SMR RPV Manufacturing and Fabrication Technology Development

D. Gandy, Sr. Technical Executive
davgandy@epri.com
C. Stover, Sr. Technical Leader
cstover@epri.com
Electric Power Research Institute

NRC/EPRI Technical Exchange
May 23, 2018

Outline

- Background and Objectives
- New Technologies for SMRs
  - Electron Beam Welding
  - Powder Metallurgy/Hot Isostatic Pressing
  - Elimination of Welds via Heat Treatment
  - Diode Laser Cladding
- Project Tasks
- Component Fabrication
- Manufacturing
- Project Status
- Summary

What if it only took 12 months to produce a reactor pressure vessel?

Representative Model of NuScale Power Reactor Vessel

Background

- EPRI, DOE, and various vendors have been working on a number of advanced manufacturing technologies over the past 7 years:
  - EB and LVEB welding
  - Powder metallurgy-HIP
  - Diode laser cladding
  - Dissimilar metal weld joining
  - Cryogenic machining

- Industry is looking to develop and demonstrate new technologies for the manufacture/fabrication of SMRs
- The current project will support work to fabricate specific large scale components using these technologies

Advanced Manufacturing -Objectives

- Rapidly Accelerate the Deployment of SMRs
- Develop/Demonstrate New Methods for Manufacture/ Fabrication of a Reactor Pressure Vessel (RPV) in **<12 months**
- **Eliminate 40%** from the cost of an SMR RPV, while **reducing** the Schedule by **18 Months**

200mm Electron Beam Weld

Enabling the Next Generation of Nuclear Plants -Scope

- Manufacture Major Critical Components to **Assemble a 2/3-Scale SMR Reactor Pressure Vessel**
- Jointly Funded Collaboration
  - EPRI, Nuclear AMRC, DOE, NuScale Power
- Others
  - Synertech-PM, Sheffield Forgemasters, Sperko Engineering, Carpenter, ORNL, etc.

What Once Took Weeks,
We Can Now Do In Hours…

Photograph provided courtesy: NuScale Power

Electron Beam (EB) Welding

Why EBW?

- One-pass welding!
- No filler metal required.
- EBW can produce welds w/ minimal HAZ
- Nuclear-AMRC, TWI, Rolls-Royce & EPRI have demonstrated in-chamber and/or local vacuum on thick section alloys
  - Enables field/shop welding!
- RPV girth welds (110mm thick) in <45 min

Inspection, Costs?

- Huge savings in welding costs (again, one pass welding)
- Potential to eliminate in-service inspection!

65mm (thick) x 3m length x 1.8m diameter

Welding time: <10 minutes

Photograph provided courtesy: TWI (UK)

Photograph provided courtesy: Nuclear AMRC (UK)

Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)

Why PM-HIP?

- Near-net shape and complex components (reduces materials cost and machining)
- Alternate supply route, shorter turn-around
- Considerable EPRI/Industry development over last 7 years.
- Ideal for multiple penetration applications (RPV or CNV head) vs expensive forgings

Inspection, Costs?

- Homogeneous-Excellent inspection characteristics
- Costs roughly equivalent to forging
- Eliminates need for welds in some applications

Large 316L SS Valve Body

3700 lb BWR nozzle

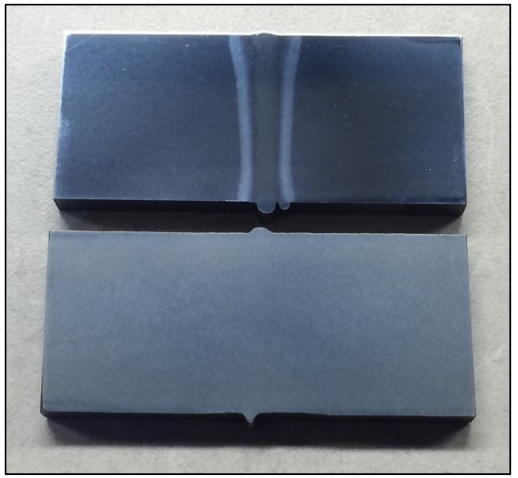
Steam Separator Inlet Swirler

Partial RPV Ring Section

Elimination of Welds via Heat Treatment --Resetting the Clock

How?

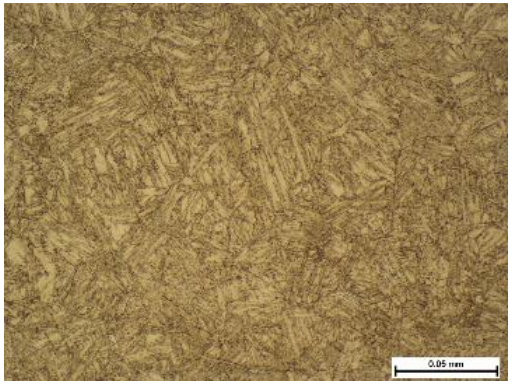
- Perform chamber EB weld of sub-assemblies
- Localized Solution HT, quench; normalize; temper
- Resulting microstructure is same as base metal
- Fracture toughness comparable to base material



$EBW+HT=0\ Weld$

Inspection, Costs?

- Perform fabrication inspection prior to and following initial solution HT, plus N&T
- Following HT, no weld is visible
- Potentially no weld inspection required at 10 year intervals???



EB Weld after Heat Treatment
WCL microstructure @ 500X

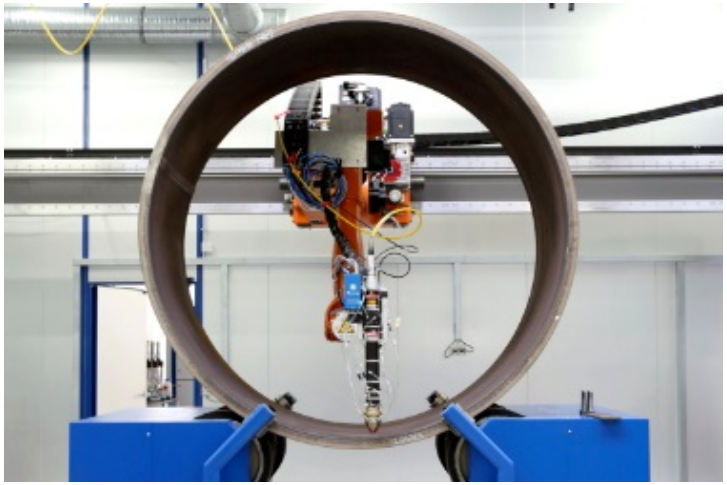
Diode Laser Cladding

Why DLC?

- Robotic machine welding
- High deposition rates
- Significantly reduces cladding thickness required (~4mm)

Inspection, Costs?

- Lbs. (or kg) of material required is significantly reduced since thinner layers can be applied.
- No machining after cladding required



Diode Laser Cladding equipment setup (courtesy of N-ARMC)

Where Do Savings Come From?

PM-HIP

- Near-net shaped components
- Eliminates 1000's of hours of machining

Electron Beam Welding

- Traditional RPV Weld
  - 120 welding/PWHT days
- Electron Beam Weld
  - 12-15 welding/PWHT days

Eliminates Long-Lead Forgings

- Traditional
  - 2-5 year lead-time
- PM-HIP
  - 6-12 months

Reactor Head

- Anticipated savings >$2-3M each

Diode Laser Cladding

- Reduces cladding material by > 50%
- No machining required after application

Advanced Machining

- Reduces machining time by up to 4X

Eliminate 40% from the Cost of an SMR RPV
Reduce Manufacturing Schedule by 18 Months

Project Tasks

1. Lower Reactor Assembly
2. Upper Reactor Assembly

3A. Thick Section EBW Development

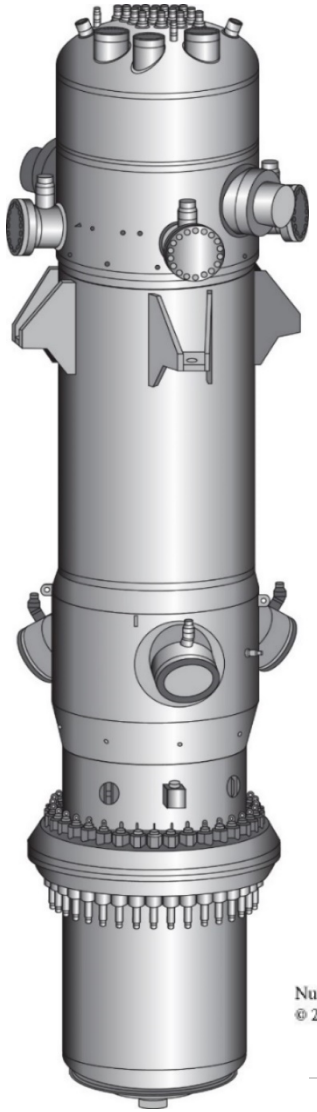
3B. Local Vacuum EBW Development

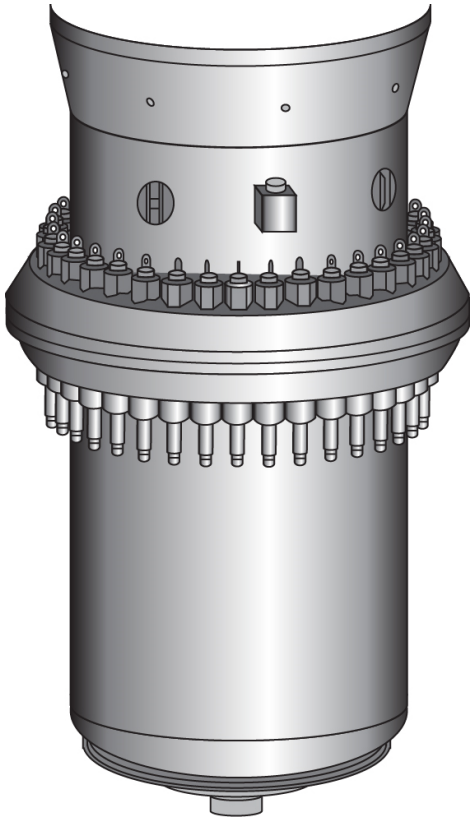
4. Diode Laser Cladding Development
5. Elimination of DMWs—for Nozzle Applications
6. Elimination of In-Service Inspection via Solution Heat Treatment
7. ASME BPVC Code Development
8. ORNL Mechanical and Metallurgical Testing

