Advanced Materials and Manufacturing:

Moving R&D to Demonstration

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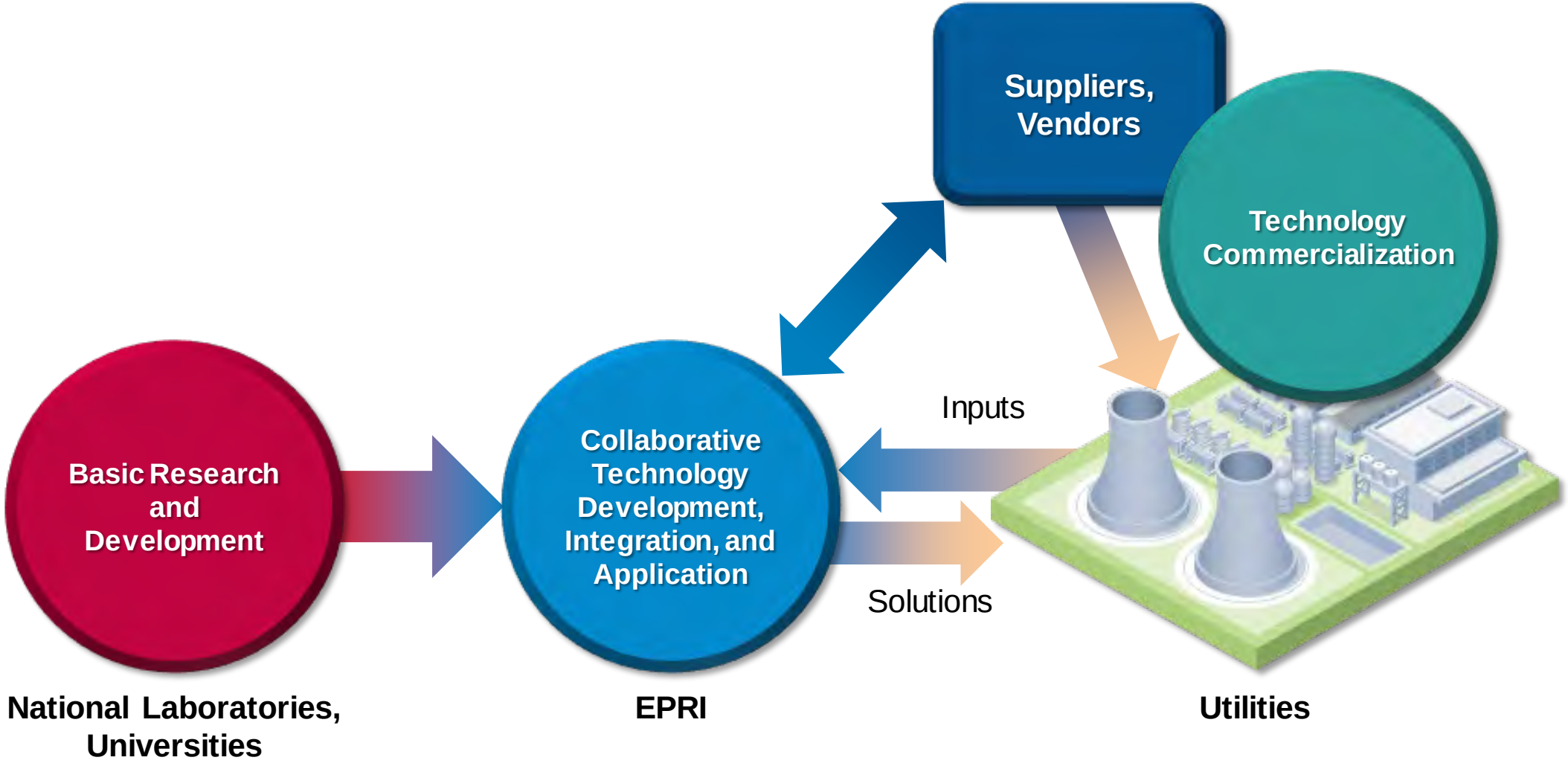
INFUSE Workshop
December 1-2, 2020

Outline

- EPRI Collaborative Model
- Cross-Sector Technologies
  - EPRI Lab Capabilities
- Tools in the Toolbox
  - Advanced Materials Development
  - Advanced Manufacturing Methods
- R&D → Demonstration

EPRI RESEARCH AREAS

How EPRI Delivers Value:
Leveraging Resources, Collaborative R&D, and Technology Transfer

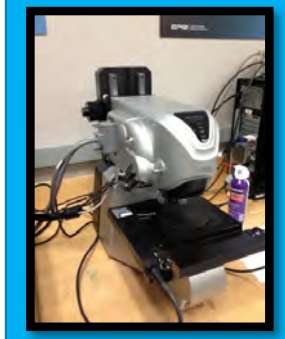


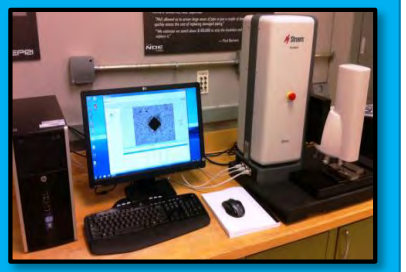
Laboratory Resources for Generation-Nuclear Sectors & Institute

Welding

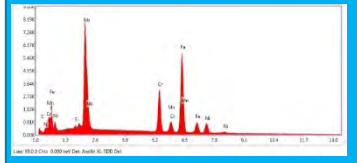
Specialist Machining

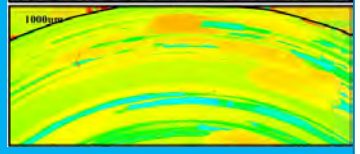
Heat-treatment & Field Simulations





Unique Characterization Equipment: Macro to Nano

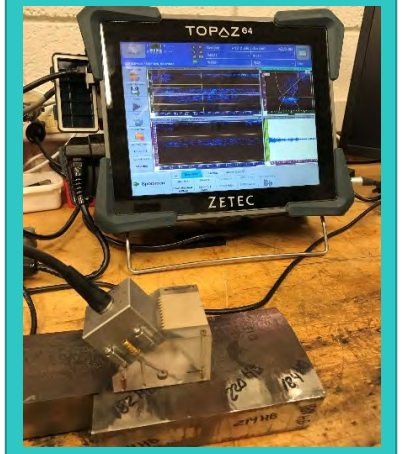




Water Treatment, Encapsulation, Corrosion

High-temperature mechanical testing

NDE: Ultrasonics, Electromagnetics



New Build: EPRI ANT Program Technical Focus Areas

- **Advance Reactor Program (AR)**
  - Strategic analysis and economics, technology assessment and tool development (ex. PHA-PRA), materials, owner-operator requirements
- **Engineering and Construction Innovation (ECI)**
  - Siting, design, construction materials, and construction activities of the plant, including modular construction
- **Advanced Manufacturing and Materials (AMM)**
  - Class 1, 2, and 3 piping systems and related components such as pressure vessels, valves, heat exchangers, and pumps
  - Optimize methods for fabrication, installation, inspection, and operations, including chemistry and new applications of materials and components
- **Commissioning and Initial Operations (C&IO)**
  - Developing the technical focus to support site transitioning from construction to startup, initial operations, and long-term operations
  - Improving technology transfer of EPRI research for nuclear operations

Ability to leverage investments in common R&D areas

Fusion Energy Technology

What will it take to bring fusion to market?

And How EPRI can Help…

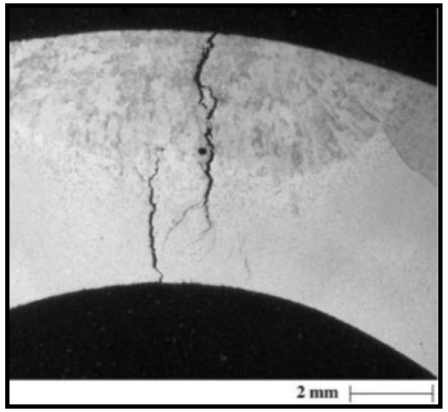
- Technologies that are:
  - mature (demonstration)
  - compelling (new attributes and capabilities, worth the risk)
  - competitive (cost and value)

- Customers who:
  - understand (informed and engaged)
  - believe (evidence of performance)
  - need (business case)

Advanced Manufacturing and Materials

Unanticipated materials challenges in first-of-a-kind applications and demonstrations in power generation

New Environments

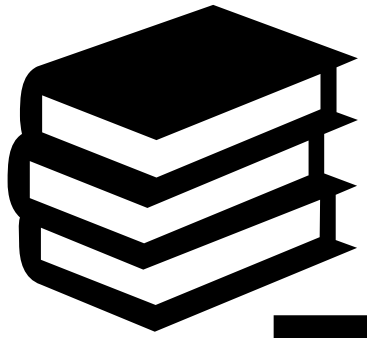


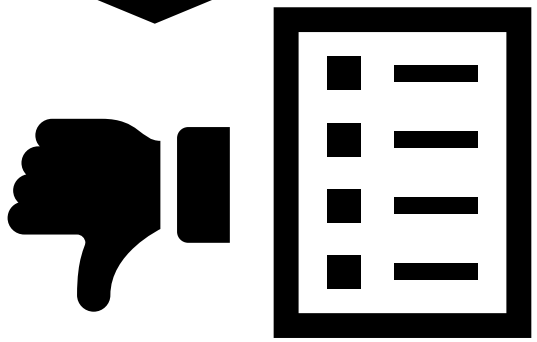
Materials election & environmental effects

New Materials

Manufacturing and fabrication challenges

Codes, Standards, and Specifications





Materials research during Design and continuing through Demonstration reduces overall project risk

Advanced Materials

Advanced Materials Development

Enable material options for Advanced Reactor designs through code qualification and data generation to support regulatory approvals.

