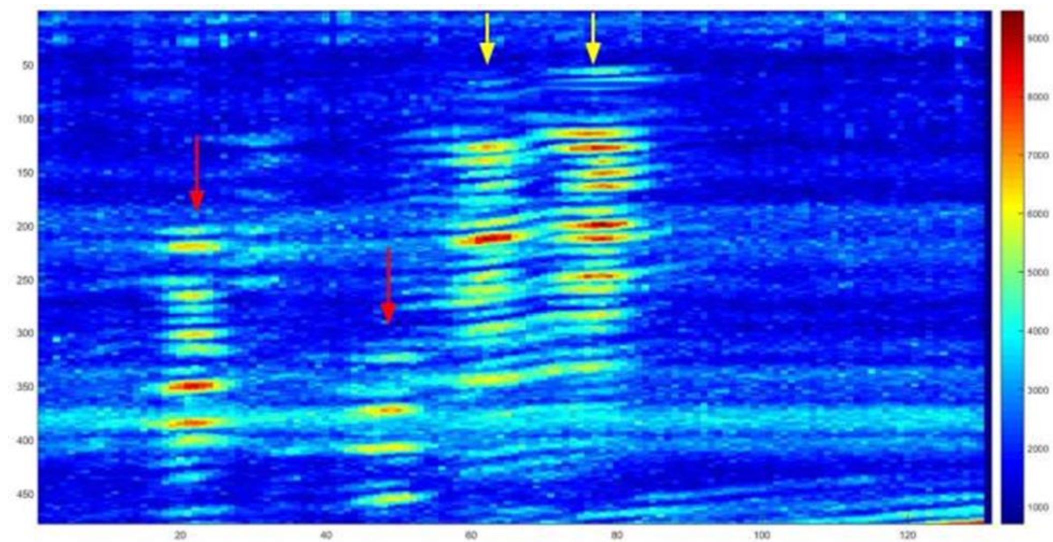
Technical Progress (FY15 - Continued)

C-scan view generated by applying different time-gates and spatial windowing to better isolate pin reflectors for resolution, sizing and characterization. Vertical pins indicated by yellow arrows, horizontal pins indicated by red arrows.



B-scan (side-view) depicting signal responses from both vertical and horizontal pins. Vertical pins indicated by yellow arrows, horizontal pins indicated by red arrows.



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Subtask: Under-Sodium Viewing

Technical Progress (FY15 - Conclusions):

Conducted successful in-sodium, raster-scan immersion testing of 22-element linear PA-UT array probe (SN2) at 260°C, and completed data analysis from these tests.

- SN2 probe now has 12+ hours of in-sodium immersion performance at 260°C with no measurable decline in functionality or performance.
- Imaging, detection, resolution, and characterization results from the target were drastically improved over what was previously achieved in past years.
- SNR from direct reflected energy off the pin tops was nearly 12 dB; capable of resolving vertical pins with edge-to-edge spacing of 1.23 mm (< 1λ apart); capable of accurately sizing vertical and horizontal pin heights to within 10% of true-state dimensions.

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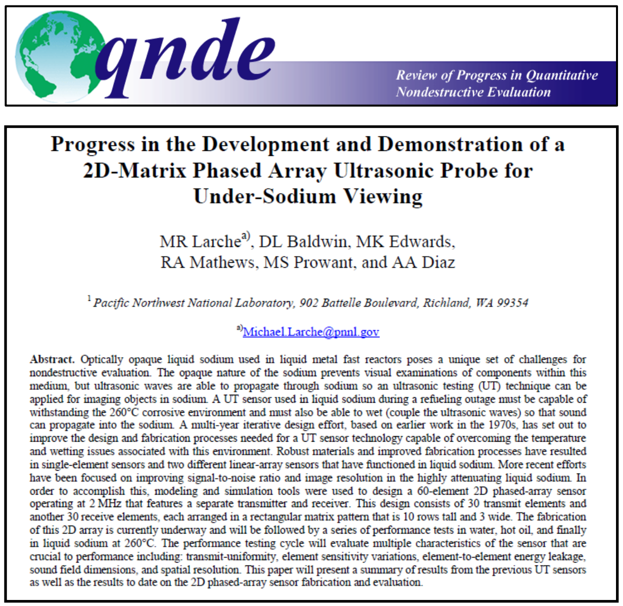
Technical Progress (FY15 - Accomplishments)



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Review of Progress in Quantitative Nondestructive Evaluation

Progress in the Development and Demonstration of a 2D-Matrix Phased Array Ultrasonic Probe for Under-Sodium Viewing

