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Mitigation of Material Degradation Associated with Long Term Operation

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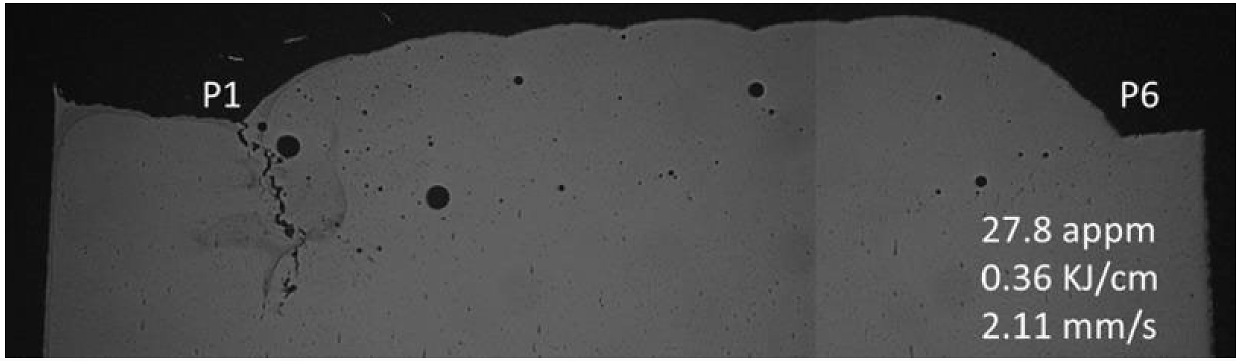
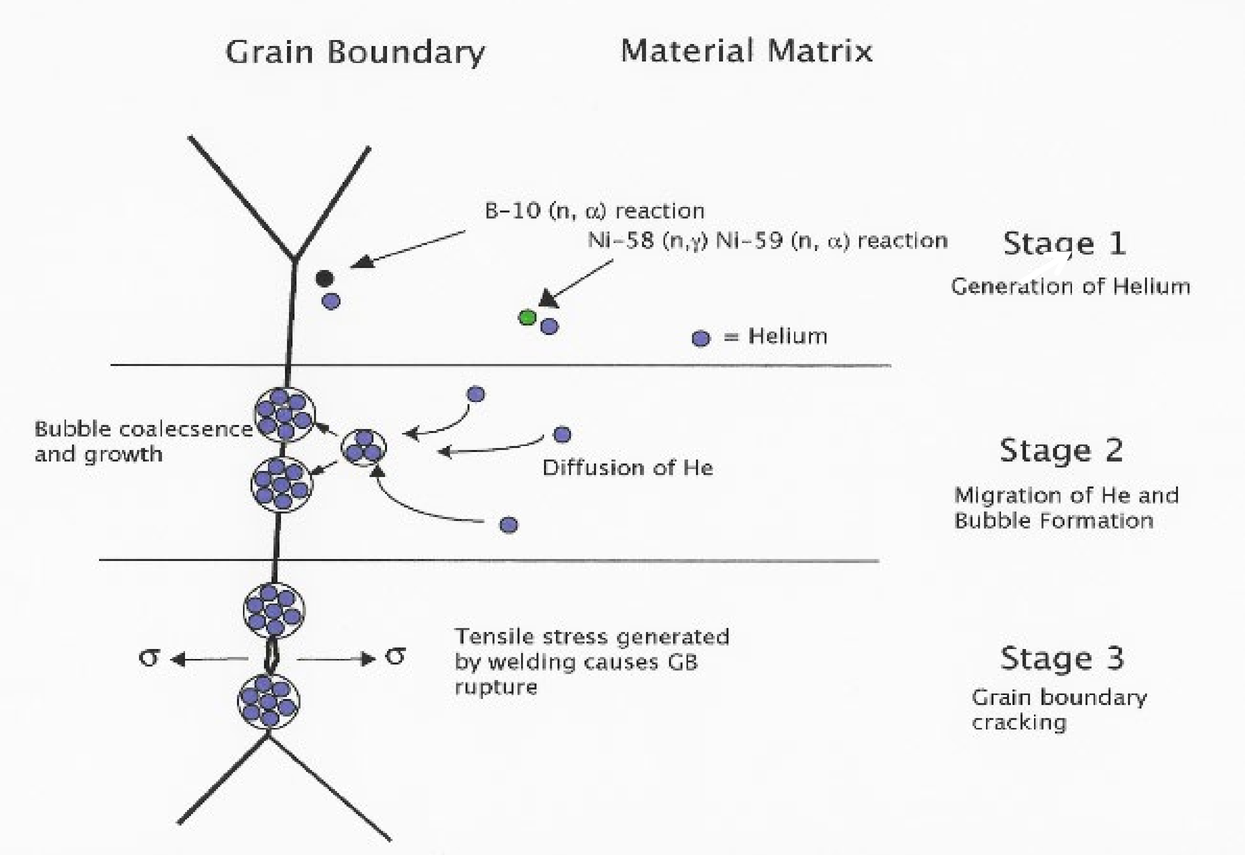
NRC Workshop on Structural Materials - Session 7 on Mitigation
October 1-4, 2024