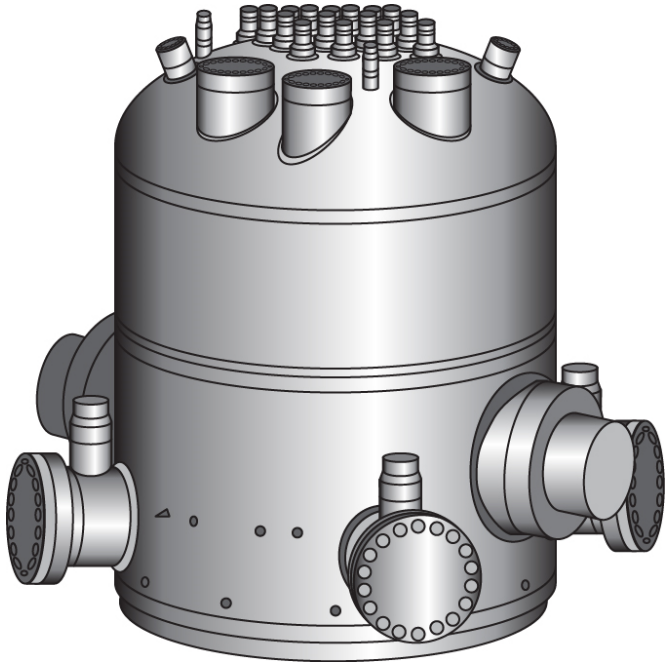
Representative Model of NuScale Power Reactor Vessel

2/3rds Scale Small Modular Reactor Manufacture/Fabrication

- EPRI
- Nuclear-AMRC
- US DOE
- NuScale Power







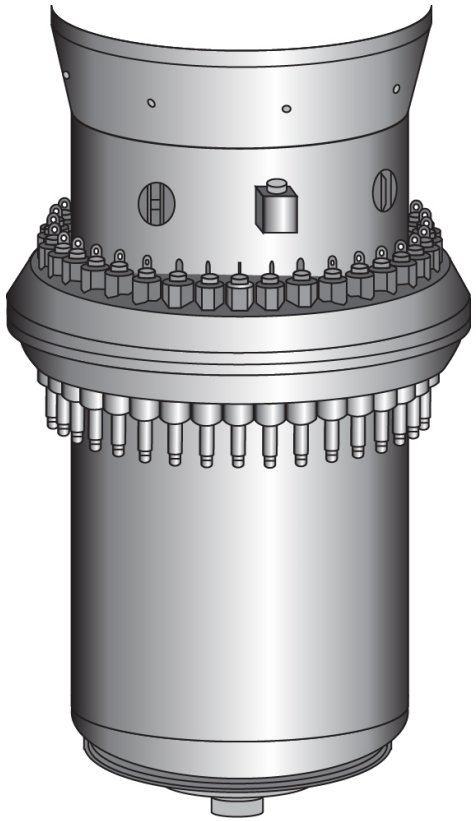
2017-18 Scope/Schedule

Fabrication

- EB Welding Development (Task 3A)
- Diode Laser Cladding Development (Task 4--partial)
- Lower RPV Assembly (Task 1)

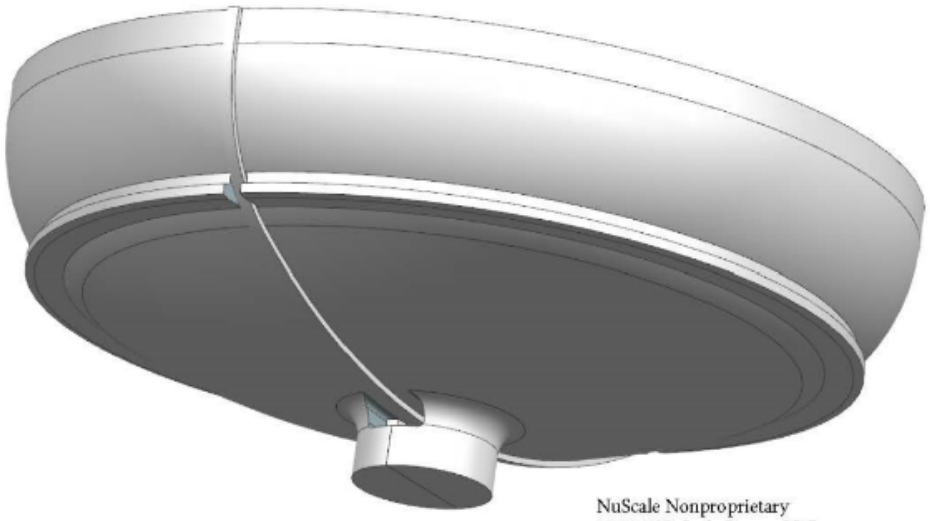
Manufacturing & Fabrication

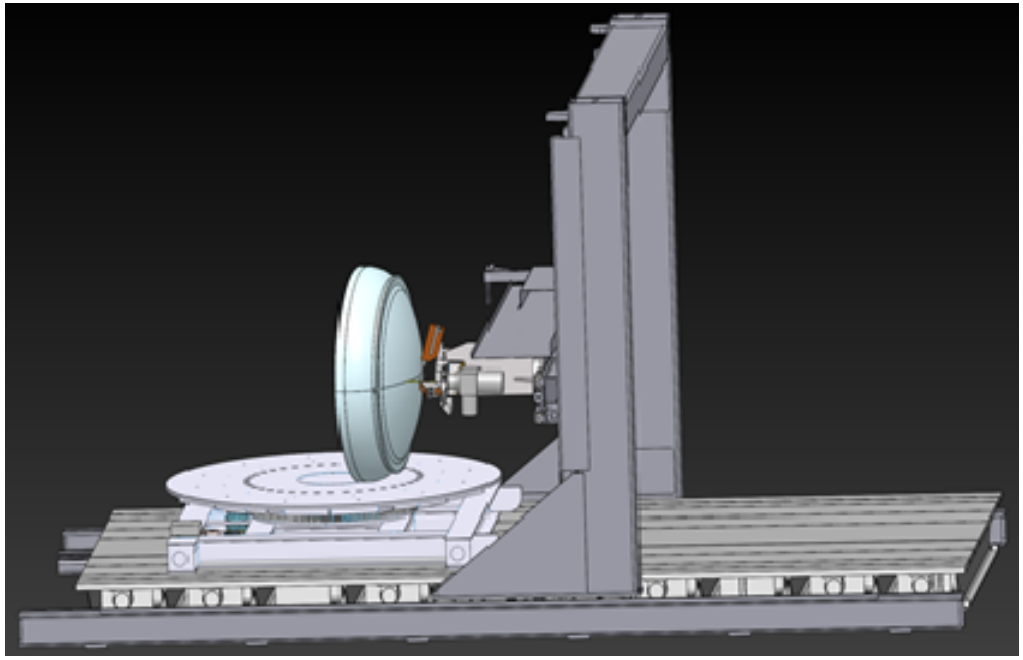
- Lower Head (Synertech PM-HIP)
- Lower RPV Flange Shell (SFEL forged)
- Two Flanges (SFEL forged)
- Upper Flange Shell (Synertech PM-HIP)



