Advanced Manufacturing to Enable the Next Generation of Nuclear Plants

David Gandy, Sr. Technical Executive
Craig Stover, Sr. Technical Leader
Electric Power Research Institute

Molten Salt Reactor Workshop 2018—Creating a Self-Sustaining Environment for MSR Success

October 3-4, 2018

Outline

- Background
- Development/Demonstration of 4 Advanced Manufacturing/ Fabrication Technologies
- 2/3-Scale SMR Manufacturing/Fabrication – Phase 1
- Component Assembly
- Applicability to Advanced Reactors -- Summary

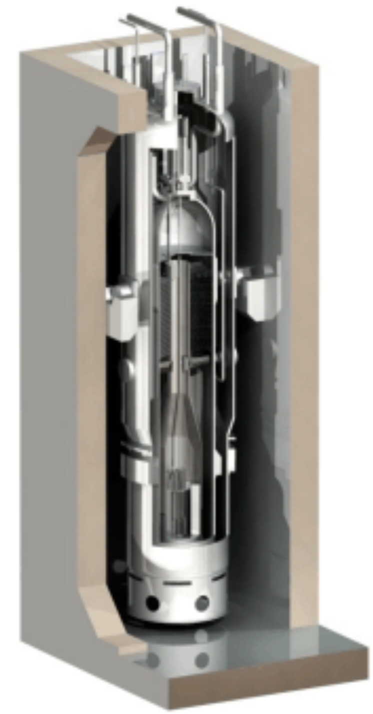
Vessel Manufacture and Fabrication

- What if it only took 12 months to produce a reactor pressure vessel?
- What if you could perform an entire SMR RPV girth weld in less than 60 minutes?
- What if you could manufacture an entire SMR head in < 3 months with no vessel dissimilar metal welds?
- What if you could eliminate the need for in-service examinations of girth welds?
- What if you could perform vertical welds to join rolled plates without subsequent embrittlement concerns?

Representative Model of NuScale Power Reactor Vessel

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.



Photograph provided courtesy: NuScale Power

DOE Project: DE-NE0008629

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

Advanced Manufacturing -Objectives

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

200mm Electron Beam Weld

Electron Beam (EB) Welding

Why EBW?

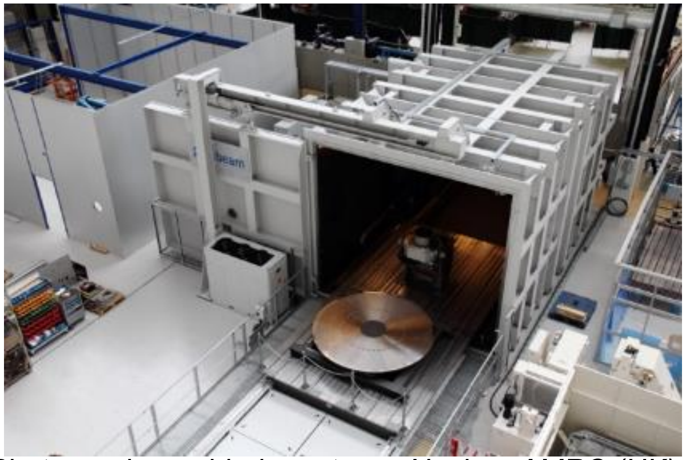
- One-pass welding!
- No filler metal required.
- EBW can produce welds w/ minimal HAZ
- Nuclear-AMRC, TWI, Rolls-Royce & EPRI have demonstrated in-chamber and/or local vacuum on thick section alloys
  - Enables field/shop welding!
- RPV girth welds (110mm thick) in <60 min

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

Steam Separator Inlet Swirler

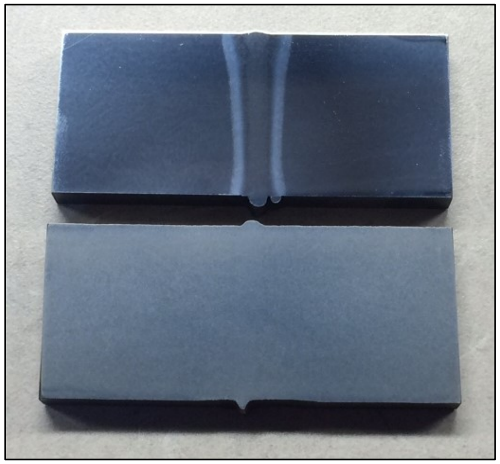
3700 lb BWR nozzle

Partial RPV Ring Section

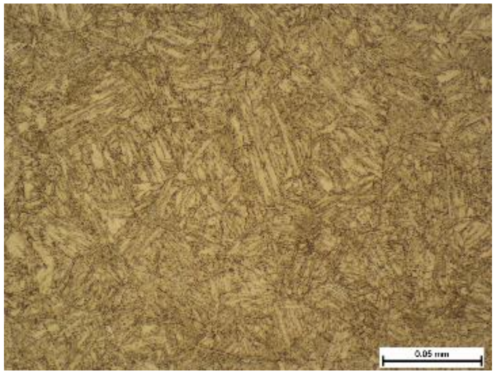
Elimination of Welds via Heat Treatment --Resetting the Clock