MISSION

Pressure boundary and structural materials

Cladding materials & methods

Engagement with industry to reduce duplication of efforts

Non-proprietary, coordinated development of new material properties

Redefine new material development paradigm

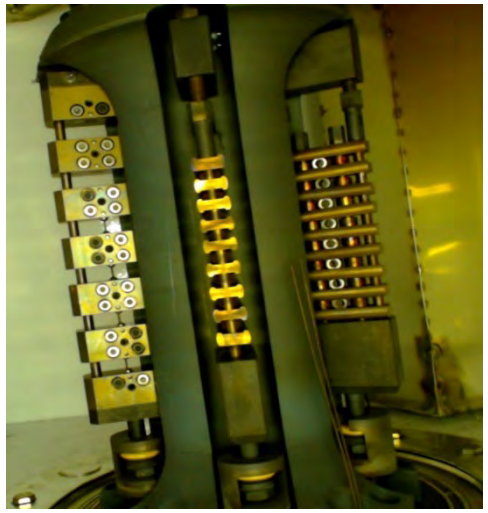
Lead innovation in novel qualification methods (AI, objective data/evaluation for streamlined regulatory process)

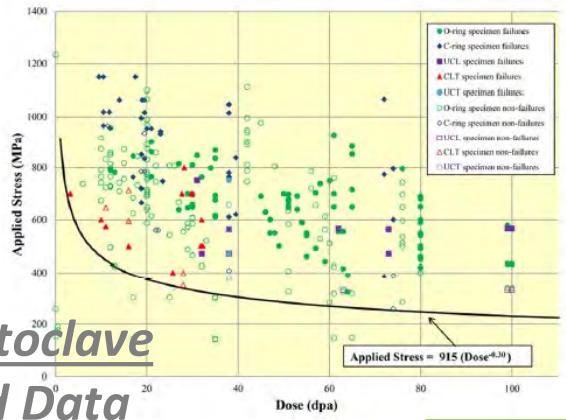
Technology Transfer

Transfer knowledge of mechanical + environmental synergistic behaviors to vendors and supply chain

The clock is ticking on advanced reactor material qualification… the time to act is now.

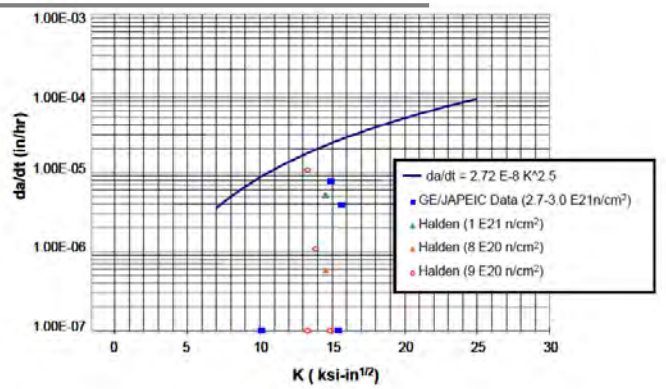
Paradigm: Data Generation for Materials and Structures in Light Water Reactors





Hot Cell Autoclave Generated Data

e.g. IFE Halden Generated Data

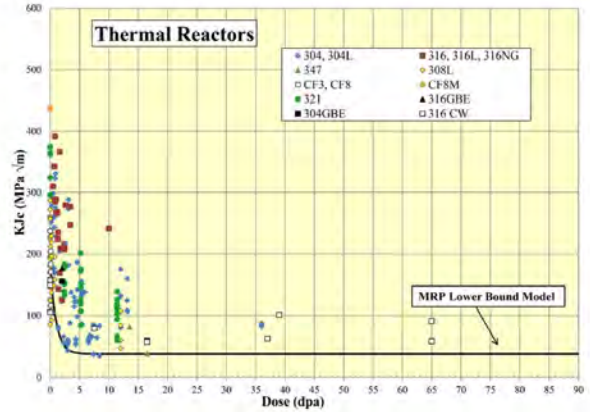


In-reactor, In-environment Mechanical Response, IASCC, Rad. Fatigue

Stress Corrosion Cracking of Pre-irradiated Material

Environmentally Assisted Fatigue (EAF) Stress Amplitude vs Life, Crack Growth Rates

Irradiation Fracture Properties



Hot Cell Generated Data

Mechanical Properties, Toughness in Environment

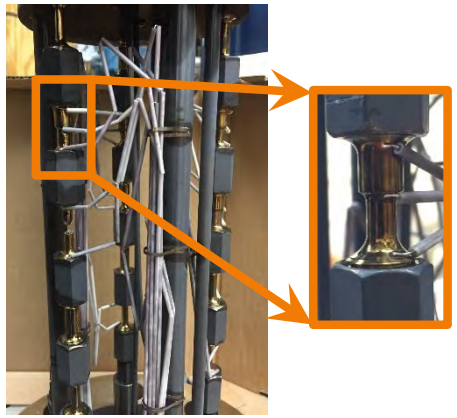
"Cold Lab" Generated Data

Stress Corrosion Cracking Stress vs Life, Crack Growth Rates

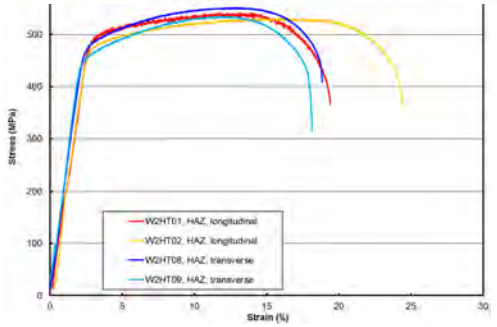
Time Dependent Creep Properties

Cyclic Properties Fatigue Life Cyclic σ/ε Curves

Tensile Properties, Hardness, Microstructure



Irradiation Effects on Hardness & Mechanical Properties



Mechanical Properties | **Environmental Effects** | **Irradiation Effects**

EPRI Thoughts on Supporting Commercialization of New Gen

- Lots of "white space" compared to the data that supports current generation fleet (fossil and nuclear)
- Immediate need for new materials/properties to be developed for high temp, irradiation, corrosion
- Some "simple properties" are available – but many gaps remain for performance over duration of service under new conditions
- Need progression from "simple properties" to developing properties under combined actions of variables
- EPRI Advanced Materials Gap studies:
  - Identify potential materials
  - Develop roadmaps for validation of materials and design data
  - Coordinate materials development and validation programs
  - ***Four Materials Gap Studies for MSRs, SFRs, LFRs, HTGRs/GFRs published in 2019 and 2020: Reports 3002010726, 3002016949, 3002016950, 3002015815***

GEN IV Material Gap Analyses Span Four Classes:

Austenitic Stainless Steels

316H SS	Extend BPV-III Div 5. Code properties to include time dependent behavior (Creep. Creep fatigue) Development and demonstration of cladding (Mo rich) for protection
316FR SS	Code qualification properties for ASME code Sec III Div 5 for 316FR including time dependent properties
Type 15-15Ti SS	Verification of swelling resistance Development of code properties for 15-15Ti material design
Alumina Forming SS	Demonstration of adequate resistance to irradiation/swelling at expected high dpa Development of processing and joining of alumina forming austenitic stainless steels
D9 Stainless Steel	Development of for ASME Code Sec III Div 5 properties (including time dependent properties) for D9 Development of swelling behavior at long times under realistic conditions – demonstrate adequacy

Ferritics-Martensitics and Low Alloy Steels

Ferritic-Martensitic--9Cr	Demonstration of adequate resistance to swelling at high fluence range. Time dependent properties for ASME Code Sec III Div 5. Development of fabrication and effective joining methods
Ferritic-Martensitic--12Cr	Demonstration of adequate resistance to swelling at high fluence range. Time dependent properties for ASME Code Sec III Div 5. Development of fabrication and effective joining methods
Ferritic Martensitic	Validation of commercial reliability – Properties sensitivity to heat treatment/local microstructures Response to fabrication processes – welding practices
LAS	Time dependent and fatigue properties for ASME code Sec III Div 5