Lower RPV Assembly

Lower Head EB Welding

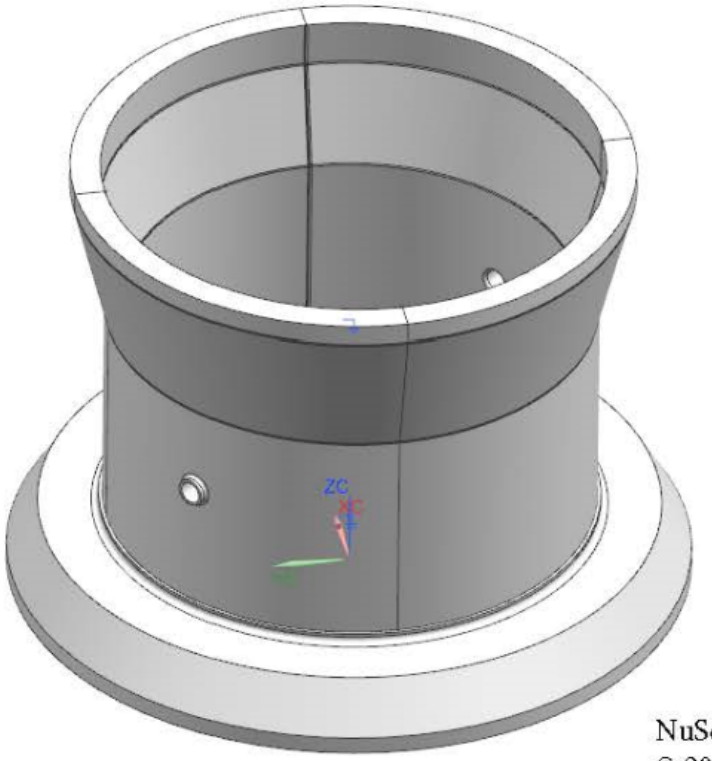




Nuclear AMRC (UK) – Responsible for All Component Assembly

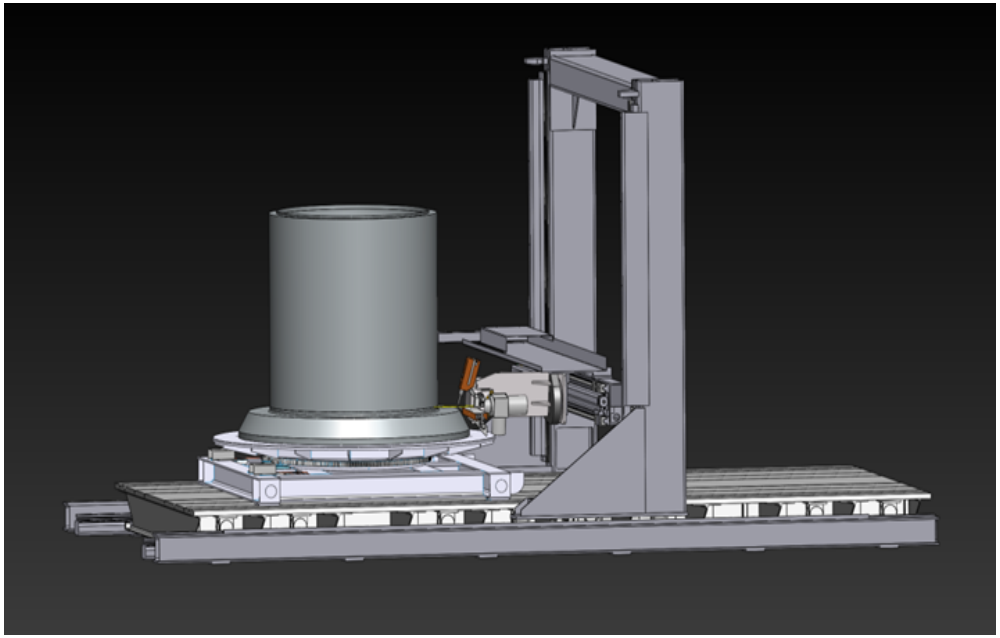
Lower and Upper Flange Shells

Thick flange to be welded to lower shell via EBW

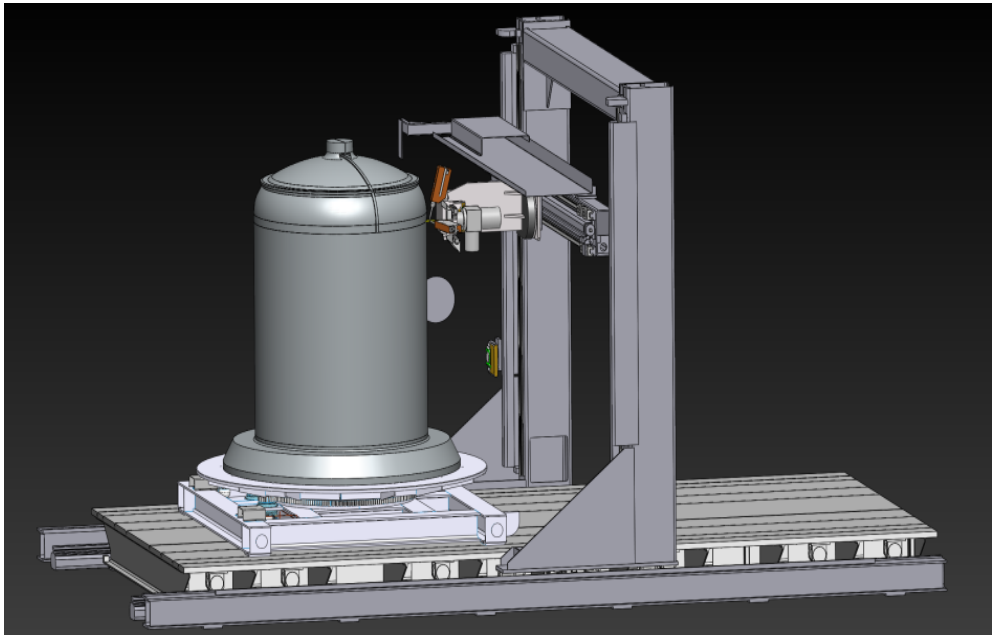


4 PM-HIP ring sections will be joined with EBW

Lower Assembly – 2 Circumferential Girth Welds (EBW)

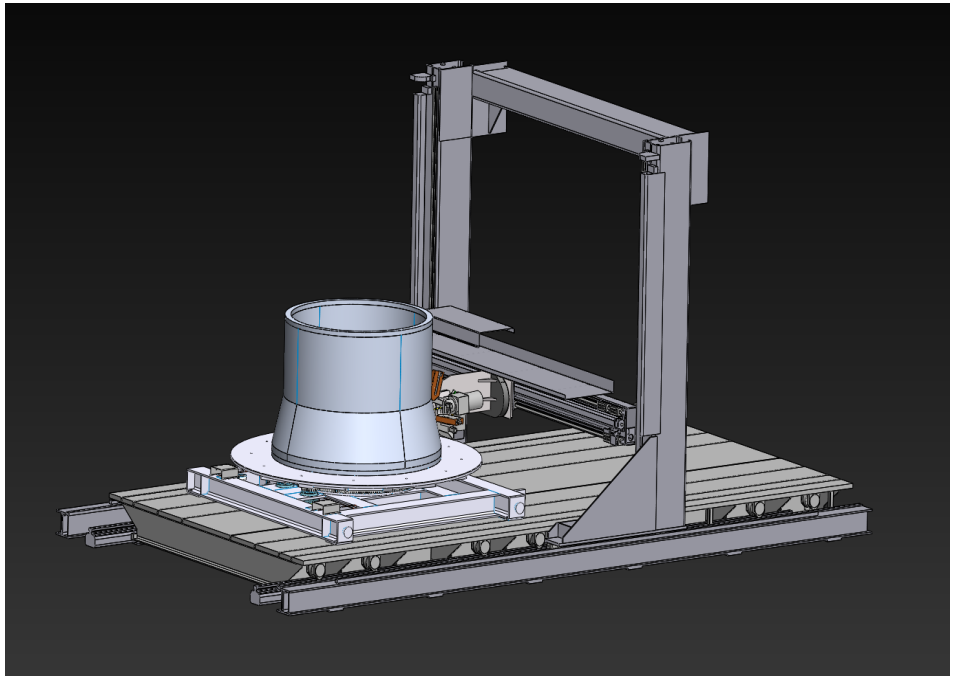


Lower Flange Shell (Note, it's upside down)

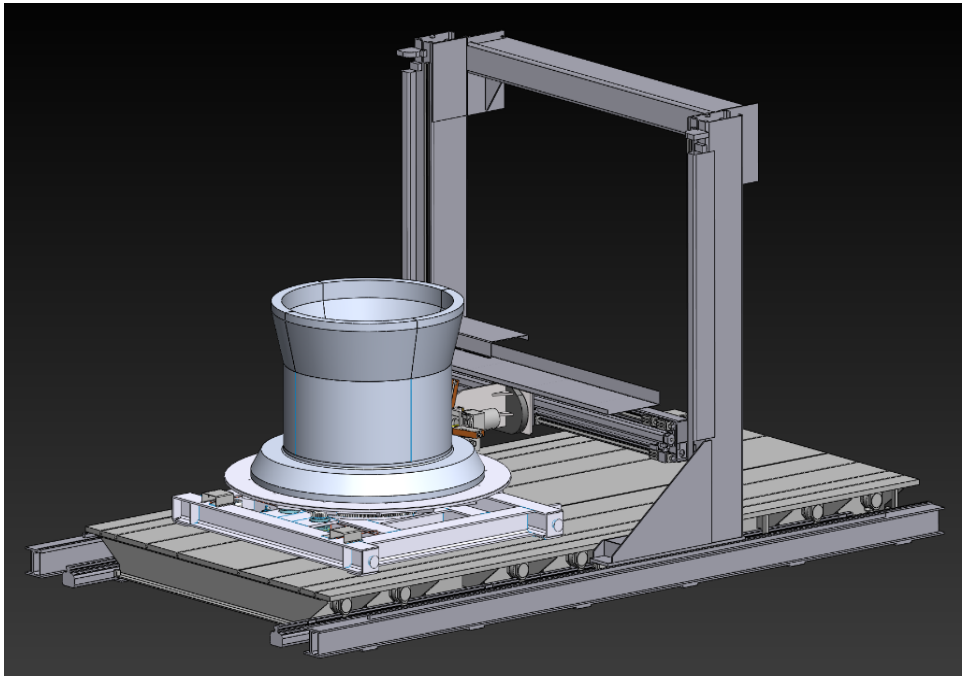


Lower head to Lower Flange Shell
(again, upside down)

Upper Flange Shell – Four sections and flange



Vertical Welding of Sections



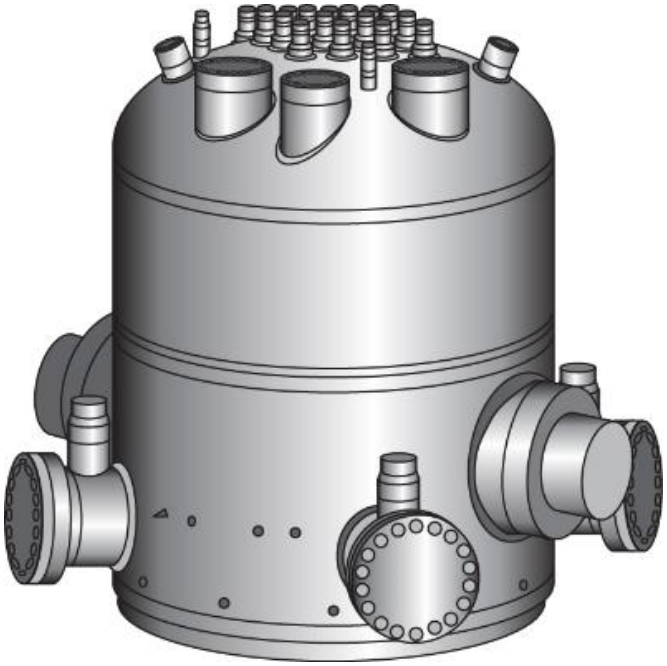
Circumferential Girth Weld to Attached Flange