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



$\boxed{EBW + HT = 0\ Weld}$



EB Weld after Heat Treatment
WCL microstructure @ 500X

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

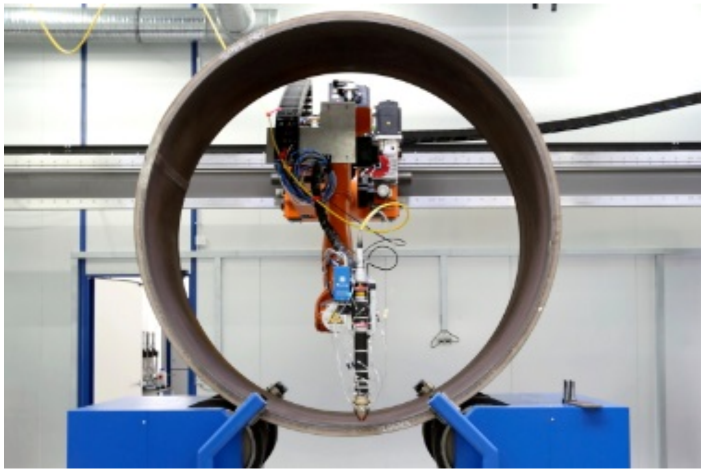
Diode Laser Cladding

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)

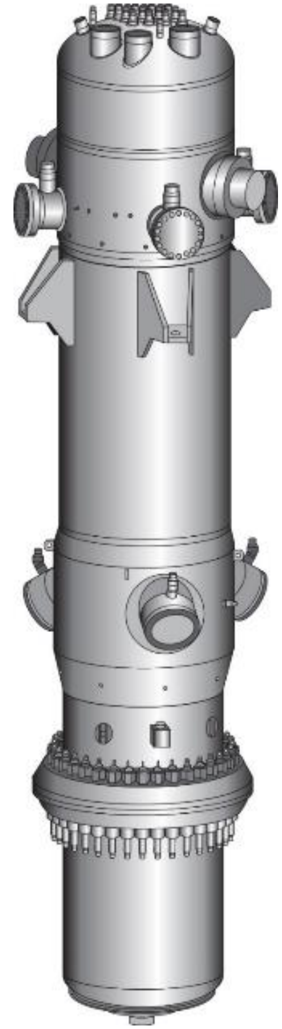
Project Tasks

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

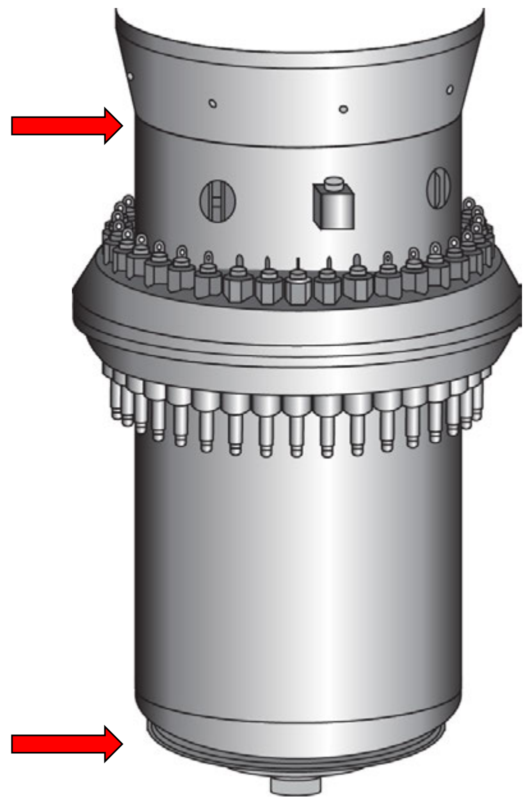


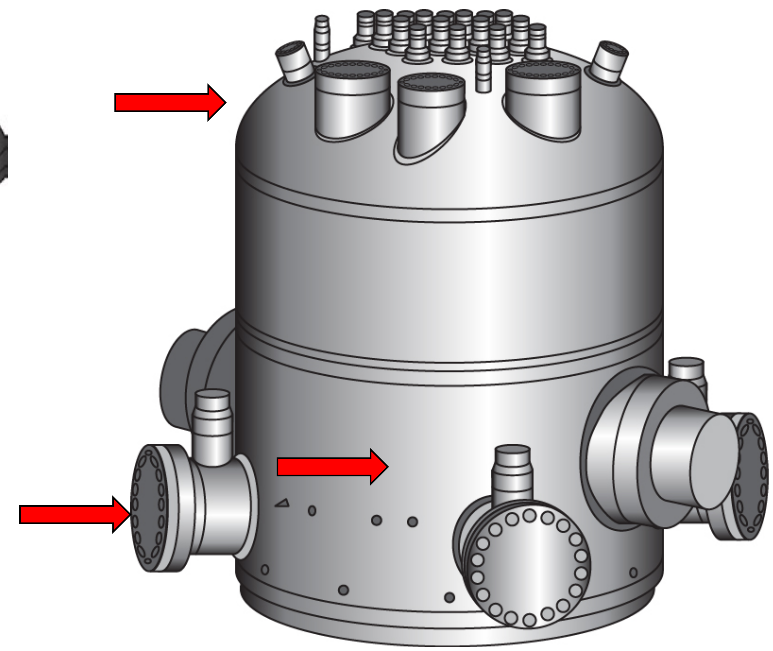
Representative Model of NuScale Power Reactor Vessel