Nickel-Based Alloys

Hastelloy N	Demonstration of radiation tolerance of Hast N variants (Proper understanding of chemistry→ microstructure → properties Development of properties for ASME Code Sec III Div 5 certification
800H and 617	Summary Document of Properties

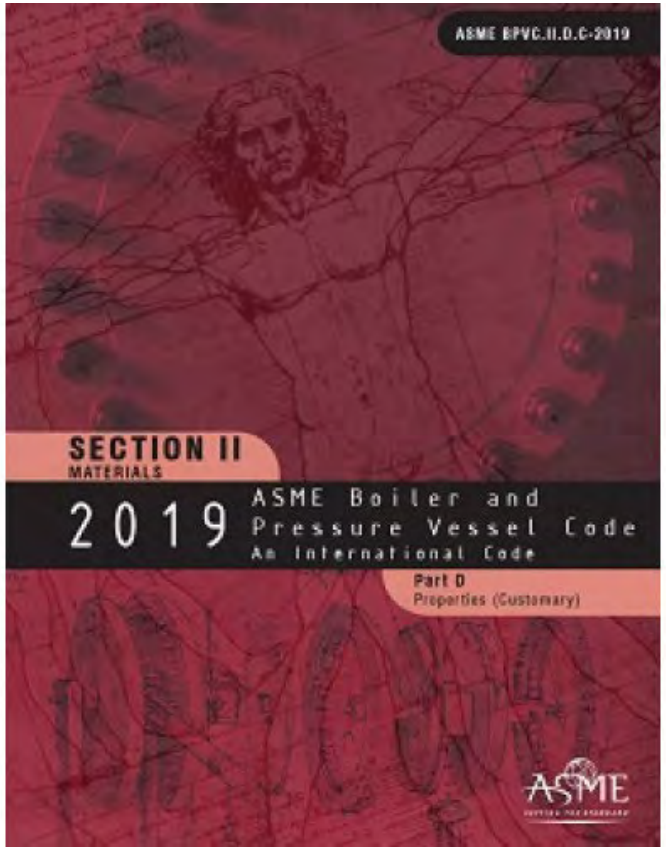
Addressing material data gaps supports more than one reactor design

EPRI AR Materials Development Roadmap

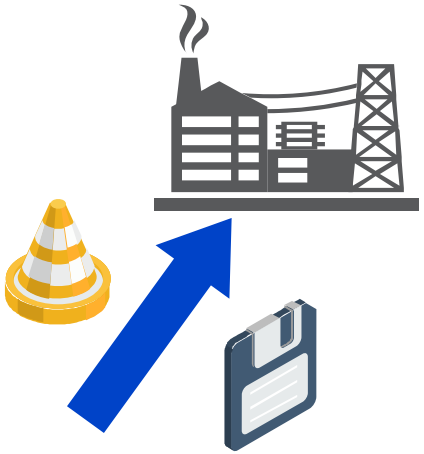
Technical Topic	2020	2021	2022	2023	2024	2025	2026	2027	2028	2028
Austentic Stainless Steels										
316H	Extend BPV-III Div 5. Code properties to include time dependent behavior (creep and creep-fatigue)									
316FR			Code qualification properties for ASME code Sec III Div 5 for 316FR including time dependent properties							
				Code qualification properties for ASME code Sec III Div 5 for D9 including time dependent properties						
D9 Stainless Steel						Evaluate resistance to irradiation/swelling at high dpa for D9 SS				
Ferritic-Martensitic and Low Alloy Steels										
Low Alloy Steel		Extend BPV-III Div 5. Code properties to include time dependent behavior (creep and creep-fatigue)--Grade 22 & 508 Properties								
F/M-9Cr				Code qualification properties for ASME code Sec III Div 5 for F/M-9Cr including time dependent properties						
						Evaluate resistance to irradiation/swelling at high dpa (9Cr and 12Cr)				
F/M-12Cr						Code qualification properties for ASME code Sec III Div 5 for F/M-12Cr including time dependent properties				Proof-of-Performance of Welds
Nickel-Based Alloys										
800H, 617, Hastelloy N	Assemble Summary Document for 800H, 617, 709SS, and Hastalloy N	Support ASME Code Data for 617 and 800H								
		Code qualification properties for ASME code Sec III Div 5 for Hastelloy N (or derivants) including time dependent properties								
		Corrosion Behavior of Hast N Variants in Molten salt (Ti program)		Evaluate resistance to irradiation/swelling at high dpa for Hastalloy N						
Graphite and Ceramic Composite	Evaluate UK experience		Evaluate new Graphite materials & move into ASME Code						Evaluate SiC-SiC structures	
Corrosion Properties										
Austentic Stainless Steels		Corrosion Behavior of Austenitic Stainless and in Molten salt - Vendor needed data ?				Prioritize resistance of Austenitic SS in Lead Environment				
Development of Testing Approaches for GEN IV Reactor Environments	Gen IV Reactor Development & VTR Test Vehicle Programs		Follow on Materials Selection and (Corrosion + Mechanical effects) Testing for materials for GEN IV reactors							
Cladding--Structural & Graphite										
Moly Cladding	Development and demonstration of cladding (Mo rich on LAS and 316H SS) for protection against Molten Salt									
Hastelloy Cladding on 316H SS		Development and demonstration of Hastelloy N Cladding on 316H SS								
Exploratory Alloys						Prioritized Investigations of Exploratory Alloys and Advanced Processing in various environments				

What Is Required To Bring These Technologies Forward For SMR, Micro-Reactor, or AR Applications?

- Code Data Packages (mechanical, microstructural, welding data)
- ASME or RCC-M Code acceptance
- Regulatory Acceptance
- Corrosion Testing
- Irradiation Studies
- Clearly separate pressure retaining applications from structural applications



Beyond Code Requirements



- Develop the additional, critical data and understanding required for informed fabrication and design of AR components and materials beyond the base data provided by the ASME Code.
- Minimize the risk of localized cracking and to develop design approaches for the damage tolerant structures necessary for long life, higher reliability, and improved safety in high temperature configurations.
  - The addition of "beyond code" information will provide confidence that robust and durable structures can be realistically developed for advanced reactors.
- The data developed will be necessary to support an effective supply chain for advanced materials.

A Call to Action for Advanced Materials to Enable Commercialization

- Cooperation/coordination between materials development tracks is needed:
  - Disparate development underway on similar alloys by industry
  - Too much for one organization to undertake
- Most effective use of resources calls for materials development and validation activities to address multiple reactor types where possible
  - e.g. High temperature properties)
- Alignment of work activities
  - Materials properties/ASME code data packages/ASME code cases (<10 alloys)
  - Irradiation effects and long term properties (4-5 alloys)
  - Effects of specific environments on properties (4-5 alloys)
- Potential development of new materials
  - Materials development
  - Robustness of processing

Advanced Manufacturing

EPRI Advanced Manufacturing Research Focus Area

GOAL & VALUE

Identify, develop, qualify and implement more economical manufacturing technologies that enable:

Higher Quality Components | Reduced Lead Times | Alternative Supply Chains | Cost Competitiveness

Additive Manufacturing

316L LPBF Code Case & Data Package
(submitted to ASME August 2020)

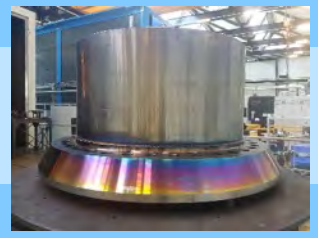
Additive Manuf. Roadmap for Nuclear Applications *(Nov. 2020)*

DED-AM Component Demonstration

Advanced Manufacturing Demonstration Project

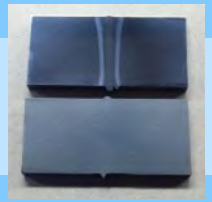
PM-HIP

EB Welding



DLC

Heat Treat



Advanced Welding Techniques

Adaptive Feedback Welding

ANT + WRTC

Modular In-Chamber EBW

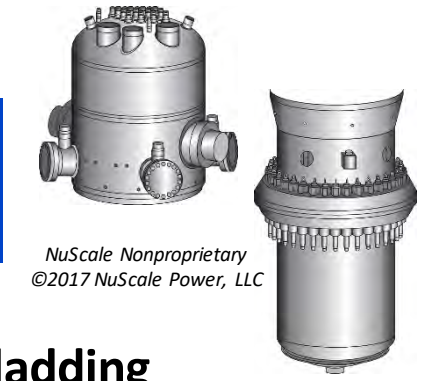
Candidate AMT Processes for Nuclear Components

- Powder Metallurgy-Hot Isostatic Pressing: PM-HIP
  - ~4 ft (1.2m) diameter
    - Larger HIP allowing ~ 10ft (3.05m) diameter, est. completion 2023/24
- Directed Energy Deposition AM: DED-AM
  - < 500 lb. (227kg) max.
- Powder Bed Fusion AM: L-PBF or EB-PBF
  - ~75 lb. (34kg) max.
- Advanced Cladding Processes:
  - e.g., diode laser cladding, hot wire laser welding, friction stir additive, cold spray & laser assisted cold spray, PM-HIP
  - Further development/qualification needed
- Electron Beam Welding: EBW
  - For large components (RPVs, SGs, pressurizers, fusion components, etc.)
- Other AMTs of interest not included with the roadmap:
  - Advanced welding technologies, machining techniques, surfacing technologies
  - Concrete & rebar and modular construction technologies