Task 2—Upper Reactor Assembly (1) --2019-2020

4. RPV Top Head
   - Manufacture via PM-HIP in two halves
   - EBW halves together, annealed, Q&T
   - DLC completed top head

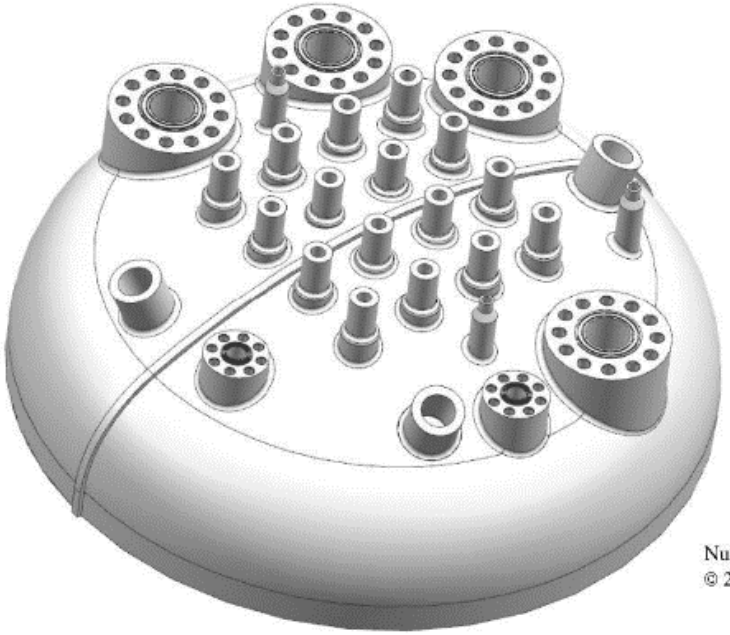
5. RPV PZR Shell
   - Forged Section

6. Steam Plenum
   - PM-HIP & EBW together



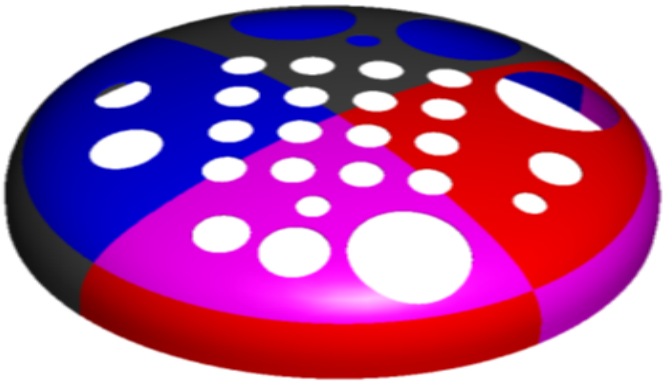
Representative Model of NuScale Power Reactor Vessel

Upper Head—27 Penetrations.



- Two half “head sections” will be produced via PM-HIP
- A508, Grade 3 Low Alloy Steel
- Penetrations will be solid and then bored/machined out
- Welded together with EBW
- At full scale, ~ 21,000 lbs (9525 kg)

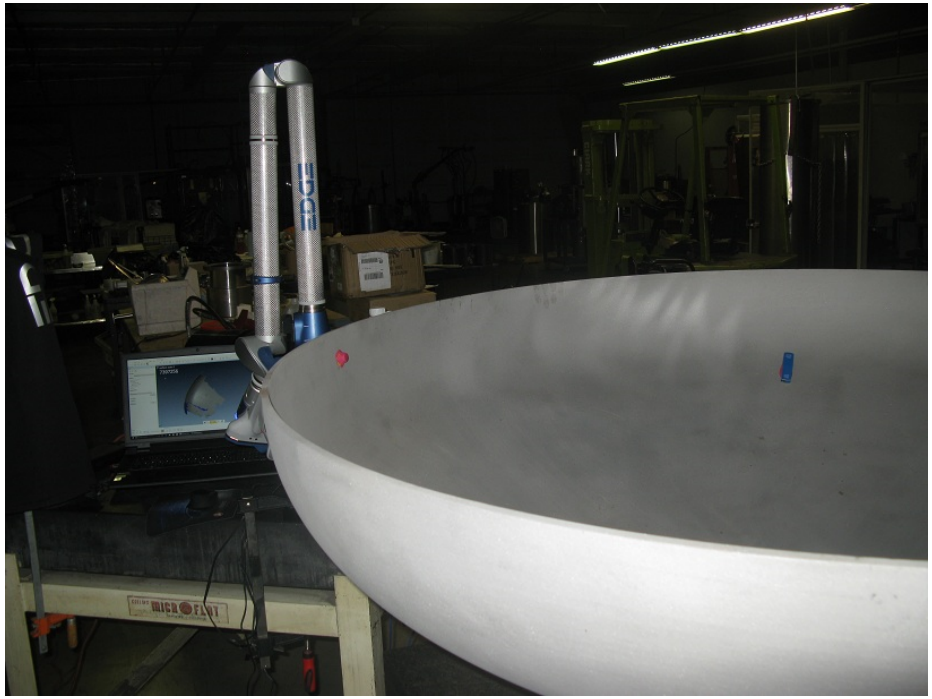
Upper Head (Stamped Inner & Outer Capsule Shells)



Upper Head Laser Dimensioning

Note: Inner Diameter
Capsule will be solid

Laser scanning of upper capsule



Laser Scanning

Upper Head Laser Machining

Note: Inner Diameter Capsule will be solid

Laser machining of the penetrations to attach CRD nozzles

Start of second penetration machining

Upper Head Laser Machining

Note: Inner Diameter Capsule will be solid

Laser machining of the penetrations to attach CRD nozzles

Machining complete for outer capsule

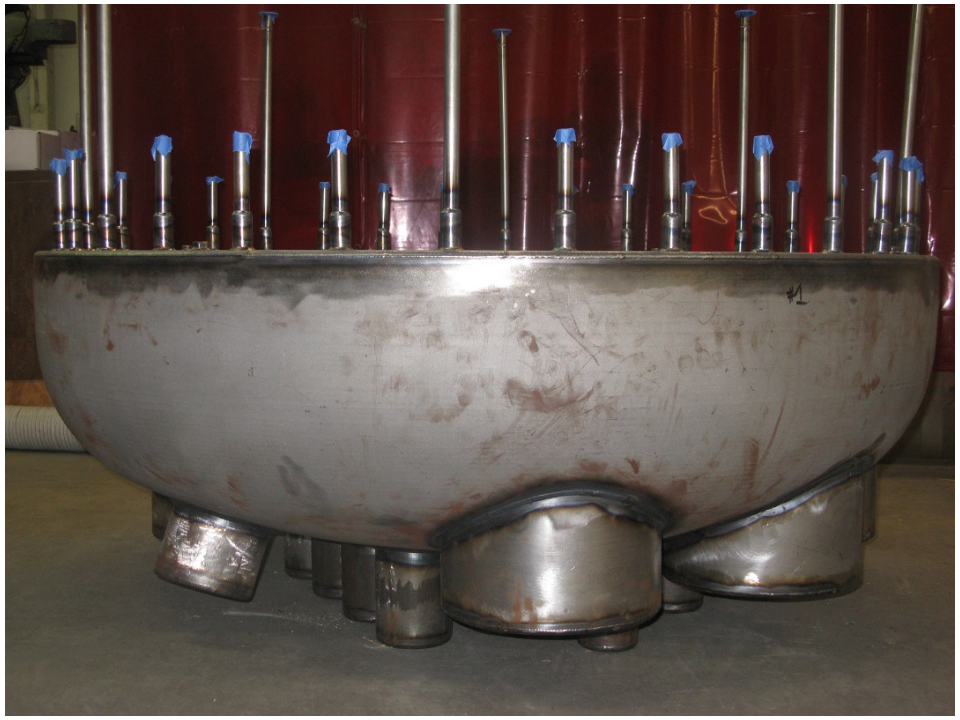
Capsules for CRD Tubes Mounted in Upper Head

Upper head at 44% scale is ~3625 lbs (1645 kg); 50-inch (1270mm) diameter

At full scale, ~ 21,000 lbs (9525 kg).