Irradiated Materials Repair Solutions

Issue with Welding on Highly Irradiated Materials

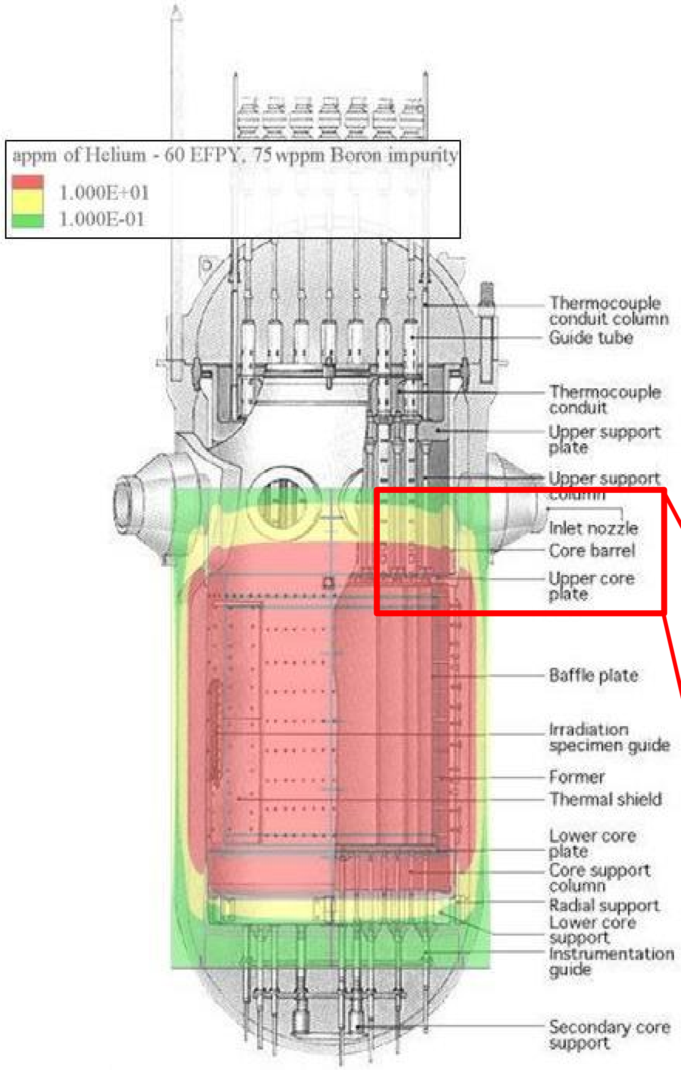
- Helium is generated in reactor internals over time as radiation levels increase
  - neutron transmutation reactions of boron and nickel
- If these irradiated materials are subjected to high temperatures (> 850°C), the helium will begin diffusing to grain boundaries
- If excessive heat is applied during welding, this diffused helium will form intergranular bubbles, resulting in "helium-induced" cracking (HeIC) in the heat-affected zone

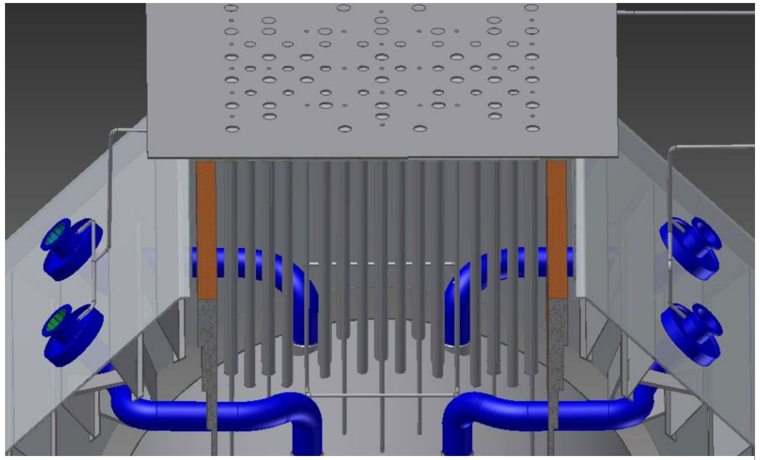




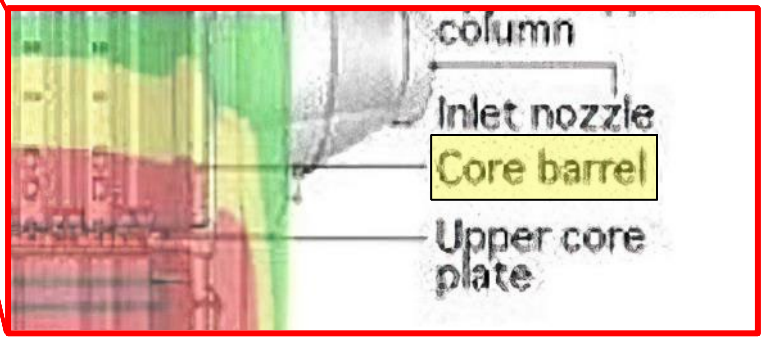
Recent Nuclear Power Plant Operating Experience

- Bruce Unit 7 Calandria Relief Duct (CANDU)
  - Volumetric inspection performed in 2016 revealed significant degradation of highly irradiated CRD [1]
  - Bruce Power currently seeking potential repair methods
- PWR Core Barrel Cracking
  - Outage inspections have detected cracking on reactor core barrel component
  - Weld repair would have been ideal, however, lack of helium data for component excluded this option





Bruce Unit 7 Calandria Relief Duct [1]



Core Barrel Location on Reactor

[1] A. Brooks, S. Gupta, "Continued Fitness for Service of the Bruce B Unit 7 Calandria Relief Ducts," 1st International Conference of Materials, Chemistry and Fitness-for-Service Solutions for Nuclear Systems May 15-17, 2019, Markham, Ontario, Canada.

