32 – Welding Program Update and Code Applications

U.S. NRC Materials Programs Technical Information Exchange Public Meeting

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ELECTRIC POWER RESEARCH INSTITUTE

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Presentation Outline

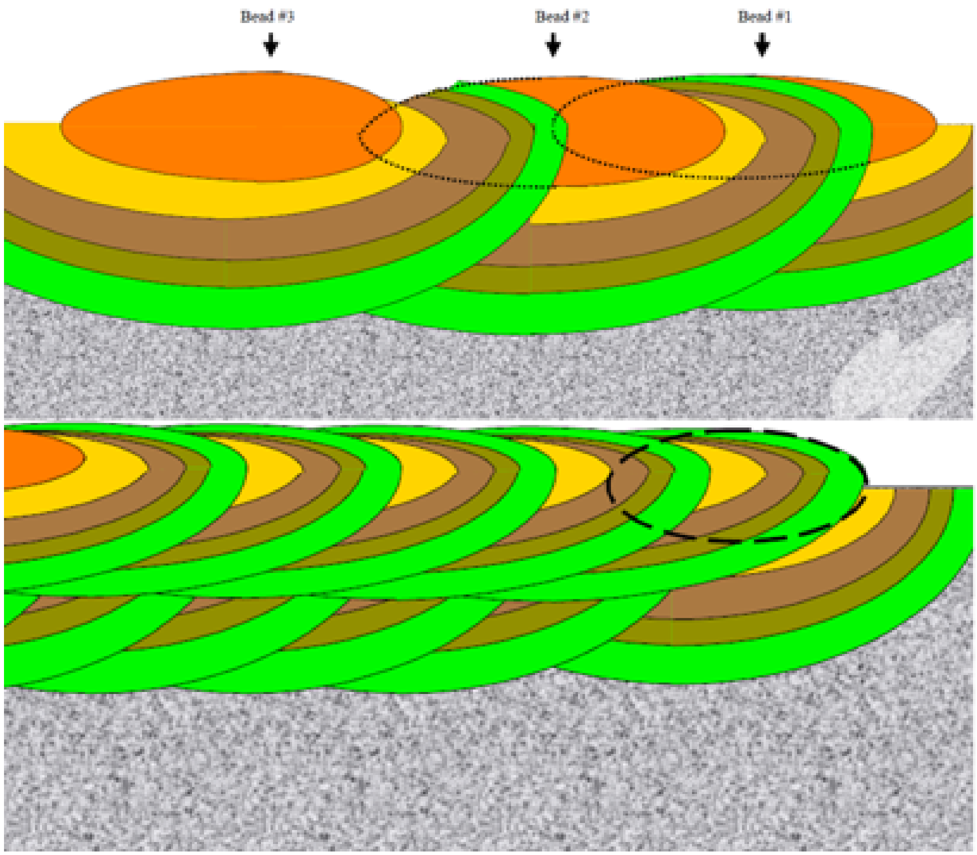
- **Welding Program Update – Key Projects**
  - Hardness Test Protocol for Temper Bead Qualification
  - Welding on Irradiated Material
- **Code Applications – Key Activities**
  - Revisions to N-638-9 and New Case N-888
  - Case N-752 for Risk-Informed R&R Activities

Hardness Test Protocol for Temper Bead Qualification

Steve McCracken, EPRI

Temper Bead Welding – Overview

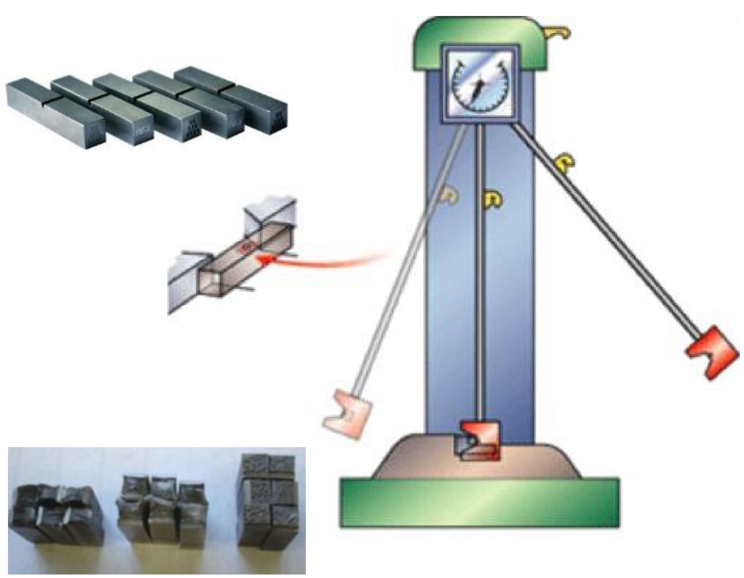
- Temper bead welding is an alternative to post weld heat treatment (PWHT)
- Weld heat-affected zone (HAZ) tempering is achieved by:
  - Adjacent weld bead heating
  - Subsequent layer 2 or layer 3 heating
- Temper bead procedures qualified by Charpy V-notch testing of the HAZ
  - Charpy V-notch impact energy (ft-lb or Joules) ≥ unaffected base material
- Other HAZ criterion often specified
  - Maximum peak hardness
  - Both peak hardness and impact properties

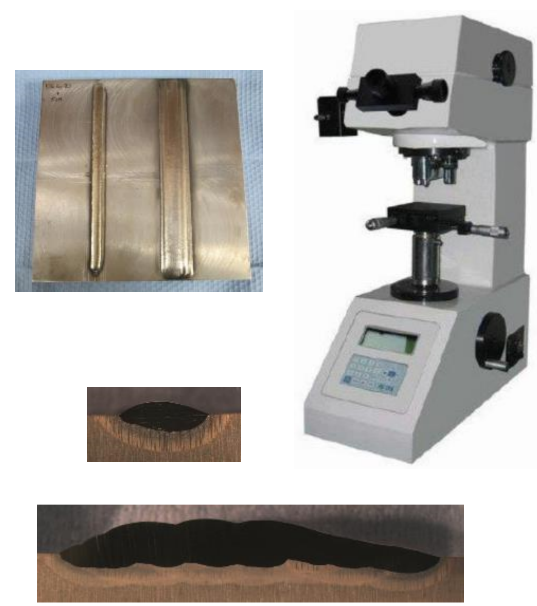


Overlapping bead HAZ during multi-pass welding [1]

Why Hardness Testing for Temper Bead Qualification?

- Benefits of hardness testing
  - Simple alternative to Charpy V-notch impact testing
  - Appropriate hardness testing approach is less costly and time consuming compared to Charpy V-notch testing





Is Hardness Appropriate for Temper Bead Qualification?

- Yes – hardness is appropriate provided the hardenability of the material is properly characterized and a proper testing approach is applied
- There are significant pitfalls with a single peak hardness criterion for TB procedure qualification [2]
  - Hardness alone, without knowing the microstructure or thermal history, is not adequate to verify appropriate HAZ tempering
  - Rejection by a single hardness reading (as often required in EN/ISO codes) is not reasonable
  - Use of maximum hardness criterion can potentially lead to acceptance of TB HAZ properties with poor impact properties

Proposed Temper Bead Hardness Qualification Protocol [3]

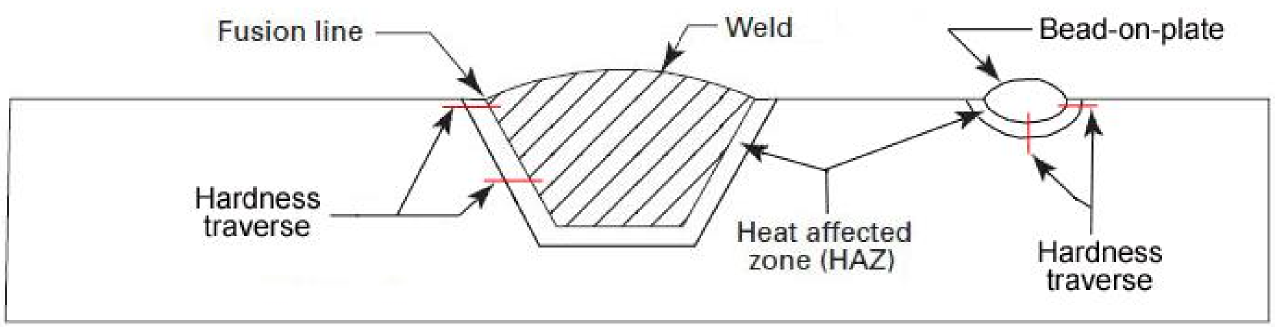
Step #1

- Make a single bead on plate and measure the HAZ hardness
- HAZ hardness should be close to calculated hardness *(example: Maynier's equation)*

$$HV_M = 127+949C+27Si+11Mn+8Ni+16Cr+21Log_{10}(V)$$ [4] Note: V=C°/hr

Step #2

- Make a temper bead pad or groove weld and measure the HAZ hardness
- Temper bead procedure is qualified with appropriate drop in hardness between untempered single bead HAZ and tempered weld HAZ