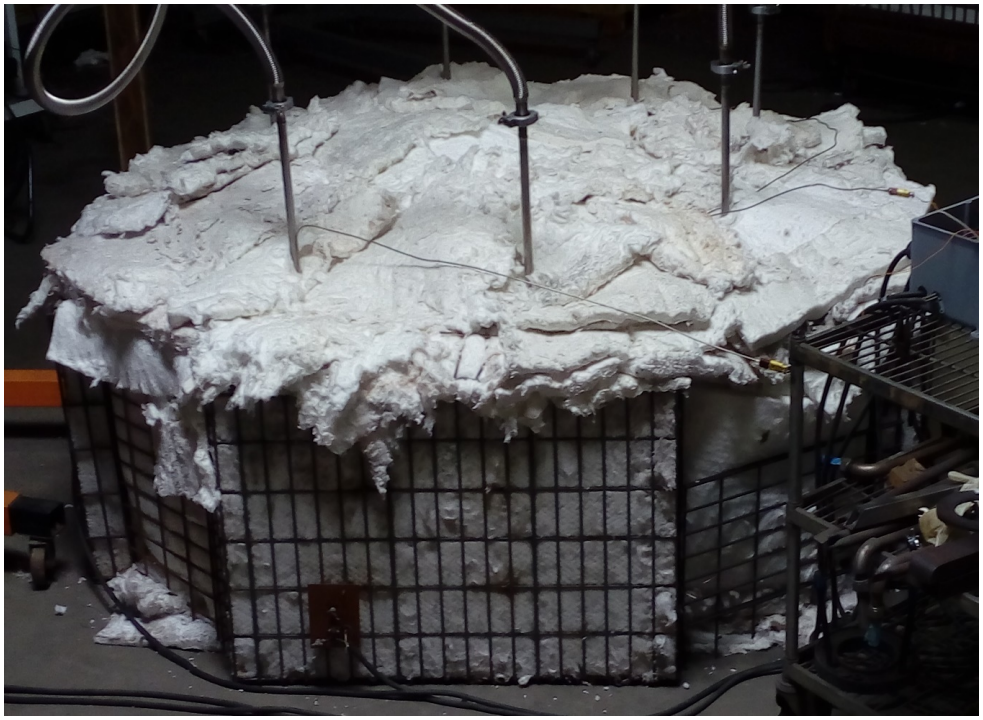
Capsules for Upper Head Completed and Ready for Powder Filling

Solid nozzles will be bored after HIP and heat treatment



Note “fill stems” on top of upside down upper head capsule

Upper Head– Hot Degassing & Crimping of Fill Stems



Hot Degassing of Powder Filled Upper Head

Following Degassing, All Fill Stems are Crimped and Welded Shut. Now Ready for HIP

44% Upper Head

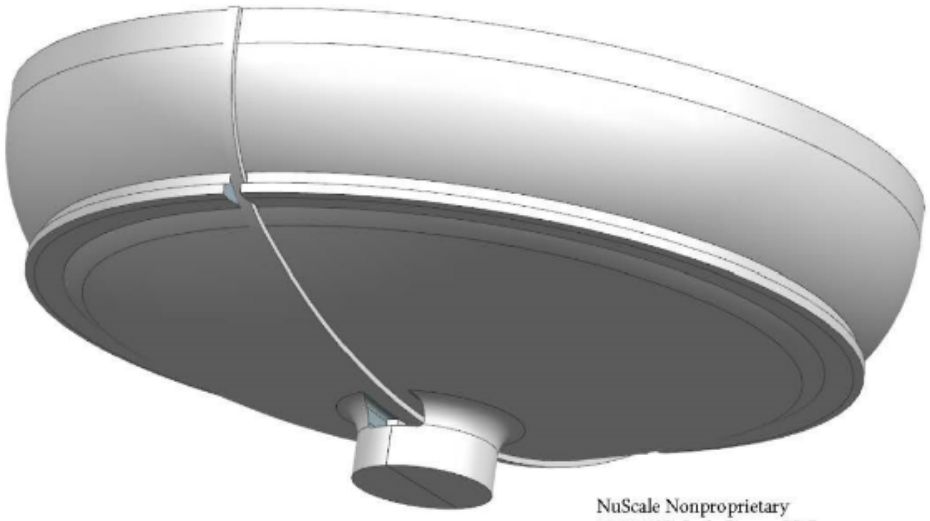
Movement of the Loaded Capsule

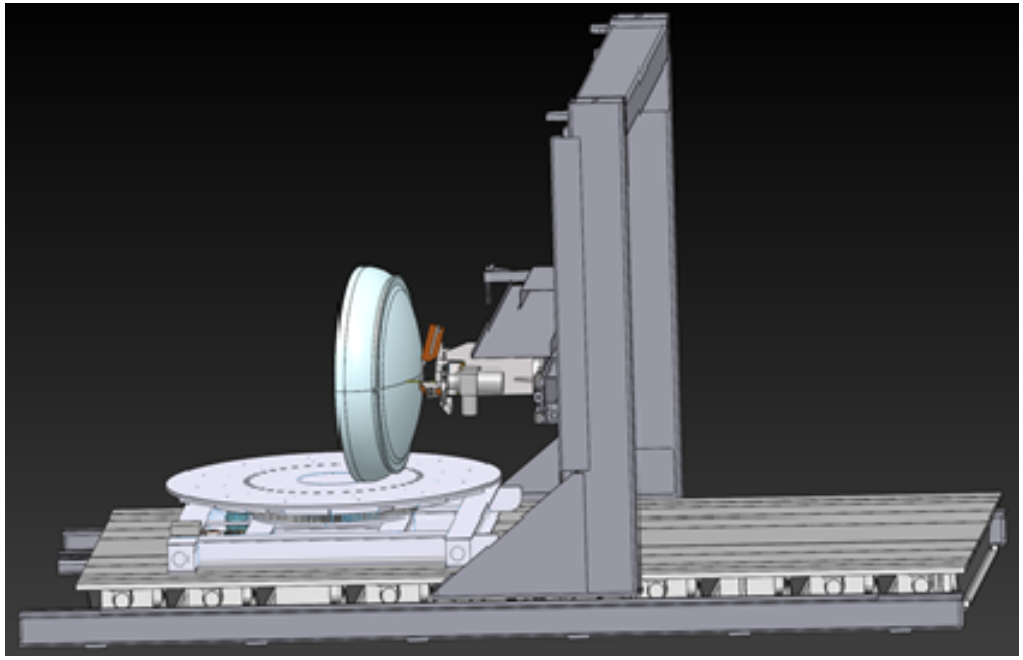
After HIP Consolidation

44% Upper Head After HIP Consolidation --Laser scanning

Lower Head – One-Half Section

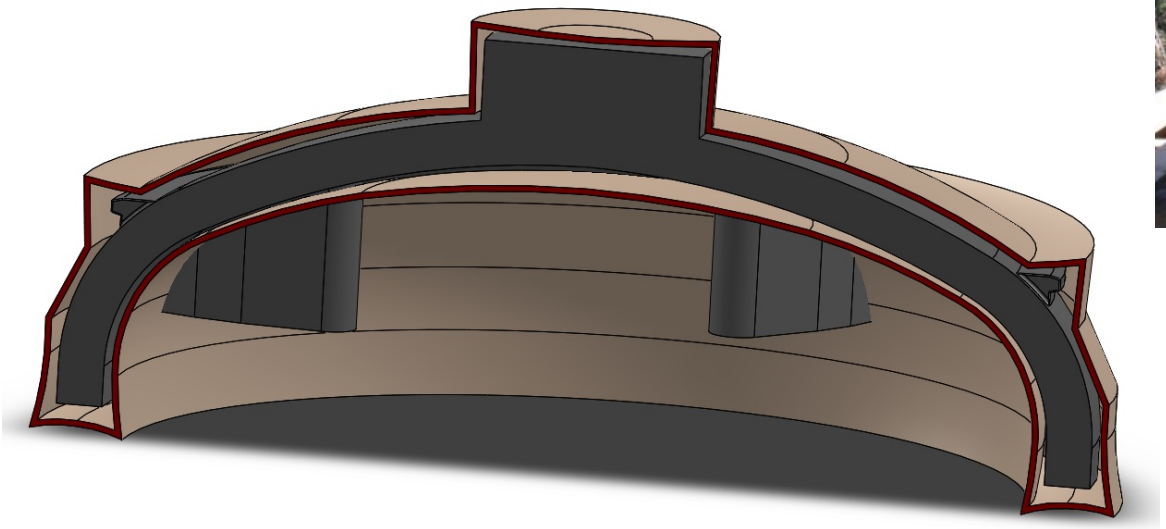
Lower Head EB Welding





Nuclear AMRC (UK) – Responsible for All Component Assembly

Lower Head—Stamped Capsule Sections



HIP Modeling—Shows Lower Head inside of the Finished Capsule

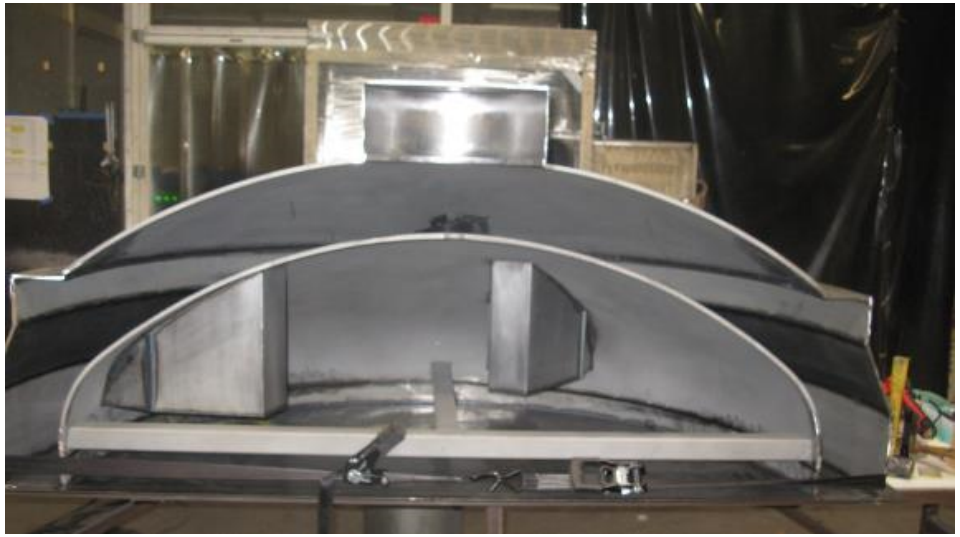
Final part: ~4300 lbs (1950 kg) @ 2/3rds scale;
Full Scale is ~11,000lbs (1/2 section) (4990kg)

