Advanced Manufacturing to Enable the Next Generation of Nuclear Plants

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Advanced Manufacturing for Nuclear: Applications, Techniques, Needs, and Challenges and AMM Annual Program Review
December 4-6, 2018

DOE Project: DE-NE0008629

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

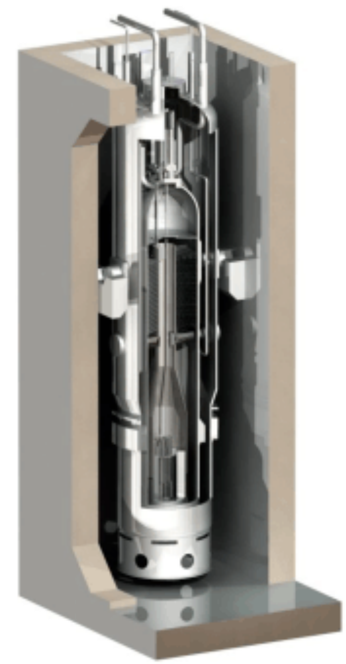
Vessel Manufacture and Fabrication

- 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 <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>** (
- **Eliminate 40%** from the cost of an SMR # RPV, while **reducing** the Schedule by # **18 Months** (

200mm Electron Beam Weld

Electron Beam (EB) Welding

Why EBW?

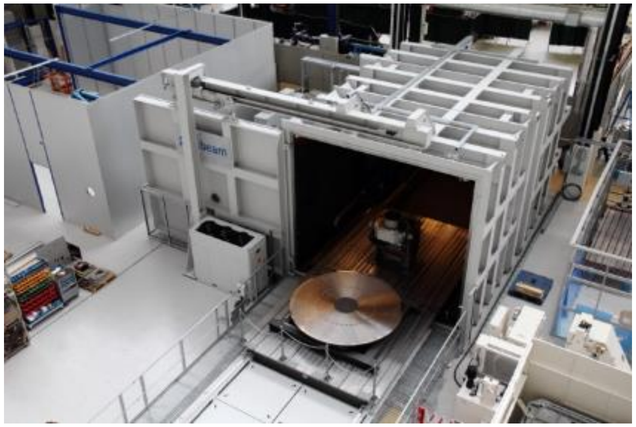
- One-pass welding!
- No filler metal required.
- EBW can produce welds w/ minimal HAZ
- Nuclear-AMRC, TWI, Rolls-Royce & EPRI # have demonstrated in-chamber and/or local # vacuum on thick section alloys
  - Enables field/shop welding!
- RPV girth welds (110mm thick) in <60 min

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

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Elimination of Welds via Heat Treatment --Resetting the Clock

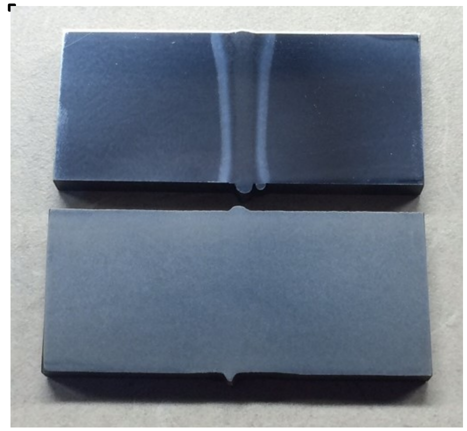
Eliminate the Weld through re-austenitzation at high temperature

How?

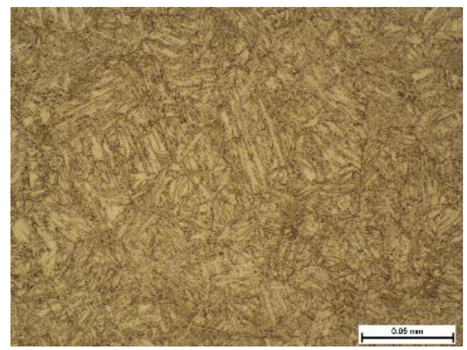
- Perform chamber EB weld of sub-assemblies
- Localized Solution HT, quench; normalize; temper
- Resulting microstructure is same as base metal
- Fracture toughness comparable to base material

Inspection, Costs?

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



$EBW + HT = 0\ Weld$



EB Weld after Heat Treatment
WCL microstructure @ 500X

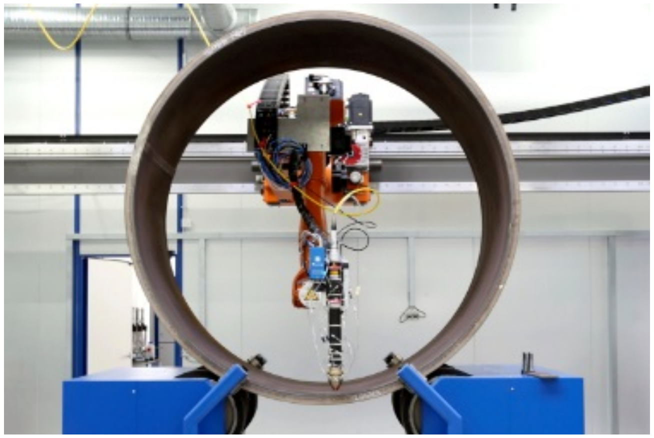
Diode Laser Cladding

Why DLC?

- Robotic machine welding
- High deposition rates
- Significantly reduces cladding thickness required (~3mm) #

Inspection, Costs?