2/3rds Scale Small Modular Reactor Manufacture/Fabrication

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

NuScale Nonproprietary





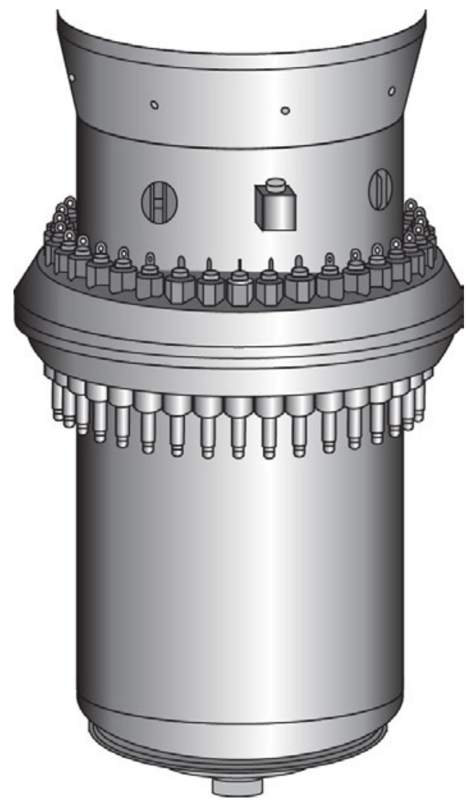
2017-18 Scope/Schedule

Fabrication

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

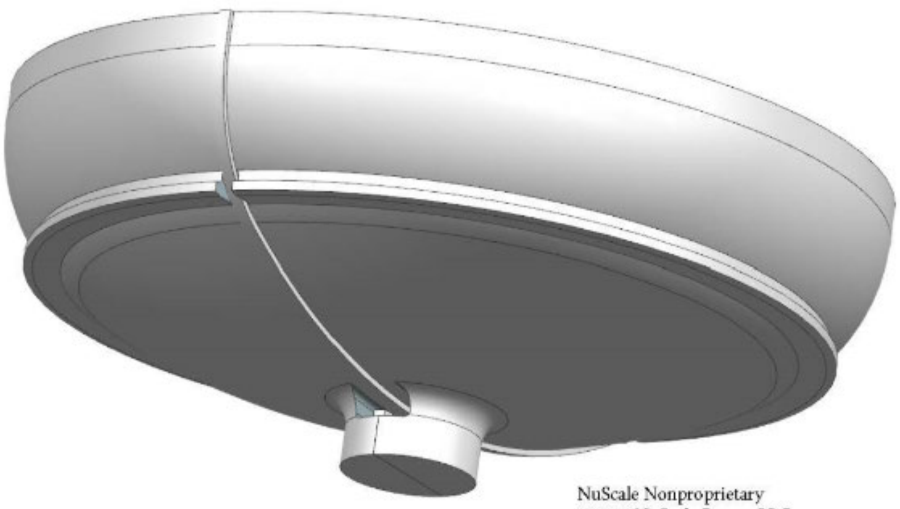
Manufacturing & Fabrication

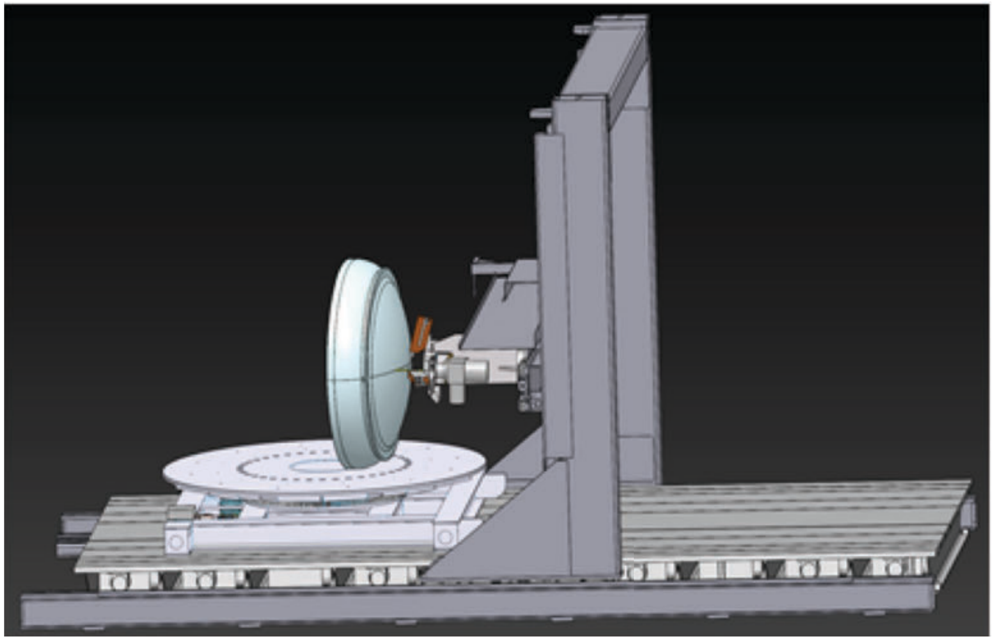
- Lower Head (Synertech PM-HIP)
- Lower RPV Flange Shell (SFEL forged)
- Two Flanges (SFEL forged)
- Upper Flange Shell (Synertech PM-HIP)



