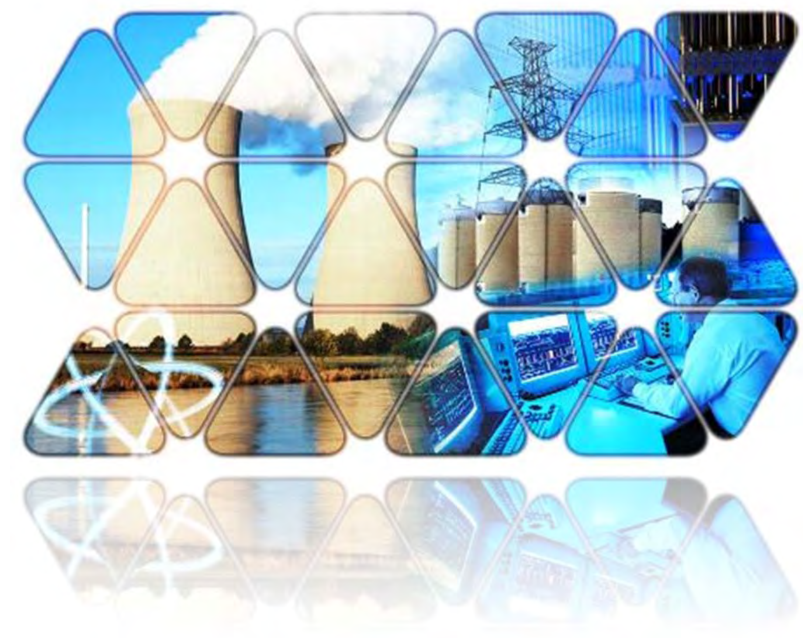
Irradiated Material Weldability Technical Update

NRC Technical Information Exchange Meeting

Jon Tatman, EPRI-WRTC

Greg Frederick, EPRI-WRTC



Rockville, MD
June 3, 2015

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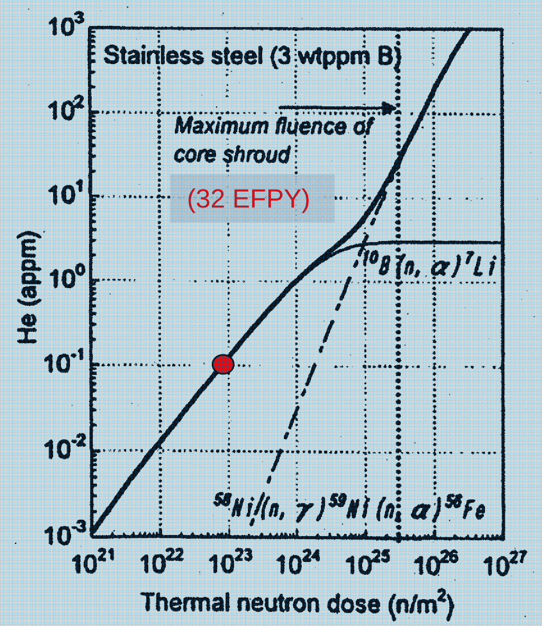
Helium Generation in Reactor Materials

- Helium is generated as a result of irradiation of boron and nickel in reactor internals materials
  - $^{10}B(n, \alpha) \rightarrow {}^{7}Li + He$
    - Occurs early in the component's life-cycle until Boron burn up is complete (below $1X10^{21}$ n/cm^2 E < 0.5 eV)
  - $^{58}Ni(n, \gamma) \rightarrow {}^{59}Ni(n, \alpha) \rightarrow {}^{56}Fe + He$ (2-step reaction)
    - Continues through the component's life (involves both fast and thermal neutrons)
- The problem with using thermal fluence as an indicator of weldability of irradiated material
  - Continues through the component's life (involves both fast and thermal neutrons) - Up to about $1X10^{21}$ n/cm^2 (E < 0.5 eV) Boron controls Helium production
  - Different materials (304, 316L, Ni-alloy and RPV steel) have different Helium concentrations threshold for cracking



Graph: Exposure of SS in the BWR environment

● = Current Helium weldability threshold

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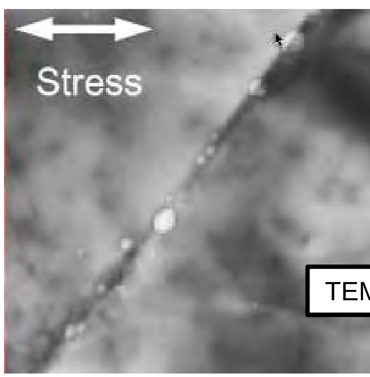
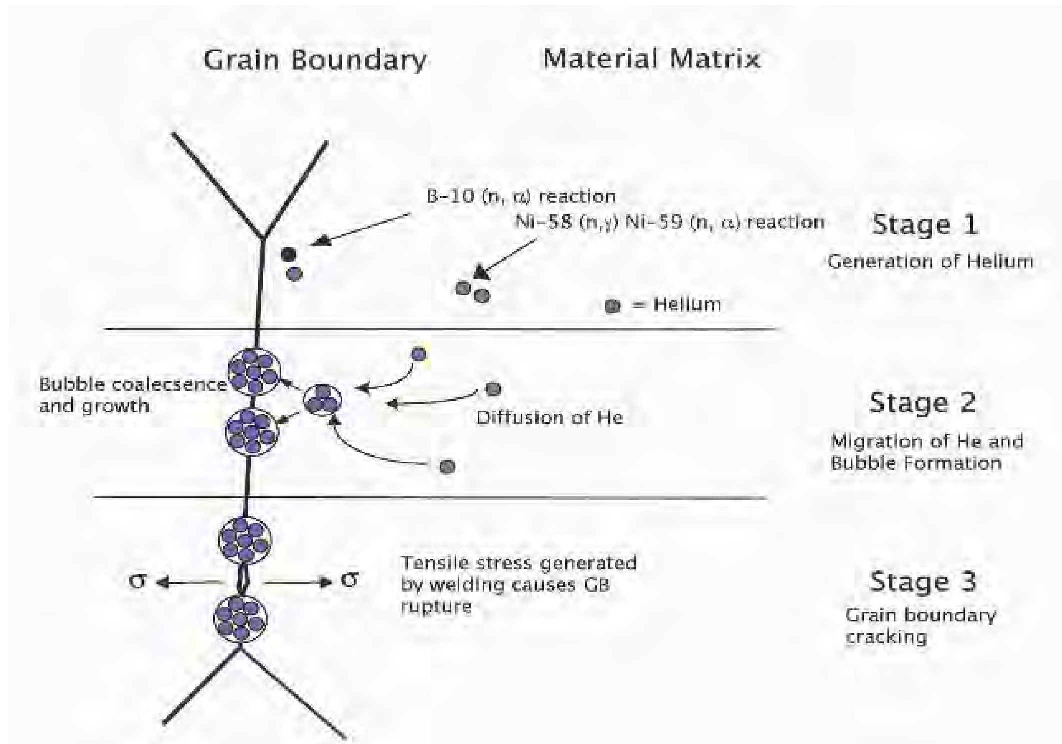
Technology Overview: Why Helium Generation Effects the Weldability of Irradiated Materials

- Key factors contributing to Helium induced cracking (embrittlement) in irradiated materials:
  - Stage 1: Generation of helium (life of plant)
  - Stage 2: Diffusion of helium into the weld HAZ grain boundaries
    - Occurs when temperatures are in excess of 800°C
  - Stage 3: Welding residual tensile stresses occur during the cooling cycle (welding)



