PNNL-SA-207635

Pacific Northwest NATIONAL LABORATORY

U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*

# NDE of CFRP Repairs


**Muthu Elen, Nicholas Conway**
Pacific Northwest National Laboratory

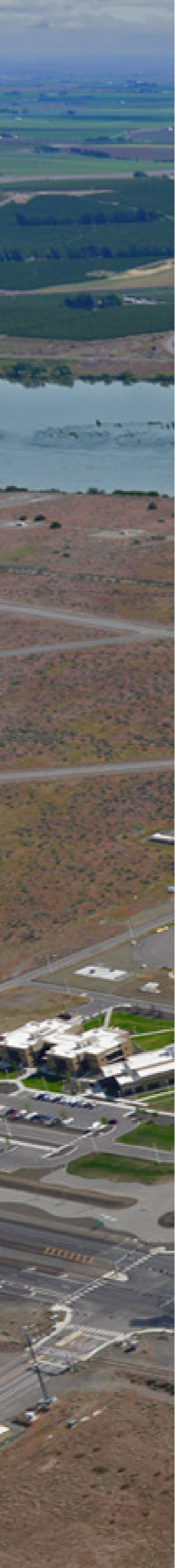

**2025 Annual NRC-Industry NDE TIE Meeting**
**NRC Headquarters, Rockville, MD**


Prepared for the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research
Under Contract DE-AC05-76RL01830
Master Interagency Agreement: A2307-031-089-048662
Task Order Number: 31310024S0062

NRC COR: Carol Nove


U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy



# Abbreviations

- ASME – American Society of Mechanical Engineers
- ATT – automated tap testing
- CC – code case
- CFRP – carbon fiber reinforced polymer
- GFRP – glass fiber reinforced polymer
- MTT – manual tap testing
- NDE – nondestructive evaluation
- NPP – nuclear power plant
- NRC – Nuclear Regulatory Commission
- PCC – Post Construction Committee
- PEC – pulsed eddy current
- PNNL – Pacific Northwest National Laboratory
- UT – ultrasonic testing

# NDE of CFRP Materials

## ***Background***

Carbon Fiber Reinforced Polymer (CFRP) composites have not been used for nuclear **safety-related applications** until recently. In 2019, the **ASME Boiler and Pressure Vessel Code Committee approved a new CC N-871 for internal repairs of Class 2 and 3 safety-related piping** using CFRP for Service Levels A, B, C, and D for a service life of 50 years. The NRC did not review N-871 for inclusion in the Code Case Regulatory Guides.

