Advanced Manufacturing to Enable the Next Generation of Nuclear Plants

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Imagine if You Could Produce a Reactor Pressure Vessel in Under 12 Months!
Advanced Manufacturing
-Objectives

- 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**
- Rapidly Accelerate the Deployment of SMRs
Background

- EPRI, DOE, and various vendors have been working on a number of advanced manufacturing technologies over the past 5 years:
  - EB and RPEB 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
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
  - Carpenter, Synertech-PM, TWI, Sheffield Forgemasters, Sperko Engineering, etc.

- Advanced Processes Employed:
  - PM/HIP, Electron Beam Welding, Diode Laser Cladding, Cryogenic Machining, and Elimination of DMWs

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
- TWI, Rolls-Royce, Nuclear-AMRC & EPRI have demonstrated low volume or reduced pressure EBW on thick section alloys
  - Enables field/shop welding!

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

Electron Beam Weld
1) as-received and
2) solution annealed and Q&T conditions
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 times
- Considerable EPRI/Industry development over last 5 years.
- Ideal for multiple penetration applications (RPV or CNV head) vs expensive forgings

Inspection, Costs?
- Homogeneous--Excellent inspection characteristics
- Costs roughly equivalent to forging
Diode Laser Cladding (DLC)

Why DLC?
- Robotic machine welding
- High deposition rates
- Significantly reduces cladding thickness required to 1mm thick
- Up to 45mm width

Inspection, Costs?
- lbs. (or kgs.) of material required is significantly reduced since thinner layers can be applied.
- No machining after cladding required
Elimination of Dissimilar Metal Welds

How Do We Eliminate DMWs?

- PM-HIP has been used to bond dissimilar metals with nickel-based powder in between.
- Successfully demonstrated A508-to-347SS and A508-to-316LSS

Inspection, Costs?

- Eliminates need for difficult to inspect weld(s)
- Metallurgical bond lines are perpendicular to surface for significantly improved inspection
- Cost is ~60% of welded costs
Advanced Machining

Advancements
- Machine Prep RPV ring sections and heads for EBW joining
- Machine Prep Horizontal and Vertical Weld Joints
- Boring of steam plenum and CRD penetrations

Costs?
- Technologies developed by N-ARMC seek 4X reduction in machining time
Where Do the Cost & Schedule Savings Come From?

- Eliminates need to procure forgings well ahead of construction
  - Often 2-5 years lead-time for forgings; Major components—produced by PM-HIP in 6-12 months
  - Reactor heads savings anticipated: >$2-3M each
  - Lengthens decision making window

- Electron Beam Welding can reduce welding time significantly:
  - For 100mm RPV shell, a reduction from 120 welding/PWHT days to 12-15 welding/PWHT days

- Diode Laser Cladding can reduce the welding material costs required by >50%

- PM-HIP provides near-net shaped components and can eliminate 1000s of hours of machining.

- Cryogenic Machining can reduce 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
   Middle Reactor Assembly (not included)
3A. Thick Section EBW Development
3B. Reduce Pressure 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
Task 1—Lower Reactor Assembly  
(508 materials)

1. **RPV Lower Head**  
   – Manufacture via PM-HIP in two halves  
   – EBW halves together, solution annealed, Q&T  
   – LDC completed lower head  
   – BAM center boss and core supports

2. **RPV Flange Shell**  
   – Manufacture shell and flange via forging  
   – EBW sections together, solution annealed, Q&T  
   – LDC completed flange shell

3. **Upper RPV Flanged Transition Shell**  
   – Manufacture 4 ring sections via PM-HIP and flange via forging  
   – EBW sections together, solution annealed, Q&T  
   – LDC completed flange shell
Task 2—Upper Reactor Assembly (1) (508 materials)

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

5. **RPV PZR Shell**  
   - Same as Item 2 above

Cont’d on next slide
Task 2—Upper Reactor Assembly (2) (508 materials)

6. **Integral Steam Plenum**
   - Manufacture via PM-HIP in two sections
   - EBW together, annealed, Q&T
   - LDC completed plenum

7. **Steam Plenum Access Port Assembly**
   - Manufacture via PM-HIP in two sections
   - Machine prep
   - EBW access port assemblies into integral steam plenum
Middle Reactor Assembly
--Not Manufactured/Fabricated In Project