TEM Image of He bubbles



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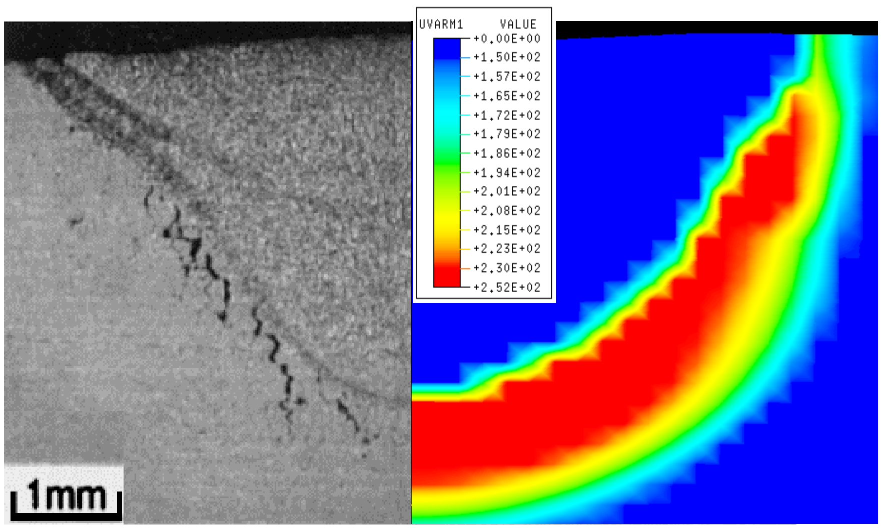
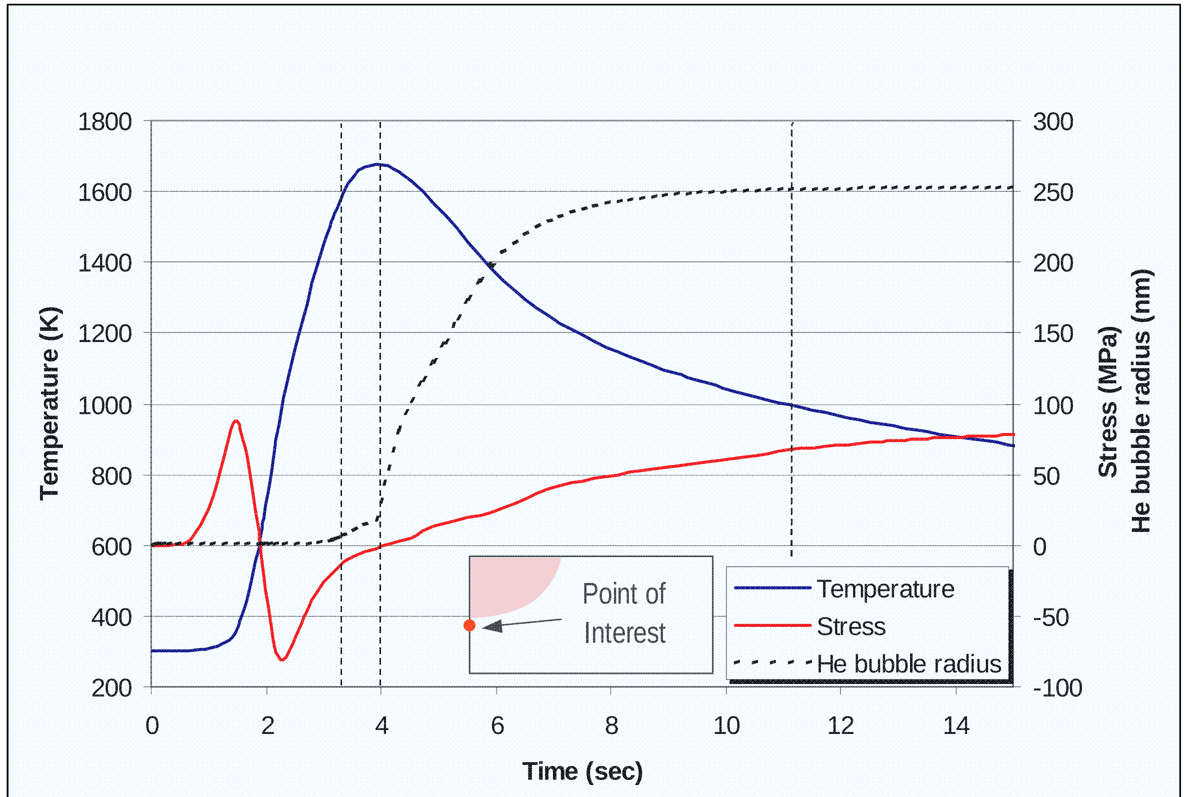
Technology Overview: Controlling Grain Boundary Helium Bubble Coalescence During Welding

Key welding factors to control the helium bubble coalescence during welding:

1) Minimize grain boundary helium bubble size by controlling welding heat input and weld thermal cycle (i.e., reduce time above 800°C)
2) Control tensile stress profile during cooling (during maximum helium bubble growth period)



High Tensile Residual Stresses Modeled



Source: Z. Feng ORNL Report

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ASME request for Clarification on Welding Irradiated Material Assessment

- There was a request by the NRC and ASME Section XI to include a weldability threshold definition with respect to irradiation to a number of Code Cases
- Most applications of repairs of DMWs have been at locations where the weldability is not affected by irradiation, i.e. RPV nozzles

- The current limitations in 10CFR50.55a state:
  - (b)(2)xii) *Underwater Welding.* The provisions in IWA-4660, "Underwater Welding," of Section XI, 1997 Addenda through the latest edition and addenda incorporated by reference in paragraph (b)(2) of this section, are not approved for use on irradiated material.

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ASME request for Clarification on Welding Irradiated Material Assessment

- Information Required:
  - Technical Basis Report(s):
    - Areas outside of concern of fluence, or numerical limitation of when or where welding can be applied.
- What's missing
  - Low alloy steel – toughness issue
  - Low alloy steel – bubbles at fusion line
  - Austenitic – helium induced cracking
  - Austenitic – flaw evaluation of cracks (toughness)

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Limitations (Wording) in ASME Code

- 5 different recommendations (current)
- If the repair area is to be subjected to……………

1. "*fast neutron fluence greater than 1019 nvt E > 1 MeV*"
2. "*thermal neutron (E < 0.5 eV) fluence of 1 x 1017 neutrons per cm2*"
3. "*0.1 APPM measured or calculated helium content generated through irradiation*"
4. "*the neutron fluence in the repair areas shall be taken into account when establishing the weld metal composition limits*"

- *Newest Words:*

5. "*consideration shall be given to the effects of irradiation on the properties of material, including weld material for applications in the core belt line region of the reactor vessel. Special material requirements in the Design Specification shall also apply to the test assembly materials for these applications*"

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Irradiated Material Welding Development: EPRI Key Product History
LTO/WRTC/BWRVIP/MRP – Welding Guideline and Technology Products

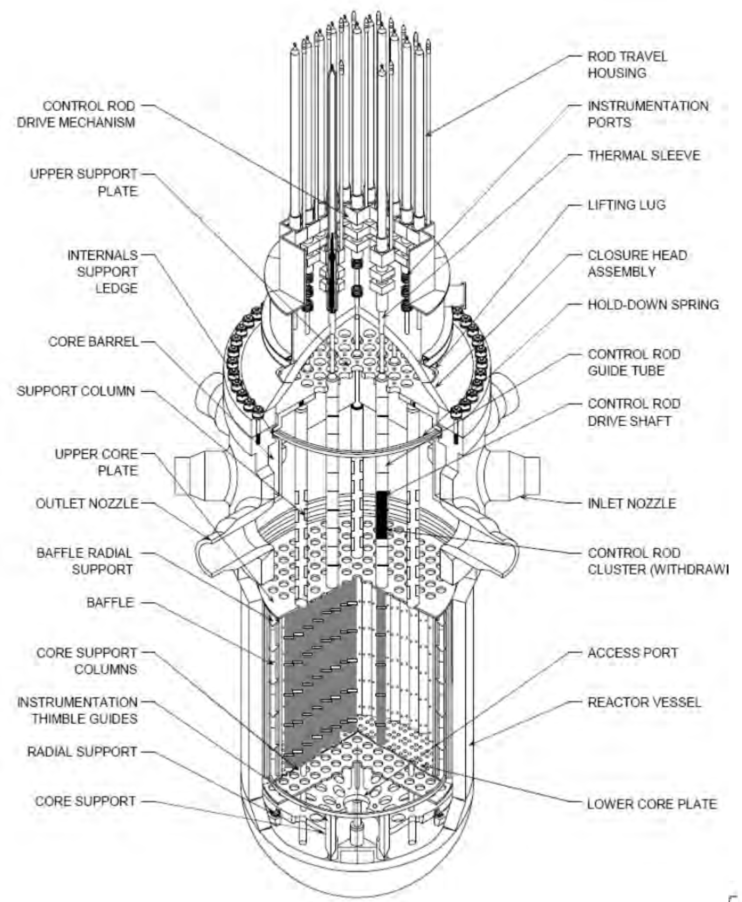
1) ***2006 (BWRVIP)*** – *Technical Basis for Revision to BWRVIP-97 Welding Guidelines (BWRVIP-151) – EPRI Report 1011692*