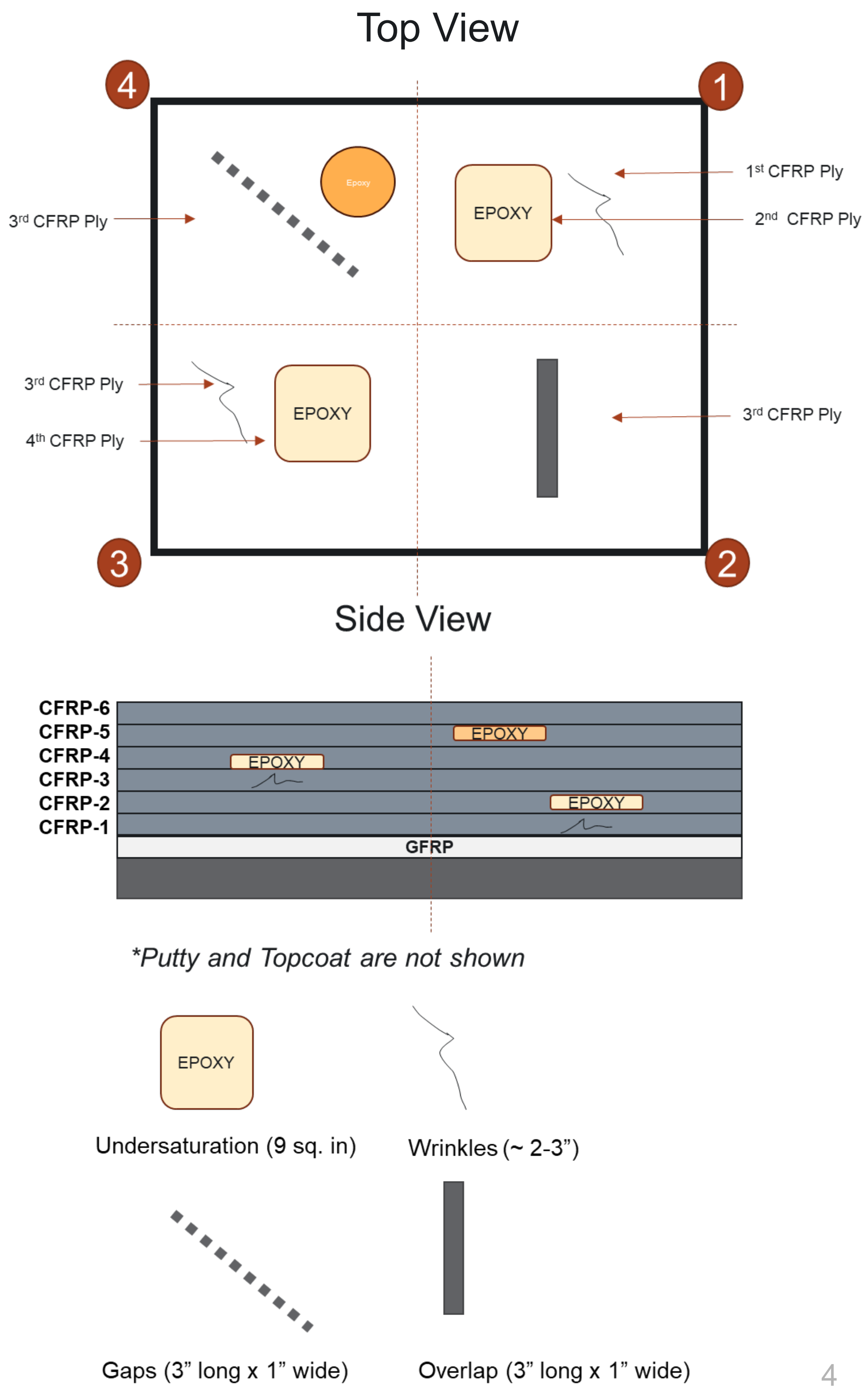
## ***Objective***

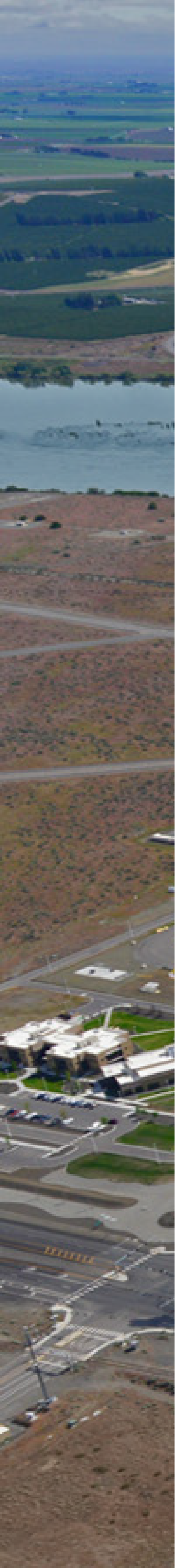
To **evaluate the capabilities and limitations** of NDE methods for examining the CFRP repairs in commercial NPPs:

- Identify guidance and best practices for qualification mockup fabrication as per ASME CC N-871-2 / PCC-2
- Fabricate mockups that include representative flaws, varying substrate and laminate thicknesses, curvature, using multiple vendors
- Assure mockups are representative of actual field applications
- Assess various commercially available NDE methods to evaluate capabilities and limitations for detecting and characterizing flaws
- Assess whether tap testing may be used as a screening tool to find flaws of interest so that more sophisticated techniques can be used to characterize flaws and provide a permanent record