Overview

- EPRI Welding & Repair Technology Center (WRTC) Program is overall lead for EPRI efforts regarding welding of irradiated materials
- EPRI work has historically been and continues to be cost shared with the U.S. Department of Energy through Oak Ridge National Laboratory (ORNL)
- EPRI role:
  - Support project planning and irradiated material data collection to ensure future needs are adequately addressed
  - Support ASME Code activities related to irradiated materials
  - Implementation of R&D results into guidance (*revision of BWRVIP-97, MRP-379*)
  - Support emergent issues related to irradiated material repair, as needed

Irradiated Component Weld Repair: Three Primary Gaps

1

Weldability Data

- Historical Welding Data Review (Japanese)
- Irradiated Materials Weldability Data Collection (304, 316, Alloy 600/82/182)
- Development of helium threshold plots
- Regulatory acceptance of extended helium thresholds for welding

2

Helium Quantification

- Boron concentration database (austenitic materials)
- Reactor component helium calculation
  - Primarily based on fluence and initial boron concentration of material
- Reactor component helium measurement guidance

3

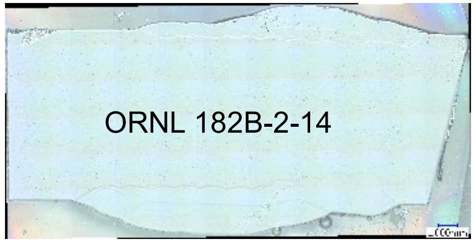
Field-Deployable Systems

- Development of underwater welding systems
  - Arc Welding: GTAW, GMAW
  - Laser welding
- Demonstration on representative mockups
- Will require service vendor support

Irradiated Material Welding Solutions - Timeline

Funded Milestones

Q3 2023



Irradiated Alloy 600/182 ORNL Weld Campaign: Characterization

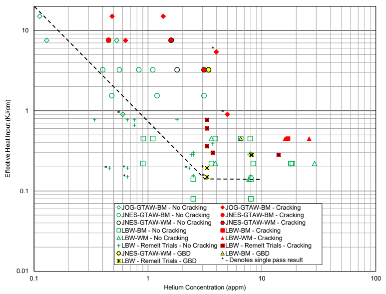
Complete characterization of first ORNL welding campaign

Q2 2024

Complete BWXT Weld Trials

Evaluation of GTAW trials on low He-bearing samples (304L, 316L, 600/182)

Q3 2024



Historical Welding Data Summarization

Publish consolidated review of historical Japanese irradiated material welding data

Q4 2024

Helium Round Robin Study/Guidance Document

Publish revised He-measurement guidance document

Q3 2025

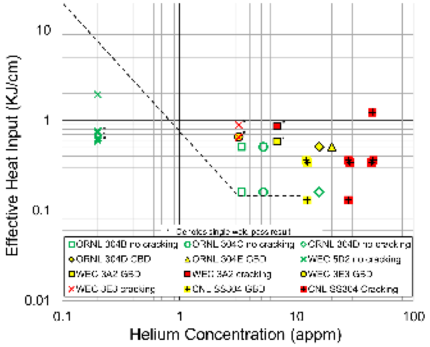
Boron Measurement Database

Comprehensive boron analysis on preservice nuclear components

Q4 2025

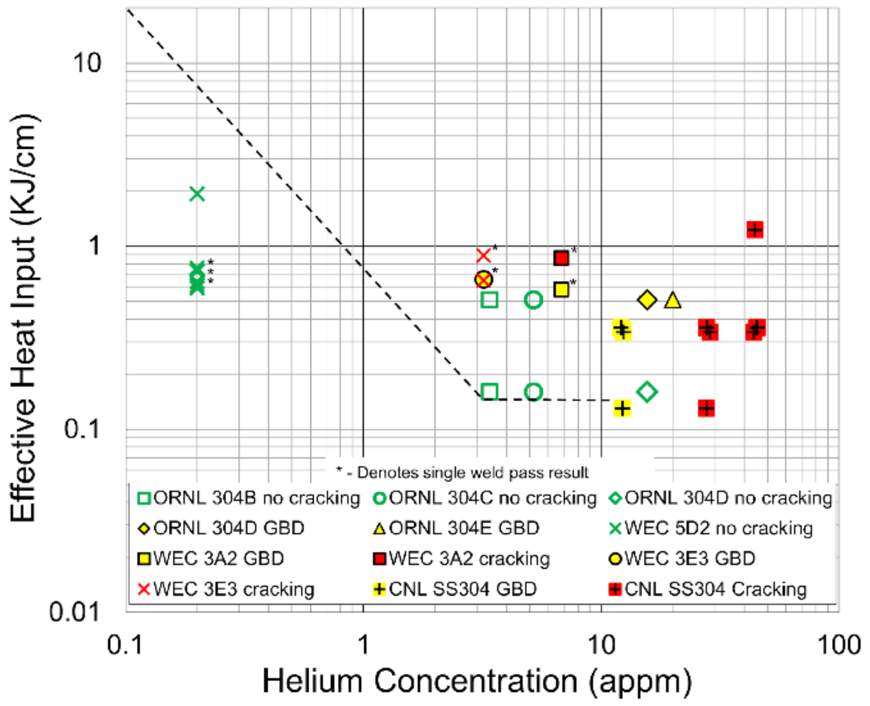
Extend Helium Thresholds/Revise Welding Guidance Documents