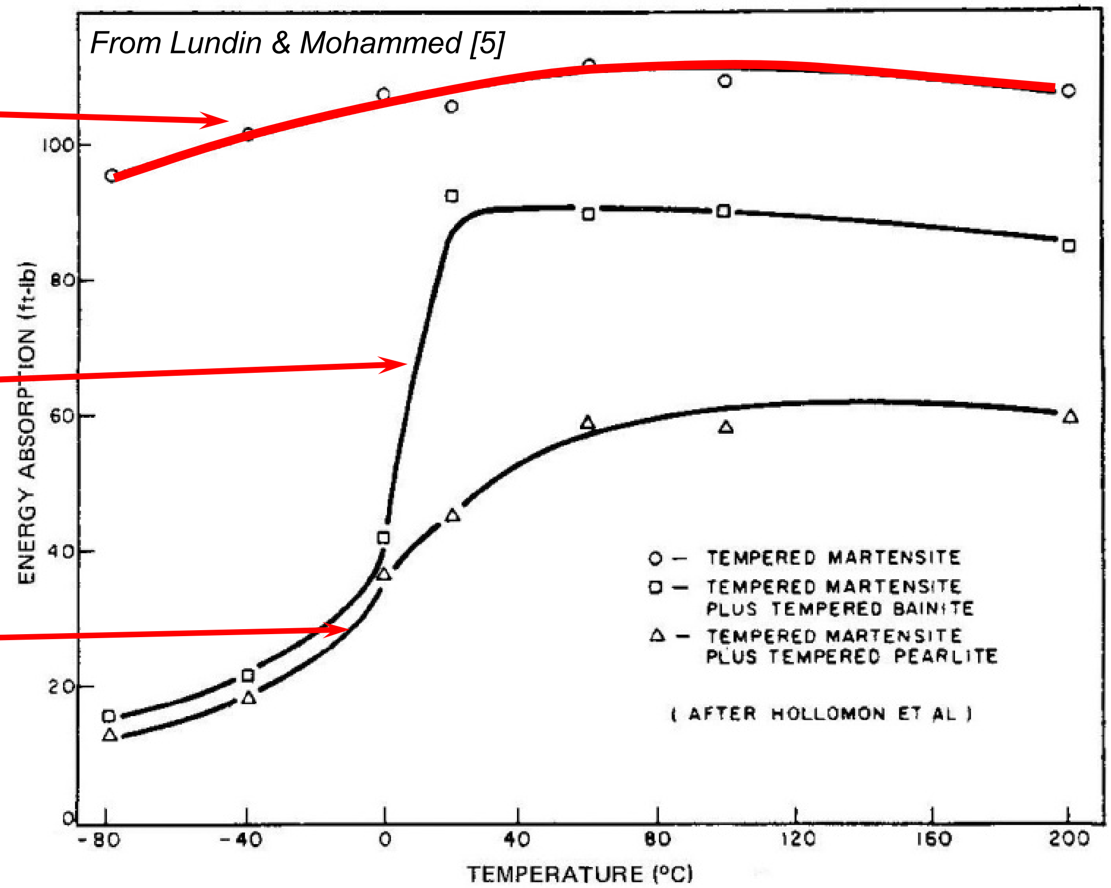


Example of possible hardness procedure qualification test coupon

Figure from Ref. [3]

Tempered Martensite Impact Energy

- **<u>Tempered martensite</u>** has superior impact energy from high to low temperatures
- **<u>Tempered martensite plus tempered bainite</u>** shows sharp temperature transition
- **<u>Tempered martensite plus tempered pearlite</u>** has poorest impact energy



HAZ Hardness, Impact Energy & Microstructure

Two Step Hardness Protocol

- Tempered martensite (TM) exhibits the highest HAZ Charpy impact energy
- Bainite (B), Tempered Bainite (TB) and TTM HAZ microstructures are all in the 200 to 300 HV10 range
- Two step hardness demonstrates a TM microstructure

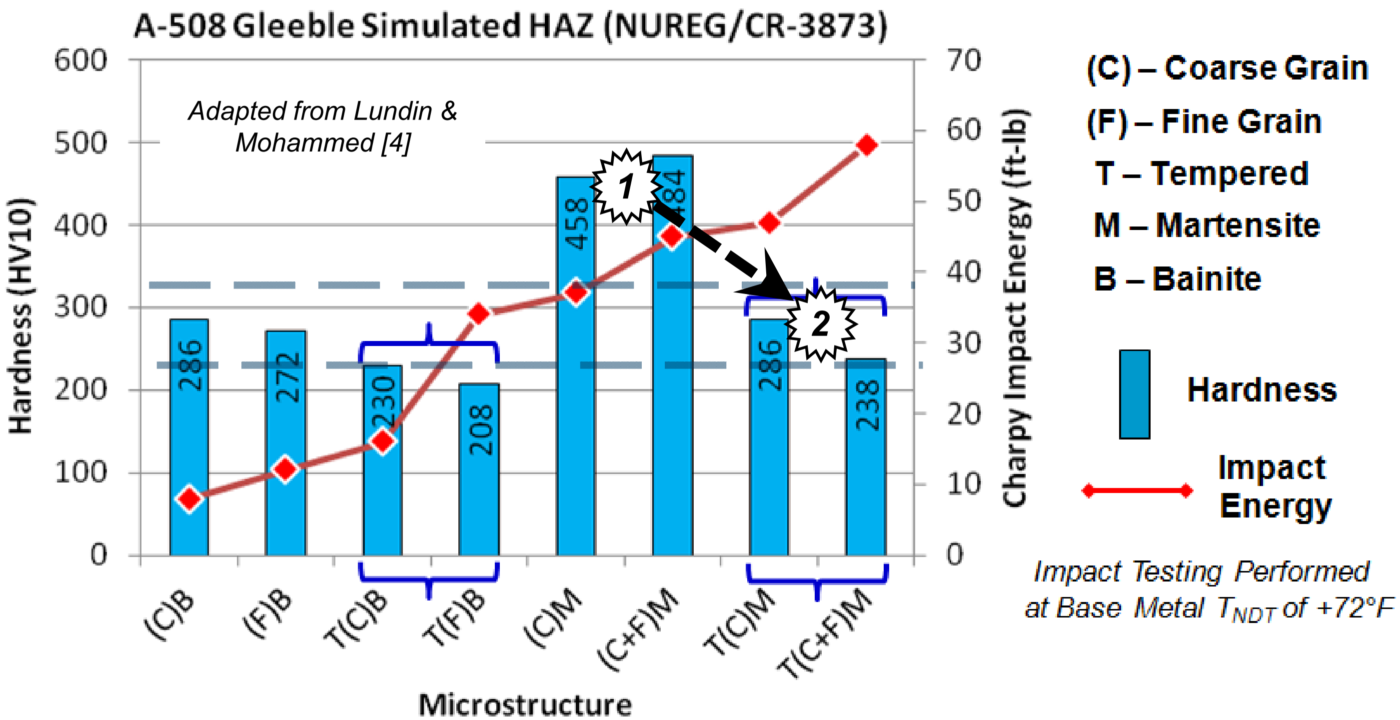


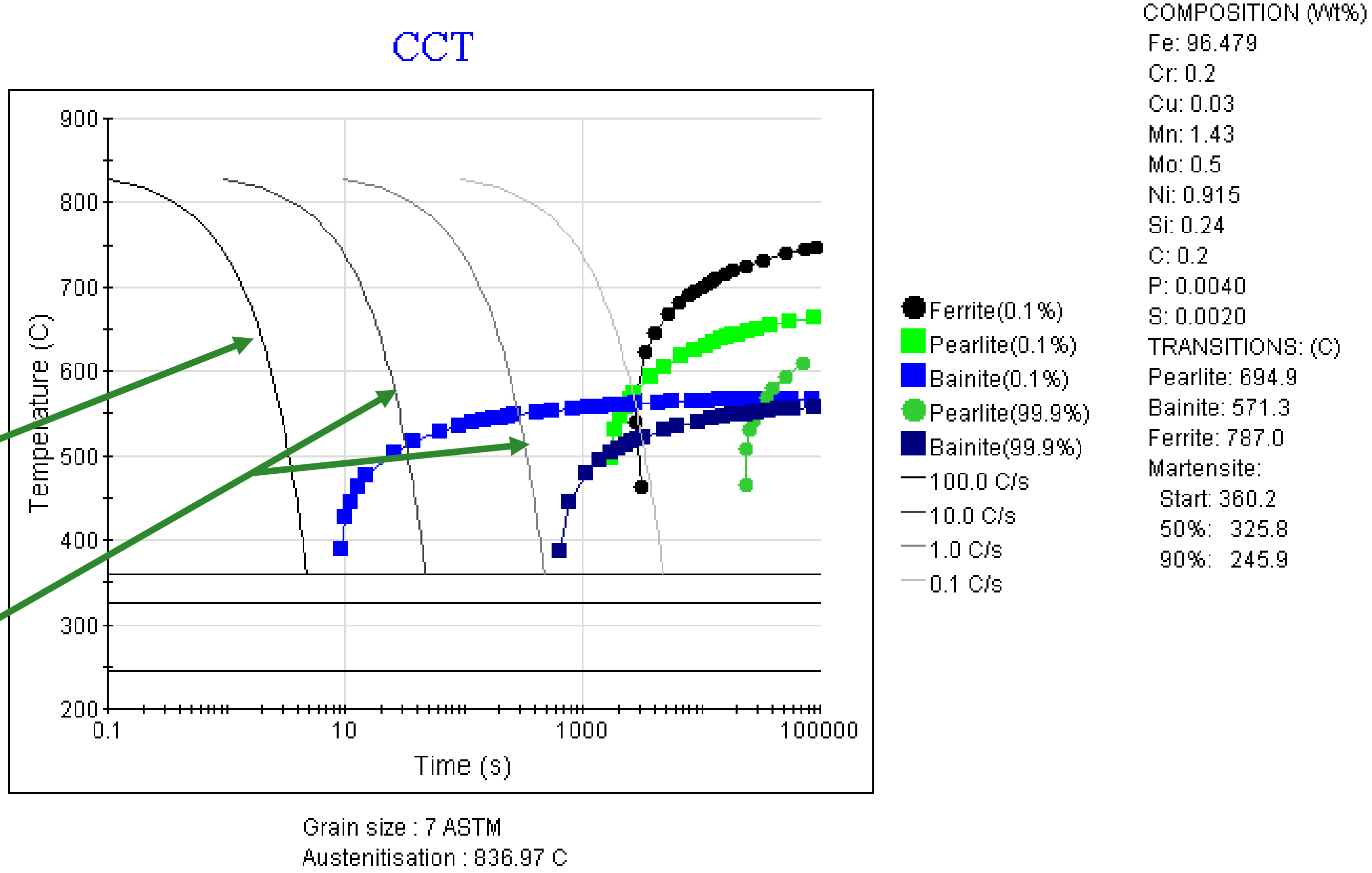
Figure from Ref. [3]