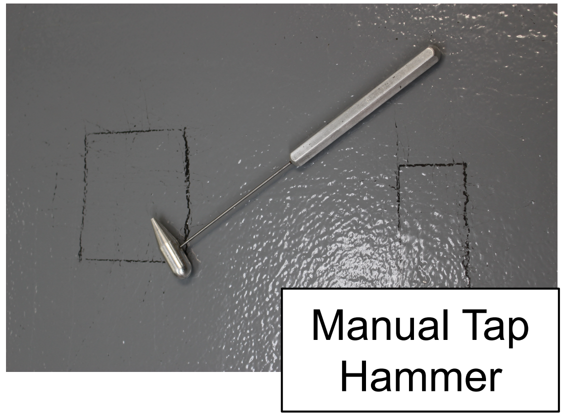
# CFRP Mockup Fabrication Parameters

- A CFRP vendor was identified to fabricate the 8 mockups, and a contract was established with the vendor by PNNL
- Each mockup consisted of 7 plies, which included 6 plies of CFRP and 1 ply GFRP as the first layer
  - The CFRP layers were placed in 0/90 orientation (horizontal/vertical) on alternate layers
  - Carbon Fiber 2339 (Toray T700S) – Unidirectional carbon fiber, 19.5 oz/yd$^2$, nominal thickness of 0.036 in.
  - Glass Fiber 1210 (Hybon 2026) – Bidirectional fiberglass, 25.8 oz/yd$^2$, nominal thickness of 0.031 in.
  - 212N Saturant – Used as a primer and saturant for fiberglass and carbon fiber
  - 130N Tack Coat – Thickened epoxy used between layers of fiber
  - Fumed Silica – Used to thicken the 130N tack coat
  - Substrate – 24 in. × 24 in. × 1/2 in. thick carbon steel plates
- Varying % of putty – 6.3%, 8.3%, 10.3%
- Varying thickness of putty – 0.031", 0.125"
- 2 mockups were fabricated with varying surface preparations



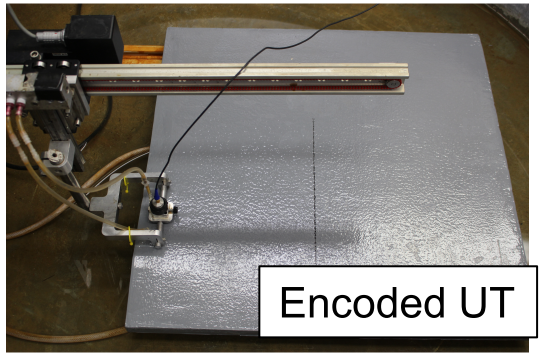


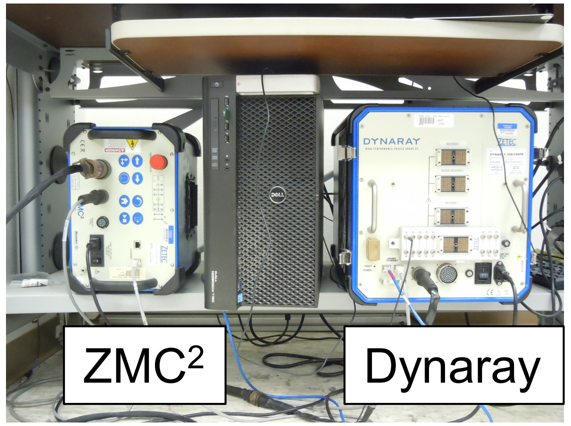
# Data Collection: NDE





- Manual tap testing (MTT)
  - Aerospace tap hammer
  - Low-cost
  - Easily deployable
  - Requires trained inspector to interpret audible responses for flaw identification
- Automated tap testing (ATT)
  - Woodpecker WP-632AM-R
  - Uses a ratio of the response to a reference “good” location the operator collects to identify flawed regions
    - ✓ Not dependent on an individual’s hearing abilities
  - Records measurements (but not position)
- Encoded/Automated pulse-echo ultrasonic testing (PE-UT) method
  - Zetec DYNARAY w/ ZMC$^2$ (UV3, 2.5-mm scan/step increment)
  - Olympus V101 (0.5 MHz, 1.0-in. diameter) and Krautkramer 389-057-070 BMC (1 MHz, 0.5-in. diameter w/ 1-in.  Rexolite delay line)
    - Frequencies are chosen based on preliminary testing
    - Normal beam (i.e., 0-degree incident angle)
    - Contact probe
    - Pulse-echo
  - Volumetric inspection
  - Widely accepted
  - Couplant: Ultragel