Extend 304/316 helium thresholds for welding and publish updated PWR/BWR welding guidance



Deliverables

- Regulatory acceptance of higher helium thresholds for repairs to irradiated materials
  - ASME Code Cases, U.S. NRC interactions
- Repair guidance including helium threshold plots
- Conventional and advanced field deployment ready repair systems for application to critical locations (e.g., riser brace RPV ID attachment welds)



Spent Fuel Pool Repairs

Spent Fuel Pool Repairs

Motivation

- Many fuel pools will be in operation for more than 100 years
- Operators need to know available options when leaks occur
- In some scenarios, non-metallic repairs (NMRs) can be faster and more cost effective than traditional welded repairs
- A summary of state-of-the-art nuclear fuel pool liner repair technologies, deployment options, and worldwide operating experience is needed

Project Objectives

Review origin and detection/localization of fuel pool leaks

- Susceptible locations
- Most successful localization techniques

Summarize industry fuel pool leak experience + industry codes/standards

- Detection/localization methods implemented
- Implemented (conventional) repair methods
- Lessons learned

Review available NMR material and deployment options

- Key properties
- Advantages/Limitations
- Operating experience

Summarize key considerations and lessons learned for various NMR options

Summary of Operating Experience

- Fuel pool leak events from 40+ plants globally
- Collection of 50+ years of fuel pool operating experience
- Leak rates ranging from < 1 L/day to > 60,000 L/day
- Documented leak repair experience:
  - 22 traditional weld repairs
  - 17 local non-metallic repairs
  - 6 non-metallic liners

Divers Performing Underwater Welding Repairs

Origins of Leaks

Mechanical Damage

Latent Weld Defect

Corrosion

Detection of Leaks

Pool volume variation

- Leaks detected by incrementally filling pool, waiting, and checking leak chases
- Does not require an external service provider to conduct the test
- Can be employed inexpensively by the plant operator

Vacuum boxes

- Leaks detected by clear boxes operating under pressure or negative pressure on liner
- Conducted by divers

Alternating current field measurement (ACFM)

- Locates leaks by detecting disturbances in induced electric field
- Does not require close contact with liner surface, can be done submerged or in air

Visual inspection

- Pool inspected by unaided eye, particularly welds or locations of known damage

Other

- Eddy current testing
- Ultrasonic testing
- Acoustic emission / ultrasonic leak detection

Key Findings

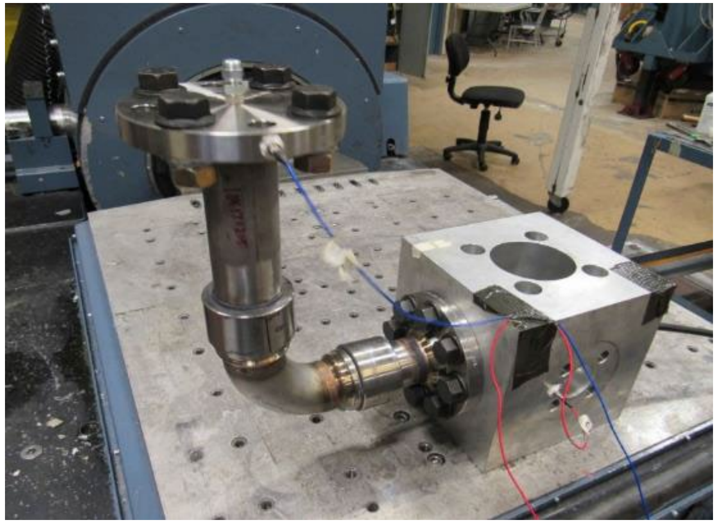
- NMRs can offer some key advantages over more conventional fuel pool repair techniques, in particular when repairs involve relatively large areas
- Several product families and deployment approaches are available and compatible with nuclear fuel pool applications
- NMR solutions must be chosen based upon whether the location can be drained
  - Epoxies and MSPs can be applied dry or submerged and are generally the only option in fuel pools (i.e., non-drainable applications)
- NMRs with sufficient flexibility should be used in drainable locations (e.g., transfer canals, reactor cavities)
  - Flexibility is needed to accommodate liner movement during thermal and fill/drain cycles
- Radiation exposure must be accounted for in NMR solution selection and post-implementation management, especially within a few meters of stored fuel