2) ***2011 (BWRVIP)*** – *Guidelines for Performing Weld Repairs to Irradiated BWR Internals (BWRVIP-97-A) – EPRI Report 1019054*

3) ***2014 (WRTC)*** – *WRTC: Development of Low Heat Input Laser Beam Welding for Repair of Irradiated Reactor Components - EPRI Report 3002003146*

4) ***2014 (MRP)*** – *Irradiated Materials Guideline (MRP-379) – EPRI Report 3002002954*

5) ***2014 (WRTC)*** – *WRTC: Advanced Welding Methods for Irradiated Materials – EPRI Report 3002003143*



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Irradiated Material Welding Development: Product Overview

WRTC/BWRVIP/MRP – Welding Guideline and Technology Products

- *BWRVIP-97-A: Guidelines for Performing Weld Repairs to Irradiated BWR Internals*
  - BWRVIP welding guideline approved by NRC in 2011 (BWRVIP-97-A)
    - Defines generic BWR weldability boundaries where helium concentration allows conventional welding processes to be used
    - For other regions, defines plant specific methodology
      - Determine local fluence and helium concentration
      - Use threshold chart to select allowable heat input
      - Also provides guidance on available welding technologies, required inspections, Code rules, etc

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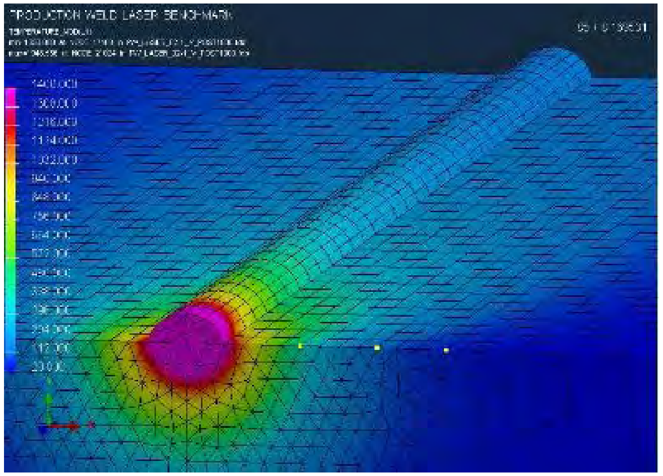
Irradiated Material Welding Development: Product Overview

Welding Guideline and Technology Products

<u>WRTC</u>: Development of Low Heat Input Laser Beam Welding for Repair of Irradiated Reactor Components - EPRI Report 3002003146



- Developed improved heat input estimation techniques to establish definitive helium induced cracking threshold
- Validated welding parameters and technique
  - Determine limitation of weld process heat input and induced strain field
- Established modeling and thermal profile measurement techniques
  - Guidance for welding process development
  - Weldability prediction for highly irradiated material

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Irradiated Material Welding Development

Development of Effective Weld Heat Input Equation

Effective Heat Input Equation – Conduction Limited LBW

- Contrary to theoretical HI, effective HI incorporates:
    1. Laser heat used to melt added filler metal
    2. Heat loss to atmosphere due to reflection of laser power

- Result – **A definitive helium induced cracking threshold line**

laser absorption efficiency factor

laser power

Heat required to melt a volume of filler wire

$$Q_{eff\_LBW}\left(\frac{J}{in}\right) = \frac{\mu_T P_L}{TS} - \frac{\tau\,(WFS)\,(A_{wire})}{TS}$$

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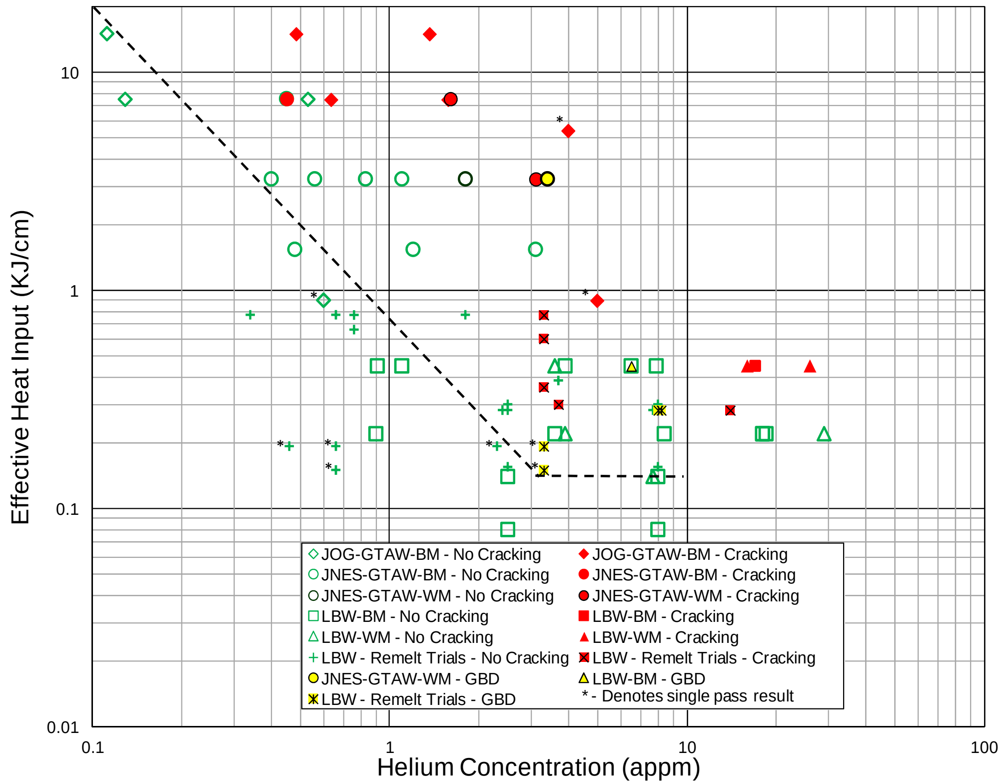
Irradiated Material Welding Development