Pacific Northwest
NATIONAL LABORATORY

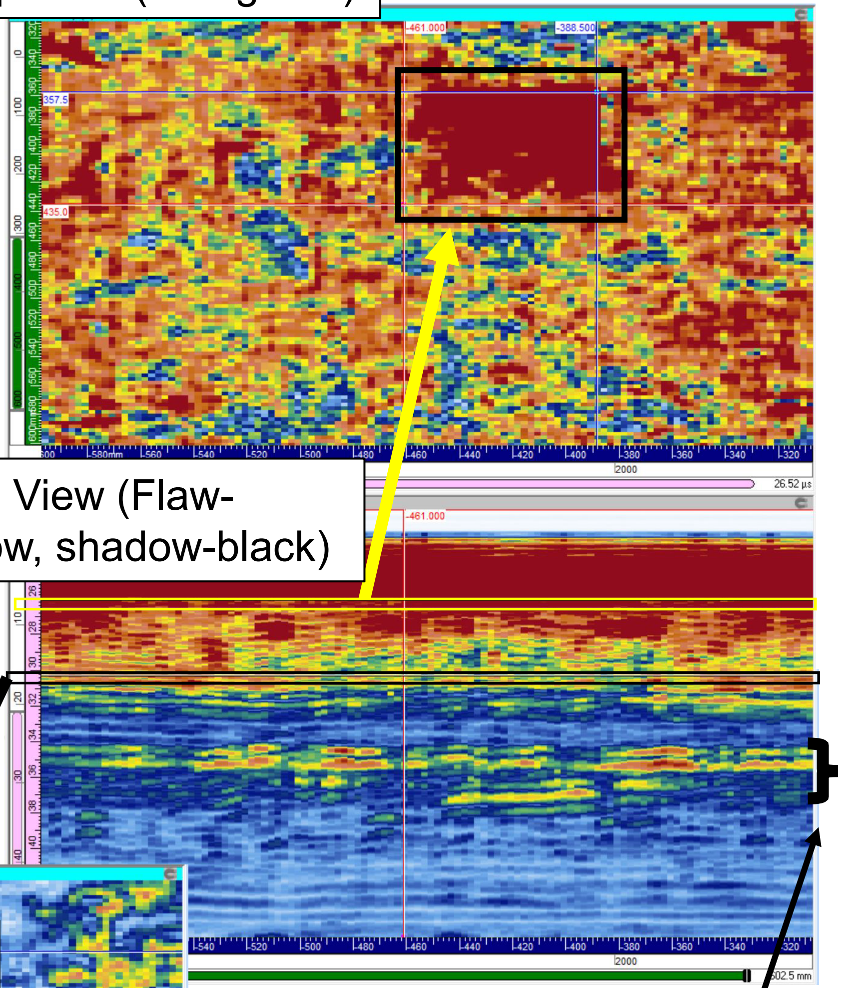
# Data Collection: Flaw Matrix

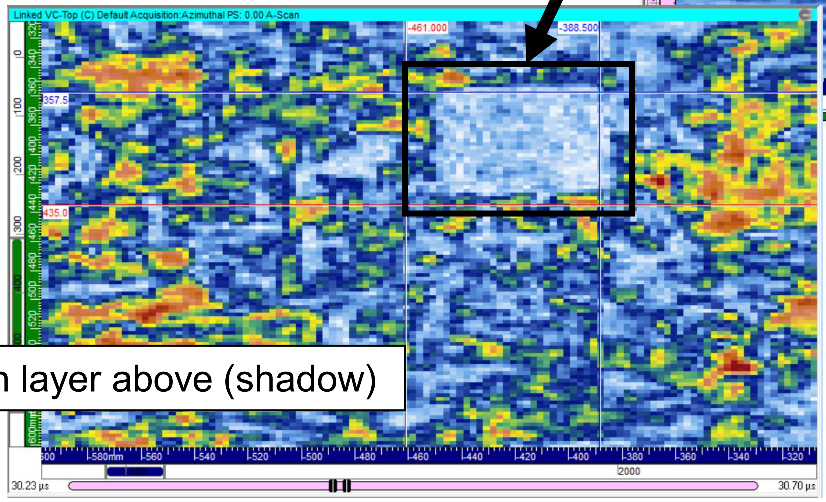
- 8 plates with a variety of fumed silica percentage, trowel sizes, and defect types were examined
- The quadrants with large square dry spots were scanned with UT, and they will be the focus of this comparison
  - Primarily quadrants 1 and 3 on each plate
  - Areas not scanned are blacked out in the matrix
- **Detections over the flawed region for each detection method are marked with a check in the table**
  - UT detection: A region that was identifiable as different from the surrounding areas in amplitude and consistency
  - Tap hammer detections: An indication within the flaw zone
- Sizing of defects was not performed
  - Qualitative comparison across different NDE techniques
  - Detected regions were marked and documented for future consideration