Small-Bore Piping Issues

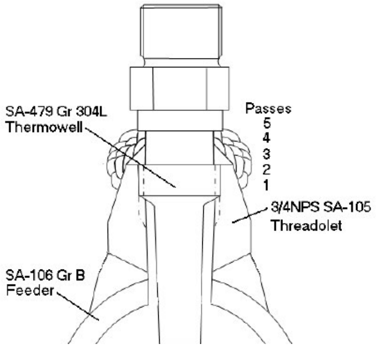
Small Bore Piping Issues

Understand small bore (≈ NPS 2 or 50 mm and under) piping issues and maximize small bore piping reliability

- Socket welds,
- Butt welds,
- Weld Overlays,
- Mechanical fittings



High cycle fatigue testing of elbow mechanical fitting



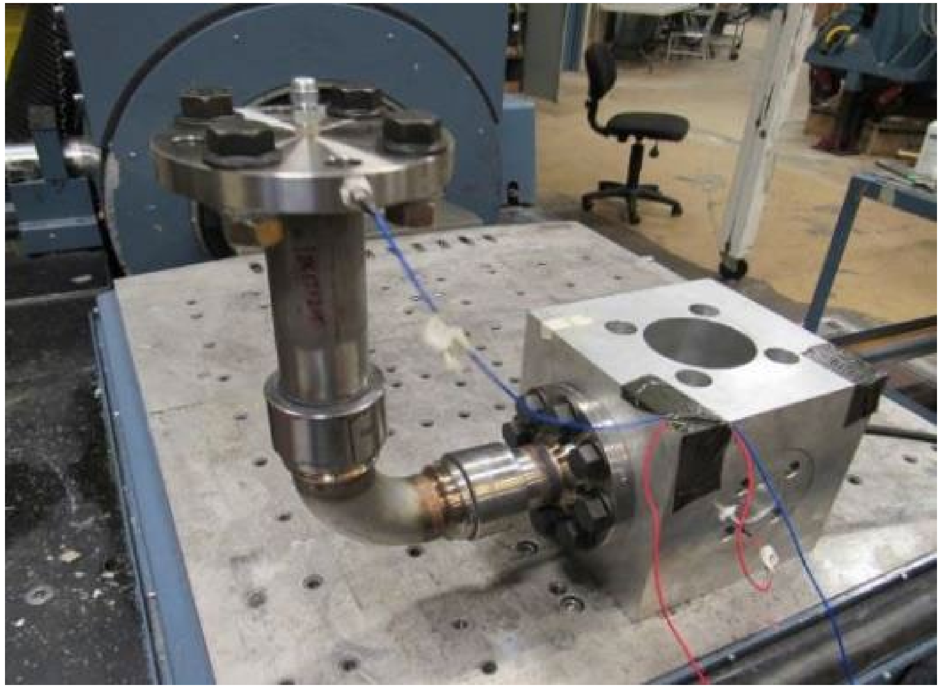
Socket weld overlay

Small Bore High Cycle Fatigue

- Objective: Testing to understand fatigue resistance of different fittings and welds
- Approach: Shaker table testing to calculate fatigue strength reduction factors, with the potential for post testing failure analysis

Guide to Small Bore Vibration Risk

- Current scope to address larger Lokring (4 or 5 inch) mechanical fittings



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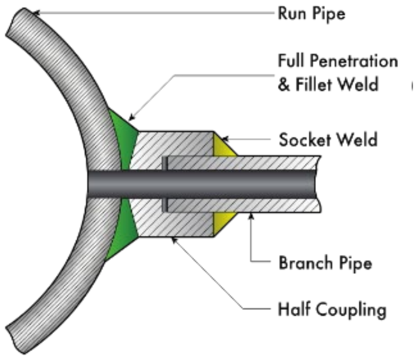
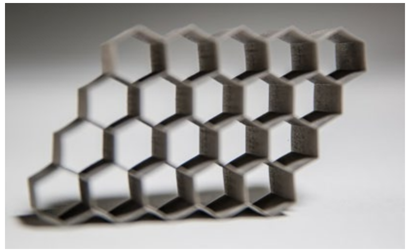
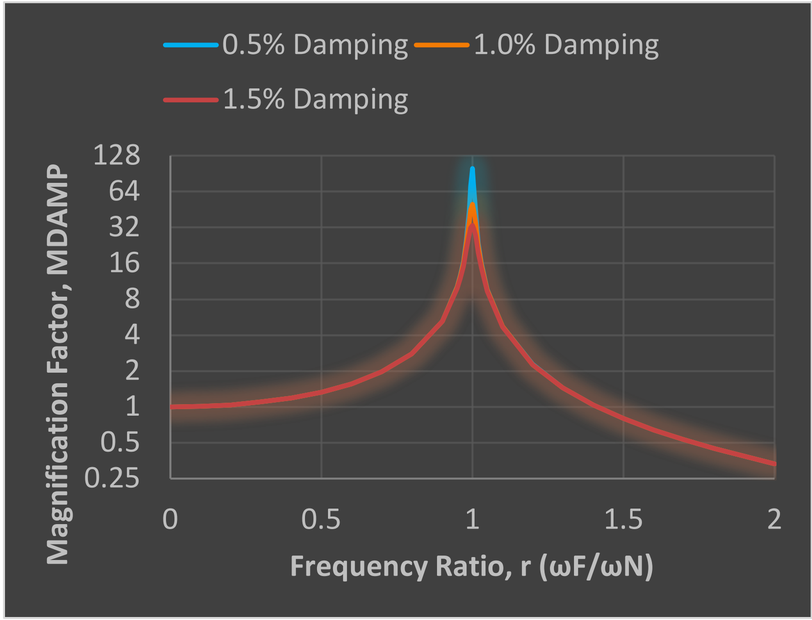
Improved Small Bore Fittings and Supports Development

- Objective: Evaluate potential fitting or support designs with improved fatigue performance
- Do new manufacturing techniques give ability to produce complex geometries or vary material properties that help with vibration fatigue?