Advanced Manufacturing Demonstration Project

Manufacture Major Components of a 2/3-scale SMR Reactor Pressure Vessel

Team: EPRI, Nuclear-AMRC, DOE, NuScale Power

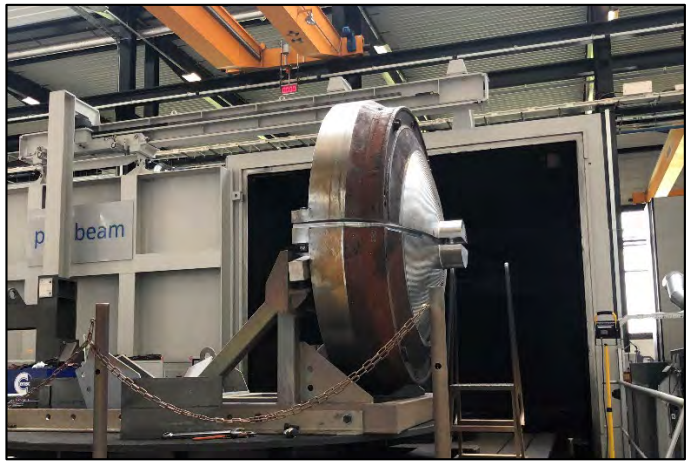


NuScale Nonproprietary
©2017 NuScale Power, LLC

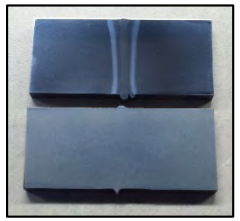
- **Eliminate Long Lead Forgings via PM-HIP**
  - Near-net shaped components
  - Eliminates 1000's of hours of machining

3002019335 – Phase 1 (Year 2) Progress Report (direct link)
And related Technical Report: Demonstration of PM-HIP - 3002010500

- **Electron Beam Welding**
  - What Once Took Weeks, We Can Now Do In Hours



WELD COMPLETED IN ~20 MINUTES

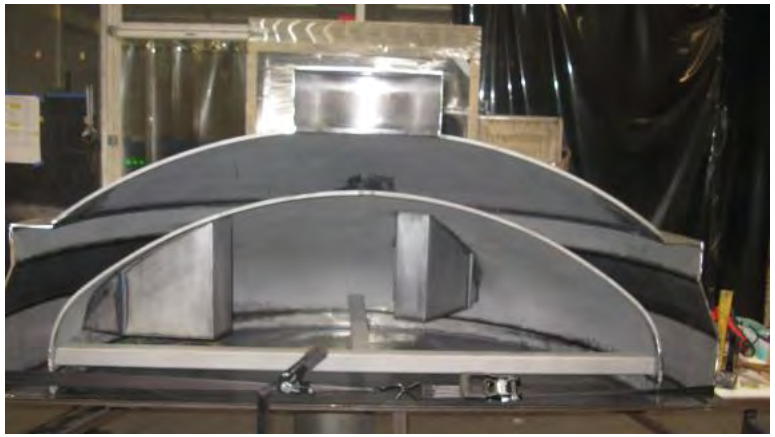


$$EBW + HT = 0\,Weld$$

- **Diode Laser Cladding**
  - Reduces cladding material by > 50%

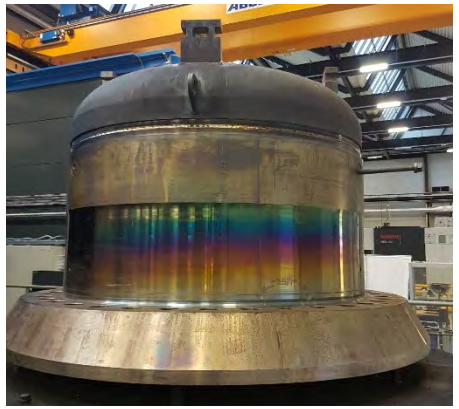
Advanced Manufacturing and Fabrication Program (TI, DOE)

PM-HIP can



PM-HIP complete

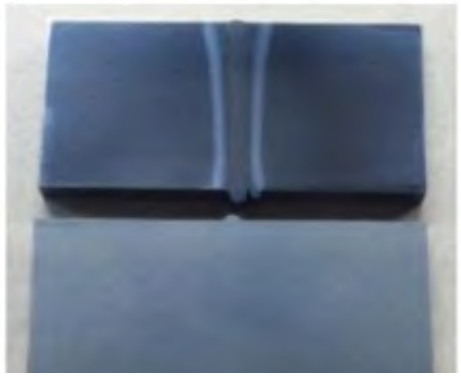
Electron Beam Welding



Lower Flange Shell Mockup ~6 ft (1.82m) dia.