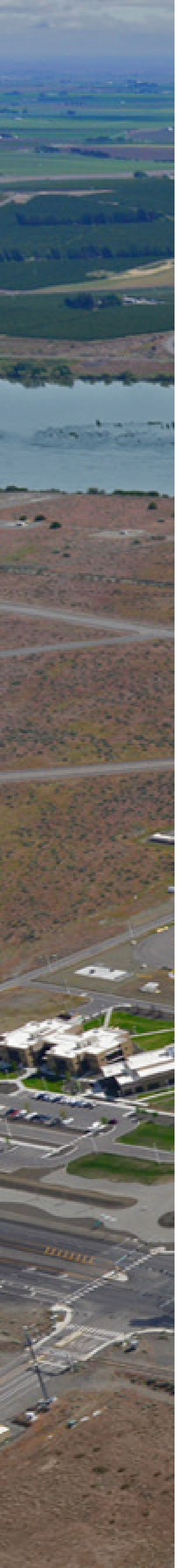
| Plate # | Fumed Silica (%) | Trowel Notches | Quadrant | Ply # | Flaw Type | Planned Size | PE-UT | | Manual Hammer | Woodpecker 632AM-R |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 500 kHz | 1MHz | | |
| 1 | 6.3 | 1/16" | 1 | CF1 | Wrinkle | 4.5"L | | | | |
| | | | 1 | CF2 | Dry Spot | 3"x3" | √ | √ | √ | √ |
| | | | 2 | CF3 | Overlap | 3"x1" | | | | |
| | | | 3 | CF3 | Wrinkle | 4"L | | | | |
| | | | 4 | CF3 | Gap | 3"x1" | | | | |
| | | | 3 | CF4 | Dry Spot | 3"x3" | √ | √ | √ | |
| | | | 4 | CF5 | Dry Spot | 2"dia. | | | √ | |
| 2 | 8.3 | 1/16" | 1 | CF1 | Wrinkle | 2.5"L | | | | |
| | | | 1 | CF2 | Dry Spot | 3"x3" | √ | √ | √ | √ |
| | | | 2 | CF3 | Overlap | 3"x1" | | | | |
| | | | 3 | CF3 | Wrinkle | 2.5" | | | | |
| | | | 4 | CF3 | Gap | 3"x1.25" | | | | √ |
| | | | 3 | CF4 | Dry Spot | 3"x3" | √ | √ | | √ |
| | | | 4 | CF5 | Dry Spot | 2"Dia. | | | √ | √ |
| 3 | 10.3 | 1/16" | 1 | CF1 | Wrinkle | 2.5"L | | | | |
| | | | 1 | CF2 | Dry Spot | 3"x3" | √ | √ | √ | √ |
| | | | 2 | CF3 | Overlap | 2-7/8"x1" | | | | |
| | | | 3 | CF3 | Wrinkle | 3"L | | | | |
| | | | 4 | CF3 | Gap | 3"x1" | | | | |
| | | | 3 | CF4 | Dry Spot | 3"x3" | √ | √ | √ | √ |
| | | | 4 | CF5 | Dry Spot | 2"Dia. | | | | |
| 4 | 6.3 | 1/4" | 1 | CF1 | Wrinkle | 4.5"L | | | | |
| | | | 1 | CF2 | Dry Spot | 3"x3" | | | √ | √ |
| | | | 2 | CF3 | Overlap | 1-3/8"x3" | | | | |
| | | | 3 | CF3 | Wrinkle | 4.25"L | | | | |
| | | | 4 | CF3 | Gap | 3"x1" | | | | |
| | | | 3 | CF4 | Dry Spot | 3"x3" | √ | √ | | |
| | | | 4 | CF5 | Dry Spot | 2"dia. | | | | √ |
| 5 | 8.3 | 1/4" | 1 | CF1 | Wrinkle | 3"L | | | | |
| | | | 1 | CF2 | Dry Spot | 3"x3" | √ | √ | √ | √ |
| | | | 2 | CF3 | Overlap | 1.25"x3" | | | | √ |
| | | | 3 | CF3 | Wrinkle | 3.5"L | | | | |
| | | | 4 | CF3 | Gap | 3"x1" | | | | √ |
| | | | 3 | CF4 | Dry Spot | 3"x3" | √ | √ | √ | √ |
| | | | 4 | CF5 | Dry Spot | 2"dia. | | | | √ |
| 6 | 10.3 | 1/4" | 1 | CF1 | Wrinkle | 3"L | | | | |
| | | | 1 | CF2 | Dry Spot | 3"x3" | | √ | | √ |
| | | | 2 | CF3 | Overlap | 3"x1" | | | | |
| | | | 3 | CF3 | Wrinkle | 2"L | | | | |
| | | | 4 | CF3 | Gap | 2-5/8"x1" | | | | |
| | | | 3 | CF4 | Dry Spot | 3"x3" | √ | √ | √ | √ |
| | | | 4 | CF5 | Dry Spot | 2"dia. | | | | |
| 7 | 8.3 | 1/16" | 1 | FG | Dry Spot | 2"dia. | | | | |
| | | | 1 | FG | Dry Spot | 3"x3" | | | | √ |
| | | | 2 | FG | Partial Cure | 2'x2' | | | | |
| | | | 3 | FG | Poor Surface | 2'x2' | | | | |
| 8 | 8.3 | 1/4" | 1 | FG | Dry Spot | 2"dia. | | | | √ |
| | | | 1 | FG | Dry Spot | 3"x3" | | | | √ |
| | | | 2 | FG | Partial Cure | 2'x2' | | | | |
| | | | 3 | FG | Poor Surface | 2'x2' | | | | |