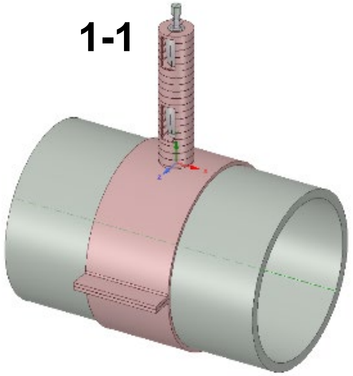




Fittings and Supports Down Selection for Testing

- FEA predicts designs 1-2 and 3-9 have the most potential for improvement
- Testing to validate results in progress

1-1



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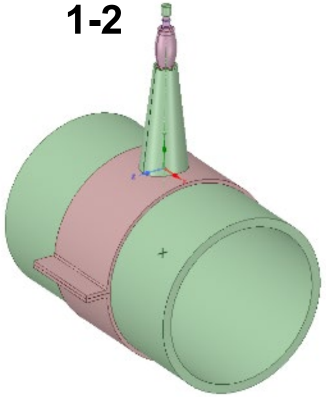

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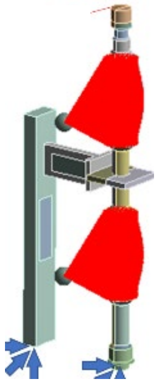

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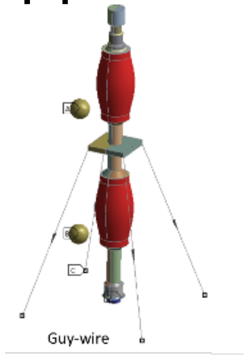

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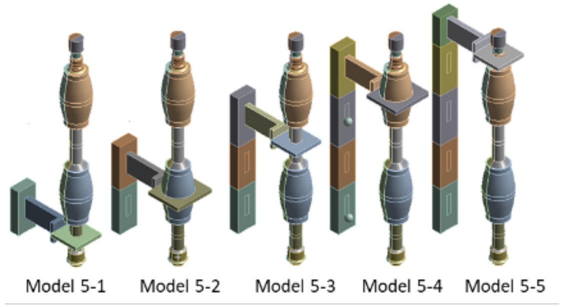
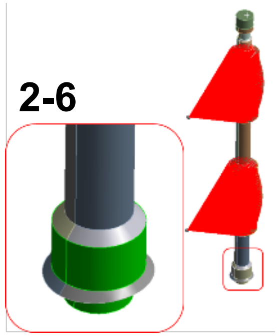


2-6



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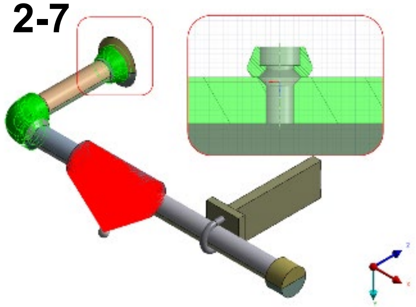
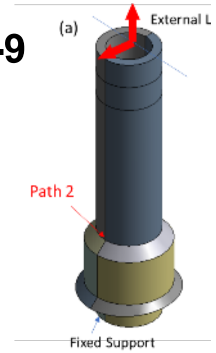