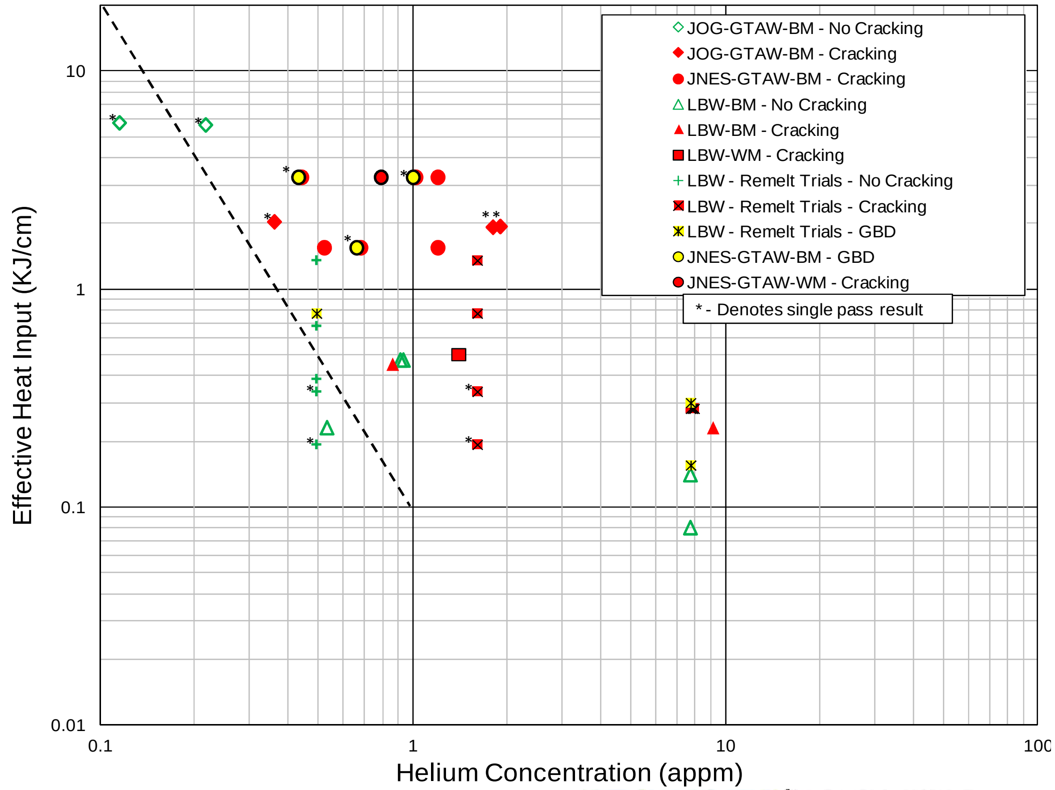
Development of Improved Threshold Plots

- **Incorporation of "Effective" Weld Heat Input**

304L SS



316L SS



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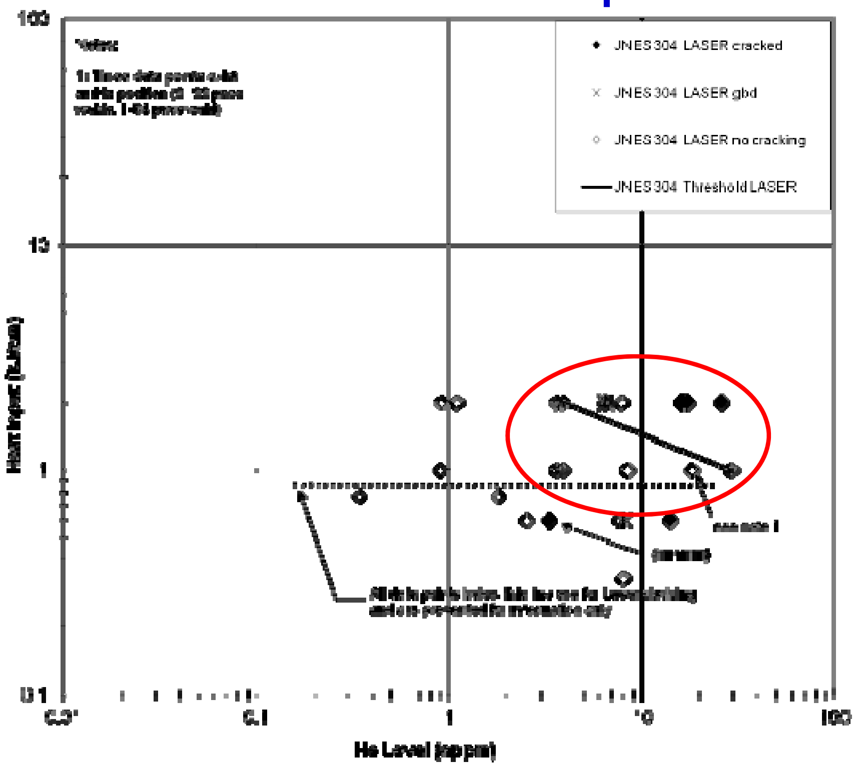
Irradiated Material Welding Development

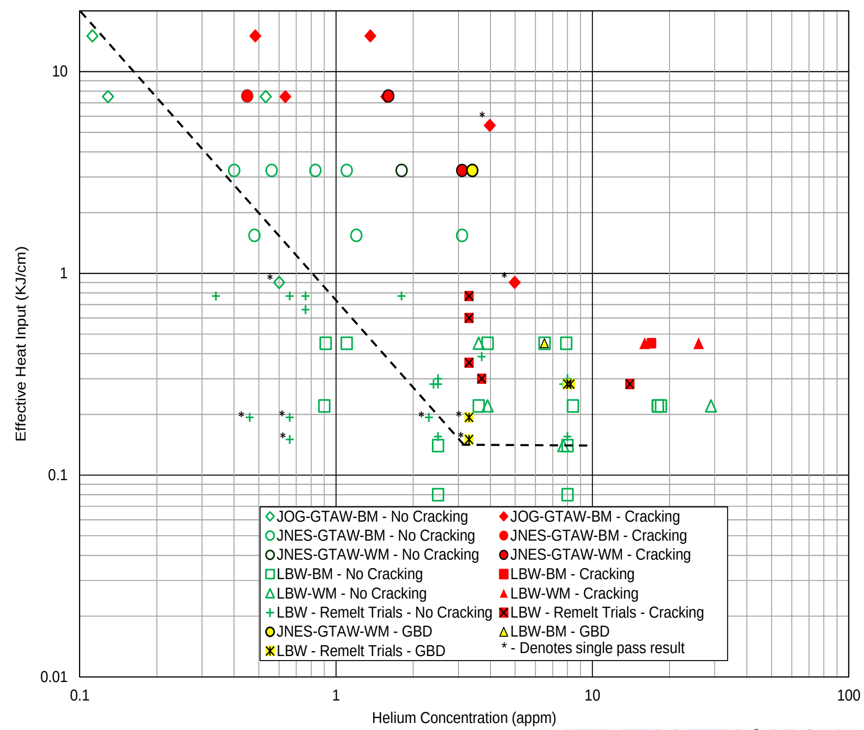
Effective Versus Theoretical Weld Heat Input

- Incorporation of effective heat input provides:
  - Clear threshold for cracking and integration of GTAW and LBW data on a single plot

Theoretical Heat Input



Effective Heat Input



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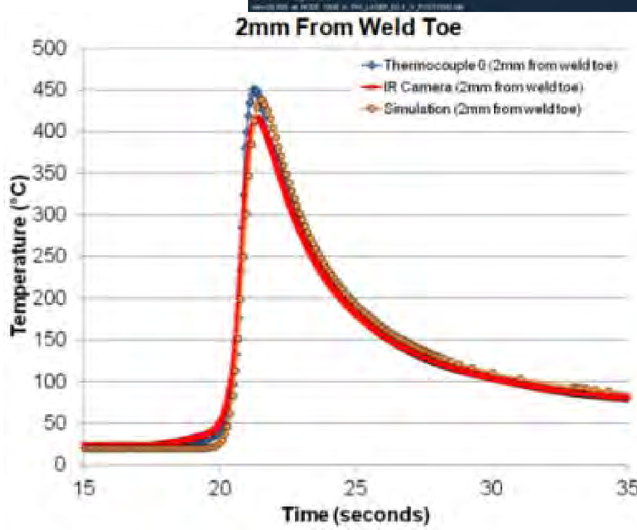
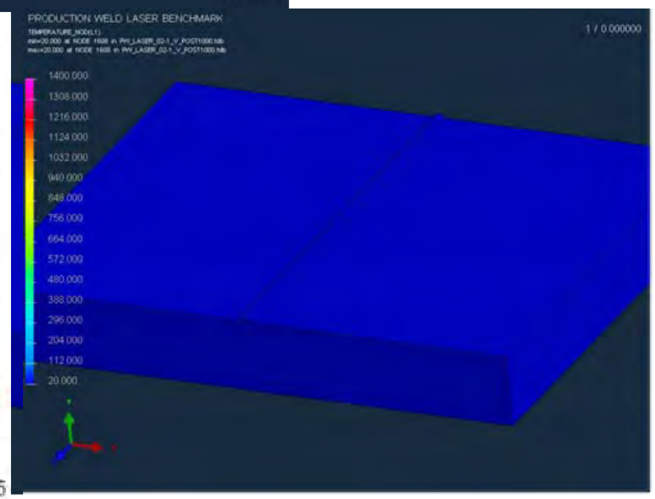
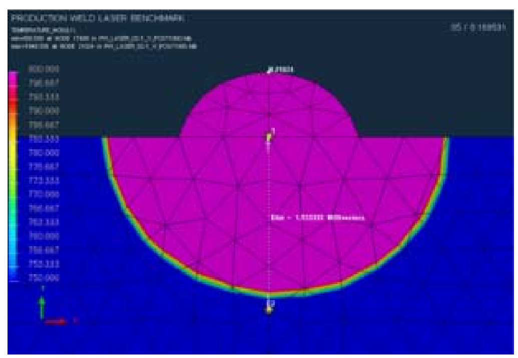
Irradiated Material Welding Development

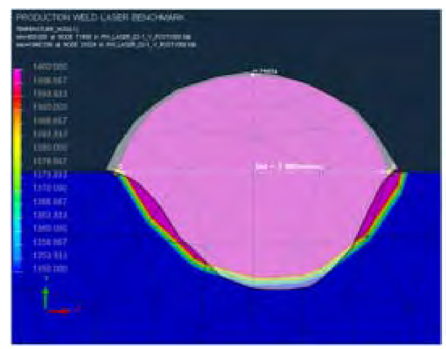
Optimized Low Heat Input Weld Parameter Development