Completed in 47 minutes

Heat Treatment



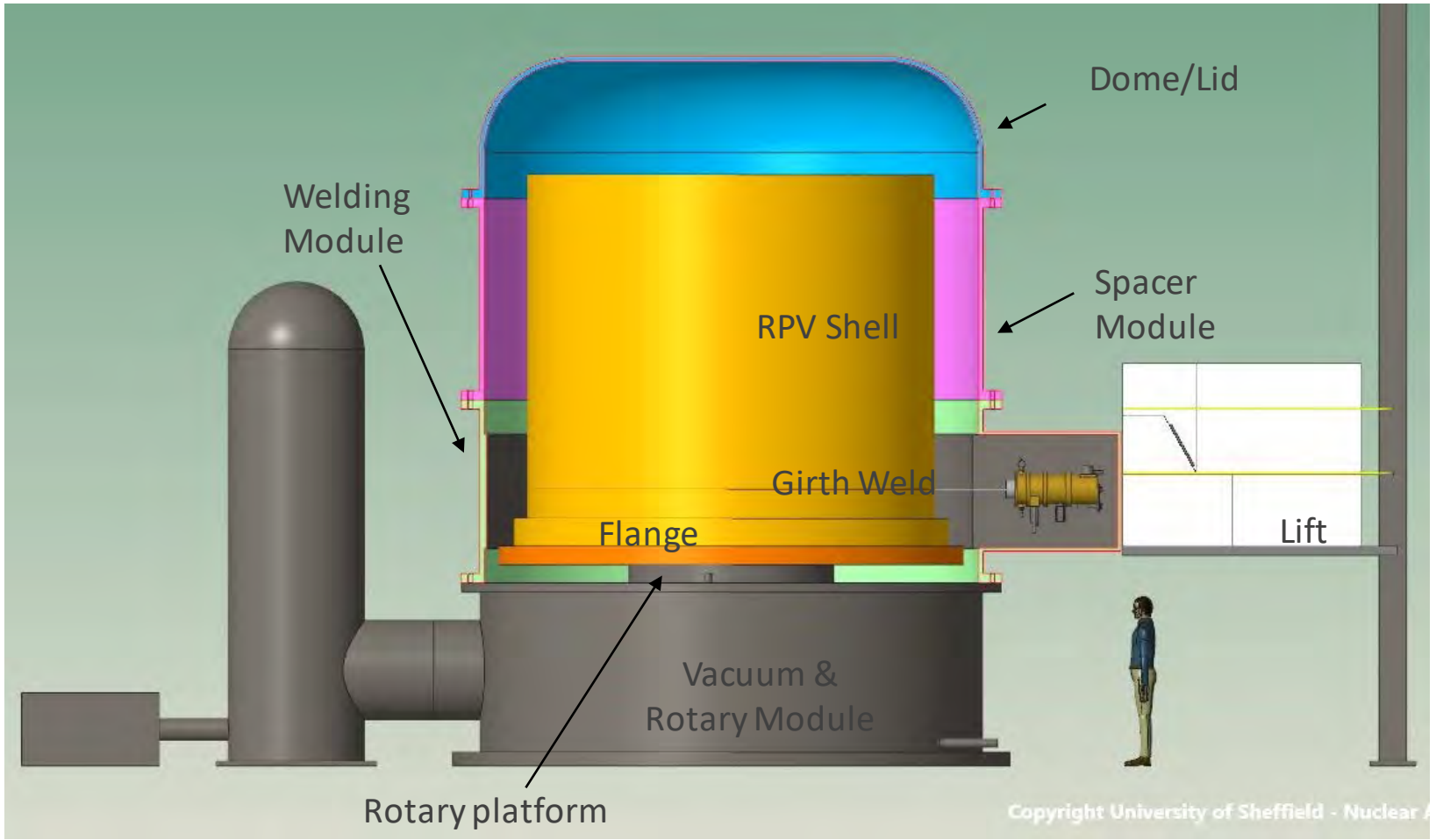
$EBW + HT = 0\ Weld$

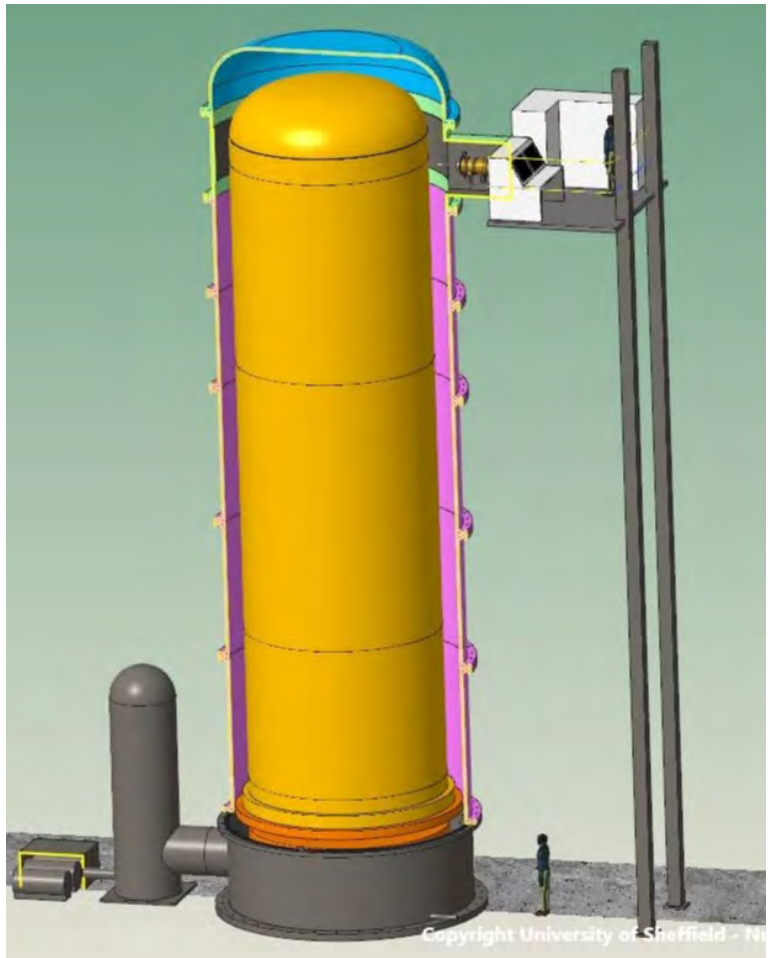
Diode Laser Cladding

Modular In-Chamber EBW – Phase 1 Complete

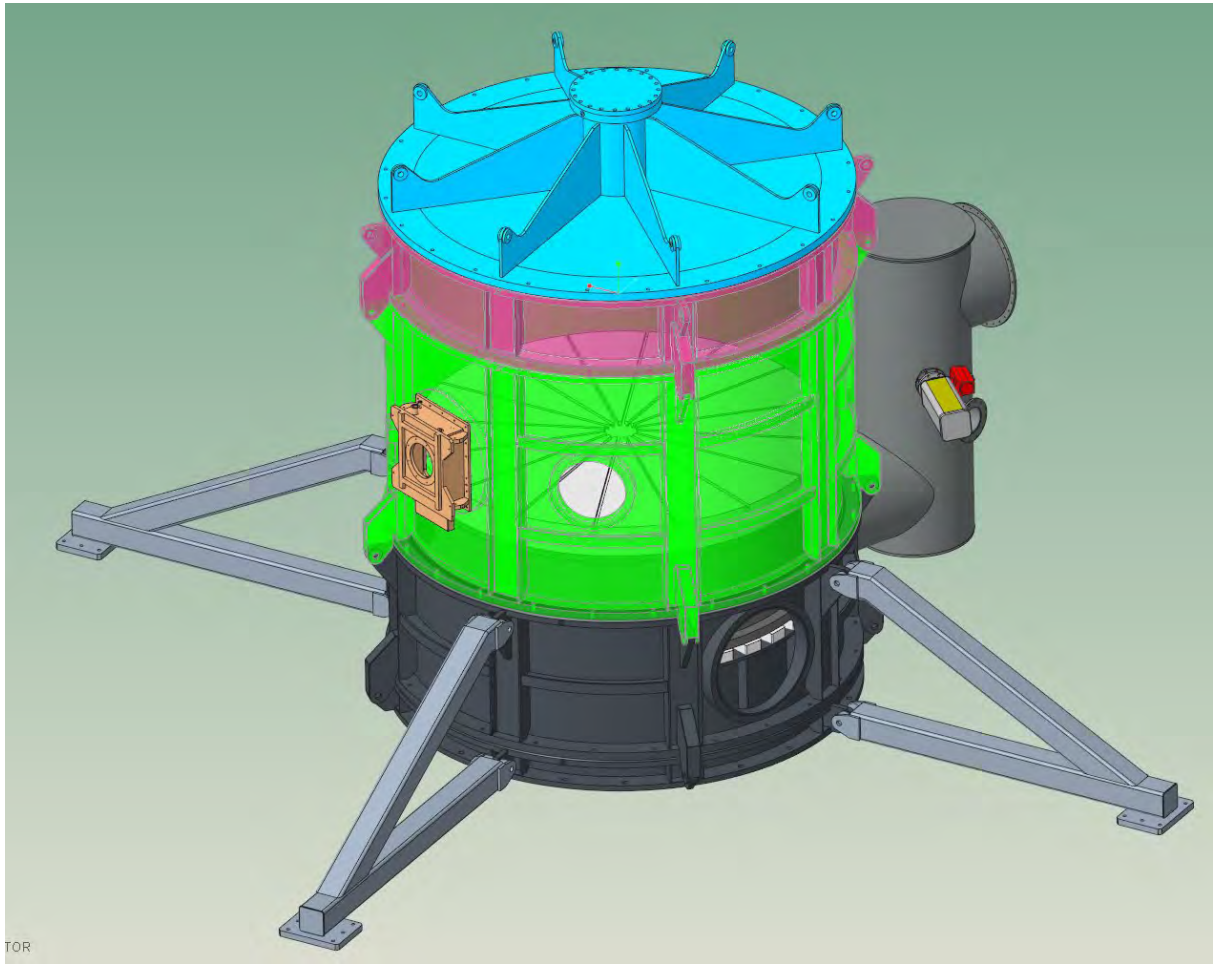
DOE Project DE-NE0008846

Report on Phase 1: 3002018146
Team: EPRI, Nuclear-AMRC, DOE, NuScale Power

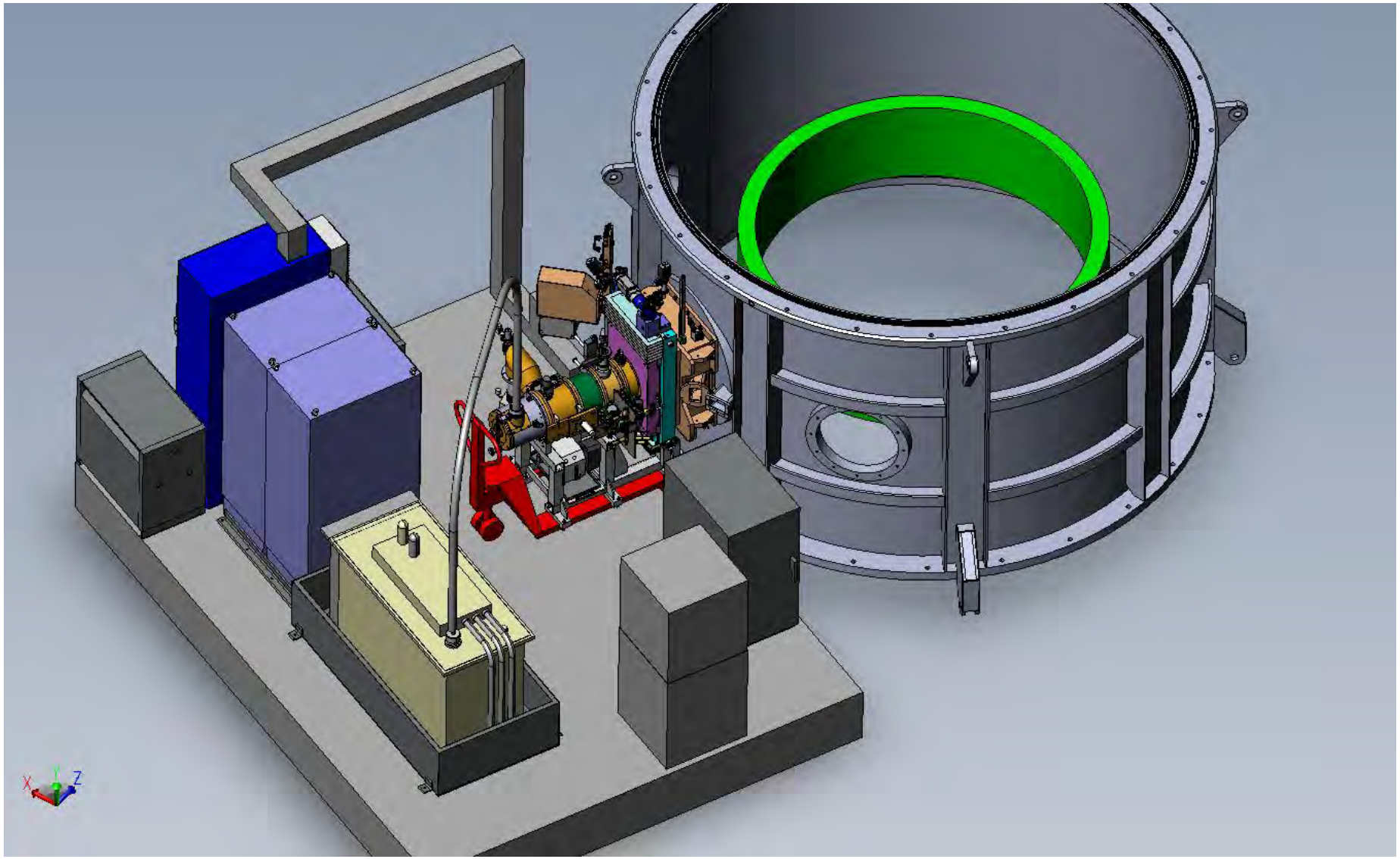