# UT Observations

- To capture the interface response (CFRP to base plate), the gain was increased substantially
  - Surface saturation drowns out some of the shallow layers
- Images show a dry spot two layers below the surface
  - Top image is gated based on the layer location (yellow lines)
    - Response from the defect is at a higher amplitude than the surrounding signal
  - Lower image is based on gating on a deeper layer (black lines)
    - Lack of signal penetration due to dry spot
    - Shadow under the defect
- The lower image shows the potential for gating under shallow flaws for detection via the flaw shadow (blocked UT signal)

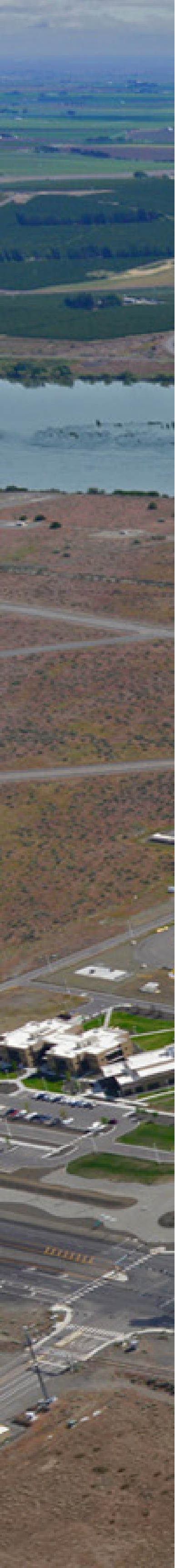




# Tap Testing Observations

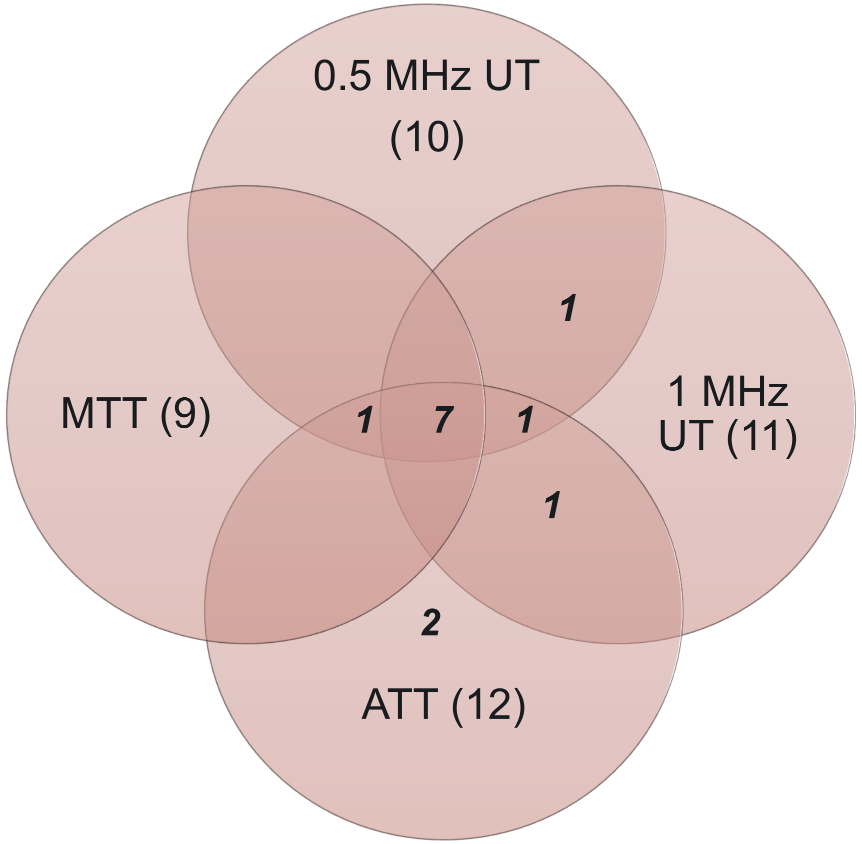
- The ATT system (632 AM-R) had difficulties providing consistent responses
  - The system is designed for thin ($\leq$ 4 mm or 0.16 in.) laminates such as those used in aerospace
  - Multiple single locations within a flawed region would be reported, but nothing coherent across the region of interest to indicate area defect
- MTT testing requires the inspector to clearly hear the sound response
  - Additional background noise (such as that present in industrial environments) can mask the audible defect noise