Cooling Rate Effect on Microstructure

CCT Diagram for SA-508 Forged Material (JMatPro®)

Microstructure of 100% martensite with high cooling rate

Mixed microstructure of martensite and bainite with slower cooling rate



SA-508 Simulated Temper Bead HAZ Experiments

- SA-508 simulated temper bead HAZ samples made with Gleeble® thermal mechanical simulator
  - Cooling rate used to develop HAZ microstructures with varying martensite (M) and bainite (B) phase fractions
    - Samples austenized at 969ºC for 5 min
    - Controlled cooling between 800º to 500ºC
- Phase fractions verified with quantitative metallography
- Tempered with Gleeble® for 1 second at 635°C
- Hardness drop between untempered and tempered determined for each martensite / bainite microstructure

Cooling Rate	M%	B%	Std. Dev	Untempered Hardness (HV 0.5)	Hardness after 1s tempering at 635ºC (HV 0.5)	Hardness Drop (HV 0.5)
5 C/s	19	81	9	305 ± 2	276 ± 1	29 ± 2
8 C/s	28	72	17	353 ± 2	302 ± 1	51 ± 2
10 C/s	60	40	17	386 ± 3	307 ± 2	80 ± 3
15 C/s	84	16	5	432 ± 2	329 ± 1	103 ± 2
20 C/s	77	23	12	419 ± 2	325 ± 1	94 ± 2
30 C/s	93	7	4	455 ± 1	330 ± 1	126 ± 1
40 C/s	91	9	4	441 ± 2	329 ± 1	112 ± 2
55 C/s	99	1	1	462 ± 1	342 ± 1	120 ± 1
SA-508 BM	NA	NA	NA	207 ± 8	NA	NA

Hardness drop values for Gleeble® simulated SA-508 HAZ samples with varying martensite/bainite microstructures [6]

Martensite Percentage and Hardness Drop Relationship

- Linear relationship for percentage of martensite in untempered microstructure and hardness drop after temper bead welding

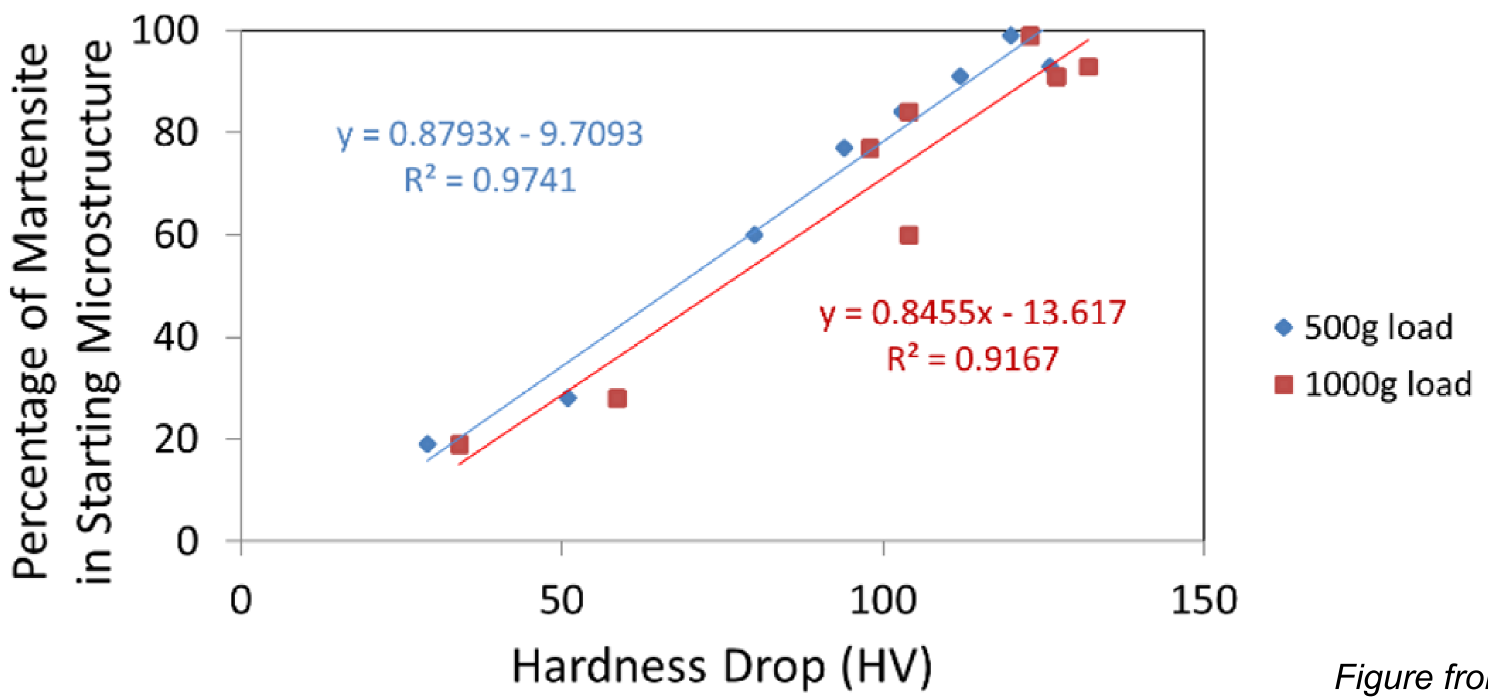


Figure from Ref. [6]

Potential Hardness Drop Acceptance Criterion

- Flowchart showing peak hardness and hardness drop as indicators of appropriate level of tempered martensite in temper bead HAZ
  - Criterion 1: Peak hardness ≥ 440 HV and hardness drop ≥ 110 HV

    or

  - Criterion 2: Hardness drop ≥ 125 HV

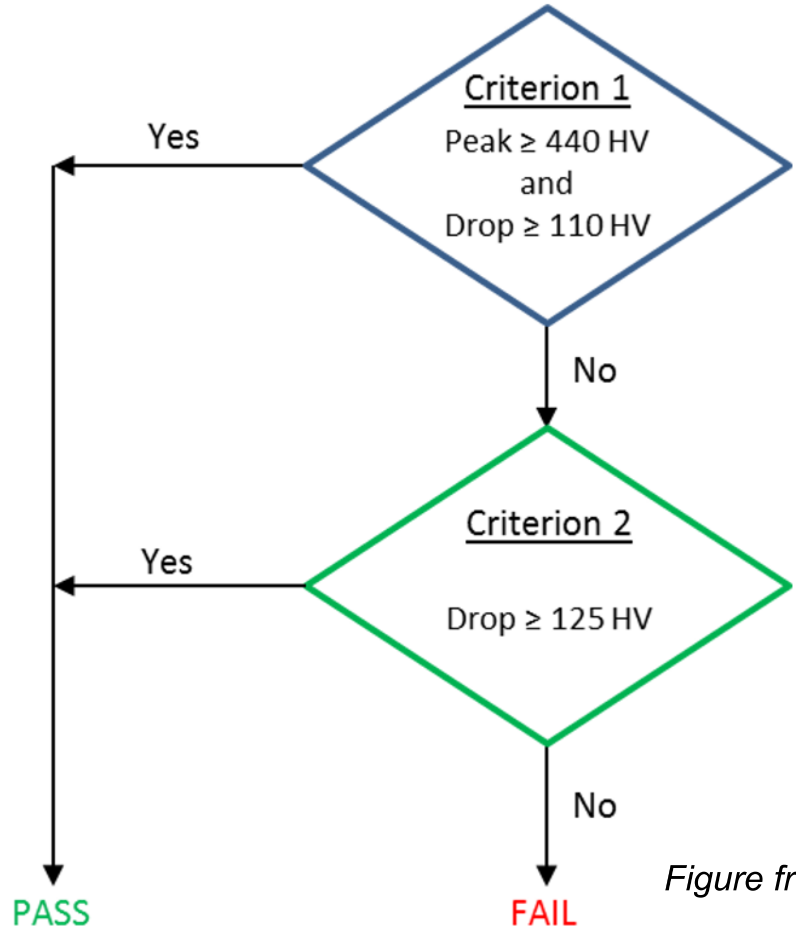


Figure from Ref. [6]