Inner Capsule Shell

Outer Top Capsule Shell

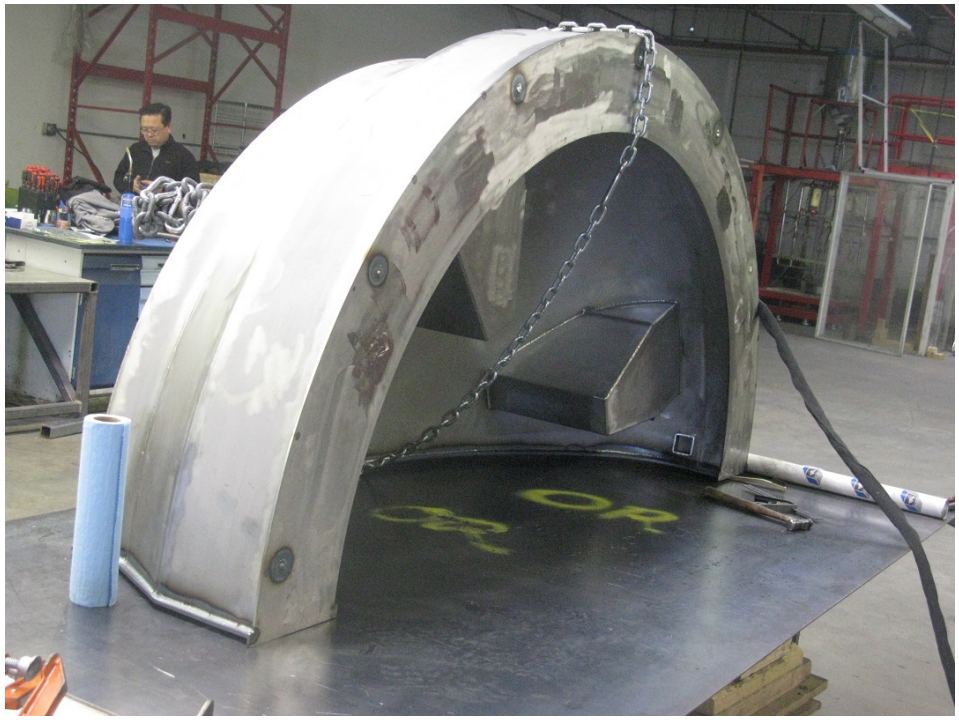
One half lower head under construction

3/8-inch (9.5mm) thick lower head construction;
~70-inches (1780mm) diameter (2/3rds scale)



Note: Two reactor internals support structures are included for each RPV head half

Completed Capsule for Lower Head



One-half of Lower Head. Note Support Legs inside of the Structure

One-half of Lower Head Read for Powder Filling

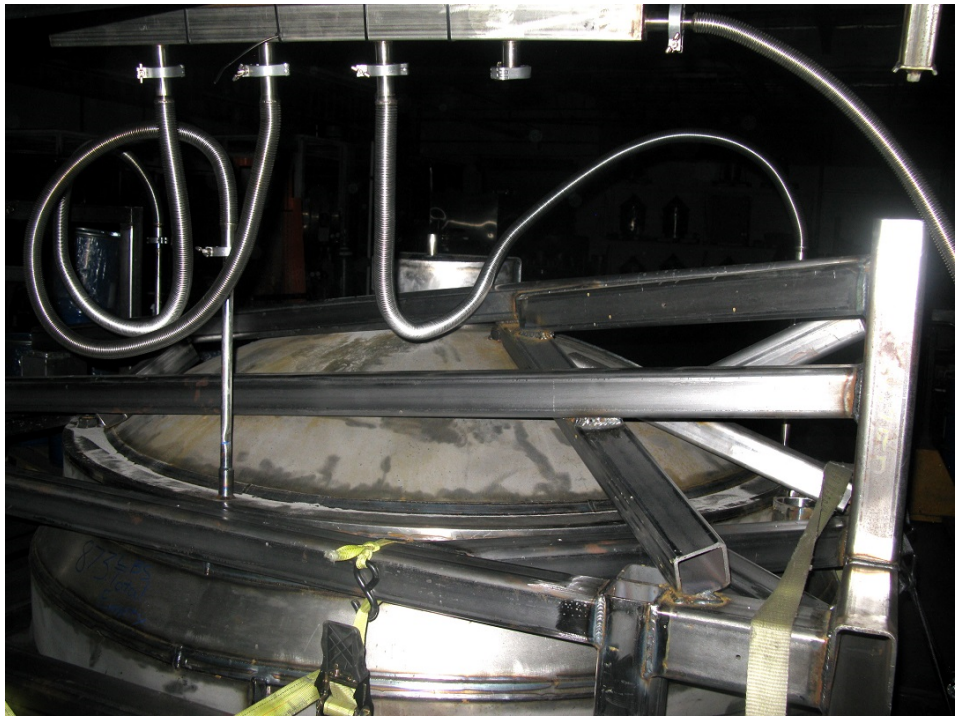
Custom Rack Build for the One-Half Lower Head Section

- Custom rack required due to size of existing HIP furnaces in USA.
- 1.67m (66 inches) diameter in USA; 2m (78.5 inches) in Japan
- Must be stood upright in custom rack/frame
- Remember, this is a non-symmetrical component in one-half section.

Custom Rack Build for the One-Half Lower Head Section

Vibratory (shaker) Table

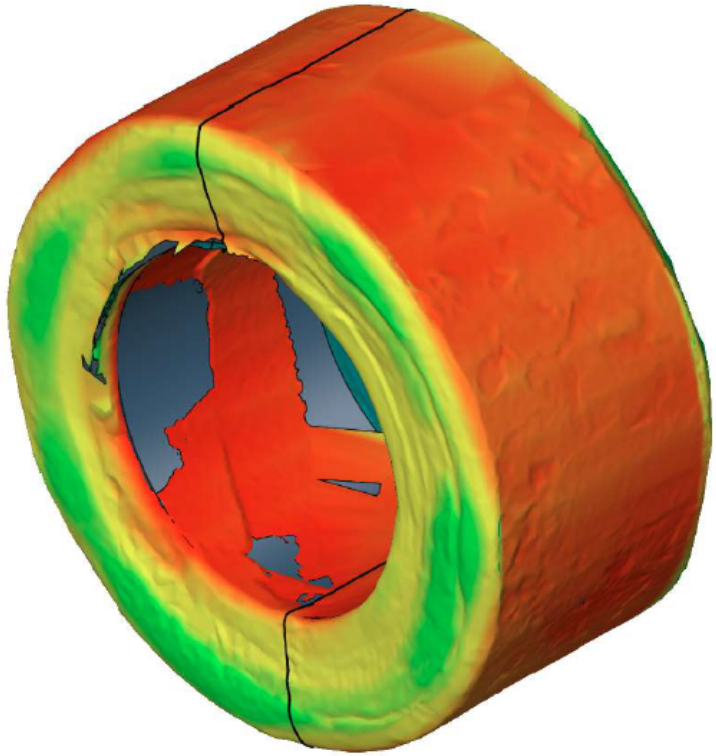
Degassing of Lower Head Section



Four SA508, Grade 3 Class 2 Forgings Produced

- PZR Shell
- Lower RPV “Flange”
- Lower RPV Shell
- Upper RPV Transition Shell “Flange”

- Primary HT performed.



Forging for Two Flanges

Flange and Shell Forgings

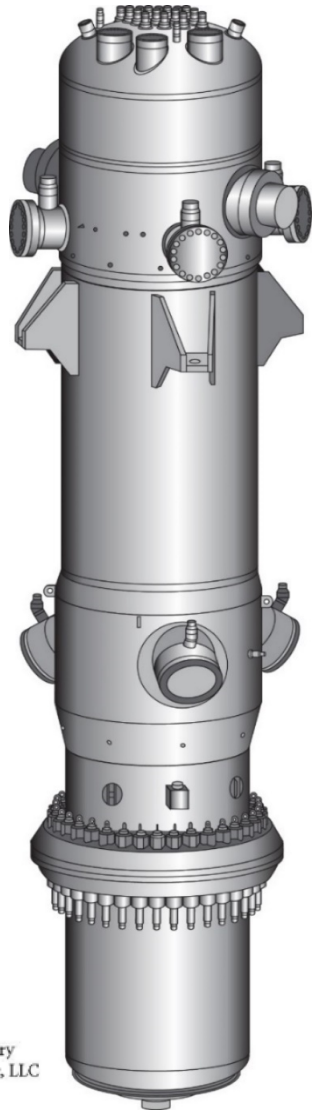
Flange and Shell Forgings

Project Status (May 2018)

- Work packages developed for:
  - EBW, DLC, Machining, PM-HIP, Heat Treatment, etc.
  - Flange welding, head welding, vertical welding, circumferential welding
  - Lower assembly
- Steam plenum access port completed (EPRI ANT)
- 44% diameter (50-inch) A508 top head completed (EPRI ANT)
- Forgings for flanges, PZR shell, lower RPV section, and HT completed
- One-half section A508 lower head, Just HIP'ed
- EBW & DLC development underway @ Nuclear AMRC
- Heat treatment development underway soon.