- All responses from the ATT are based on the user-defined reference location
  - No complete true state region (“good”) or calibration specimen to use for reference
    - ✓ Choosing an appropriate area for a reference signal is critical for these units
    - ✓ By comparison, UT showed a broad variation in signal responses across each plate, suggesting that a “good” region is subjective and potentially difficult to find



Pacific Northwest NATIONAL LABORATORY

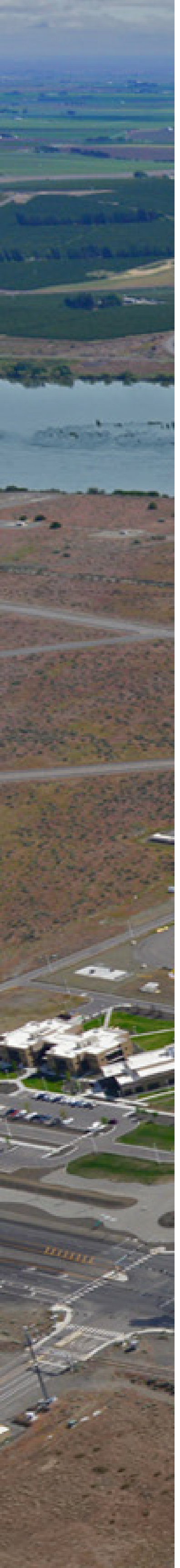
# Summary

- CFRP repairs in NPPs are not typical in the nuclear industry compared to other industry applications (e.g., aerospace)
  - On-site fabrication process, use of putty, and other process parameters
  - NDE methods must be evaluated for inspecting these applications
- 8 CFRP repair mockups were fabricated with varying amounts and thicknesses of putty, under-saturated (dry) spots, wrinkles, ply-gaps, and overlaps, in various layers
- Both UT and MTT were evaluated on 3 in. × 3 in. dry spot regions across plates (14 defect zones)
  - Only defect detection was compared
  - 11 of the 14 were detected by UT for at least one frequency (1 MHz)
  - 9 of the 14 were detected by MTT
  - ATT was not consistent through this thickness of CFRP (instrument is designed for much thinner composites)