Status of Hardness Protocol Activities

Completed Work

- Statistical study for temper bead hardness mapping protocol
  - Optimal load of 500 gram with 250 micron spacing
- Verified that hardness drop criterion is effective for predicting a tempered microstructure

On-going Work

- Charpy impact testing of SA-508 and P-22 temper bead HAZ Gleeble® samples

Future Work

- Evaluate effect of hard spots (carbides, nitrides, etc.) on impact properties
  - Build samples with varying fractions of hard spots
  - Characterize effect on impact properties
- Temper bead modeling module
  - Applies EPRI effective heat input equation and empirical temper bead response relationships

Temper Bead and Hardness Protocol References

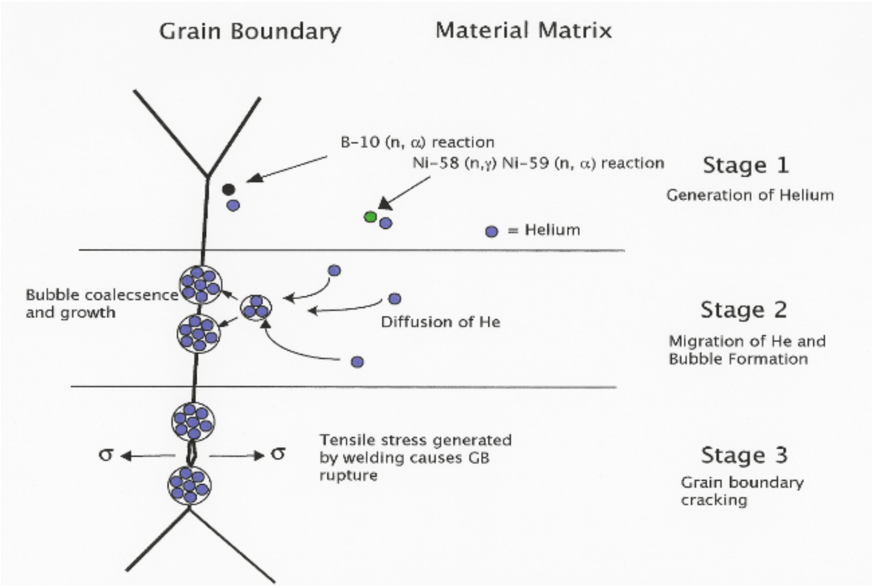
1) W.J. Sperko, Exploring Temper Bead Welding, *Welding Journal* 84(7): 37 to 40
2) McCracken, S.L., Smith, R.E., and, Barborak, D., "Validity of Hardness Criteria to Demonstrate Acceptable Temper Bead HAZ Impact Properties for Nuclear Power Applications", 2013 ASME Pressure Vessels & Piping Division Conference, Paris, France, July 14-18, PVP2013-97793
3) McCracken, S.L., Sutton, B., "Qualification of Temper Bead Welding by an Alternative Hardness Testing Approach," 2015 ASME Pressure Vessels & Piping Division Conference, Boston, Massachusetts, July 19-23, PVP2015-45663
4) P. Maynier, B. Jungmann, J. Dollet, Creusot-Loire System for the prediction of the mechanical properties of low alloy steel products, Hardenability Concepts with Applications to Steel, The Metallurgical Society of AIME (1978) 518-545
5) Lundin, C.D. And Mohammed, S., "Effect of Welding Conditions on Transformation and Properties of Heat-Affected Zones in LWR Vessel Steels," NUREG/CR-3873, November 1989
6) Smith, B., Ramirez, A.J, McCracken, S.L., Tate, S., "Investigation of Relationship Between Microhardness and Charpy Impact Energy for Temper Bead Welding Qualification – Part 1," 2019 ASME Pressure Vessels & Piping Division Conference, San Antonio, TX, July 14-19, PVP2019-93950

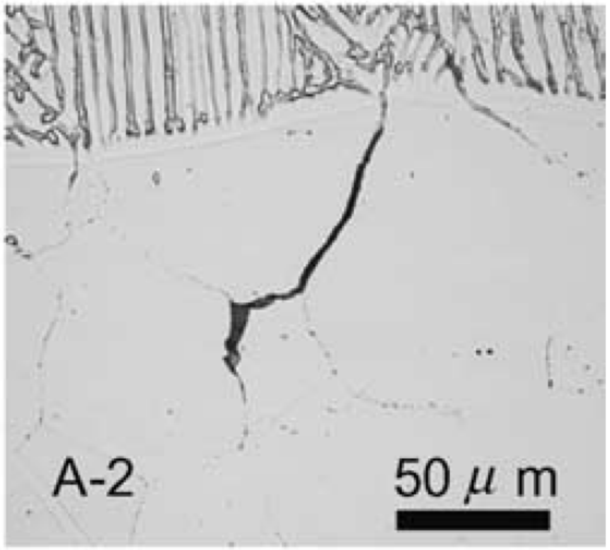
Welding on Irradiated Material

Jon Tatman, EPRI

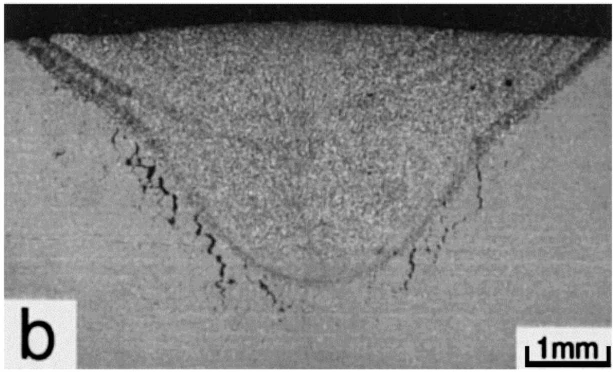
Technical Challenge – Welding on Highly Irradiated Materials

- Helium generated by neutron transmutation reactions can result in formation of helium-induced cracks when welded
- Excessive heat input from welding can result in intergranular helium bubble coalescence and growth in the heat affected zone, leading to helium-induced cracking
- It is appropriate to provide guidance for consideration of irradiation effects to prevent helium-induced cracking





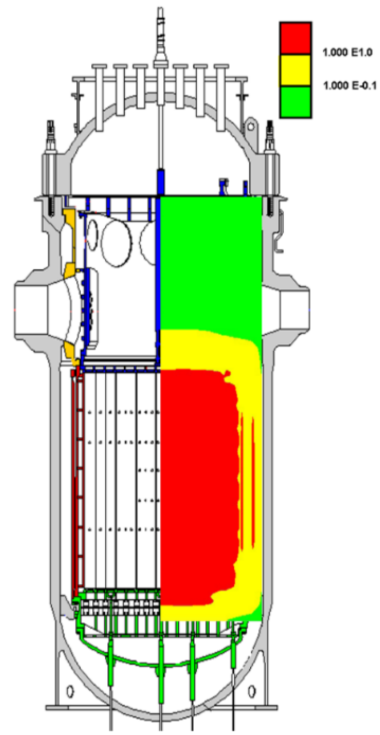
Morishima, Y., JNM, 2004



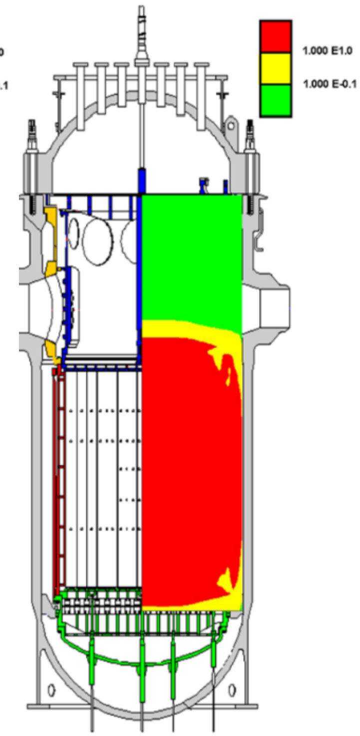
Asano, K., JNM, 1999

Industry State of Knowledge and Objectives

- Helium generation maps have been developed by EPRI for several plant designs to provide guidance on internal LWR repair (BWRVIP, MRP EPRI reports)
- Improved weld heat input estimation techniques have also been developed by EPRI to generate definitive helium induced cracking threshold plots for 304 and 316L materials
- An extensive number of irradiated stainless steel (304, 316) and nickel-base (Alloy 182) trials are required to further validate developed helium threshold plots and obtain regulatory approval of future ASME Section XI code case.