Summary (1)

- Current DOE/EPRI project is 8 months into a 4-year effort.
  - Property and process development
  - EBW, DLC, PM-HIP, Elimination of Welds
- Major PM-HIP components being produced:
  - Upper & lower heads
  - Steam plenum and plenum access ports
  - Transition shells (four quadrants)
- Electron beam welding development underway
- ATLAS – 3.55m (144-inches) HIP needed



Summary (2)

- Goal: Re-establish USA Leadership in Heavy Manufacturing
- Critical Role in SMRs and Gen IV Manufacturing
- Near-net Shaped Components & Reduced Machining
- Shorter Turn-around Processing Times & Improved Properties
- ATLAS Consortium to Drive Technology Development

40-inch HIP Design, courtesy of IFI

Acknowledgements

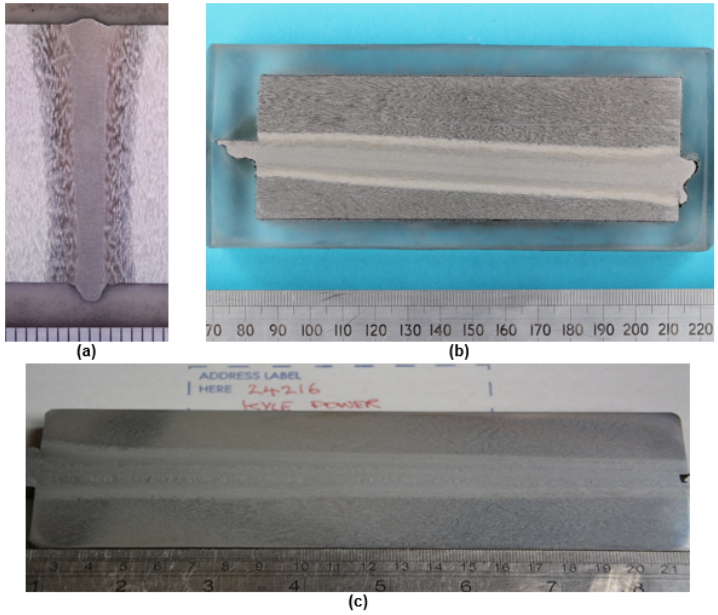
- S. Lawler, R. Hall, M. Cusworth, etc. (Nuclear AMRC)
- Keith Bridger (Bridger Welding Engineering)
- V. Samarov & C. Barre (Synertech-PM)
- M. Blackmore (Sheffield Forgemasters)

Together…Shaping the Future of Electricity

What Are The Critical Gaps That Must Be Addressed? (1)

- EBW must be demonstrated
  - 4.375-inch (110mm) thick (RPV)
  - currently demonstrated at 4-inches (100mm)

- ATLAS HIP facility must be built
  - to increase HIP size capabilities
  - up to 3.5m diameter x 5m length
  - Can manufacture 2/3rds scale coupons today.



30mm, 130mm, and 200mm EB welds

- EBW of SA508 RPV sections
  - Does a vessel that has been EB welded, annealed, and Q&T require subsequent in-service inspections?
  - Is EB really a weld after annealing? No filler metal.
  - Need to demonstrate fracture toughness following solution anneal

What Are The Critical Gaps That Must Be Addressed? (2)

- Diode Laser Cladding must be demonstrated
  - Vessels, nozzles, etc.
  - Robotic cladding up to 90mm wide, but 2-3mm thick
- Understand Irradiation Effects on PM-HIP Components
  - NEUP project for PM-HIP samples are underway
  - 304L, 316L, SA508, Grade 91, Alloys 625 and 690
- Additional development around SA508.
  - We have demonstrated good fracture toughness and other properties, but we need to develop more understanding here.
  - Utility Requirements Document modification
- ASME Code Case Development
  - PM-HIP of SA508
  - Elimination of DMWs
  - EB welding of RPV sections

Manufacturing of Steam Plenum Access Port—Full Scale --EPRI ANT funded

Can Assembly & Welding

Shaker table

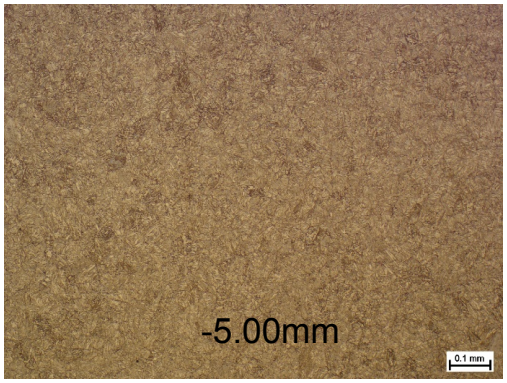
Out-gassing

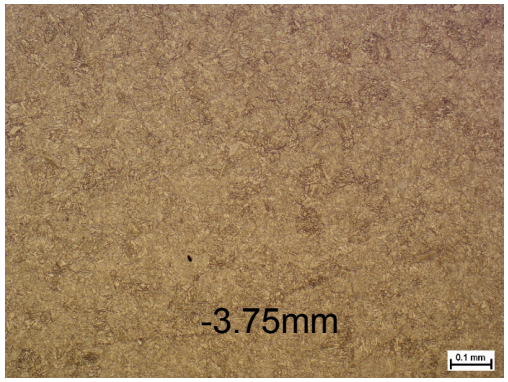
Final Product

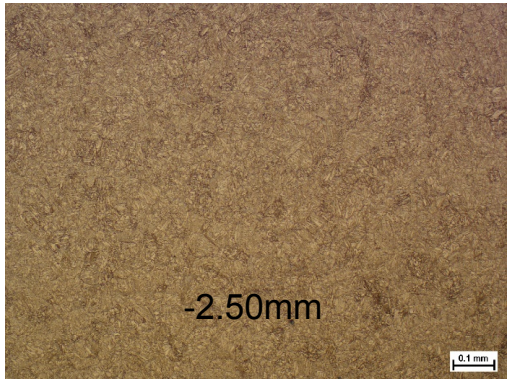
A508 Grade 3 Low Alloy Steel

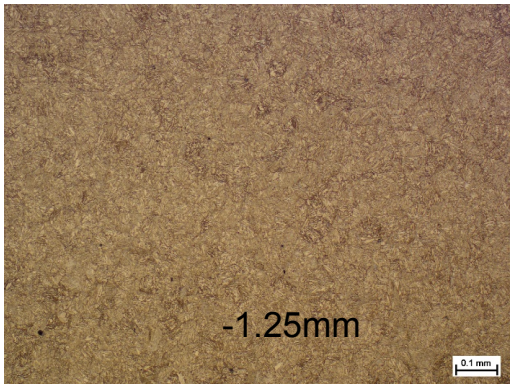
~1200 lbs

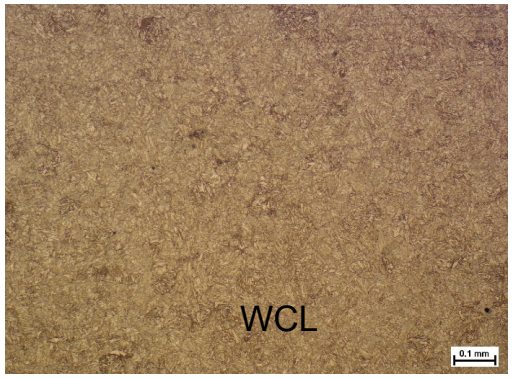
Synertech PM responsible for Capsule Manufacturing