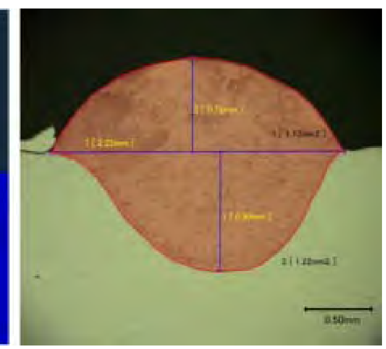
- Effective heat input versus helium concentration plot allows development of optimized low heat input parameters
- Finite element modeling and weld thermal history measurements
  - used to determine low heat input "buffer layer" thickness
  - requirements before switching to higher deposition rate (higher heat input) LBW parameters











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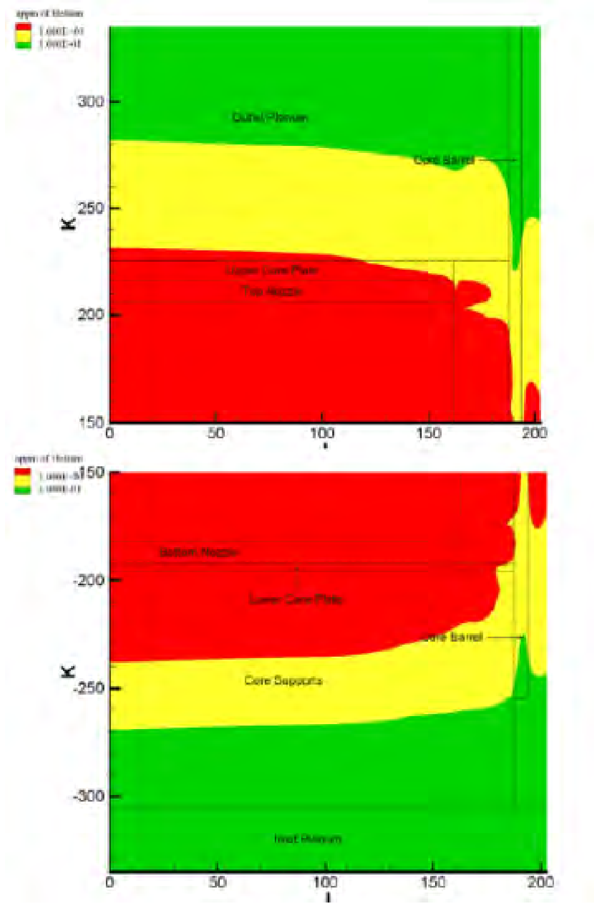
Irradiated Material Welding Development: Product Overview

Welding Guideline and Technology Products



Typical He generation plot (10 wppm initial boron)

Irradiated Materials Guideline (MRP-379) - EPRI Report 3002002954

- Report based on the most recent He generation evaluations and welding data
  - Includes generic weldability plots for PWRs based on distance from He thresholds.
- Thresholds defined:
  - At “very low” He, consideration of irradiation effects is unnecessary
  - At “low” He, GTAW can be used
  - At “moderate” He, low heat input laser welding is necessary
  - At “high” He, welding with conventional techniques cannot be performed
- Recent data evaluation provides basis for revised Code Case and guidance for development of advanced welding methods

- **An additional revision to BWRVIP-97-A will be required to include most recent He generation evaluations and welding data**

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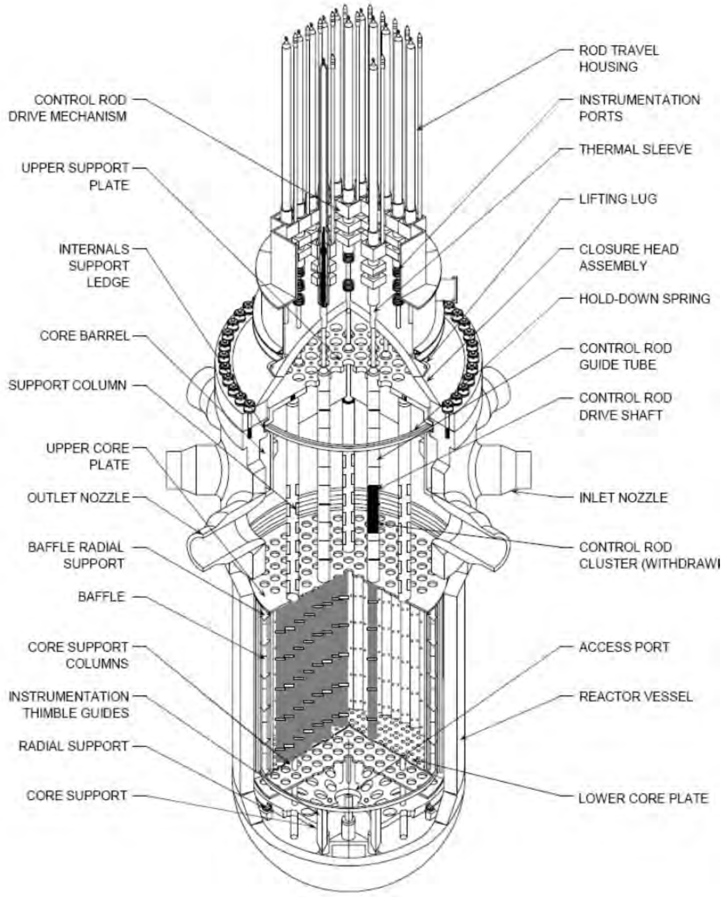
Irradiated Material Welding Development: Product Overview

MRP Welding Guidelines – Example Tabulated Data (Numbers Omitted)



Location	20 wppm B		50 wppm B	
	40-yr	60-yr	40-yr	60-yr
0.01 appm He				
Core Centerline	-	-	-	-
Core Periphery	-	-	-	-
Core Barrel ID	-	-	-	-
Core Barrel OD	-	-	-	-
RPV Surface ID [1]	-	-	-	-
0.1 appm He				
Core Centerline	-	-	-	-
Core Periphery	-	-	-	-
Core Barrel ID	-	-	-	-
Core Barrel OD	-	-	-	-
RPV Surface ID	-	-	-	-
1.0 appm He				
Core Centerline	-	-	-	-
Core Periphery	-	-	-	-
Core Barrel ID	-	-	-	-
Core Barrel OD	-	-	-	-
RPV Surface ID	-	-	-	-
10 appm He				
Core Centerline	-	-	-	-
Core Periphery	-	-	-	-
Core Barrel ID	-	-	-	-
Core Barrel OD	-	-	-	-
RPV Surface ID	-	-	-	-

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ASME request for Clarification Welding Irradiated Material Assessment - Summary

- Wording inconsistencies in pertinent ASME Code Sections needs to be addressed
- ASME Members of Working Group Welding & Special Repair Processes requested that EPRI help provide guidance on the subject.
  1. Areas where irradiation is an issue with respect to repair being made on the RPV and Reactor Internals
  2. Helium threshold cracking level for SS, Ni-alloy, and LAS
- BWRVIP-97-A and MRP-379 both provide significant guidance on this subject for Stainless Steel in the BWR and PWR environments
  - MRP-379 document is EPRI proprietary, BWRVIP-97-A requires updating
  - A request could potentially be submitted to the MRP and BWRVIP executive committees to allow these documents to be used to aid in providing clarification for ASME code application
- An extensive literature search has also been conducted to determine the state of knowledge regarding the effects of irradiation on Ni-alloy and LAS

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2014 WRTC/LTO Status Report: Key Highlights

Welding Guideline and Technology Products

WRTC: Advanced Welding Methods for Irradiated Materials - EPRI Report 3002003143

– Issued November 2014 - includes updates on:
  1. Advanced welding processes development
  2. Material fabrication and characterization
  3. Hot Cell fabrication and setup
  4. Irradiated material weld test matrix – Validation Tests
     - Crack sealing/material mitigation
     - He-induced cracking
     - Modeling and validation testing for optimal parameter Ni-based and SS materials
     - Enhanced effective heat input calculation