Lower RPV Assembly

Lower Head EB Welding

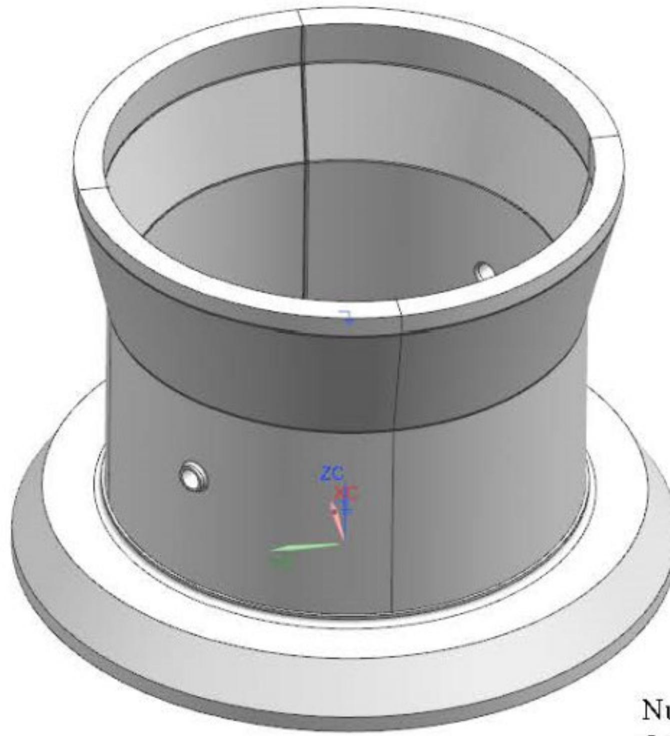




Nuclear AMRC (UK) – Responsible for All Component Assembly

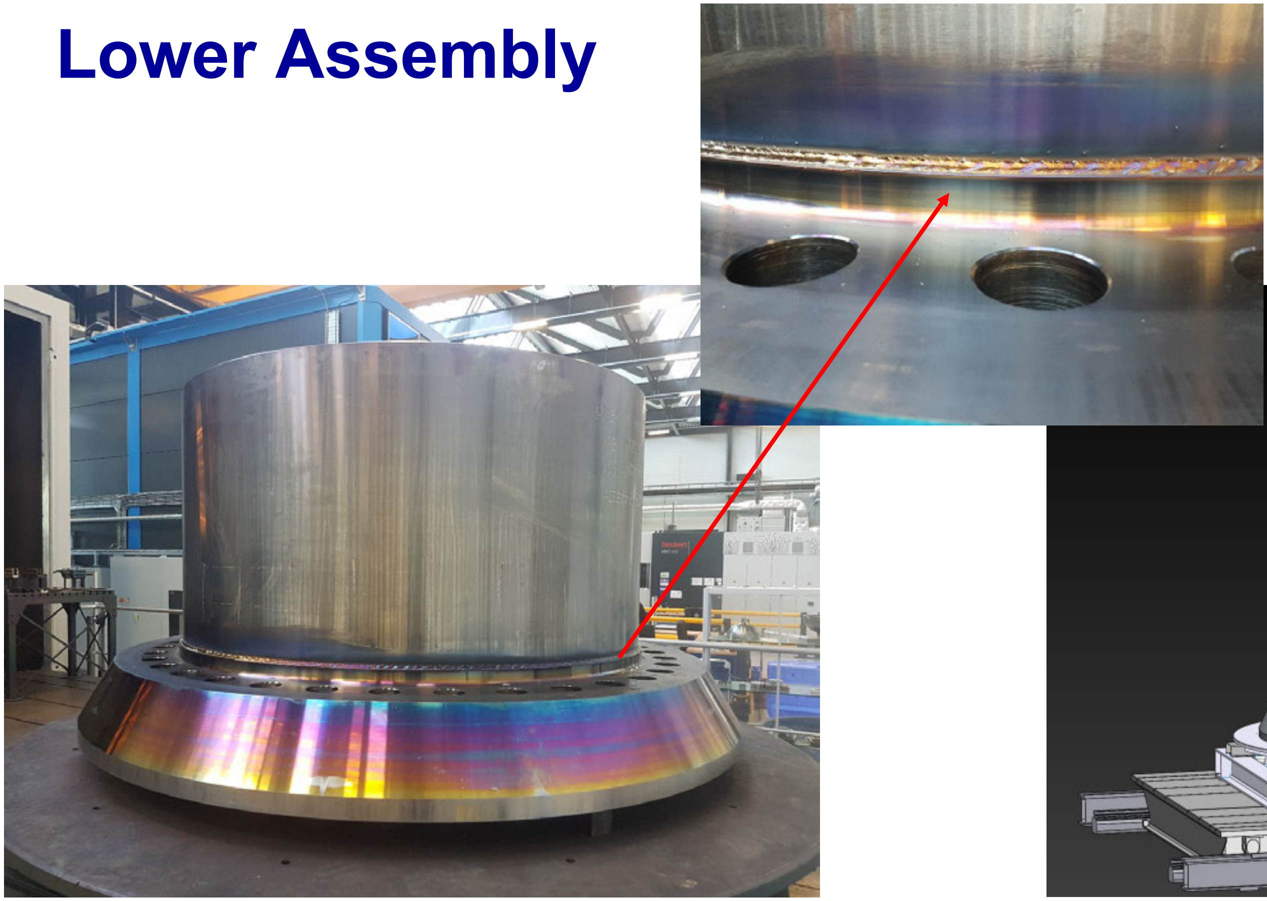
Lower and Upper Flange Shells

Thick flange to be welded to lower shell via EBW

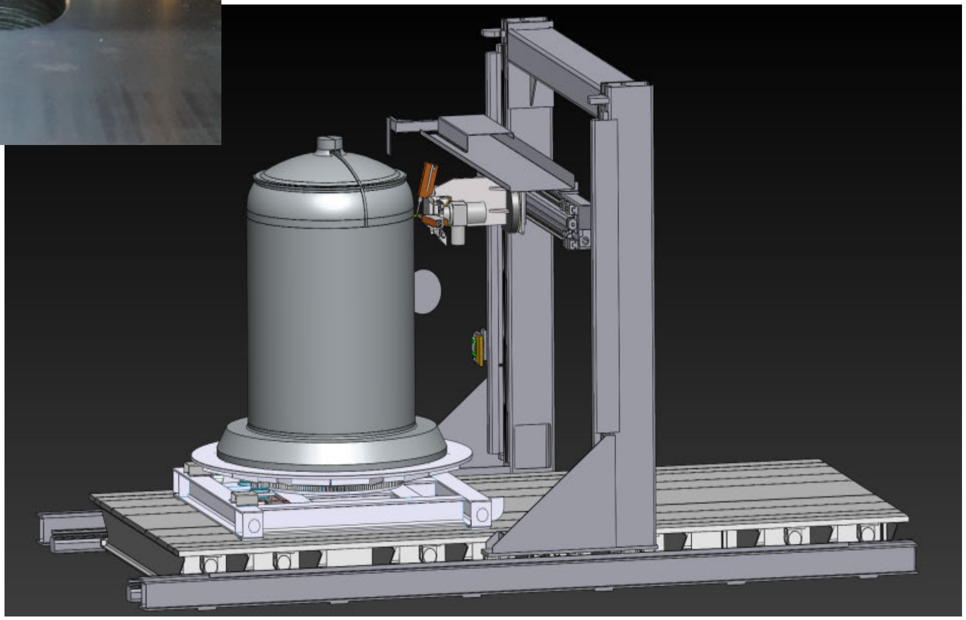