2-8

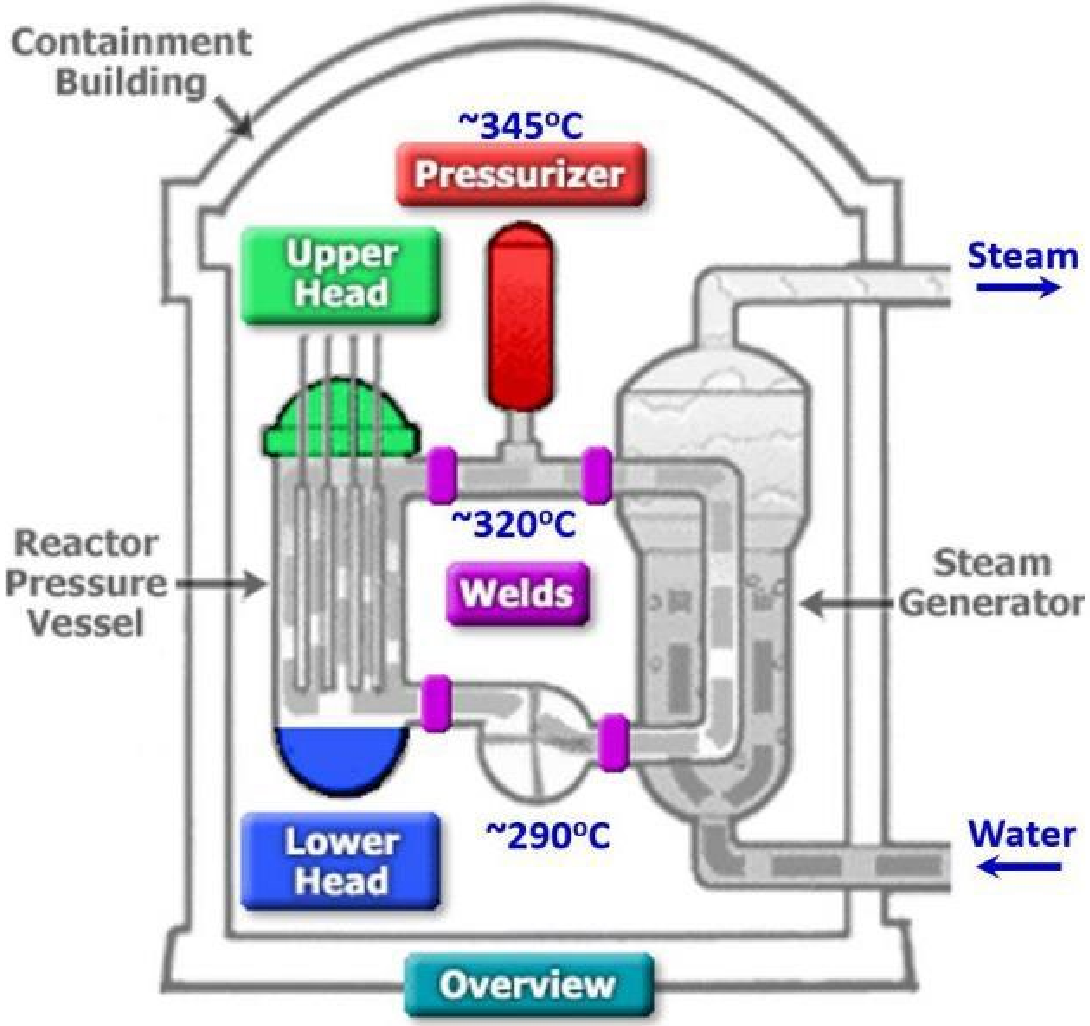
3-9



Alloy 52/152 Thermal Aging

Motivation

- Weld deposits created with a variety of alloy 52 filler metal variants are being subjected to extended, low temperatures (<450°C)
- Thermal Aging: long-term, irreversible changes in the structure, composition, and morphology of materials exposed to temperatures that they encounter in service.
- While interest in thermal aging in PWRs is a long-standing research area, little data has been collected on the propensity of thermal aging in filler metals and welds.
- Perform heat treatments to understand the propensity for thermal aging of alloy 52 filler metal variants.



Schematic of PWR reactor with relevant temperatures

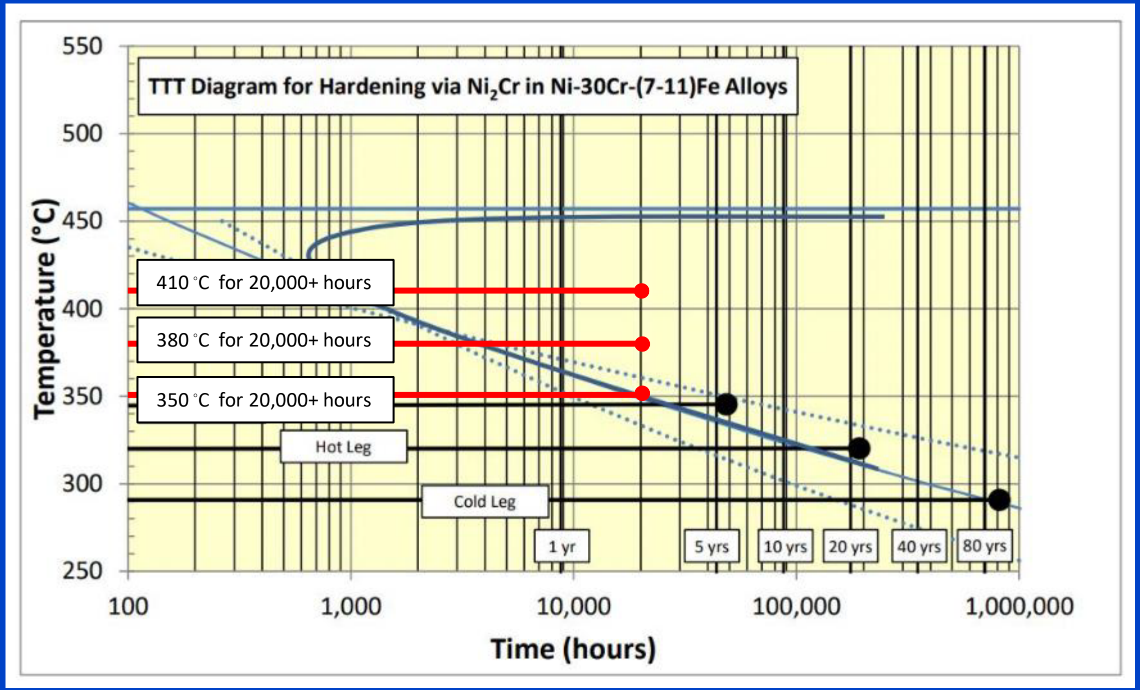
https://www.nrc.gov/reactors/operating/ops-experience/pressure-boundary-integrity.html