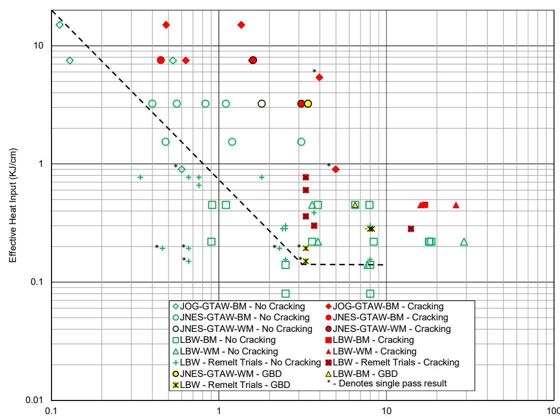
Helium Level Calculations
Low Fluence Case
40-Yr Service Life
10 wppm B



Helium Level Calculations
High Fluence Case
60-Yr Service Life
75 wppm B

- **At the moment, there are two major directions of work led by EPRI:**

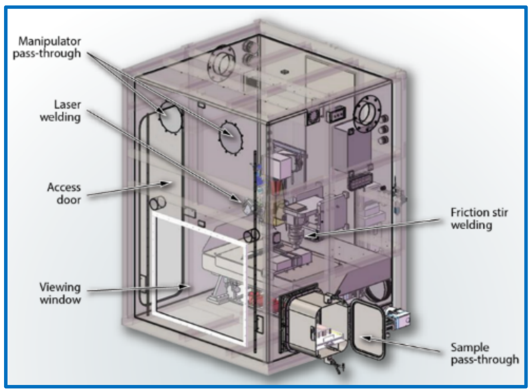
1) **Irradiated material welding at Westinghouse** (focus on pre-irradiated commercial steel); team: J.Tatman, P. Freyer, F. Garner, etc. The approach and results will be discussed here.
2) **Irradiated material welding at ORNL** (focus on model, B-enriched steel heats). Team: J. Tatman, Z. Feng, W. Tang, S. Clark, etc. The approach will be briefly discussed below.

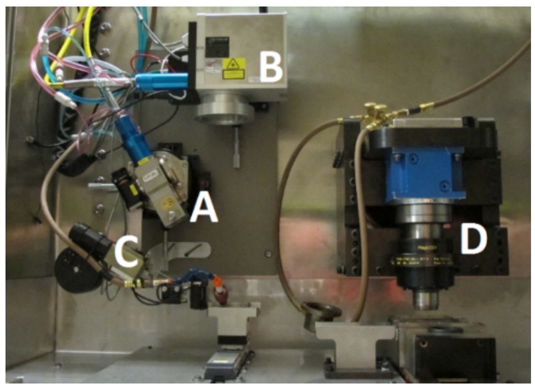


He-Induced Cracking Threshold Plot: 304 SS

Irradiated Material Welding Facility Development at ORNL

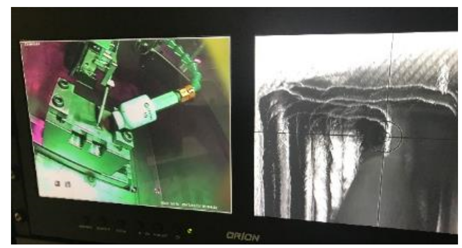
- **Welding cubicle installation at Oak Ridge National Laboratory (ORNL) hot cell facility has been completed.**
  - Electrical and Plumbing of ABSI Laser System: Completed September 2017
  - Cold Testing of Welding Systems: Completed October 2017
  - Two welding campaigns on irradiated 304L and 316L samples have been completed to-date



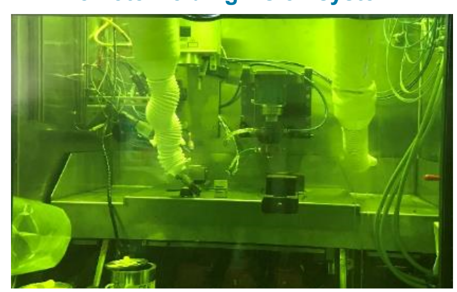


A: Laser Weld Head; B: Auxiliary Laser Scan Head; C: Wire Feeder; D: FSW Head

Control room



Remote welding vision system



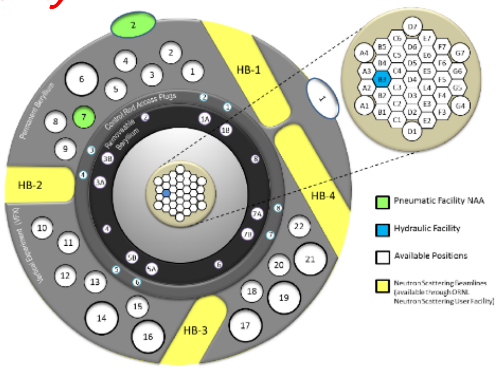
Internal cubicle view from control room

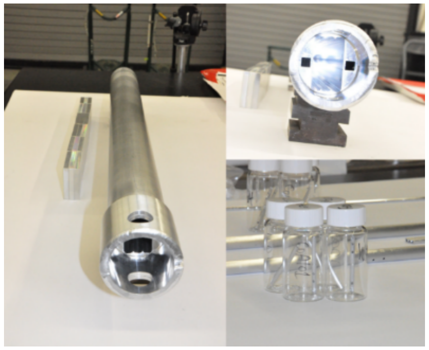
Cubicle installed in ORNL hot cell

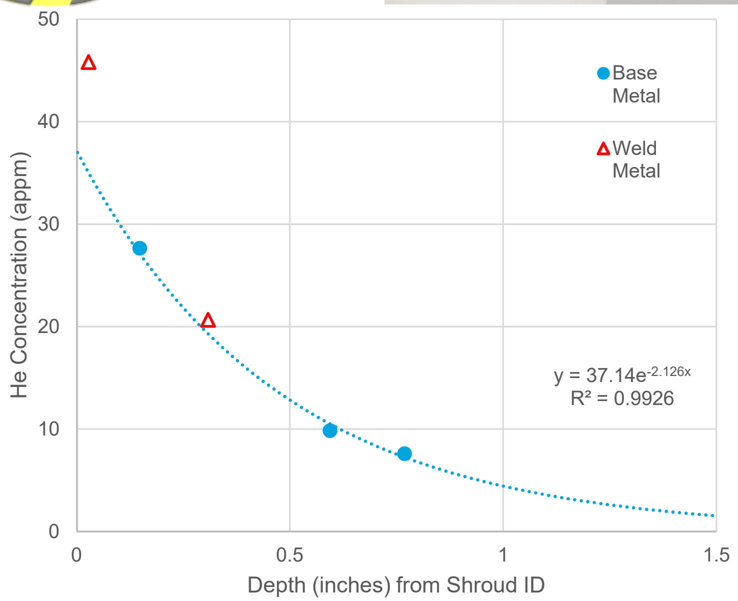
Material Irradiation at ORNL High Flux Isotope Reactor (HFIR)

Fabrication and Neutron Exposure of Materials within HFIR Facility

- **First irradiation campaign** complete and specimens are available/being used within hot cell
  - Mixture of 304L and 316L (45 samples total)
  - Target helium contents ranging from ~1 to 30 appm (controlled by B^{10} content)
  - Flux monitors included during irradiation
  - PNNL and ORNL modeling to estimate helium concentrations using composition and irradiation conditions
- **Second irradiation campaign** complete and samples are in storage
  - Mixture of 304L, 316L, and Alloy 182 (45 samples total)
  - Target helium contents ranging from ~ 1 to 30 appm
  - Similar irradiation plan as first campaign
- **Third irradiation campaign**
  - Mixture of 304L and 316L
  - Materials are currently being fabricated, 5 of 6 heats taken through rough machining
  - Target helium contents extending up to 50 appm based on the analysis of the Plant Hatch core shroud boat sample.



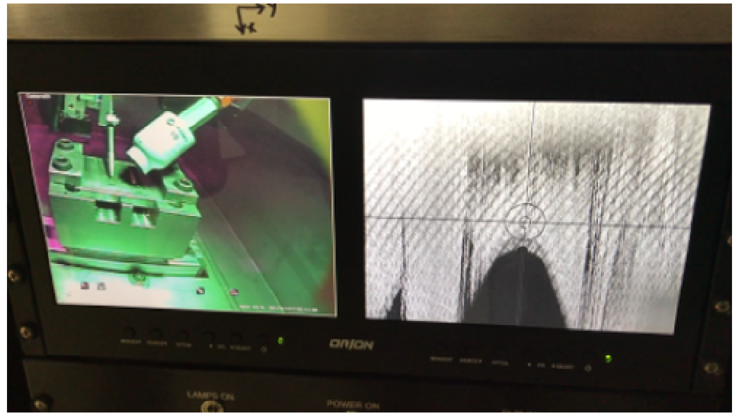


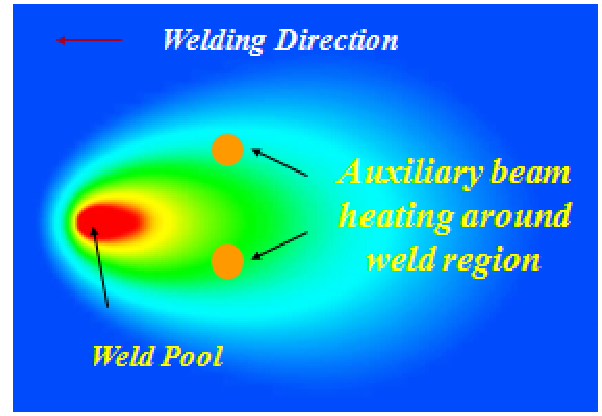


Advanced Welding Process Development for Irradiated Material Repair

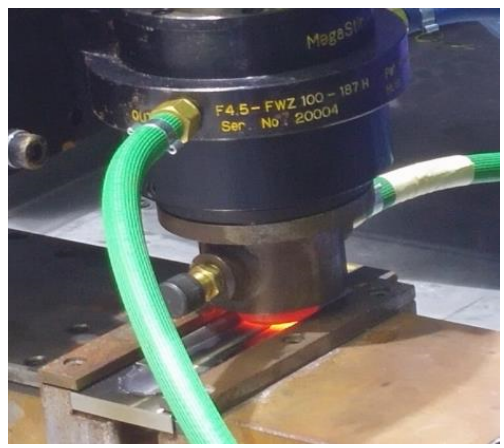
- Heat input control for fusion welding processes may not be sufficient for helium induced cracking prevention in highly irradiated materials
- Advanced welding processes under development:
  - Auxiliary beam stress improved (ABSI) laser beam welding
  - Low force friction stir welding/cladding.