4 PM-HIP ring sections will be joined with EBW

Lower Assembly



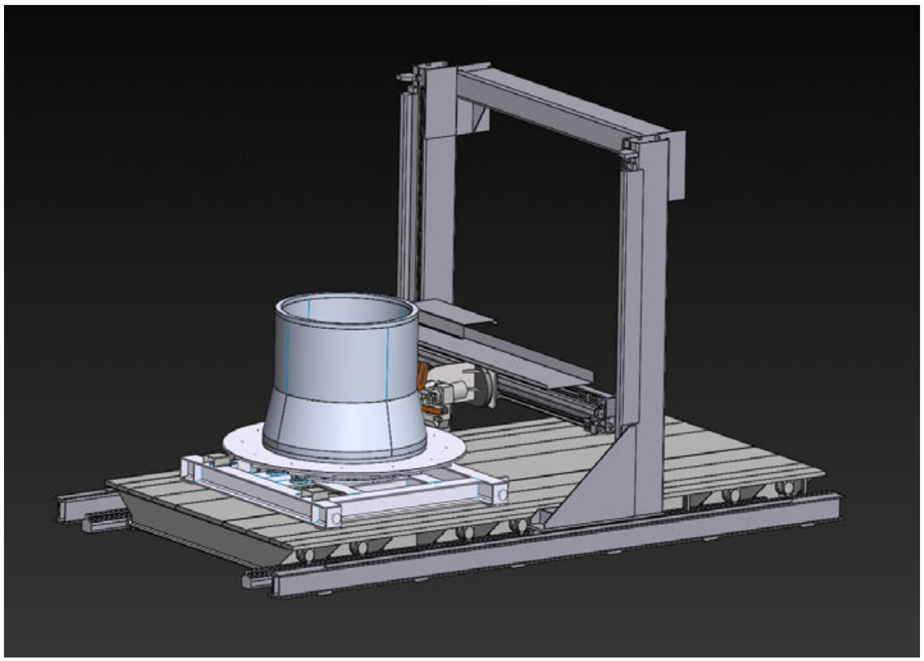
Lower Flange Shell Mockup EB Weld -- ~6 ft (1.82m) diameter (Note, mockup is upside down)



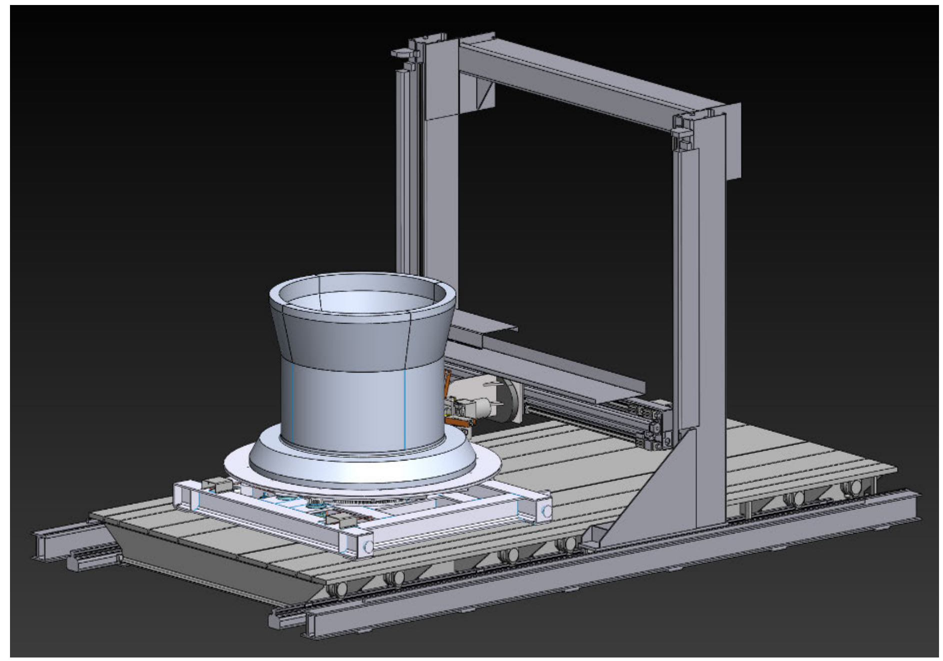
Lower head to Lower Flange Shell (again, upside down)