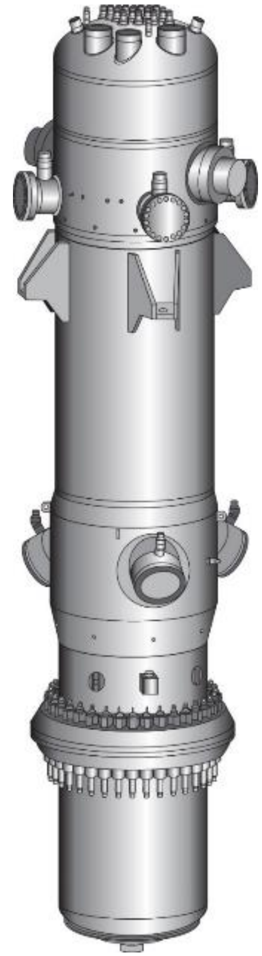
- Lbs. (or kg) of material required is significantly reduced since thinner layers can be applied.
- No machining after cladding required



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

Project Tasks

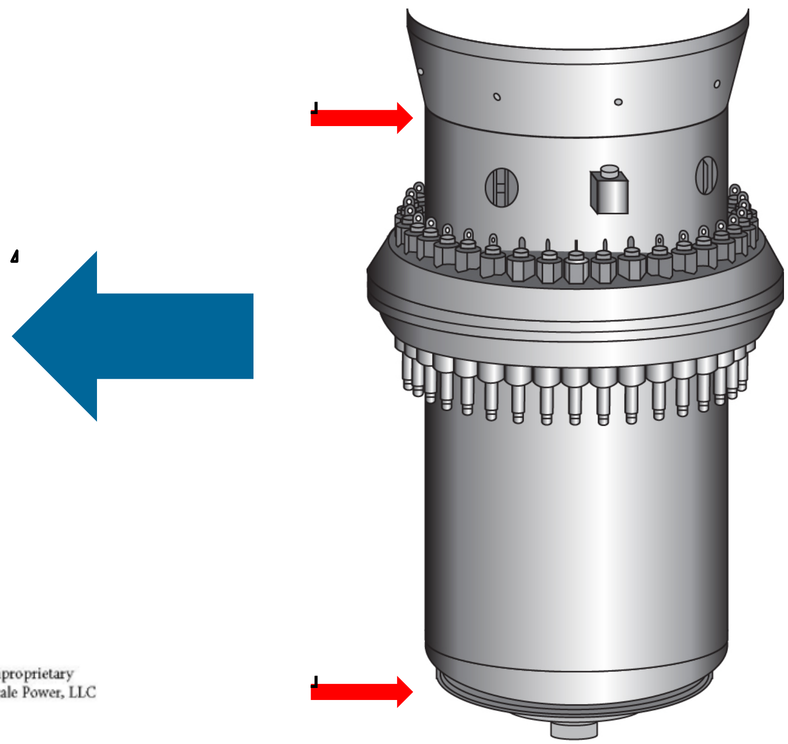
1. Lower Reactor Assembly
2. Upper Reactor Assembly
3A. Thick Section EBW Development
3B. Local Vacuum EBW Development
4. Diode Laser Cladding Development
5. $ Elimination of DMWs—for Nozzle Applications
6. $ Elimination of In-Service Inspection via Solution Heat Treatment
7. ASME BPVC Code Development
8. ORNL Mechanical and Metallurgical Testing