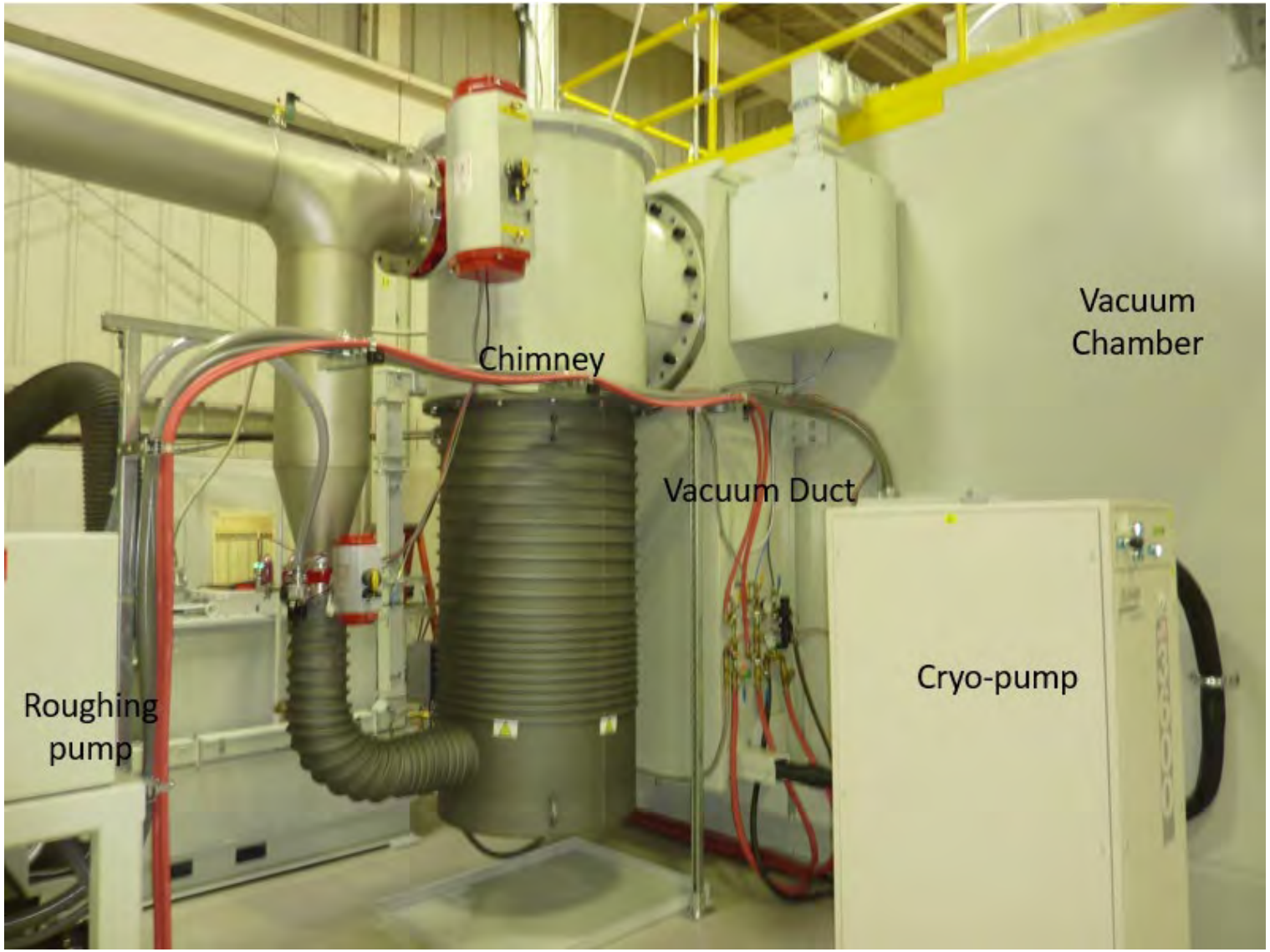
Demonstrator and Full Height EBW System



Platform & System Layout

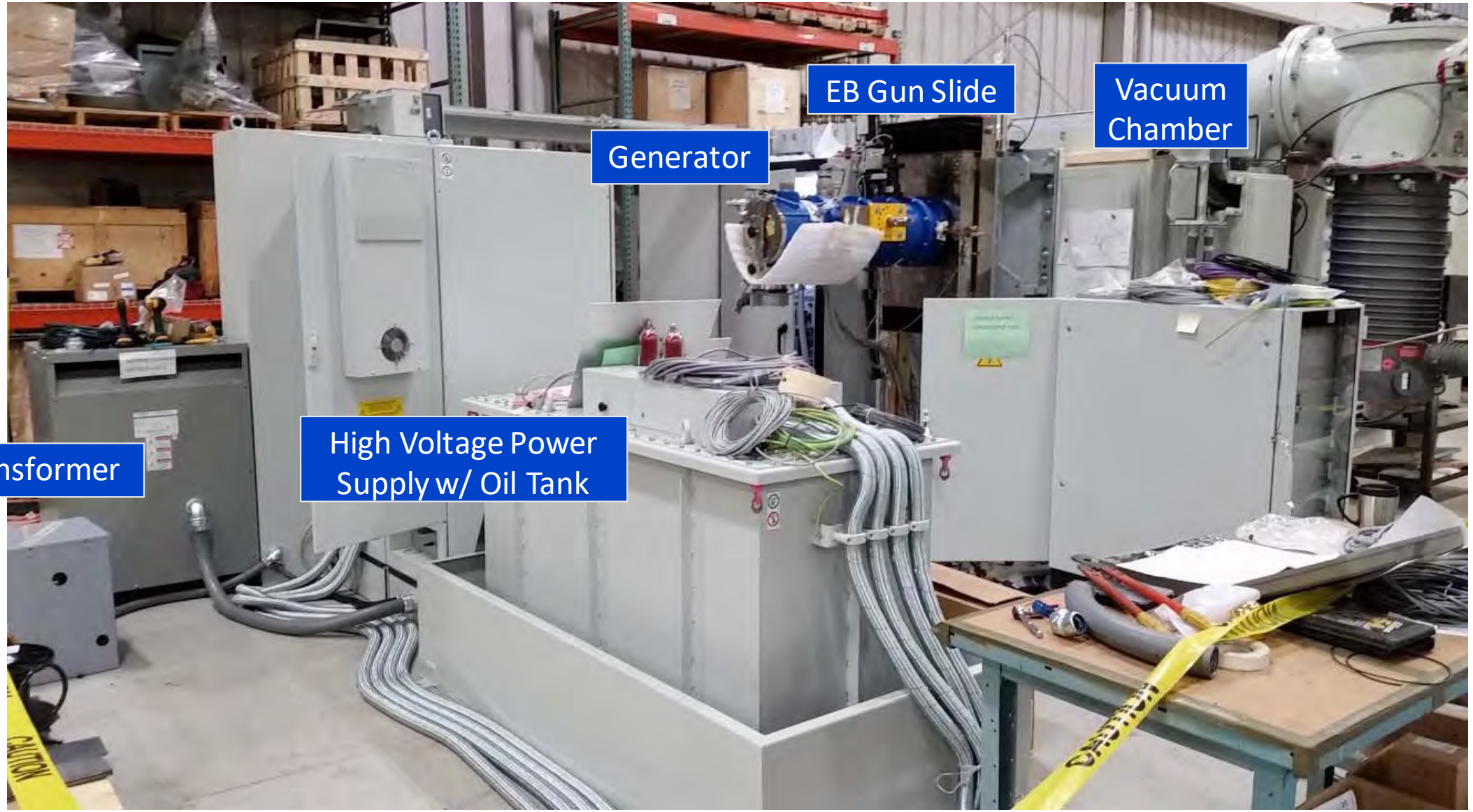


Mechanical pump package

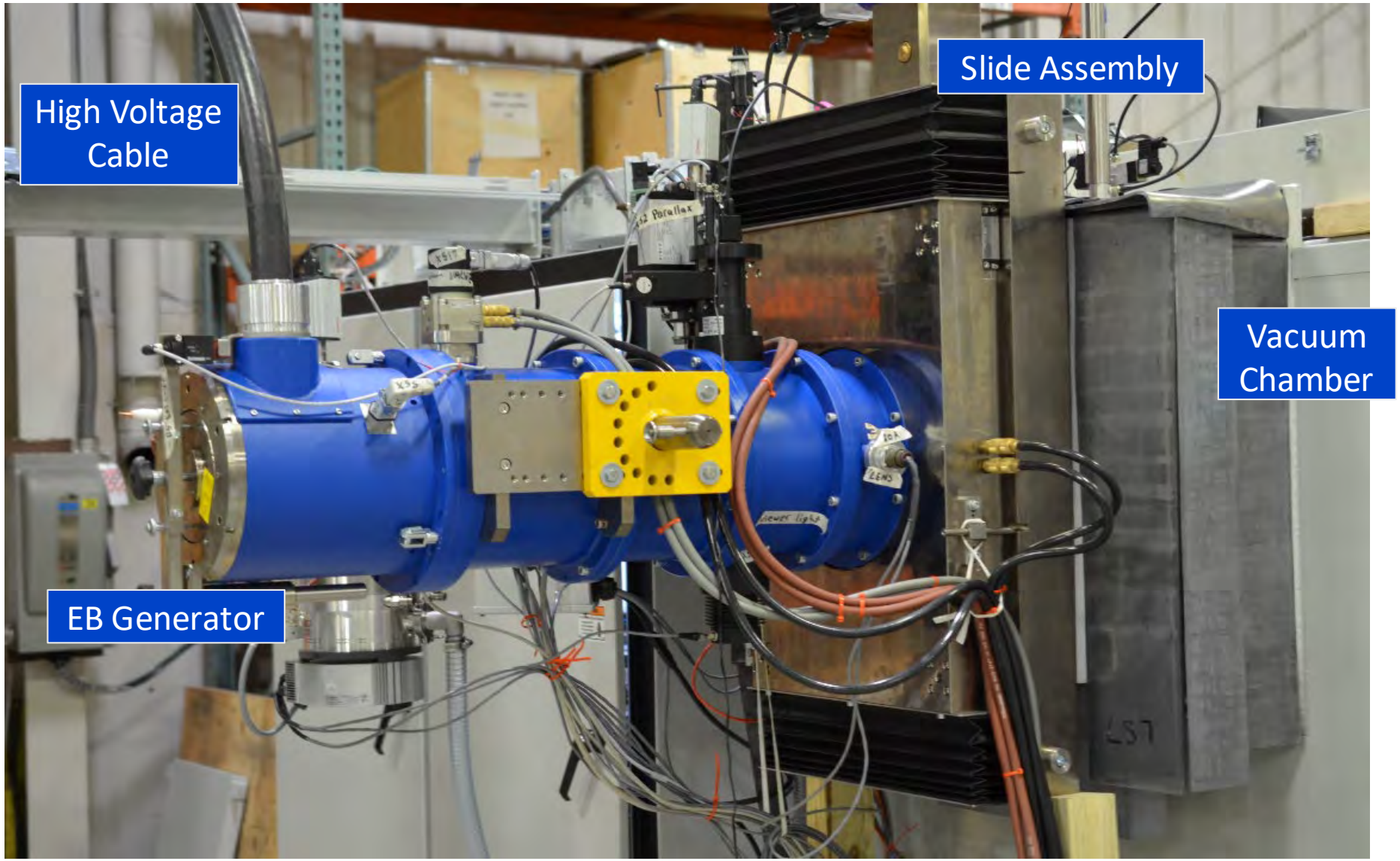


EBW Equipment Assembled

PTR
PRECISION TECHNOLOGIES, INC.



EB Generator and Slide attached to the vacuum chamber



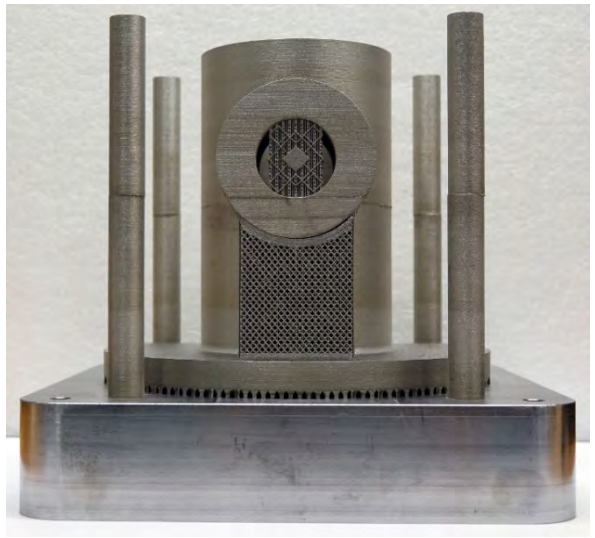