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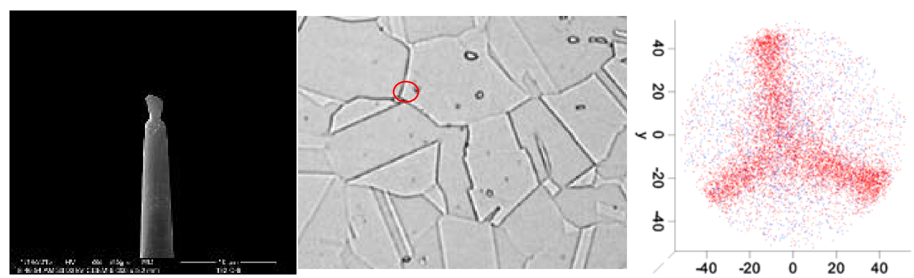
Irradiated Material Weldability Testing

Development of Representative Irradiated Materials

- Fabrication of representative materials
  - Neutron irradiation plan complete for first round of materials
    - Neutron irradiation in HFIR facility at ORNL (targeted helium ranges to 30ppm)
  - Boron doped stainless steel and nickel based materials fabricated (304L, 316L) (Nickel alloy delayed (182))
    - Characterization of materials (on-going)
    - He and Boron distribution
    - Helium measurements and flux monitors measured
  - He containing Powder metallurgy material fabricated for screening evaluations
    - allow baseline processes and conditions prior to validation tests on IM

Neutron Exposure at High Flux Isotope Reactor (HFIR)



Boron distribution evaluation (atom probe)

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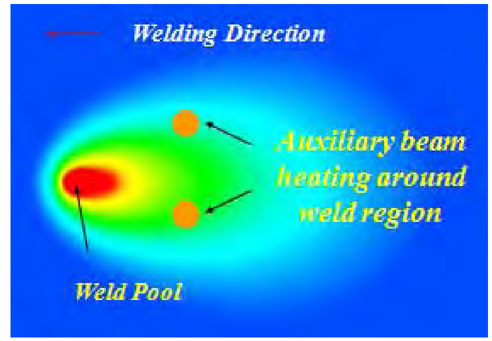
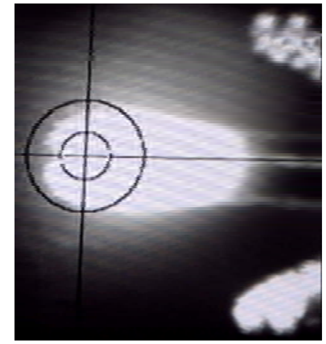
Advanced Welding Process Development

- Goal of this work is to develop a generic welding specification and validation testing of advanced weld repair processes
- Processes under investigation
  - Low force friction stir welding
  - Low force friction stir cladding
  - Low dilution laser beam welding
  - Auxiliary beam laser welding (ABSI)
- Weld process testing, setup and modeling conducted in preparation for hot cell validation tests





FSW process in-air and underwater

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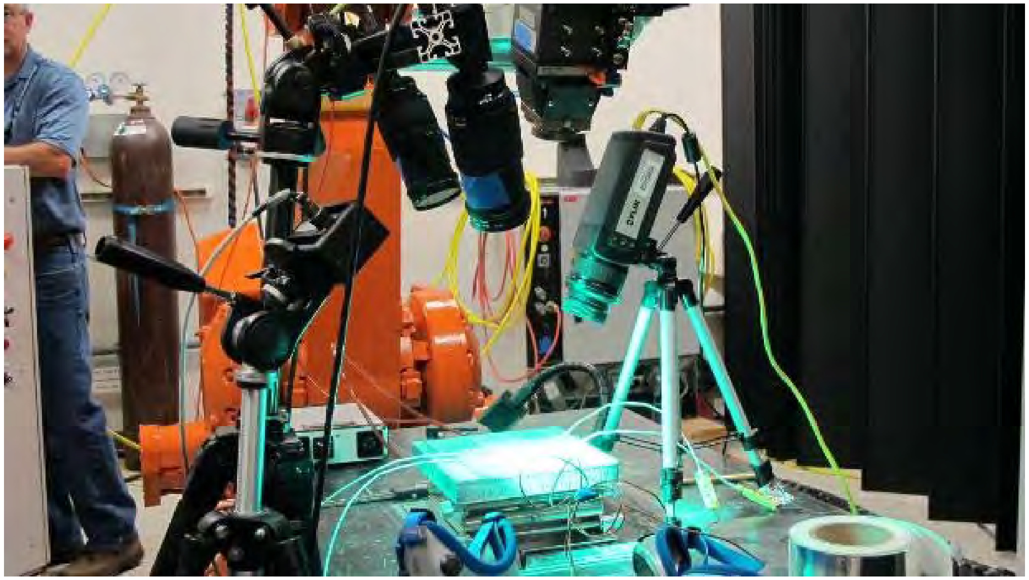
Advanced Welding Process Development

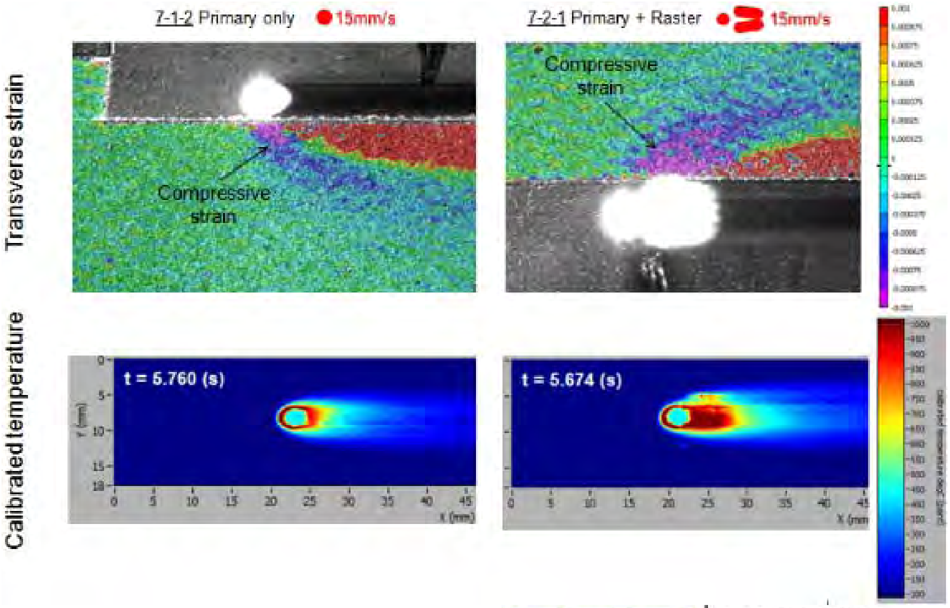
Modeling and In-Situ Strain Measurement Capabilities

- Establish modeling and thermal profile measurement techniques
  - Improved guidance for welding process development
  - Increased weldability of highly irradiated material

Digital Image Correlation (DIC) – Experimental Setup



DIC Experimental Result



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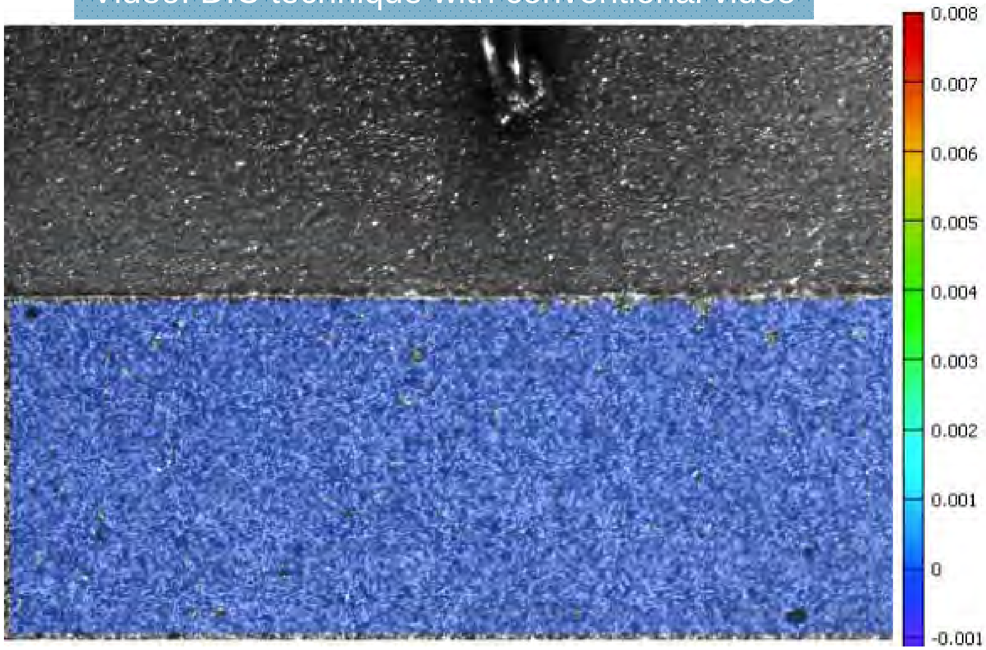
Welding and Repair Technology Center