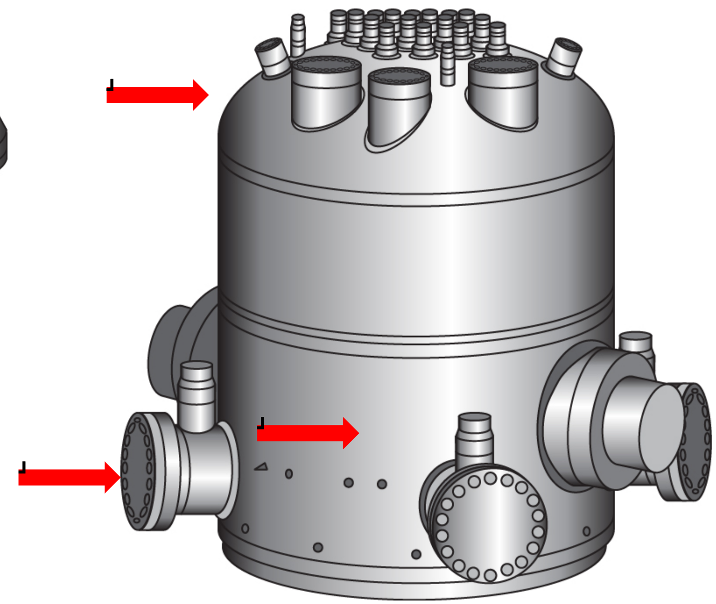


Representative Model of NuScale Power Reactor Vessel

2/3rds Scale Small Modular Reactor Manufacture/Fabrication

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





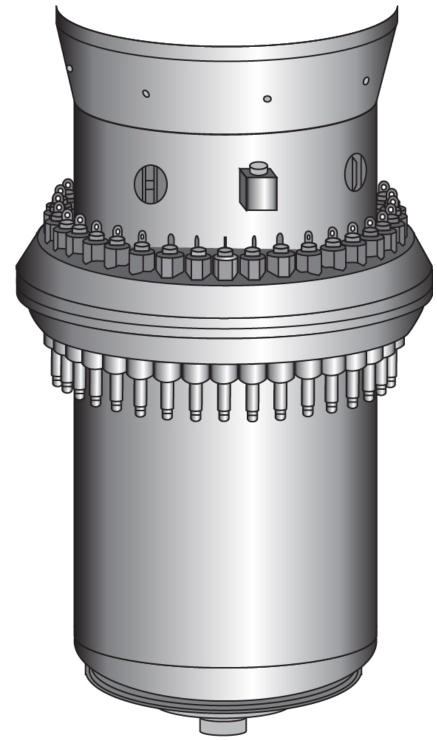
2017-19 Scope/Schedule

Fabrication

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

Manufacturing & Fabrication

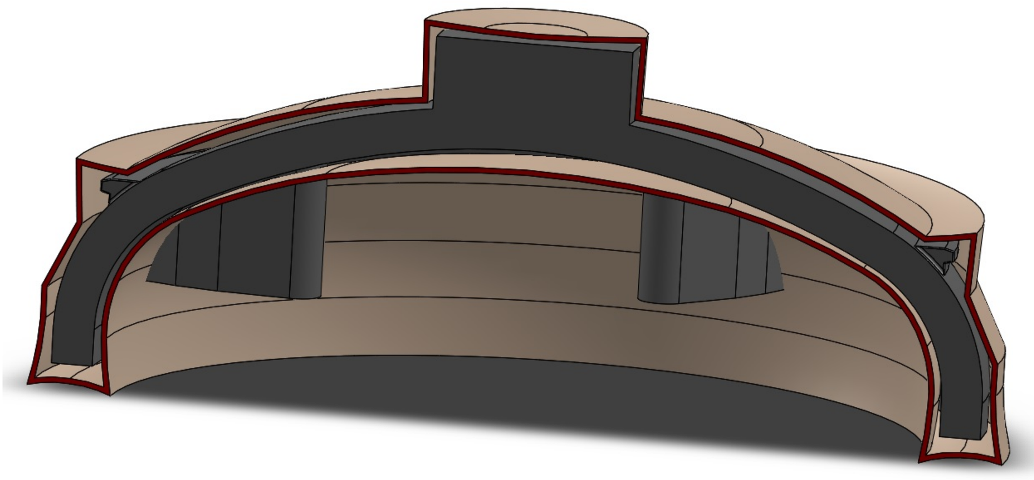
- Lower Head (Synertech PM-HIP)
- Lower RPV Flange Shell (SFEL forged)
- Two Flanges (SFEL forged)
- Upper Flange Shell (Synertech PM-HIP)



Lower RPV Assembly

Lower Head – One-Half Section

Lower Head—Stamped Capsule Sections &



HIP Modeling—Shows Lower Head inside of the Finished Capsule

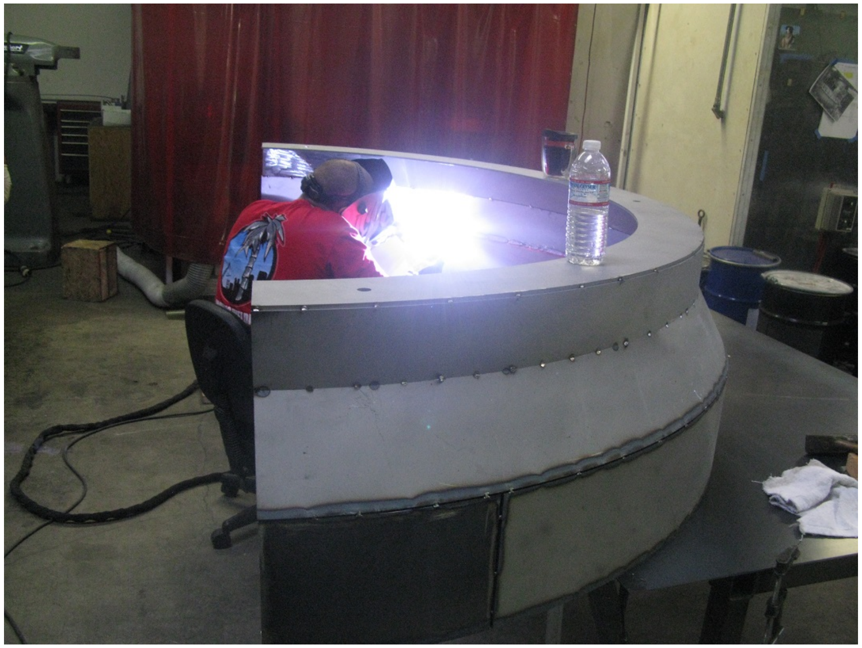
Final part: ~6500lbs (2950 kg) @ 2/3rds scale;
Full Scale is ~11,000lbs (1/2 section) (4990kg)

Inner Capsule Shell $

Outer Top Capsule Shell $

Two Lower Halves– Outer Capsule Assembly $

Two Lower Halves– Outer Capsule Assembly $



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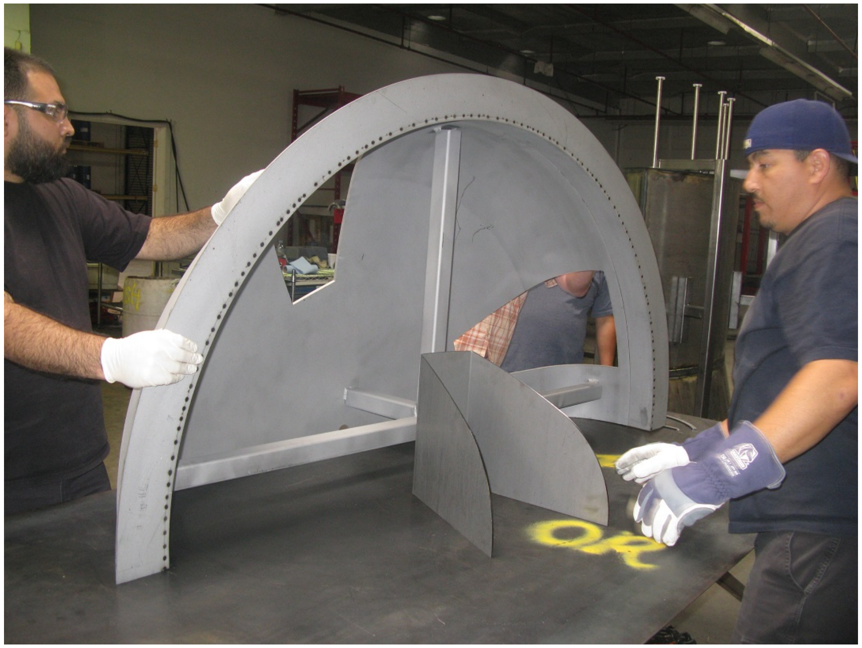
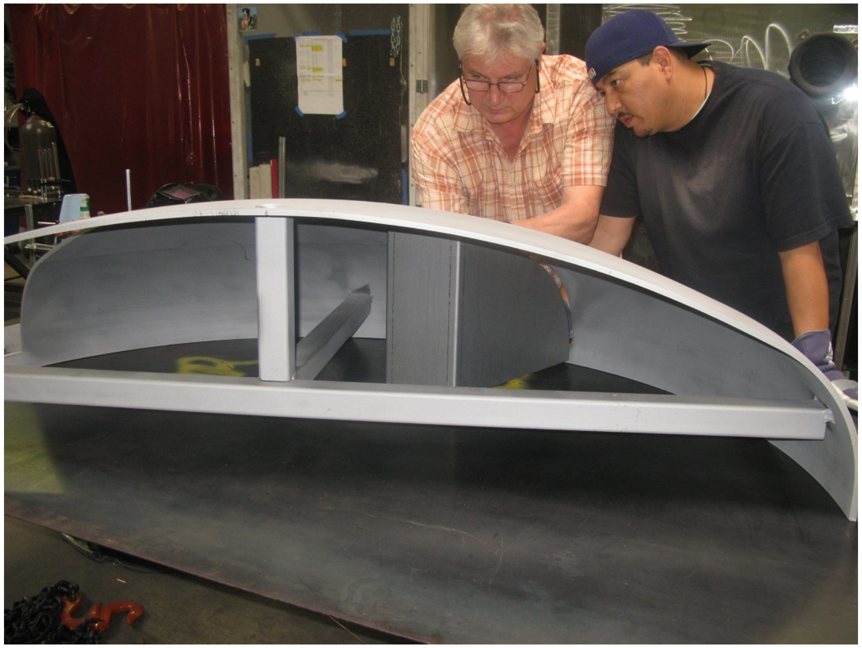
One half lower head under construction $