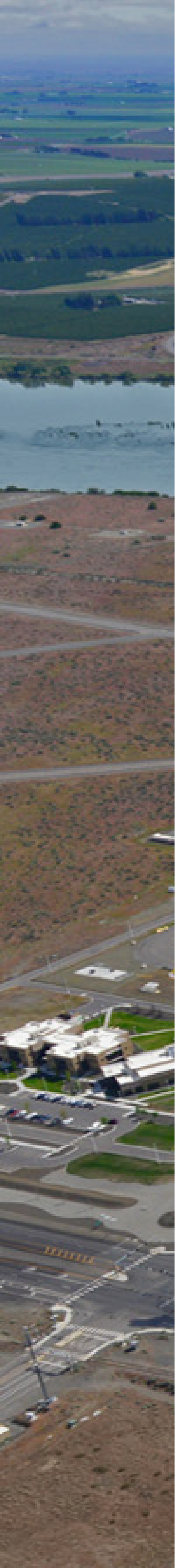
# Thank you

Muthu Elen
Muthu.Elen@pnnl.gov
Nicholas Conway
Nicholas.Conway@pnnl.gov



# References


- Elen M., N.A. Conway, and A.A. Diaz. 07/26/2023. "NDE of CFRP and Concerns on Mockup Fabrications." Presented by M. Elen at CFRP Technical Information Exchange - July 2023, Charlotte, North Carolina. PNNL-SA-187967.
- Elen M., N.A. Conway, and A.A. Diaz. 01/24/2024. "Fabrication and NDE Analysis of CFRP Repair Mockups." Presented by M. Elen at NDE Technical Information Exchange meeting, Washington, District Of Columbia. PNNL-SA-194066.
- Nove, C. (2021) ”NDE of Carbon Fiber Reinforced Polymer Composites – Some Thoughts”, NDE Public Meeting, NRC ADAMS ML21012A002, pages 103-122.
- “Non-contact Nondestructive Evaluation Technology: Dynamic Response Spectroscopy and Pulsed Eddy Current.” EPRI-Report 3002013174, 2018.
- “Nondestructive Evaluation of Metallic Substrates through Carbon Fiber Reinforced Polymer (CFRP) Composite Repair Systems ”EPRI-3002020823, 2022.



# Terminology

- Substrate – The original metallic component to be repaired/modified (typically the base pipe)
- Fiber – One or more filaments in an ordered assemblage; acts as a primary load-carrying member in a composite
- Matrix / Resin / Epoxy – Material in which reinforcing fiber of a composite is embedded. A thermosetting polymer containing one or more epoxide or oxirane groups, curable by reaction with amines or alcohols. Does not include fillers or thickening agents. It is a two-part mixture
- Fabric – A material constructed of interlaced yarns, fibers, or filaments. May be unidirectional or bi-directional or other forms depending on the fiber orientation
- Ply or Lamina or Laminae – Fabric (CFRP or GFRP) when saturated with epoxy
- Composite – Thermoset plastic (polymer) that is reinforced by fibers, matrix, also known as composite laminate
- CFRP Repair or Composite Repair – The complete composite system, consisting of primers, lamina, epoxy, putty, and top coatings installed in accordance with defined laminate architecture
- Putty or Thickened Epoxy – A mixture of epoxy and prescribed thickening agent (e.g., fume silica) in the appropriate ratio that provides a smooth surface for the application of the CFRP laminate
- NDE – NDE stands for nondestructive examination or nondestructive evaluation, a process that examines the condition of a material or component without damaging it. NDE is also known as nondestructive testing (NDT) or nondestructive inspection (NDI). The process is also referred to as the NDE method or NDE technique