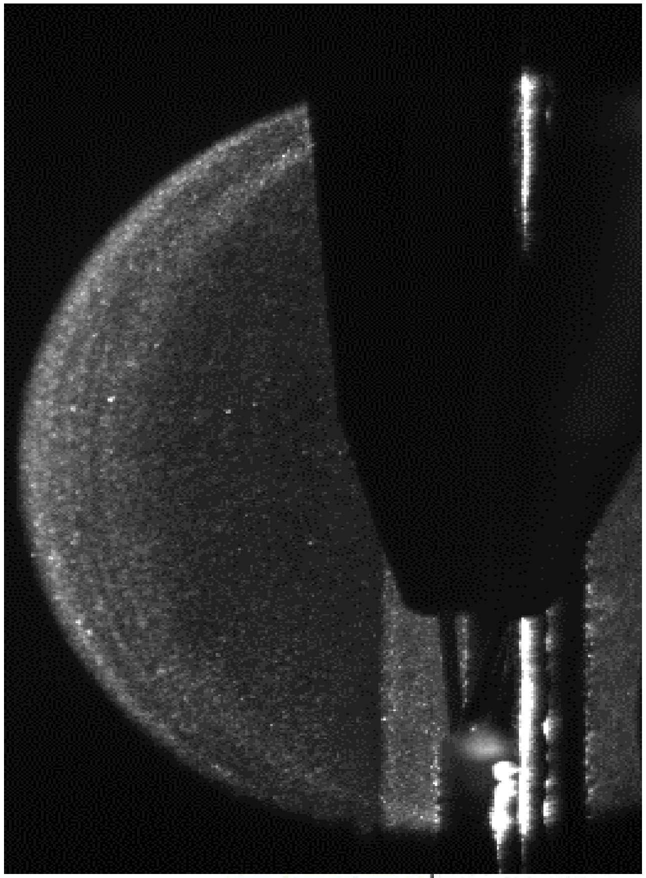
Advanced Welding Process Development
Modeling and In-Situ Strain Measurement Capabilities

- Advanced optical filtering technique being tested with DIC – may reveal more accurate strain values within closer proximity to weld fusion zone.
- Further ABSI laser weld testing/modeling using DIC and advanced video filter technique has been conducted at EPRI

Video: DIC technique with conventional video

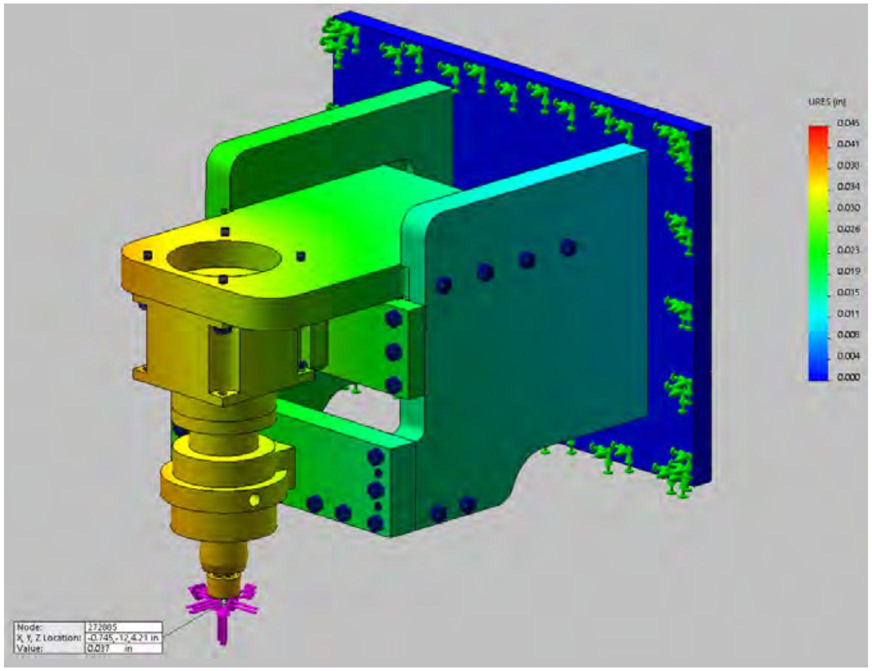


Video: Advanced filter technique



Friction Stir Welding

- Solid state process. Material temperature controlled below melting temperature.
- Temperature can be held constant during the welding process
- Homogenous joining occurs by the “stirring” of the plasticized material.
- Unlike conventional arc welding FSW eliminates risk of shock and fume exposure.
- Can be effectively operated UW



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Development of a new FSW process

- The goal is to minimize the stress and heat effect to the helium containing irradiated materials, with the potential to repair at helium concentration levels much higher than today's repairable levels
- Integrity of standard FSW of stainless steel weld (no helium) was evaluated and showed superior bonding strength and control of residual stress
- Additional FSW development and advance welding techniques completed
  - Previous work on helium containing irradiated materials clearly illustrated the challenges
  - Details are protected under invention disclosure

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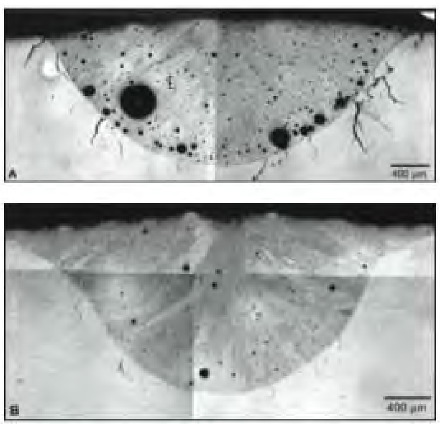
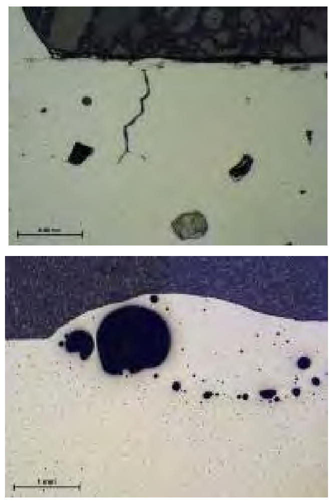
Friction stir welding on Helium Containing Materials made by Powder Metallurgy (Carried out at ORNL)

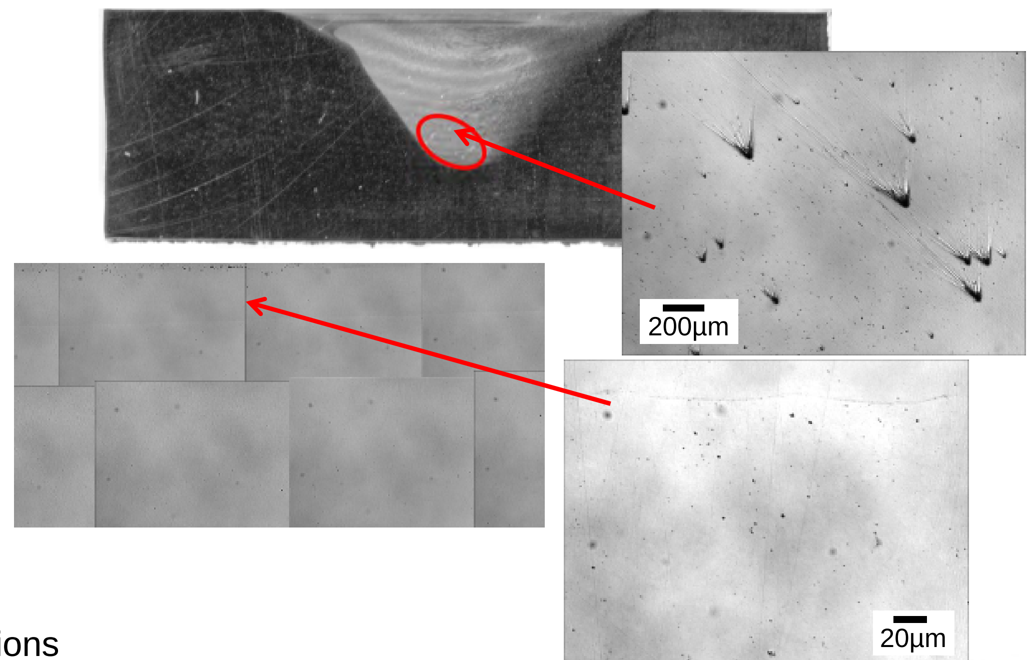
- New joining technology has the potential to revolutionize repair welding of irradiated metals in nuclear industry.
  - Baseline evaluation have shown significant improvements in weldability
  - High quality defect free welds successfully produced on helium containing materials made by powder metallurgy at ORNL
  - No bubble formation or crack observed.