Auxiliary Beam Stress Improved Laser Beam Welding





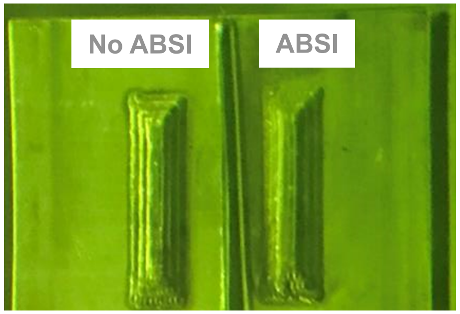
Friction Stir Welding



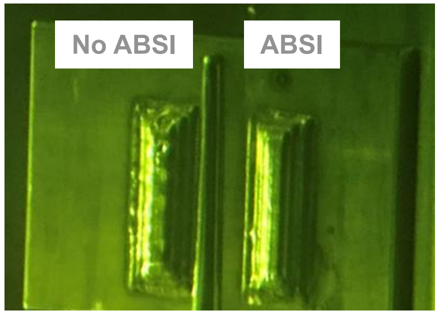
In-Cell ORNL Irradiated Material Welding Campaigns

First Irradiated Material Welding Campaign at ORNL

Sample 1: Laser Weld Pads (304L, 20 appm target He)

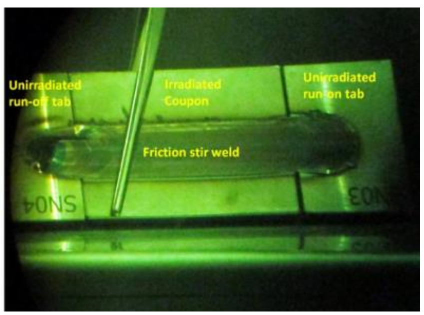


Sample Side 1: "Low" Heat Input Pads

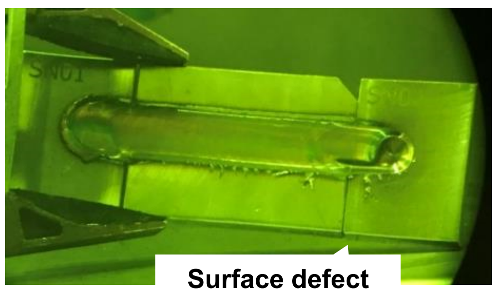


Sample Side 2: "High" Heat Input Pads

Samples 2 & 3: Friction Stir Welds (304L, 5 & 10 appm target He)



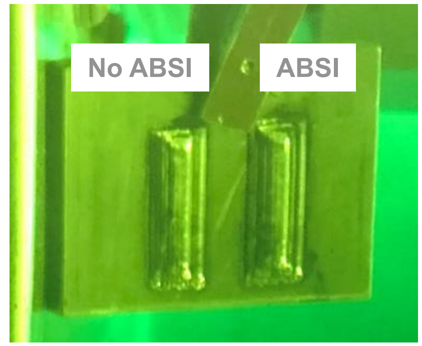
Completed Friction Stir Weld (5 appm target He Sample)



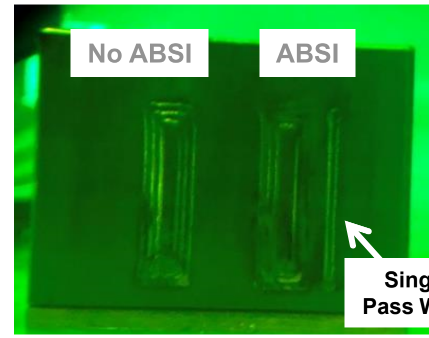
Completed Friction Stir Weld (10 appm target He Sample)

Second Irradiated Material Welding Campaign at ORNL

Samples 1 and 2: Laser Weld Pads (304L and 316L, 10 appm target He)

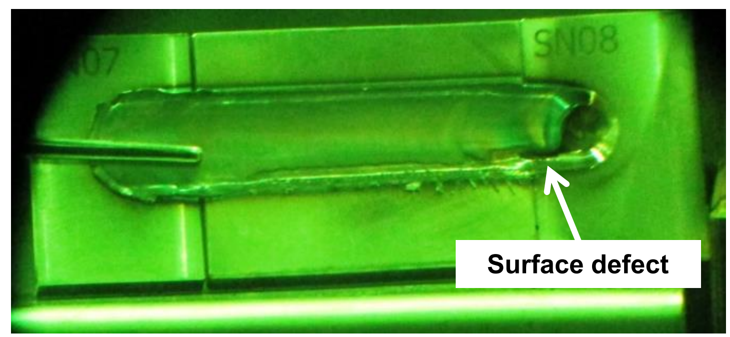


304L Sample, Side 2: "High" Heat Input Pads



316L Sample, Side 2: "High" Heat Input Pads

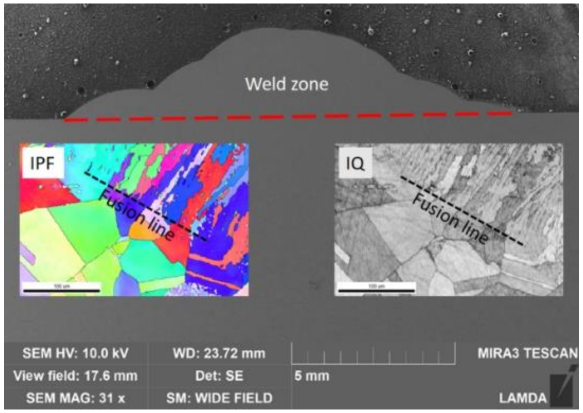
Sample 3: Friction Stir Weld (304L, 20 appm target He)

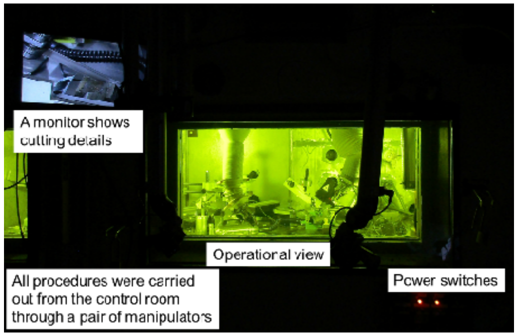


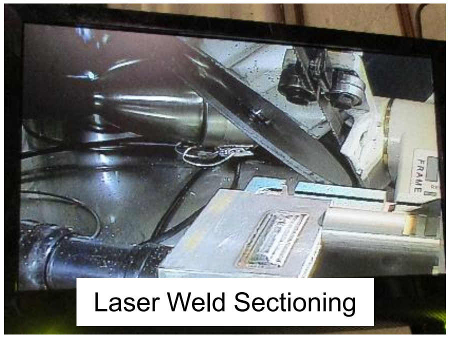
Completed Friction Stir Weld

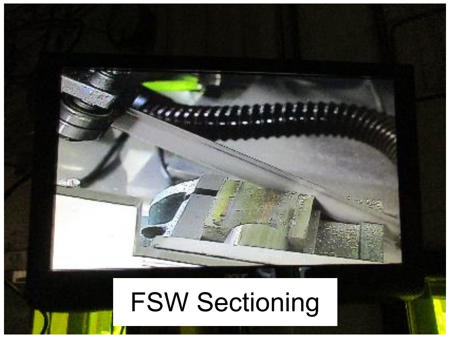
Irradiated Material Weld Characterization at ORNL Low Activation Materials Design and Analysis Laboratory (LAMDA)

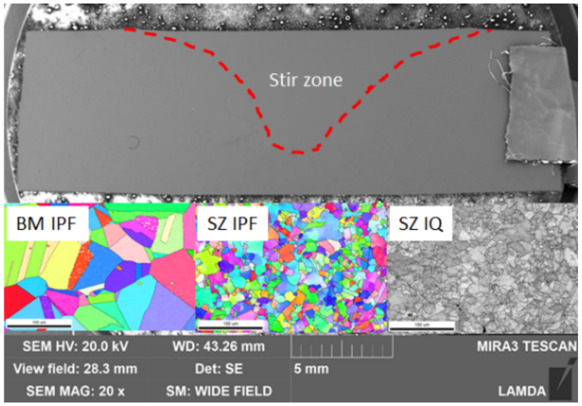
- Sectioned welds shipped to ORNL LAMDA facility for helium measurements, microstructure characterization, and mechanical testing
- Laser ablation mass spectroscopy (LAMS) used for helium measurements
- Initial microstructure results:
  - LBW 304L (20 appm target He)
    - Microporosity in fusion zone, potential HAZ degradation
  - FSW 304L (5 appm and 10 appm target He)
    - Apparent microporosity in highly sheared regions of stir zone and HAZ
  - No macro-scale cracking observed
- Further analysis in-progress (thermal desorption spectroscopy, hardness testing, tensile testing)