Completed in 47 minutes

Upper Flange Shell – Four sections and flange



Vertical Welding of Sections



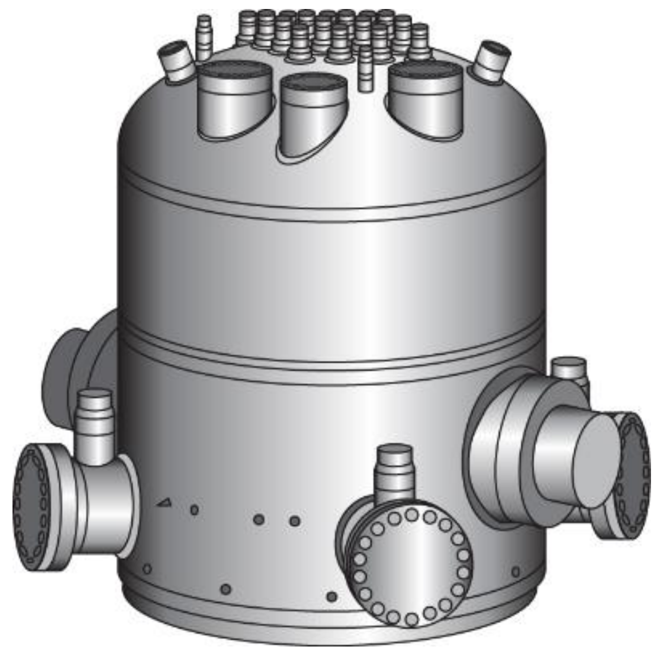
Circumferential Girth Weld to Attached Flange

Task 2—Upper Reactor Assembly
--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

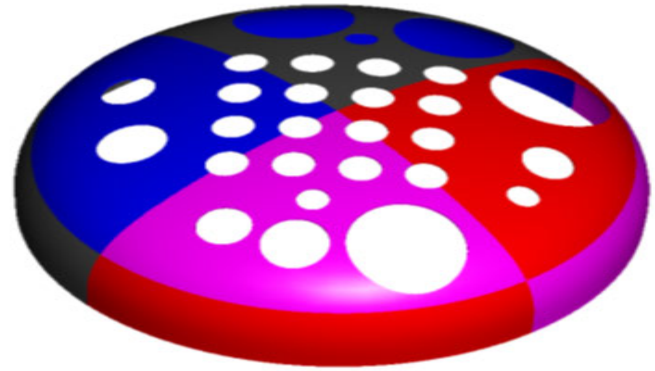


Representative Model of NuScale Power Reactor Vessel

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)



44% Upper Head Demonstration - Laser Machining

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 40% scale is ~2370 lbs

At full scale, ~ 21,000 lbs.

Capsules for Upper Head Completed and Ready for Powder Filling

Solid nozzles will be bored after HIP and heat treatment

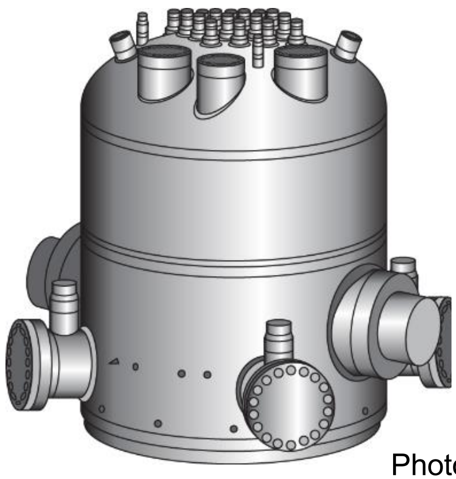
Note “fill stems” on top of upside down upper head capsule

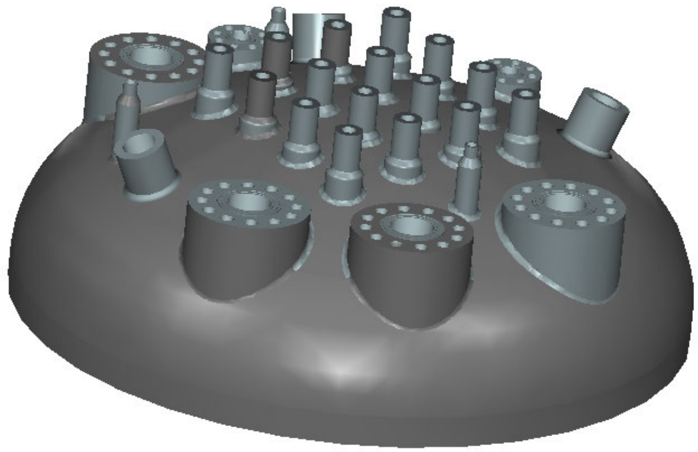
Upper Head– Hot Degassing & Crimping of Fill Stems

Hot Degassing of Powder Filled Upper Head

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

Small Modular Reactor Upper Head





Photographs courtesy of EPRI and NuScale Power

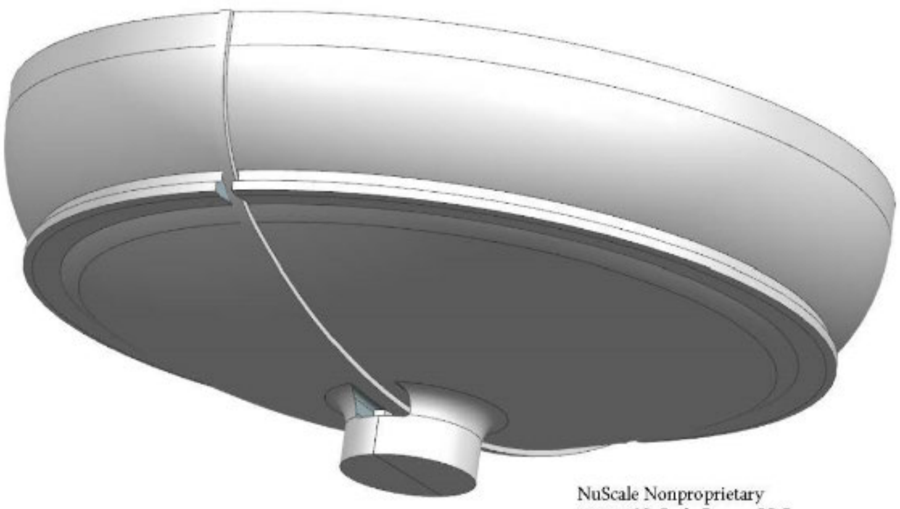
- ~44% scale
- A508 Class 1, Grade 3
- 27 penetrations
- 1650kg (3650lbs); 1270mm (50 inches) diameter
- Next, 2/3-scale head
- Need larger HIP Vessel -- ATLAS