Additive Manufacturing Qualification (DOE) – Laser Powder Bed Fusion

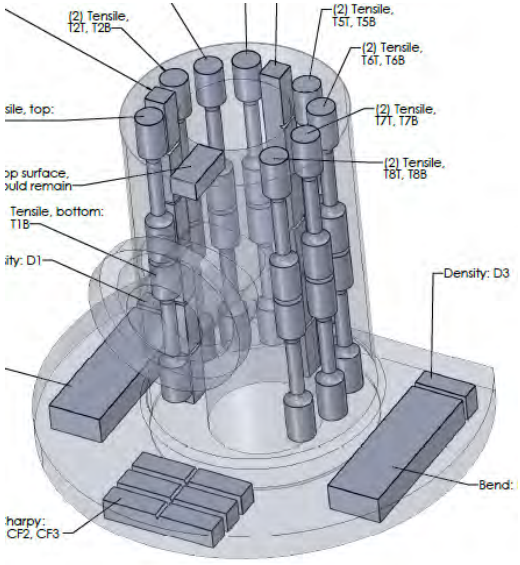
Objectives

- Develop and demonstrate innovative qualification strategy/approach for additively manufactured nuclear components
  - Incorporate Integrated Computational Materials Engineering (ICME) and in-situ process monitoring
- ASME Code Case for 316L Additively Manufactured (to be submitted in late 2019)