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

Lower Halves– Inner Capsule Assembly &





Lower Halves– Capsule Assembly & Measurement &

Lower Halves– Capsule Completed &

Custom Frame Built for the One-Half Lower Head Section '

- **Non-symmetrical component** in one-half 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 frame

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Lower Head Inserted Into HIP Vessel and Final Component &

One-Half Lower Head HIP'ed & Dimensioned)

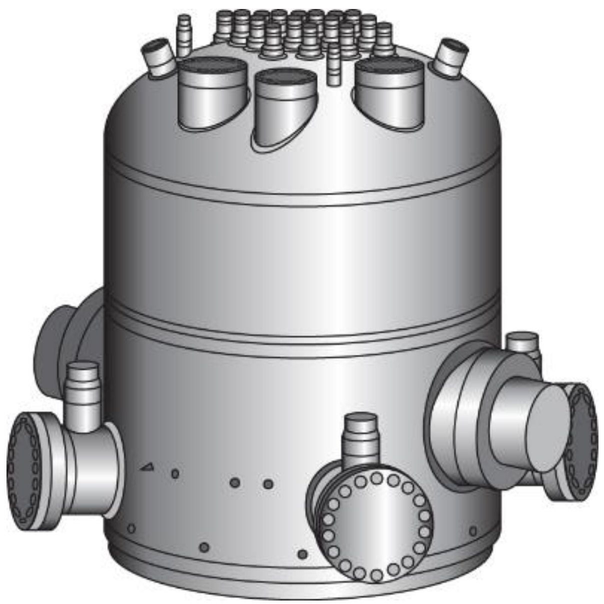
6910 lbs (3134kgs)

Task 2—Upper Reactor Assembly --2019-2021

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

RPV PZR Shell
- Forged Section

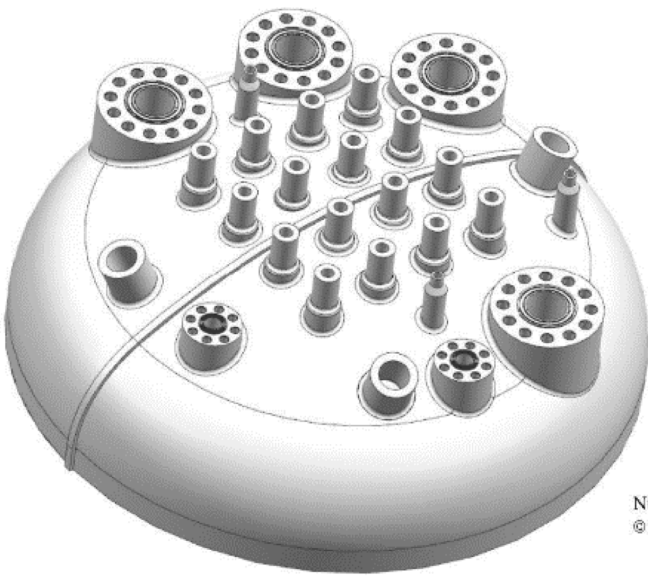
Steam Plenum
- PM-HIP & EBW together



Representative Model of NuScale Power Reactor Vessel

Upper Head– 44% Scale

Upper Head—27 Penetrations.



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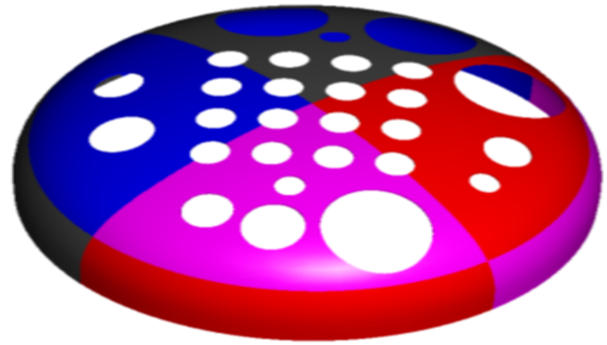
- Two half "head sections" will be produced via PM-HIP
- A508, Grade 3 Low Alloy Steel
- Penetrations will be solid and then bored/machined out
- Welded together with EBW
- At full scale, ~ 21,000 lbs (9525 kg)

Upper Head (Stamped Inner & Outer Capsule Shells) %



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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 ~3600 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

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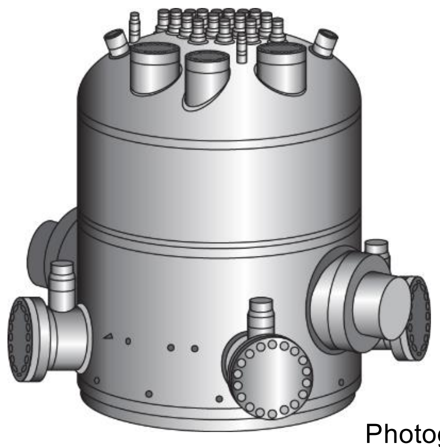
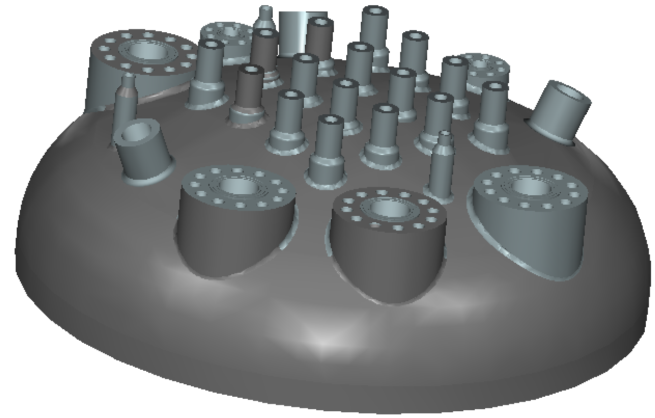
Small Modular Reactor Upper Head %