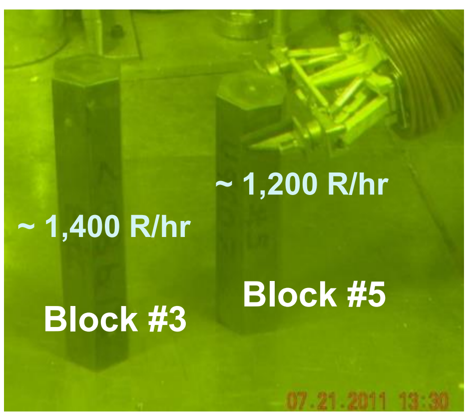


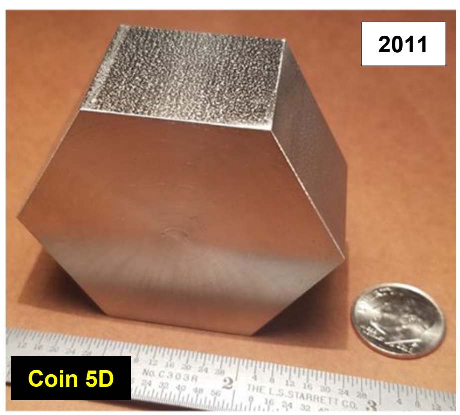


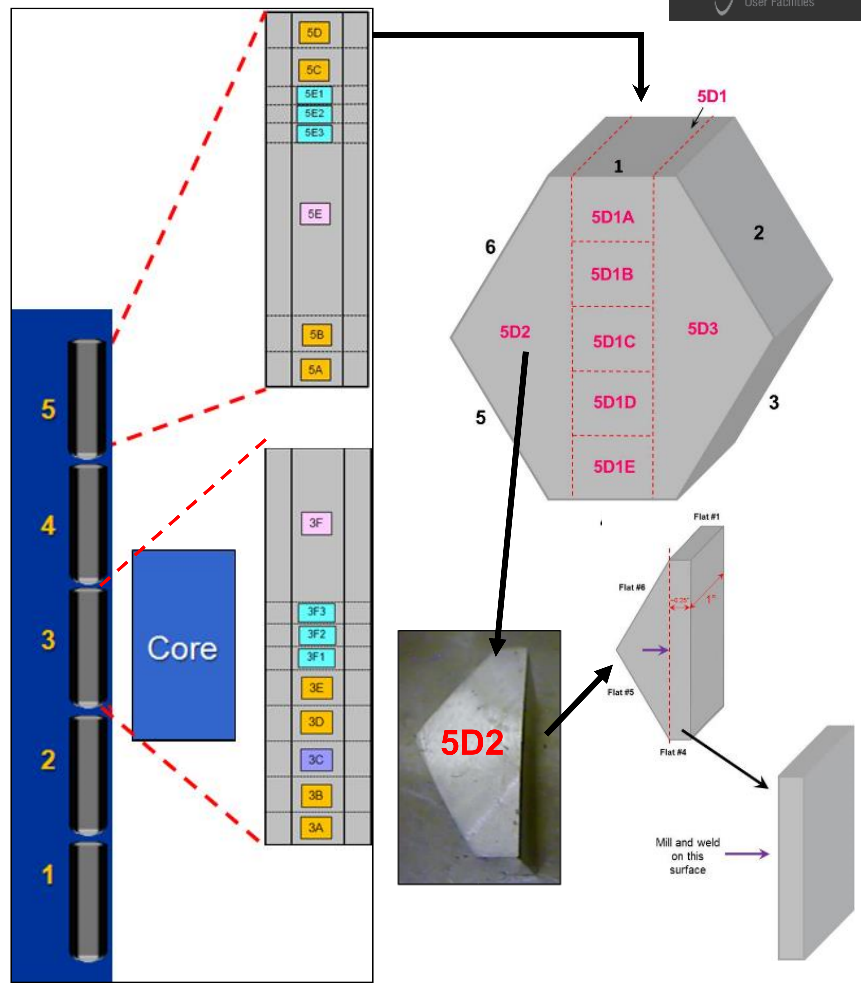
EBR-II Irradiated Type 304 Stainless Steel

DOE-Owned Materials Available at Westinghouse / INL

- Westinghouse Materials Center of Excellence has direct in-house access to DOE-owned (NSUF), highly irradiated 304 SS hexagonal blocks from EBR-II (sodium-cooled breeder reactor)
- Wide range of material conditions: helium levels up to ~8 appm and damage up to ~30 dpa
- Two of the irradiated 304 hex blocks (blocks 3 and 5) are currently stored at Westinghouse
  - Hex blocks have been sectioned significantly from previous testing efforts
- Triangular blocks 5D, 3A, and 3E were selected for initial weld testing
  - Helium levels for 5D, 3A, and 3E triangular blocks are 0.2 appm, ~3 appm, and ~8 appm, respectively.





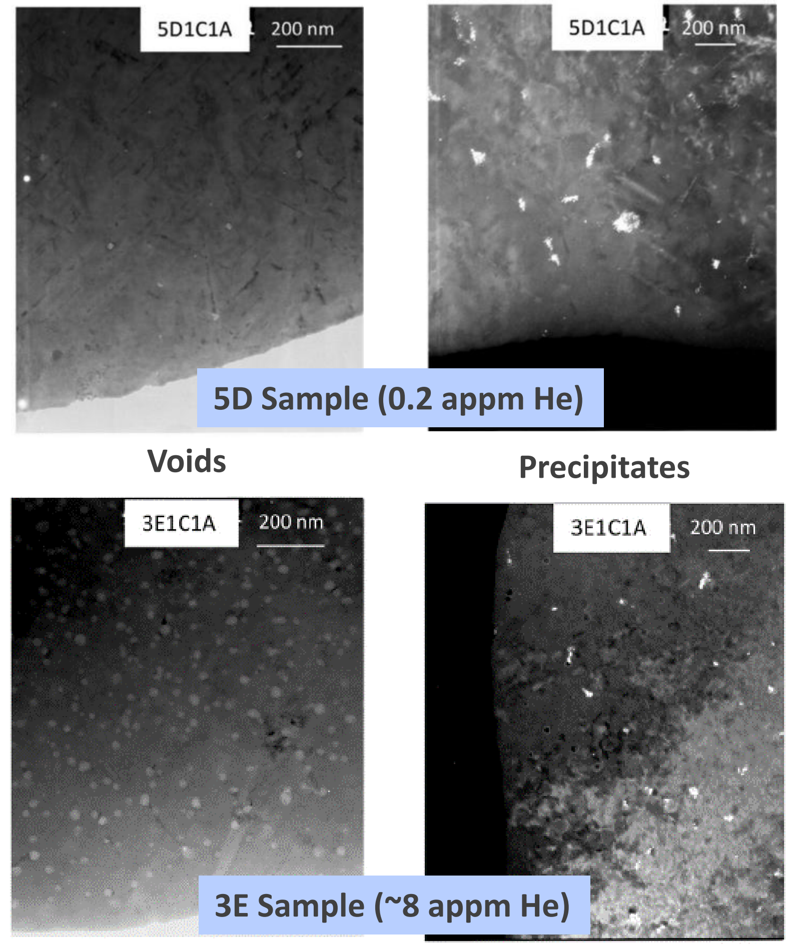


Dose Rates of Samples Used for Welding

Westinghouse

Hex block triangle samples 3A2 and 3E3 removed from storage and removed from screw cap aluminum storage vials in preparation for radiation dose rate measurements

	Measured Dose Rates, R/hr						
5-Sided Triangle ID	At 1 meter	At 1 foot	At 1 inch	On contact	Approx He, appm	Westinghouse Measurement Date	Thin Plate Thickness (Relative)
5D2	0.154	1.2	30.4	51.4	1	Oct 16, 2016	
3A2	0.135	1.0	32.7	112.0	3	Mar 10, 2017	
3E3	0.143	1.3	38.0	133.0	8	Mar 10, 2017	
Thin Plate ID for Laser Welding							
5D2	0.073	0.623	19.6	33.3	1	Nov 29, 2016	Thickest
3A2A	0.031	0.398	8.3	41.0	3	Apr 17, 2017	Thinnest
3E3A	0.052	0.556	13.1	71.0	8	Apr 17, 2017	Mid-Thickness

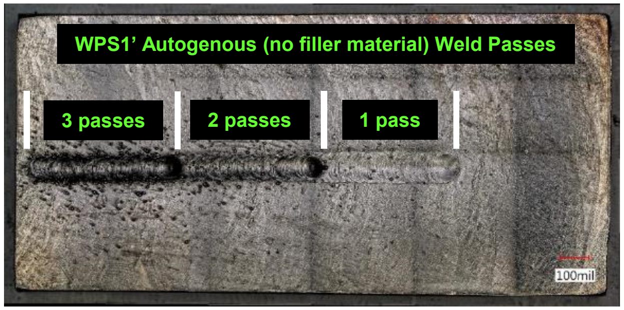


Welding Activities at Westinghouse Materials Center of Excellence

Westinghouse

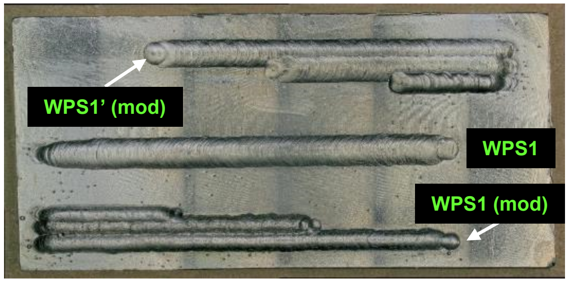
- Previous irradiated welding research studies have been performed on helium bearing irradiated stainless steel materials not containing damage representative of highly irradiated PWR components
  - HFIR irradiated samples used at ORNL for weld testing contain insignificant microstructural damage
- DOE-owned 304 irradiated material currently available at Westinghouse is very well characterized: void swelling, microstructure evolution, segregation behavior, mechanical properties, NDE inspection, etc.
  - Material contains both irradiation damage and helium content
- Laser welding studies on hex block material are providing essential data points to confirm that the damage from irradiation does not have an influence on helium-induced cracking susceptibility