- Upper RPV SG Shell
- Lower RPV SG Shell
- Technologies addressed elsewhere in project (under Tasks 1 & 2)

Carbon steel pipe welded with EBW
Photo courtesy of TWI
Tasks 3A and 3B

Task 3A. Thick Section EBW Development

- Several organizations (NAMRC, EPRI, TWI, RR, UOM) have been developing EBW for thick RPV materials
- Nuclear-AMRC has a 4.5m x 5.0m x 9m chamber which permits a 6m x 3.5m (19.7 x 11.5m) coupon to be fabricated in the chamber.
- 3A will focus on additional process/parameter development for handling RPV sections

Task 3B. Reduce Pressure EBW Development (optional task)

- Additional development is required for out-of-chamber welding
- TWI has demonstrated capability up to about 3 inches (75mm)
- More development will be required to move to 4.375 inches (110mm)
Task 4—Diode Laser Cladding Development

- Develop/demonstrate cladding for:
  - RPV Shell
  - Upper and Lower Heads
  - Nozzles
  - Plenum

Task 5—Elimination of DMWs for Nozzle Applications (optional task)

- Produce test blocks to demonstrate:
  - A508-to-690
  - A508-to-304L
- Manufacture/demonstrate nozzle-to-safe end (A508-to-690)
- Manufacture/demonstrate nozzle-to-safe end A508-to-304L
Task 6—Elimination of In-Service Inspection via Solution Heat Treatment

- **Modeling:**
  - flange to RPV shell
  - circumferential shell weld

- **Local PWHT** — safe handling of shells/head

- **Plate Trials**
  - Understand distortion and microstructure
  - Cladding, EB welds, PWHT, Soln Anneal, Q&T
  - Inspection

- **Distortion Measurements**
  - Circumferential weld
  - Weld to join two halves of torispherical head together
  - Inspection

- **Full Section Heat Treatment**
  - Lower flange shell
  - Model and solution HT
  - Distortion measurements

[Image: Thick section RPEB weld. Courtesy of TWI]
Task 7 -- ASME BPV Code Development

- Task will focus on working with ASME and EPRI Utility Requirements Document (URD)

- Example Code Cases/Changes anticipated:
  - Elimination of periodic ISI for solution HT, quench and tempered EB welds
    - Volumetric upon manufacturing only
  - Acceptance of 508 using PM-HIP as Code Case for production of vessel materials
  - Inspection criteria for Diode Laser Cladding on RPV materials (shells, nozzles, etc)
  - Reduce Pressure EB welding
  - Bulk Area Manufacturing
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 3.1m diameter x 5m length
  - Can manufacture 2/3rds scale coupons today.

- **EBW of SA508 RPV sections**
  - Does a vessel that has been EB welded, solution annealed, and quenched and tempered require subsequent in-service inspections?
  - Is EB really a weld after solution 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 <5mm 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
How Do We Get There?  
- Strategic Plan

- Not aimed at First-of-a-Kind
- Could use ring forgings (or PM-HIP rings).
- Definitely PM-HIP for top head, bottom head, plenum caps, and elimination of DMWs
- EBW & Solution Anneal eliminates several major shell horizontal welds

What Once Took Weeks, We Can Now Do In Hours…
Applicability of Advanced Manufacturing Processes

- Multiple SMR Plant Designs
- ALWR Plant Components
- GEN IV Designs
  - multiple nickel-based alloys will be required
- Ultra-Supercritical Plant Components
- Supercritical $\text{CO}_2$ Plant Components
Summary

Utilizing Adv. Manufacturing/Fabrication Technologies (eg., PM-HIP and Electron Beam Welding), EPRI/Nuclear-AMRC project will:

 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
 Rapidly Accelerate the Deployment of SMRs
 Technologies are applicable across SMRs, ALWRs, and Gen IV units
Together…Shaping the Future of Electricity
WCL of EB Weld vs 5mm distance (following Solution Anneal and Q&T) – 100X

WCL microstructure @ 100X

Microstructure 5mm from WCL @ 100X
WCL microstructure @ 500X

Microstructure 5mm from WCL @ 500X
“We choose to go to the moon!... We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win.”

JFK Speech – September 12, 1962