MR Larche[a)], DL Baldwin, MK Edwards, RA Mathews, MS Prowant, and AA Diaz

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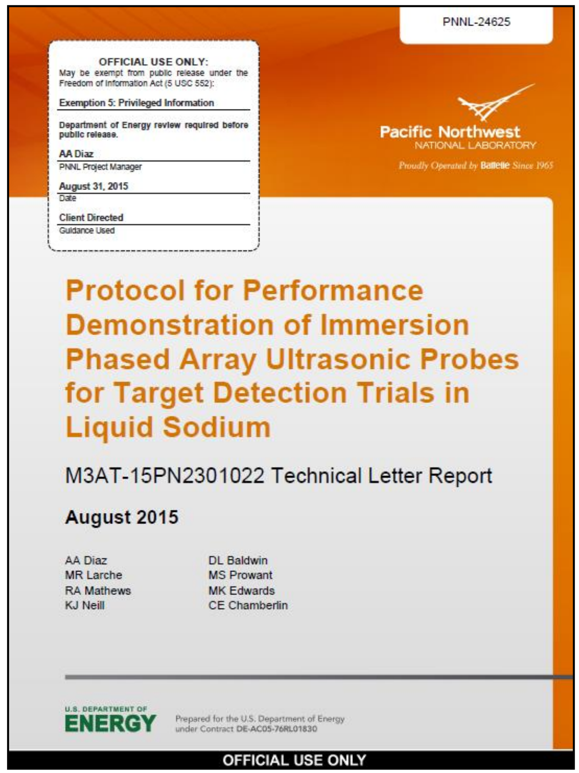
Abstract. Optically opaque liquid sodium used in liquid metal fast reactors poses a unique set of challenges for nondestructive evaluation. The opaque nature of the sodium prevents visual examinations of components within this medium, but ultrasonic waves are able to propagate through sodium so an ultrasonic testing (UT) technique can be applied for imaging objects in sodium. A UT sensor used in liquid sodium during a refueling outage must be capable of withstanding the 260°C corrosive environment and must also be able to wet (couple the ultrasonic waves) so that sound can propagate into the sodium. A multi-year iterative design effort, based on earlier work in the 1970s, has set out to improve the design and fabrication processes needed for a UT sensor technology capable of overcoming the temperature and wetting issues associated with this environment. Robust materials and improved fabrication processes have resulted in single-element sensors and two different linear-array sensors that have functioned in liquid sodium. More recent efforts have been focused on improving signal-to-noise ratio and image resolution in the highly attenuating liquid sodium. In order to accomplish this, modeling and simulation tools were used to design a 60-element 2D phased-array sensor operating at 2 MHz that features a separate transmitter and receiver. This design consists of 30 transmit elements and another 30 receive elements, each arranged in a rectangular matrix pattern that is 10 rows tall and 3 wide. The fabrication of this 2D array is currently underway and will be followed by a series of performance tests in water, hot oil, and finally in liquid sodium at 260°C. The performance testing cycle will evaluate multiple characteristics of the sensor that are crucial to performance including: transmit-uniformity, element sensitivity variations, element-to-element energy leakage, sound field dimensions, and spatial resolution. This paper will present a summary of results from the previous UT sensors as well as the results to date on the 2D phased-array sensor fabrication and evaluation.



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Exemption 5: Privileged Information
Department of Energy review required before public release.
AA Diaz
PNNL Project Manager
August 31, 2015
Date
Client Directed
Guidance Used

Pacific Northwest NATIONAL LABORATORY
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Protocol for Performance Demonstration of Immersion Phased Array Ultrasonic Probes for Target Detection Trials in Liquid Sodium

M3AT-15PN2301022 Technical Letter Report

August 2015

AA Diaz, MR Larche, RA Mathews, KJ Neill, DL Baldwin, MS Prowant, MK Edwards, CE Chamberlin

U.S. DEPARTMENT OF ENERGY
Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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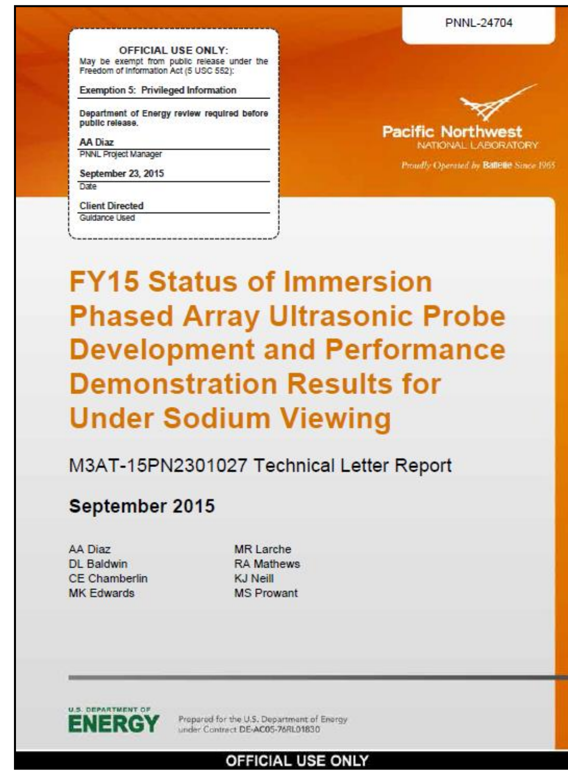

PNNL-24704

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Department of Energy review required before public release.
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PNNL Project Manager
September 23, 2015
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Client Directed
Guidance Used

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FY15 Status of Immersion Phased Array Ultrasonic Probe Development and Performance Demonstration Results for Under Sodium Viewing

M3AT-15PN2301027 Technical Letter Report

September 2015

AA Diaz, DL Baldwin, CE Chamberlin, MK Edwards, MR Larche, RA Mathews, KJ Neill, MS Prowant

U.S. DEPARTMENT OF ENERGY
Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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FY16 Next Steps

Address array design that optimizes the balance between element size, number of elements, and matrix specifications for generating a higher energy sound field that is more symmetric and has a tighter focus in both passive and active axes

- 2D symmetric pulse-echo PA design

Control of noise sources, including grounding noise, internal probe noise, cable/connector noise, and system/motor noise

- Specify and procure custom-made cables from PA-UT experts
- Employ new PA-UT data acquisition system with enhanced features and electronics
- Design enhancements to probe housing and insulation

Identify and begin to engage an industrial commercial partner for future technology transfer plan development

Thank You! Questions?

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