Welds performed at WEC on front side of irradiated sample 5D2 (0.2 appm He)



Welds performed at WEC on back side of irradiated sample 5D2 (0.2 appm He)

Welds performed at WEC on irradiated sample 3A2A (~3 appm He)



Welds performed at WEC on irradiated sample 3E3A (~8 appm He)

Parameter Set	Average Power	Wire Feed Speed	Travel Speed	Lens-to-Work Distance
WPS1	425.6 W	17 in/min	2.5 in/min	200 mm[1]
WPS1'	425.6 W	10 in/min	2 in/min	200 mm[1]
WPS1 (mod)	425.6 W	17 in/min	2.5 in/min	196 mm
WPS1' (mod)	425.6 W	10 in/min	2 in/min	196 mm

[1]Laser focal point

Irradiated Material Welding Session at 2019 PVP Conference

1. **PVP2019-93316 – Hot Cell Pulsed Laser Welding of Neutron Irradiated Type 304 Stainless Steel with a Maximum Damage Dose of 28 dpa**

   Paula Freyer (Westinghouse), Frank Garner (Radiation Effects Consulting), Jonathan Tatman, Ben Sutton and Greg Frederick (EPRI)

2. **PVP2019-93667 – Auxiliary Beam Stress Improved Laser Welding for Repair of Irradiated Light Water Reactor Components**

   Jian Chen, Zhili Feng, Roger Miller, Wei Tang, Maxim Gussey, Keith Leonard (ORNL) and Jonathan Tatman, Ben Sutton and Greg Frederick (EPRI)

3. **PVP2019-93865 – Characterization of Single-Pass Laser Welds on Irradiated 304L Stainless Steel with Post-Weld High-Dose Ion Irradiation**

   Janelle Wharry, Keyou Mao, Zachary Kroll, Michael Pavel (Purdue University), Emmanuel Perez, Cheng Sun (INL), Paula Freyer (Westinghouse), Frank Garner (Texas A&M)

4. **PVP2019-93899 – Friction Stir Welding And Preliminary Characterization Of Irradiated 304 Stainless Steel**

   Wei Tang, Maxim Gussev, Zhili Feng, Brian Gibson, Roger Miller, Jian Chen, Scarlett Clark, Keith Leonard, (ORNL) and Jonathan Tatman, Ben Sutton and Greg Frederick (EPRI)

Revisions to N-638-9 and New Case N-888

Section XI Temper Bead Welding Activities

- **N-638-10, Fluence Threshold & He Content Limitations for Temper Bead Welding**
  (Record # 17-1715*)*
  - Revised requirements for temper bead welding on irradiated components based on EPRI guidelines, 10 CFR Part 50 rulemaking fluence thresholds and input from NRC Staff
  - At SC XI – Recirculation Ballot (18-3540RC1)
  - Similar changes intended for IWA-4611 *(Record # 18-2877)*

- **N-638-10, Revise / Clarify Impact Test Requirement**
  (Record # 18-1921*)*
  - Clarifies alternative impact test temperature provisions and corrects adjustment temperature provisions for procedure qualification
  - Approved by Board on Nuclear C&S – 05/06/2019 (Ballot 19-1117)
  - Similar changes intended for IWA-4611 *(Record # 18-2877)*

- **N-888, Similar and Dissimilar Metal Ambient Temperature Temper Bead**
  (Record # 18-2004*)*
  - New temper bead code case that will replace N-638-10, N-839 and temper bead appendices in various repair and mitigation code cases (i.e., N-740-2, N-754. N-847, etc.)
  - Single case for all temper bead welding

N-638-10 Welding on Irradiated Material

- Revised/new paragraphs 1(i), 4(a)(3) and 4(a)(4)

New Paragraph 1(i)

(i) This Case shall not be used for repair of materials from inside the reactor vessel within the beltline region or on vessel internals within the beltline region, under the following conditions:

(1) Ferritic material where fast neutron fluence exposure is greater than 1 x 10^{17} n/cm^2 (E > 1 MeV).

(2) Nickel-base material where thermal neutron fluence exposure is greater than 1 x 10^{17} n/cm^2 (E < 0.5 eV).

(3) Austenitic stainless steel (P-No. 8), where thermal neutron fluence exposure is greater than 1 x 10^{17} n/cm^2 (E < 0.5 eV) and measured or calculated helium concentration in the P-No. 8 material is greater than 0.1 atomic parts per million (appm).

New Paragraphs 4(a)(3) and 4(a)(4)

(3) For repairs on the outside of the reactor vessel shell on ferritic material where fast neutron fluence exposure is indeterminate or greater than 1 x 10^{17} n/cm^2 (E > 1 MeV), the following additional examinations shall be performed on the adjacent vessel base material.

(-a) The surface examination shall include 1/2 inch (13 mm) of the reactor vessel base material beyond the deposited weld metal.

(-b) Where practical, the volumetric examination shall include the following:

(-1) The heat affected zone below the weld deposit.

(-2) The reactor vessel base material adjacent to the deposited weld metal to a distance of 1/2 inch (13 mm) and to a depth of 3/16 inch (5 mm).

(4) Ultrasonic examination shall be performed using procedures qualified in accordance with Section V, Article 14 Low Rigor requirements.

Case N-752 for Risk-Informed R&R Activities

Case N-752 for Risk-Informed R&R Activities

- **N-752, Risk-Informed Classification and Treatment for Repair/Replacement Activities in Class 2 and 3 Systems**
  (Record # 06-250*)*
  - Provides acceptable industry treatments for repair/replacement activities
  - Does not specify any requirements above or in addition to 10 CFR 50.69
  - Approved by SC-XI
  - At Board on Nuclear C&S – Ballot (19-1117)
- One utility currently pursuing application of N-752

Why N-752 Risk-Informed for Repair & Replacement ?

- Delivering the Nuclear Promise
- Efficiency Bulletin: 17-09 – Industry wide coordinated licensing of 10 CFR 50.69.
  - Industry-Wide Adoption of Risk Informed Engineering Programs
- Efficiency Bulletin: 17-16 – Industry coordination of categorization and alternative treatments for 10 CFR 50.69 Implementation Plans
  - Industry-Wide Implementation of 10 CFR 50.69: Categorization and Treatment
- Efficiency Bulletin: 17-16 – Recommended Industry Actions and Activities
  - "Develop alternative treatment "how to apply" process procedures consistent with NEI 16-09."
  - "EPRI to conduct periodic categorization training workshops and develop alternative treatment guidance."

N-752 Risk-Informed Repair/Replacement Activities

- 10CFR50.69 Risk-informed categorization and treatment of structures, systems and components (SSCs) for nuclear power reactors
- N-752 applies to RISC-3 "Low Safety Significant" SSCs

	Q ←	→ Non-Q
↑**High Safety**	**RISC -1** Safety Related (ASME) High Safety Significance	**RISC -2** Non Safety Related High Safety Significance
↓**Low Safety**	**RISC -3** Safety Related (ASME) Low Safety Significance	**RISC -4** Non Safety Related Low Safety Significance

N-752 Overview of Requirements

- Categorization requirements
  - Generally follows ANO-2 Relief Request and RAIs - NRC Safety Evaluation issued
  - Significant difference is the ability to categorize a single item versus the entire system
- Must meet original fracture toughness requirements
- Changes in design, configuration, materials, fabrication must be evaluated
  - Must ensure structural integrity and leak tightness sufficient to meet design basis functional requirements of the System
- Replacement items
  - Must meet Owner's requirements or revised Owner requirements
  - Must meet original Construction Code or nationally recognized codes and standards (technical requirements only)
  - Must be in accordance with the site licensing basis

N-752 Alternative Treatments for RISC-3 SSCs

- Appendix B QA program not required

  (Important Note: N-752 does not override regulatory commitments)
- AIA agreement and ANII not required
- Section XI IWA-4000 not required
- Section XI Repair/Replacement documentation not required

N-752 Alternative Treatments for RISC-3 SSCs

- Permits use of PCC-2 and API-653
- Performance of repair/replacement (welding, NDE, etc.) to meet
  - Owner’s requirements
  - Construction Code, or PCC, if there is one
  - Alternative NDE approved by owner
- Pressure testing in accordance with Construction Code or otherwise approved by Owner
- Baseline exams of the item, if included in Owner’s program for ongoing exams (FAC, raw water systems, ISI, etc.)

EPRI Resources

- *Welding and Repair Technology Center: Risk-Informed Repair and Replacement Activities – Guidance for Implementation of Code Case N-752.* EPRI, Palo Alto, CA: 2018. 3002013126.
- *10 CFR 50.69 Categorization Guidance Document.* EPRI, Palo Alto, CA: 2018. 3002012984.
- *Risk-Informed Repair/Replacement Methodology.* EPRI, Palo Alto, CA: 2011. 1022945.
- *Welding and Repair Technology Center: Risk-Informed Repair and Replacement Case N-752 – Implementation Guideline*. EPRI, Palo Alto, CA: 2019. 3002015823
  (Sept 2019 publication date)

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