Considerations when Selecting Heat Treatment Temperature and Exposure Times:

- Parts of interest subjected to approximate temperatures of 290 °C, 320 °C, and 345 °C
- Equivalent service times of 40 – 80 years are of interest
- There is a lack of low temperature data

Experimental Plan

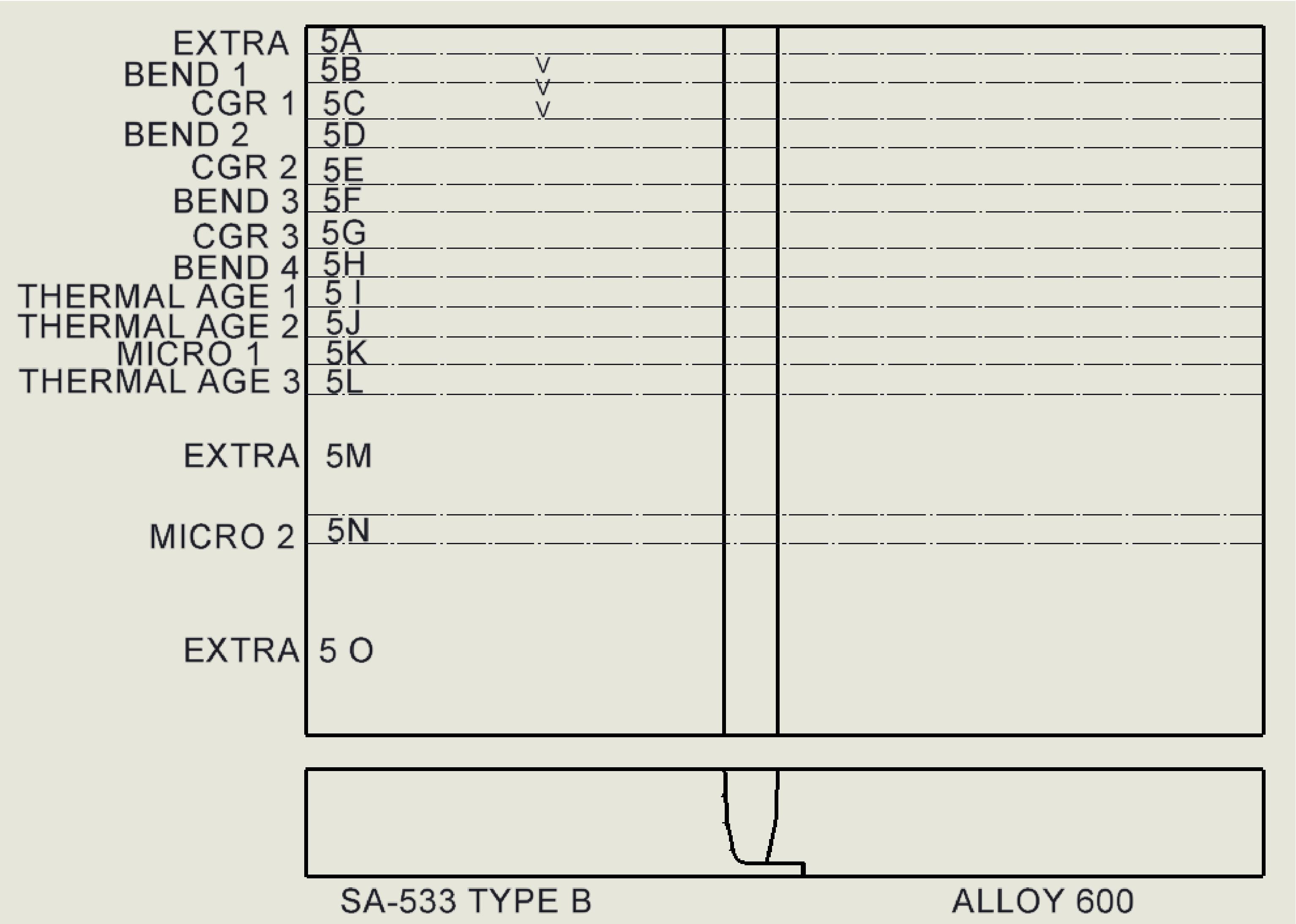
- Temperatures
  - 410 °C for 20,000+ hours
  - 380 °C for 20,000+ hours
  - 350 °C for 20, 000+ hours
- Interruptions
  - 1,000 hours (completed)
  - 5,000 hours
  - 10,000 hours
  - 20,000 hours
- Hardness measurements will be conducted at each interruption
- Microscopy to be conducted if a significant increase in hardness is detected
- Mechanical test samples also being aged



TTT Diagram with Proposed Times and Temperatures

Weld Filler Metal Variants And Plate Layout

Plate	Variant	Heat
2	52M	NX7206TK
3	52MSS	NX79W1UK
4	52MSS-Ta Low Fe	HV1673
5	52MSS Low Fe	HV1500
6	52XL (52-Ta-Mo)	S2768-2
7	52M	NX79W5TW
8	52MSS-Ta	VX131WXW
9	52M	NX77W2TK
10	52MSS-Ta	VX135WXW



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