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

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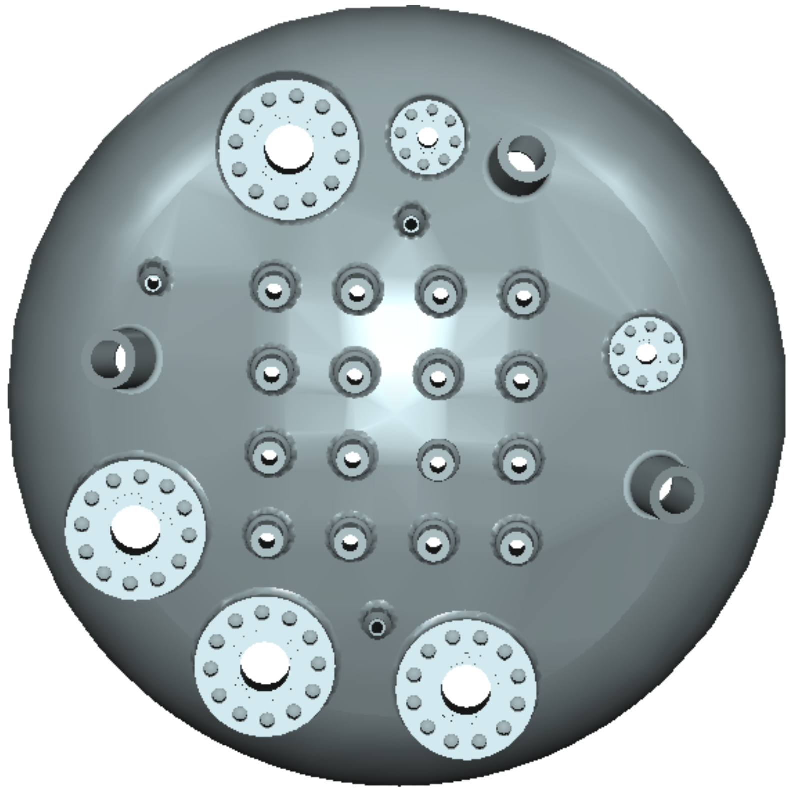
Tomorrow's PM-HIP



3.55m (140in) Diameter x 2m (79in) (T) HIP Vessel

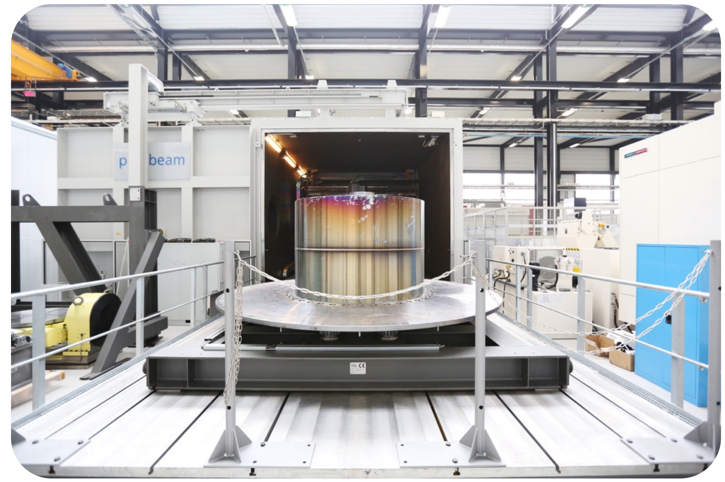
ATLAS

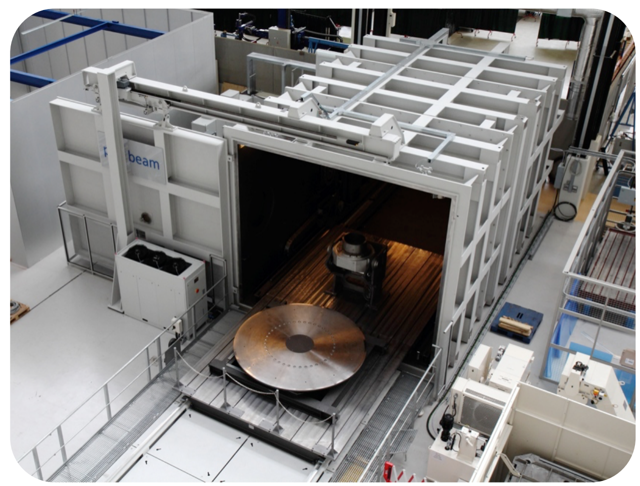
Load capacity = 250,000 lbs (113,000kgs)

EB Welding Development

Nuclear AMRC capabilities
Pro-beam K2000

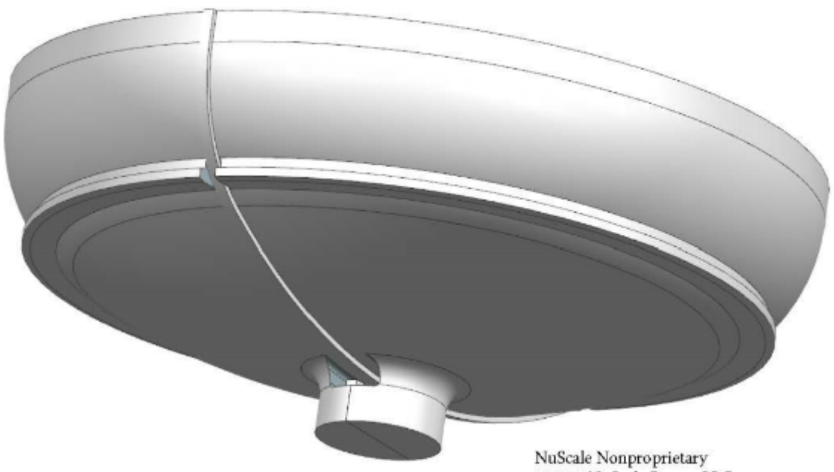
	Pro-beam K2000
Chamber size	8.7 x 5.2 x 4.6 m³
Chamber volume	208 m³
Max Work piece size	6.4 x 4.0 x 3.2 m³ at 100 tonne
Acceleration voltage	60 or 80 kV
Max beam power	30 or 40 kW
Wire feeder	2 off
Pump down time	45 min