DOE Project: DE-NE0008629

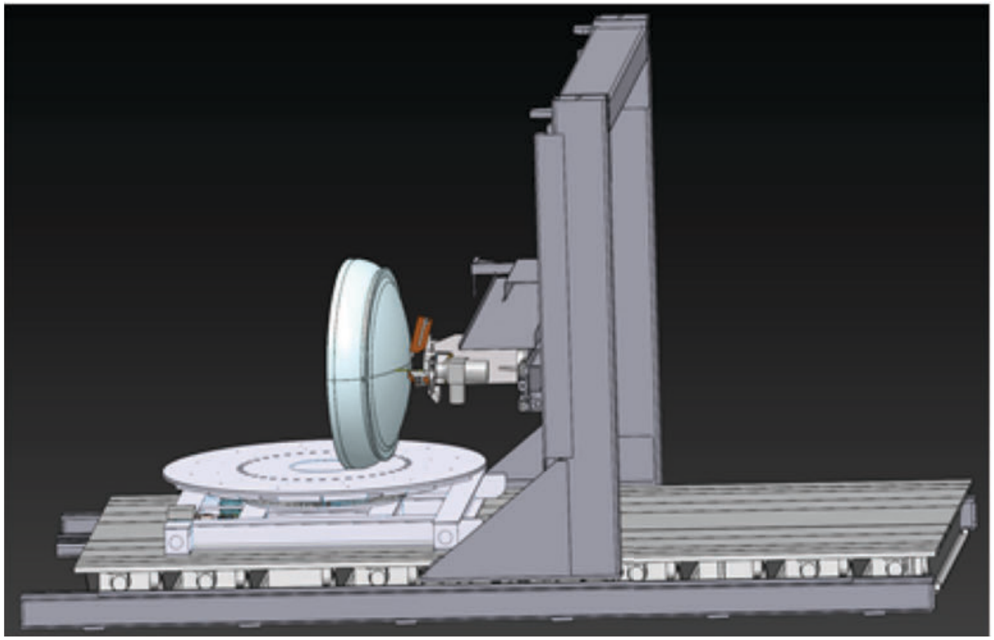
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Lower Head – One-Half Section