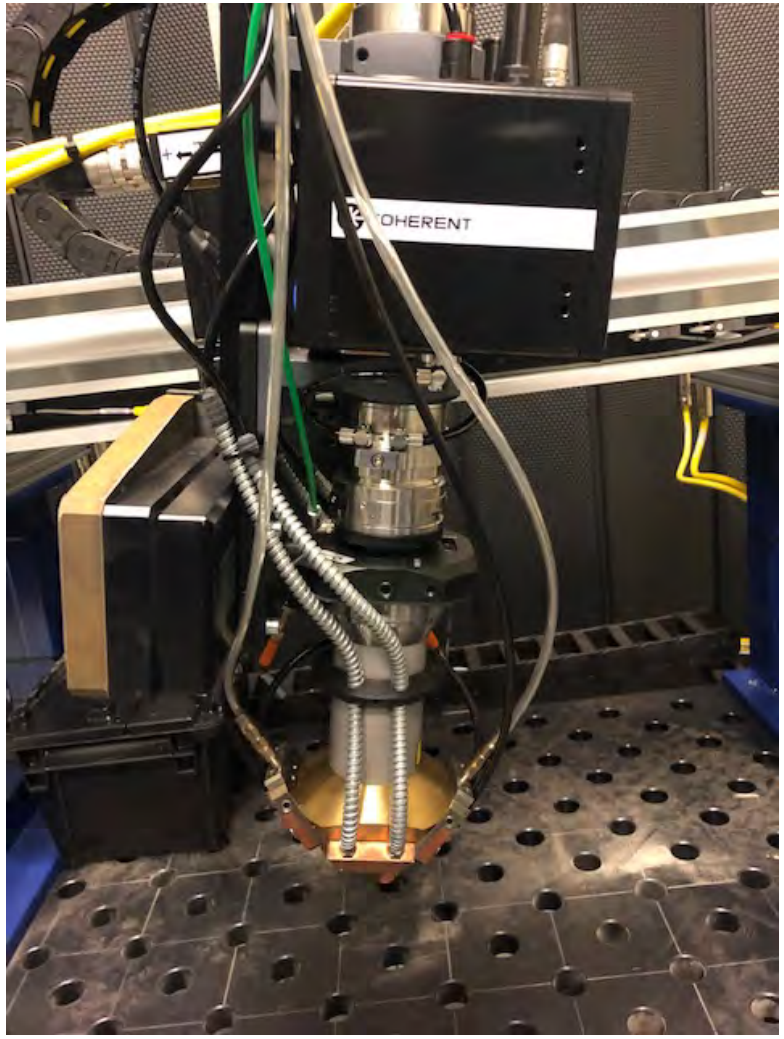
Scope

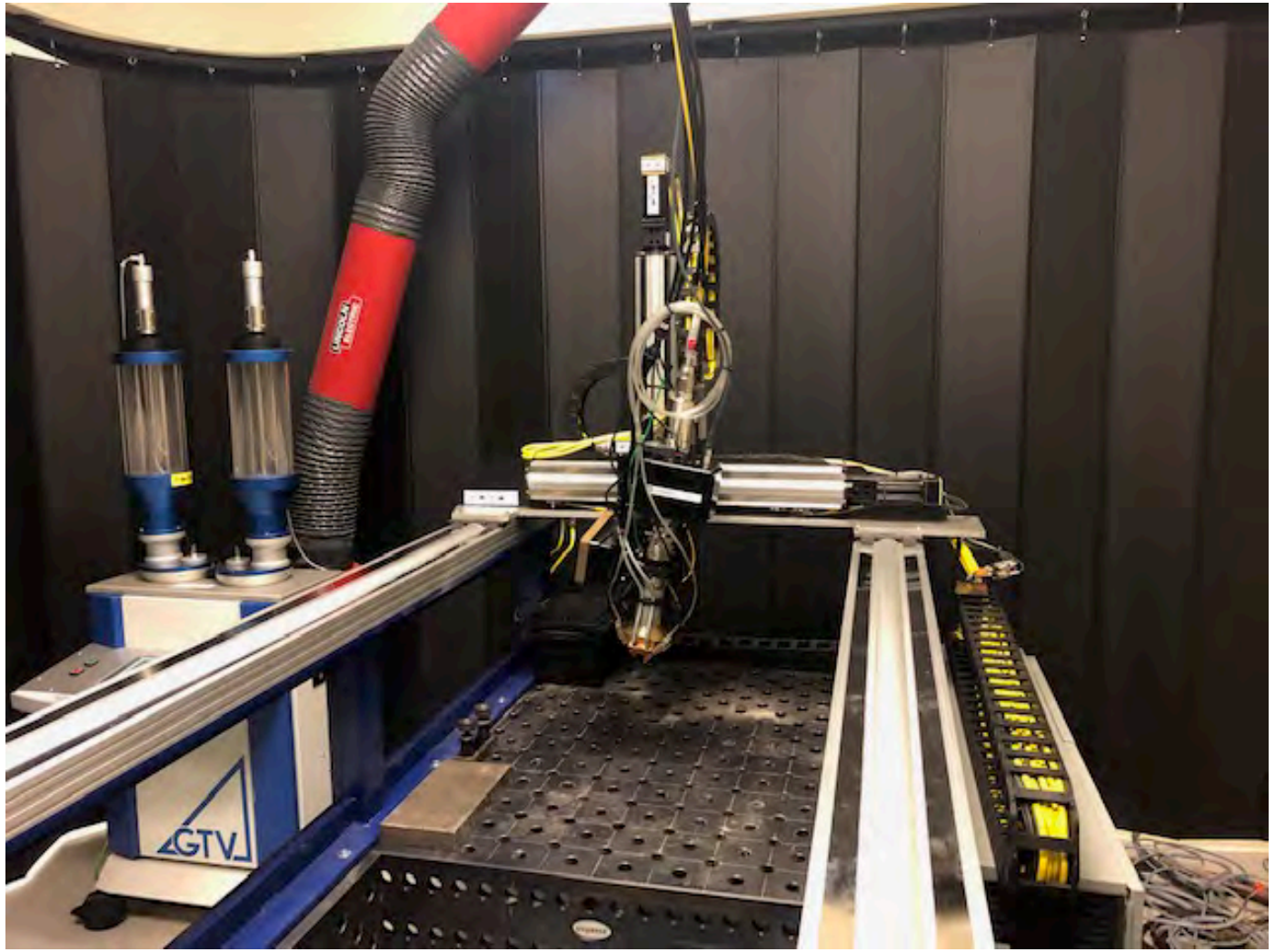
- 3 component geometries, built by 5 manufacturers (Rolls Royce, Westinghouse, Auburn, Oerlikon, UTK-ORNL), on 3 types of machines, from 5 heats/lots of material
- Mechanical & microstructural testing is in process





EPRI Diode Laser Cladding Equipment

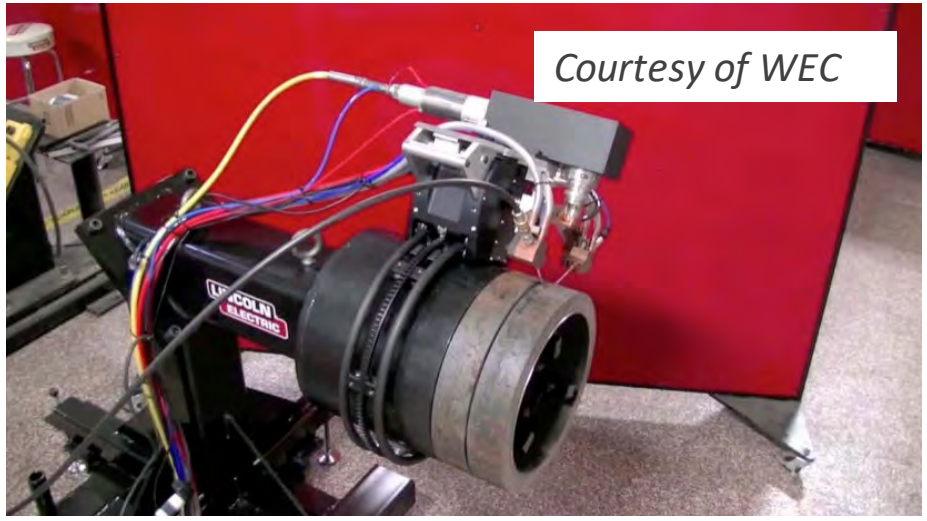


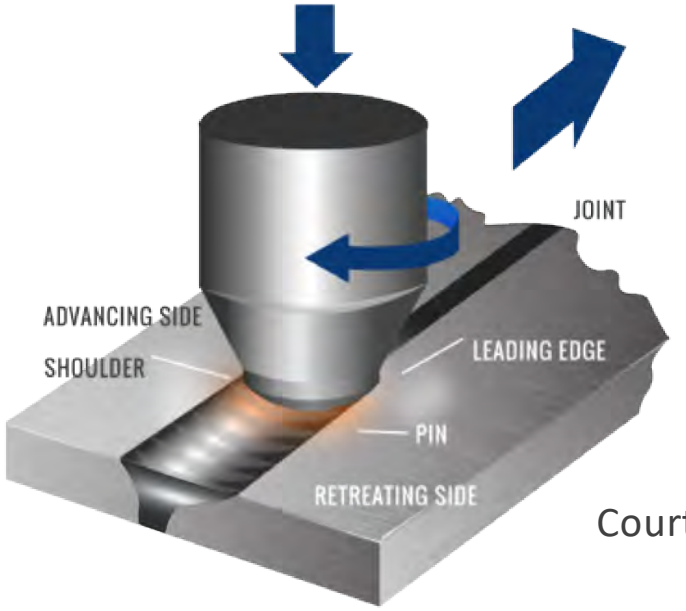


Advanced Welding & Joining Techniques

- Electron Beam Welding
- Adaptive Feedback Welding
- Friction Stir Welding / Ultrasonic Welding
- Hot-Wire Laser Welding
- Real-time Flaw Recognition

Courtesy of FLIR





Courtesy of MegaStir

Advanced Machining & Metrology

- Cryogenic machining
- Ultrasonic machining
- Metrology

Courtesy of 5ME

Advanced Manufacturing & Robotics

Remote maintenance/replacement →

- Mechanical connections

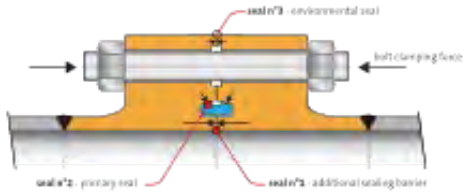


Image courtesy of Freudenberg Oil & Gas Technologies

- Embedded Sensors…Advanced Manufacturing

Courtesy of Fusion for Energy

← Diode Laser Cladding

Adaptive Feedback Welding →

Summary

- EPRI Collaborative Model
- Cross-Sector Technologies
  - EPRI Lab Capabilities
- Tools in the Toolbox
  - Advanced Materials Development
    - Collaboration is key
  - Advanced Manufacturing Methods: R&D → Demonstration
    - Additive Manufacturing (3D Printing)
    - Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)
    - Advanced Cladding Techniques
    - Advanced Welding & Joining Techniques
    - Advanced Machining & Metrology
    - Surfacing Technologies
    - Concrete and Rebar
    - Modular Construction Methods

Together…Shaping the Future of Electricity