Tosten et al, 2007



Arc welding (GTAW) evaluations



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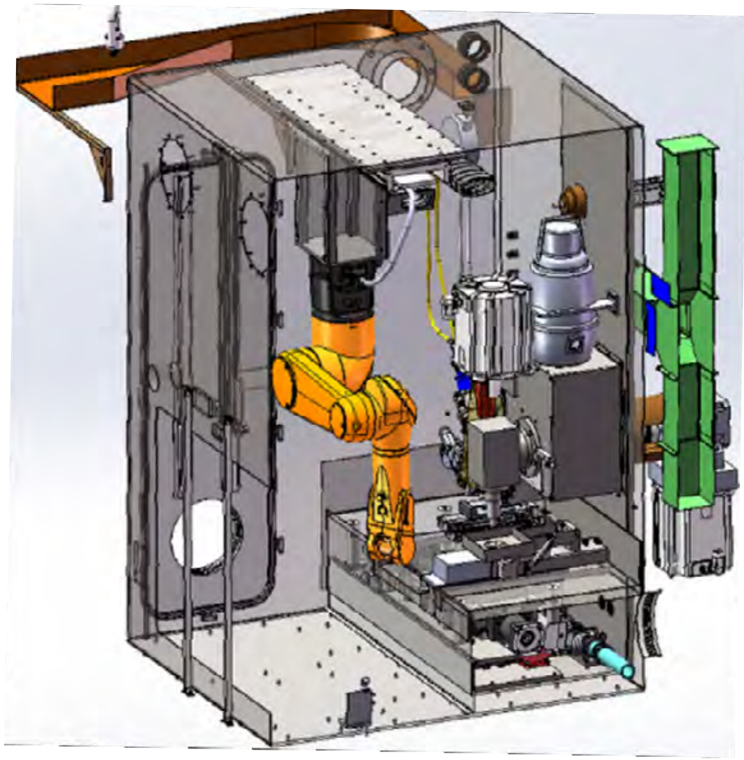
Irradiated Material Weldability Testing

Irradiated Material Welding Facility Development

- Hot cell fabrication for verification testing:
  - Equipped with friction stir welding (FSW)
  - Equipped with laser welding with wire feed capabilities
  - Equipped with material handling and welding manipulation equipment
- Status
  - Cell fabrication and stand complete
  - Debugging and setup planned for mid-2015



Welding Hot Cell Design with welding processes

Welding Hot Cell fabrication at ORNL

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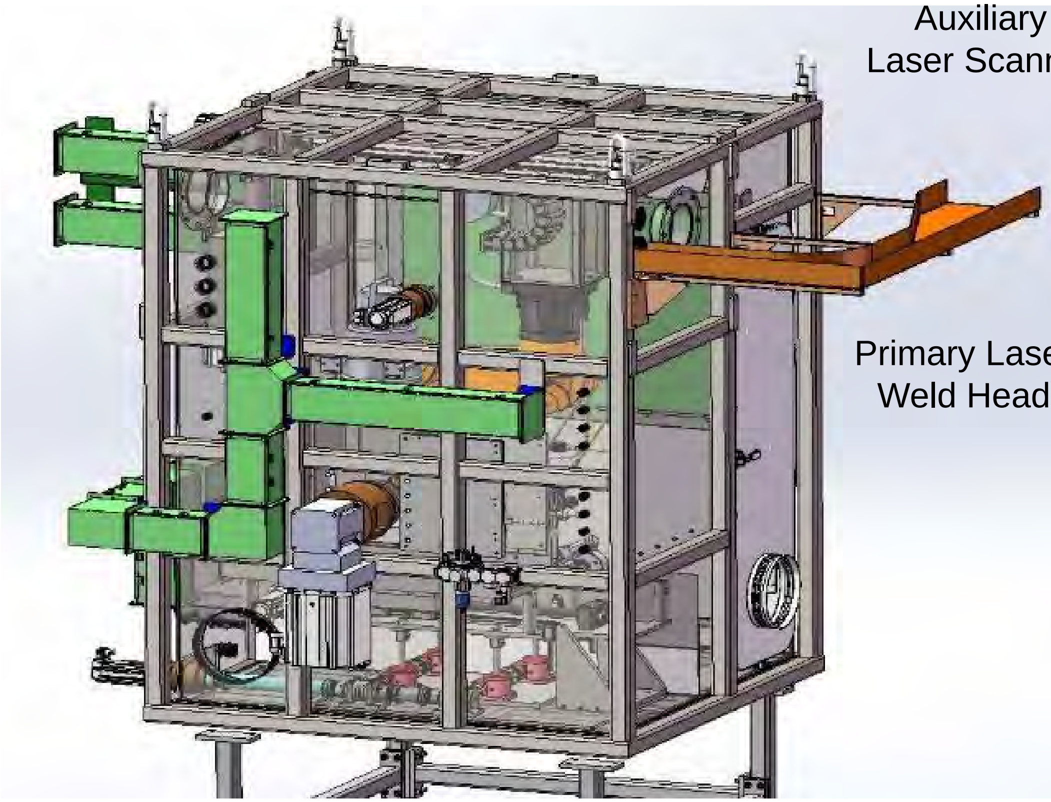
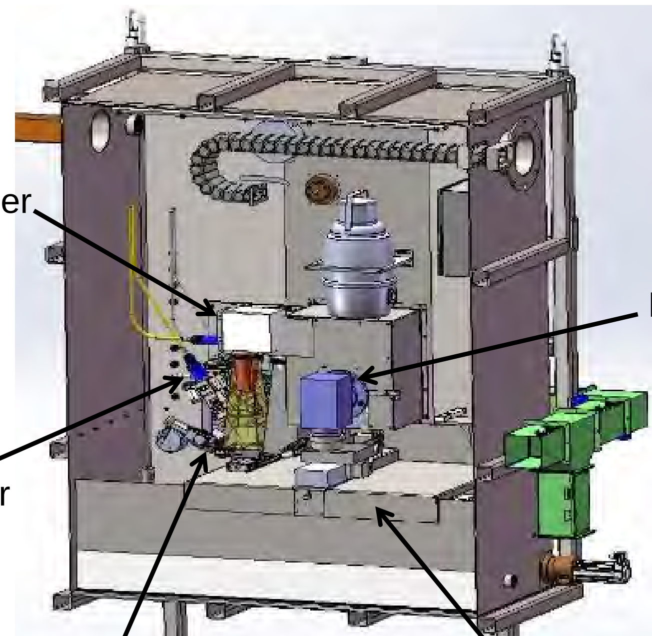
Welding Hot Cell Cubicle Equipment Integration





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2015/2016 Future Milestones/Schedule

Milestone	Estimated Completion Date
Irradiation of first sample set (304 and 316 stainless steel)	Completed in 2014
Mechanical and Electrical Design	April, 2015
Finalize fabrication of ORNL hot cell cubicle	August, 2015
Laser and friction stir welding of first irradiated material sample set	December, 2015
Irradiation of second sample set (304 & 316 stainless steel, Alloy 182)	December, 2015
Mechanical and metallurgical examination of first sample set welds	Early-2016
Laser and friction stir welding of second irradiated material sample set	Mid-2016
Mechanical and metallurgical examination of second sample set welds	End of 2016

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