pro beam

Lower Head EB Welding



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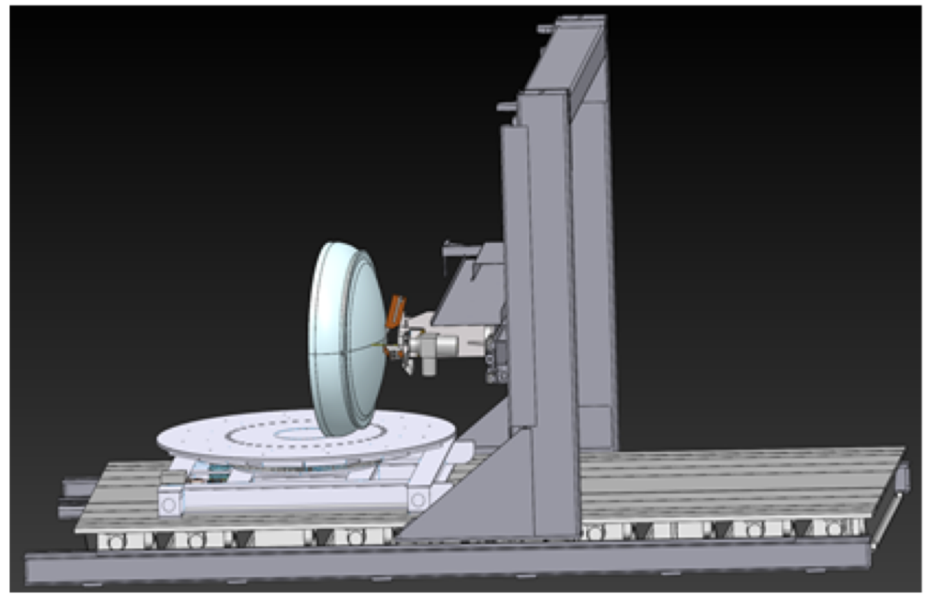

Nuclear AMRC (UK) – $
Responsible for All $
Component Assembly $

Lower and Upper Flange Shells &

Thick flange to be welded to lower shell via EBW

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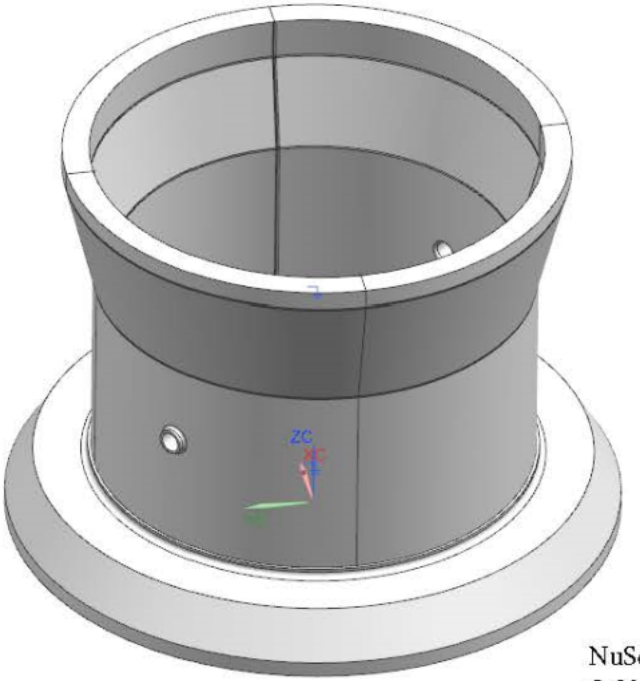