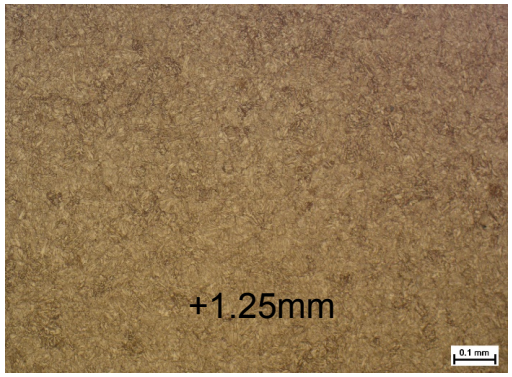

-5.00mm
0.1 mm

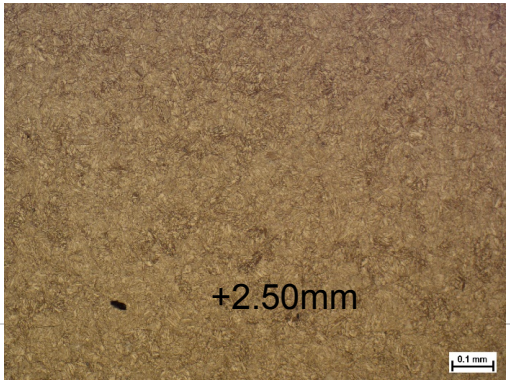

-3.75mm
0.1 mm

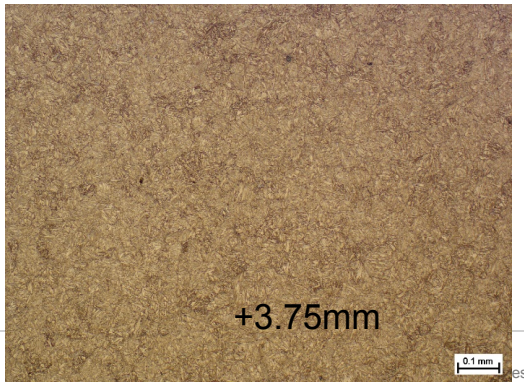

-2.50mm
0.1 mm

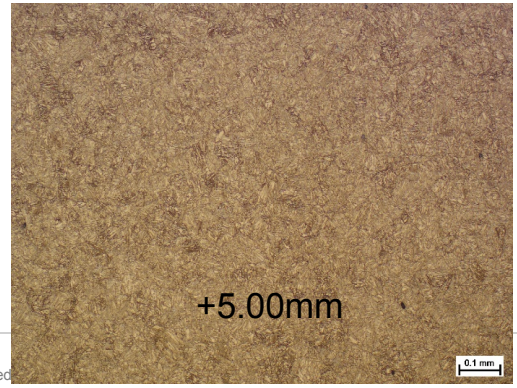

-1.25mm
0.1 mm


WCL
0.1 mm

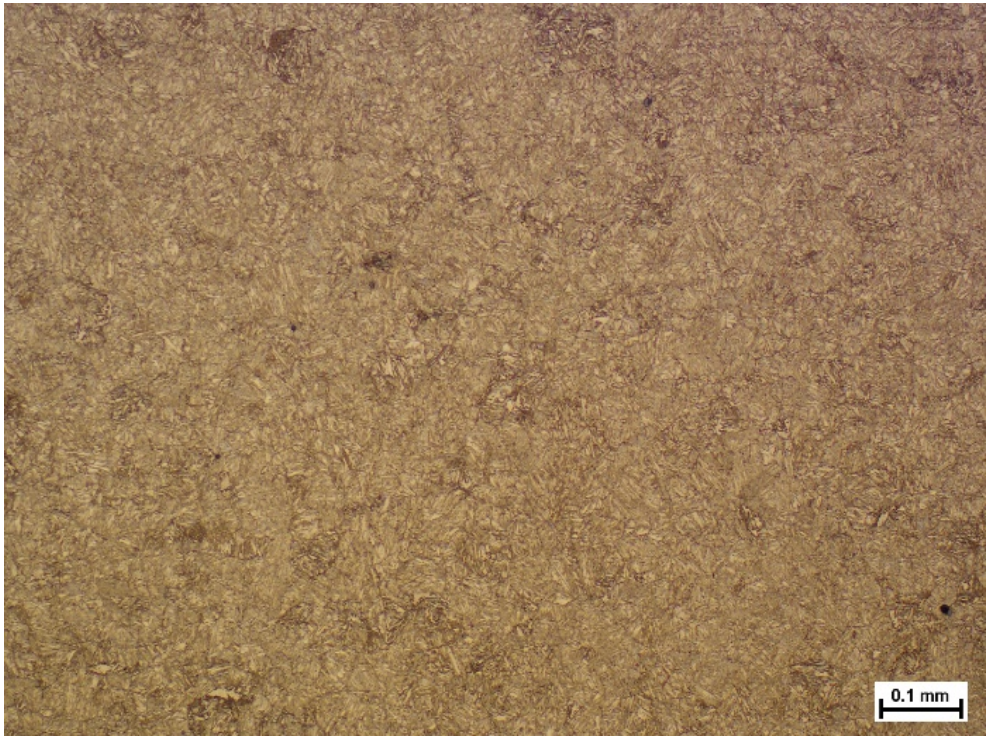

+1.25mm
0.1 mm


+2.50mm
0.1 mm

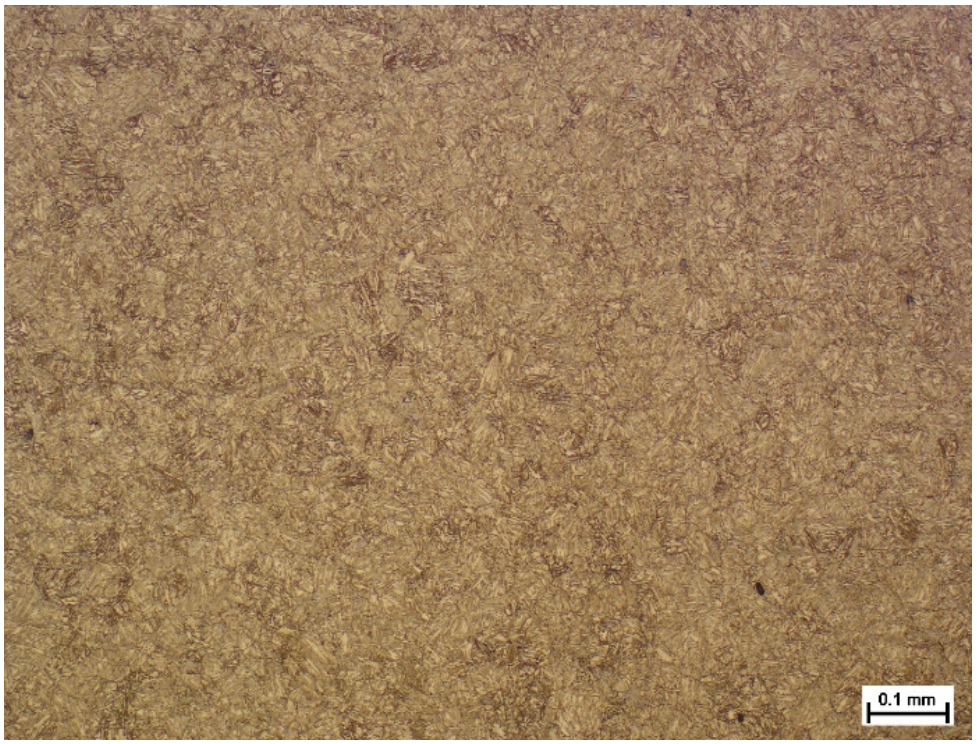

+3.75mm
0.1 mm


+5.00mm
0.1 mm

WCL of EB Weld vs 5mm distance (following Solution Anneal and Q&T) – 100X

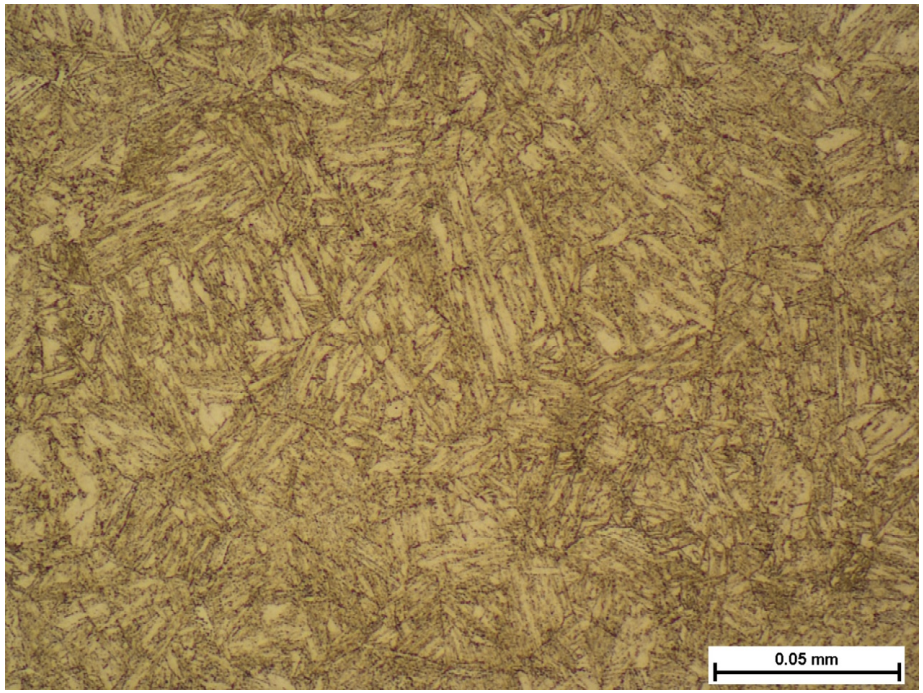


WCL microstructure @ 100X

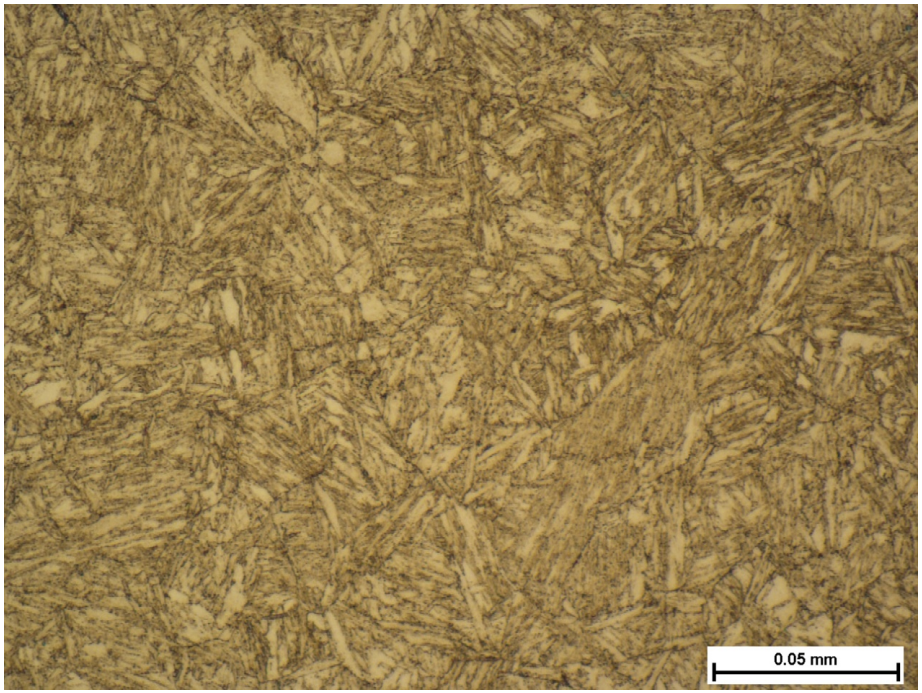


Microstructure 5mm from WCL @ 100X

WCL of EB Weld vs 5mm distance (following Solution Anneal and Q&T) – 500X



WCL microstructure @ 500X



Microstructure 5mm from WCL @ 500X