Lower Head EB Welding

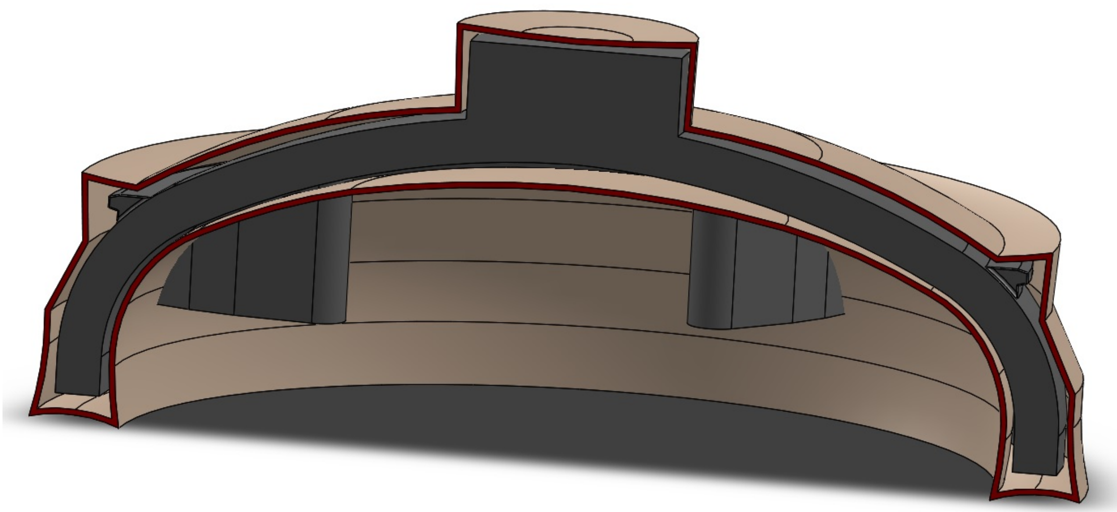


NuScale Nonproprietary
© 2017 NuScale Power, LLC



Nuclear AMRC (UK) –
Responsible for All
Component Assembly

Lower Head—Stamped Capsule Sections



HIP Modeling—Shows Lower Head inside of the Finished Capsule

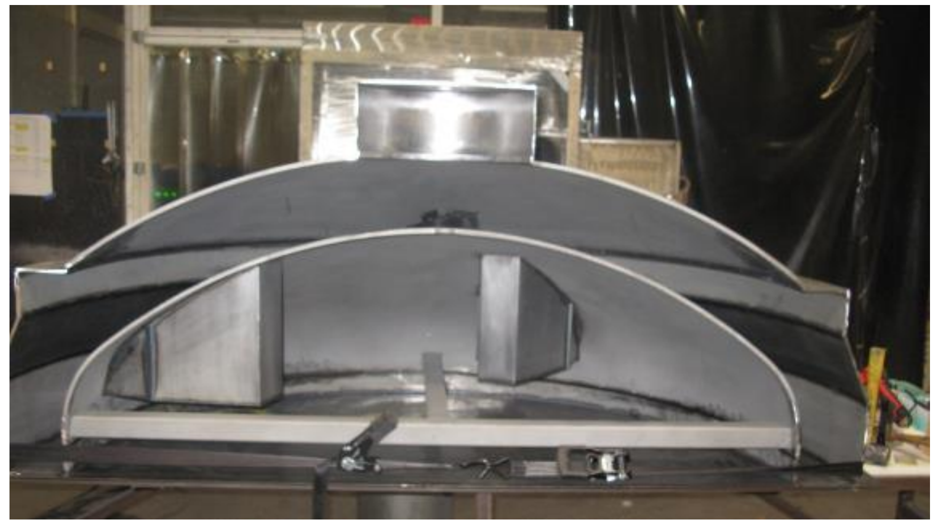
Final part: ~4300 lbs (1950 kg) @ 2/3rds scale; Full Scale is ~11,000lbs (1/2 section) (4990kg)

Inner Capsule Shell

Outer Top Capsule Shell

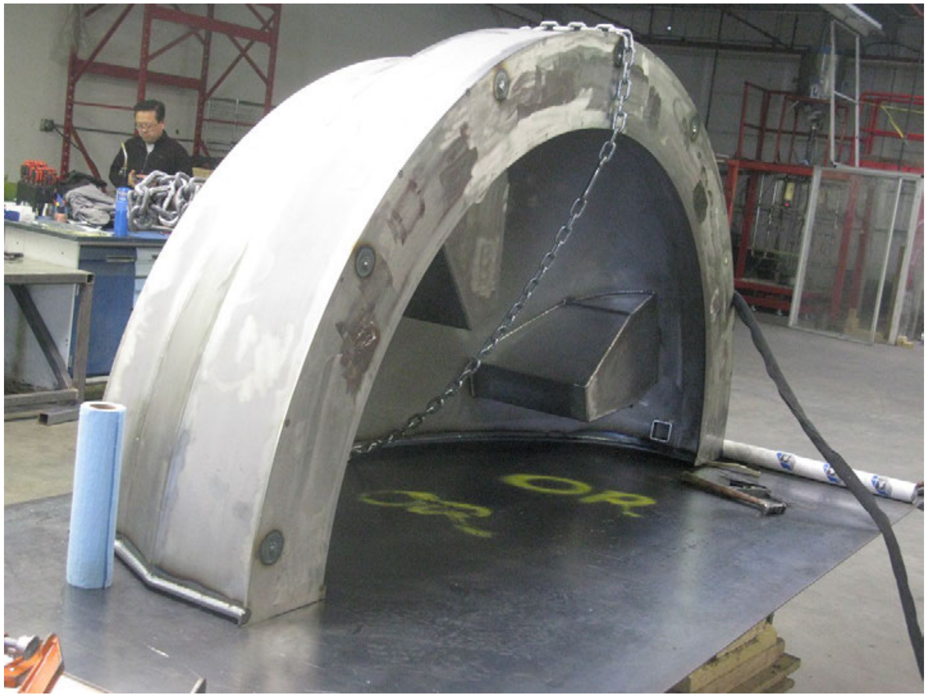
One half lower head under construction

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.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Custom Rack Build for the One-Half Lower Head Section

Lower Head Inserted Into HIP Vessel and Final Component

One-Half Lower Head HIP'ed & Dimensioned

Project Status (August 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, completed
- EBW & DLC development underway @ Nuclear AMRC
- Heat treatment development underway soon.

Applicability to Advanced Reactors -- Summary

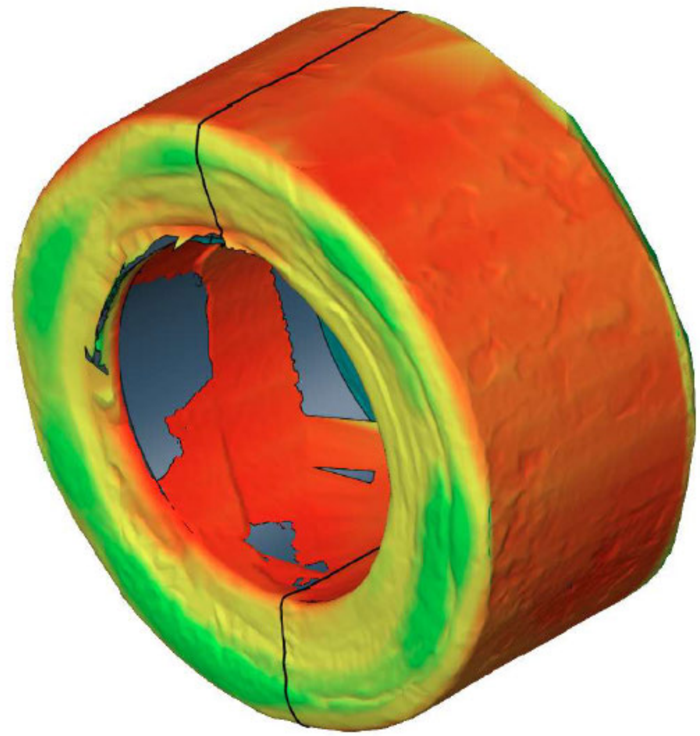
- Must change the way we manufacture RPVs to be cost competitive!!!
- Four technologies will have direct applicability:
  - **PM-HIP** -- for higher alloyed components; eliminate long lead-time forgings; improve inspectibility
  - **EB Welding** – significantly reduced welding time; for difficult to join components
  - **Diode Laser Cladding** – robotic cladding of vessels; difficult materials
  - **Re-setting the Clock** – elimination of welds via heat treatment; eliminates in-service inspection

Together…Shaping the Future of Electricity

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