4 PM-HIP ring sections will be joined with EBW

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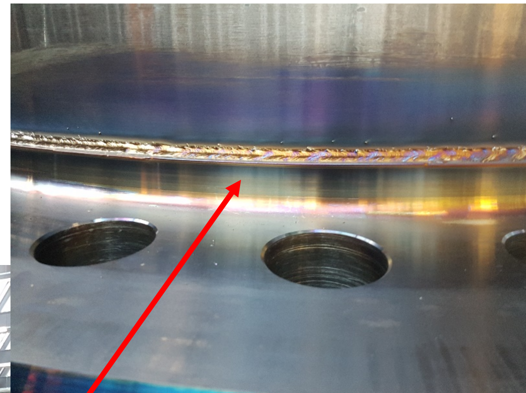
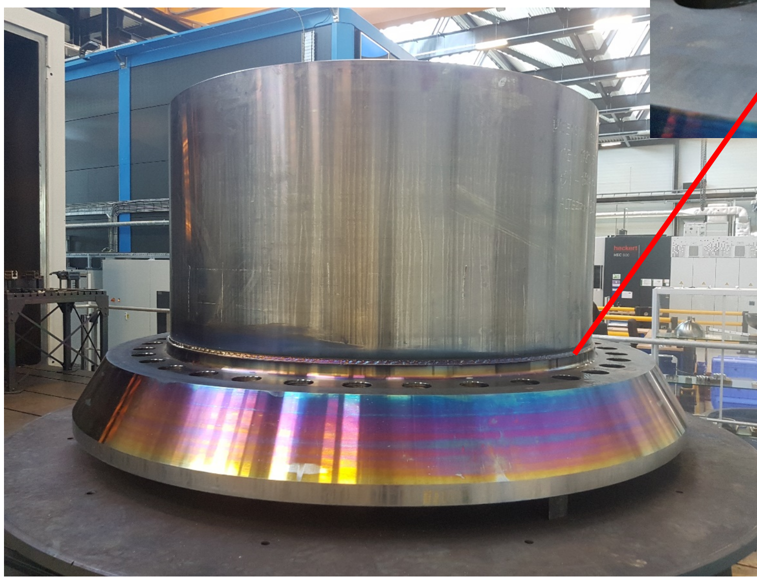
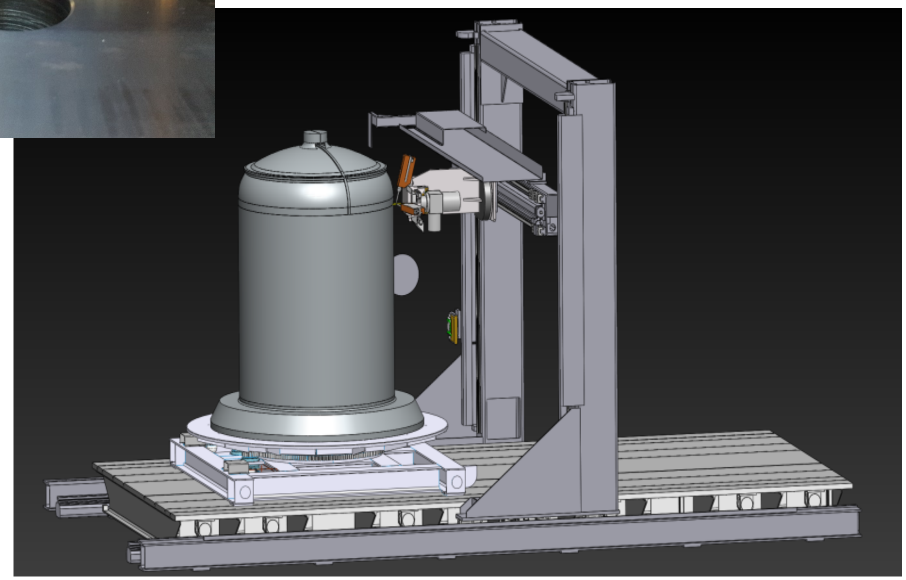
Lower Assembly





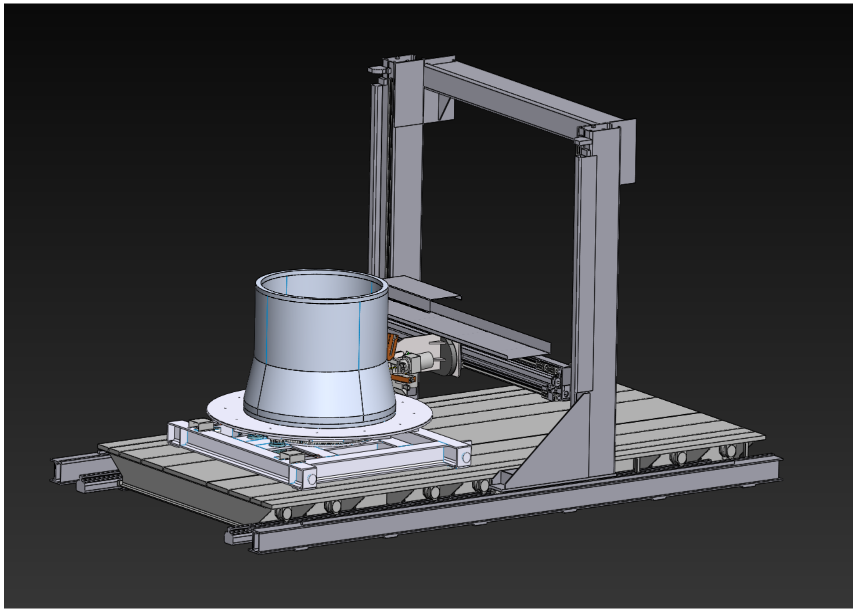
Lower Flange Shell Mockup EB Weld -- ~6 ft (1.82m) diameter (Note, mockup is upside down)



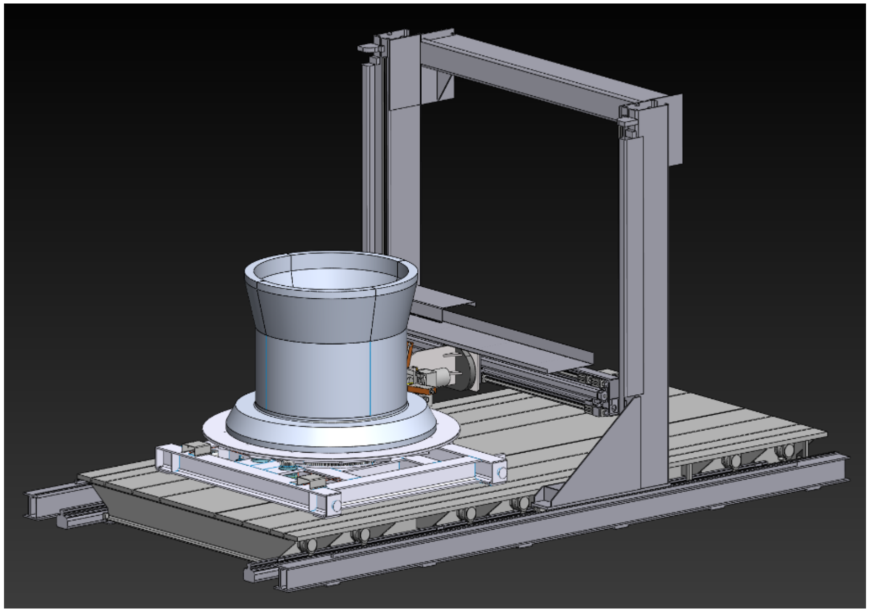
Lower head to Lower Flange Shell (again, upside down)

Completed in 47 minutes

Upper Flange Shell – Four sections and flange %



Vertical Welding of Sections



Circumferential Girth Weld to Attached Flange $

Project Status (thru November 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 program)
- 44% diameter (50-inch) A508 top head completed (EPRI ANT program)
- Forgings for flanges, PZR shell, lower RPV section, and HT completed
- One-half section A508 lower head, completed; two additional halves by end of year.
- EBW & DLC development underway @ Nuclear AMRC
- Heat treatment development underway
- Assembly to begin in Q1-2019

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

Acknowledgements

US Department of Energy

- Tom Miller, Tansel Selekler, Bruce Landrey, Alison Hahn $

Nuclear AMRC

- Matt Cusworth, Will Kyffin, Thomas Dutilleul

Bridger Welding Engineering

- Keith Bridger

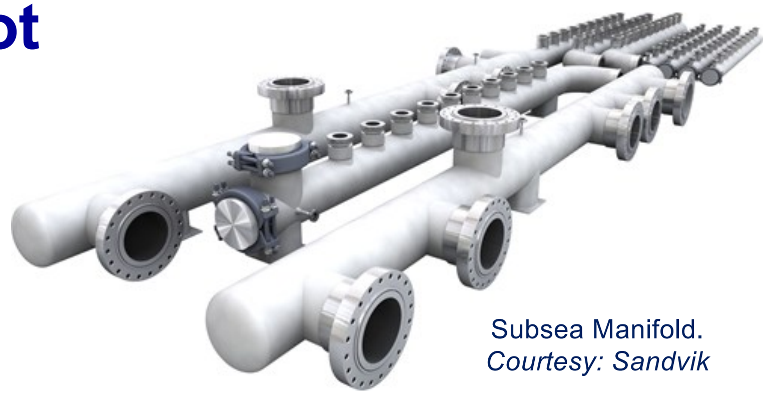
Synertech-PM

- Victor Samarov, Charlie Barre, Alex Bissikalov

Together…Shaping the Future of Electricity

Powder Metallurgy-Hot Isostatic Pressing

- Near-net shaped components
- Homogenous microstructure
  - Ease of inspection!
- Elimination of welds
- 4-6 months lead times typical

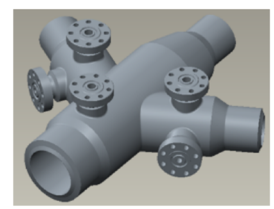


Subsea Manifold.
Courtesy: Sandvik

40” diameter HIP Vessel
*Courtesy: Isostatic Forge * International **

Large Bore Valve
(courtesy Roll-Royce) #

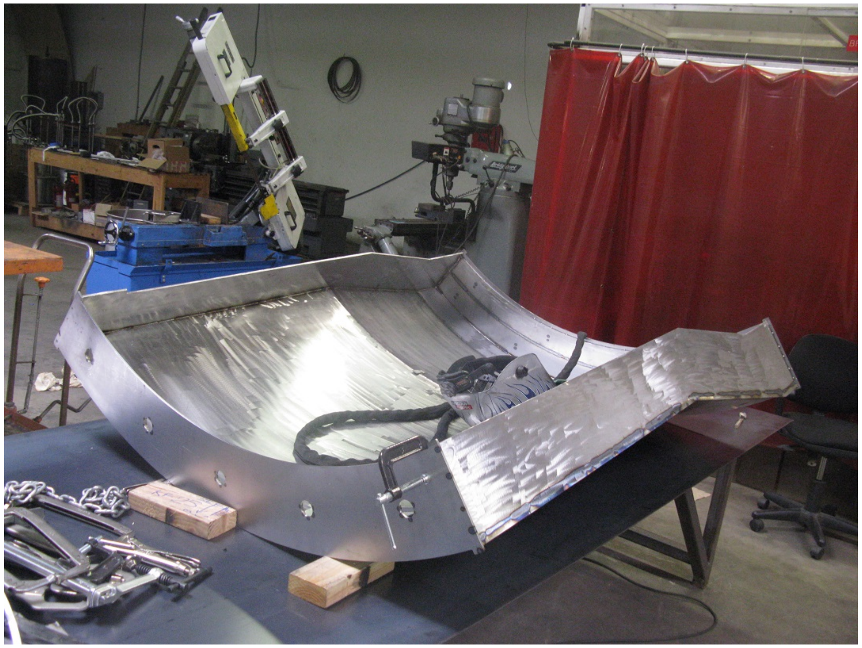
NNS Reactor Coolant Pump # Impeller (courtesy Framatome # and Albert & Duval) #



Subsea Manifold.
Courtesy: BP

Transition Shell – Capsule Assembly Underway)

Transition Shell – Capsule Assembly Tacked Together)



Transition Shell – Capsule Assembly)

Transition Shell – Capsule Assembly)

Transition Shell – Capsule Assembly)

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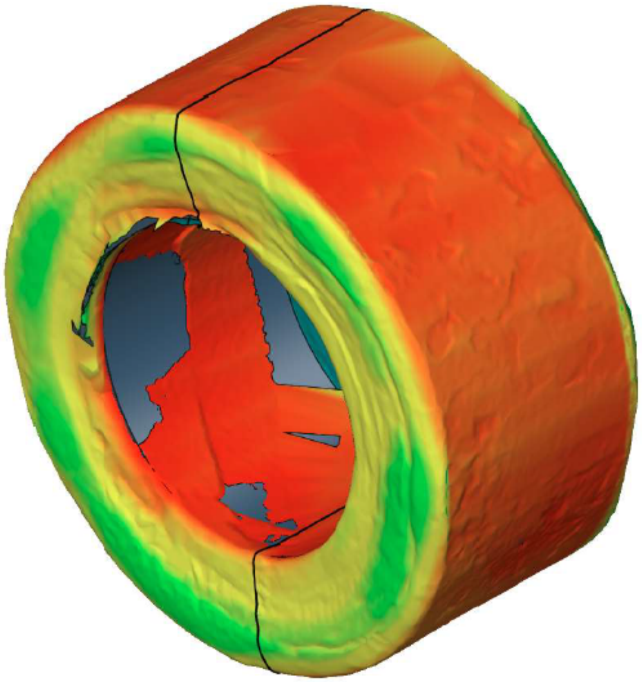
Four SA508, Grade 3 Class 2 Forgings Produced

- PZR Shell
- Lower RPV "Flange"
- Lower RPV Shell
- Upper RPV Transition Shell "Flange"

- Primary HT performed.



Forging for Two Flanges

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Flange and Shell Forgings '

Flange and Shell Forgings '