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Small Modular Reactor Vessel Manufacture/Fabrication Using PM-HIP and Electron Beam Welding Technologies

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Abstract. Many of the same manufacturing/fabrication technologies that were employed for light water reactors (LWR) plants built 30-50 years ago are also being employed today to build advanced light water reactors (ALWRs). Manufacturing technologies have not changed dramatically for the nuclear industry even though higher quality production processes are available which could be used to significantly reduce overall component manufacturing/fabrication costs. New manufacturing/fabrication technologies that can accelerate production and reduce costs are vital for the next generation of plants (Small Modular Reactors (SMR) and GEN IV plants) to assure they can be competitive in today's and tomorrow's market.

This project has been assembled to demonstrate and test several of these new manufacturing/ fabrication technologies with a goal of producing critical assemblies of a 2/3rds scale demonstration SMR reactor pressure vessel (RPV). Through use of technologies including: powder metallurgy-hot isostatic pressing, (PM-HIP), electron beam welding, diode laser cladding, bulk additive manufacturing, advanced machining, and elimination of dissimilar metal welds (DMWs), EPRI, the US Department of Energy, and the UK-based Nuclear-Advanced Manufacturing Research Centre (Nuclear-AMRC) (together with a number of other industrial team members) will seek to demonstrate the hypothesis that critical sections of an SMR reactor can be manufactured/fabricated in a timeframe of less than 12 months and at an overall cost savings of >40% (versus today's technologies). Major components that will be fabricated from PM-HIP include: the lower reactor head, upper reactor head, steam plenum, steam plenum access covers, and upper transition shell.

The project aims to demonstrate and test the impact that each of these technologies would have on future production of SMRs, and explore the relevance of the technologies to the production of ALWRs, SMRs, GEN IV, Ultra-supercritical fossil, and supercritical CO2 plants. The project, if successful, may accelerate deployment of SMRs in both the USA and UK, and ultimately throughout the world for power production.

Introduction

Over the past decade, EPRI, DOE, Nuclear-AMRC, and various OEMs and vendors have investigated a number of advanced technologies to support the manufacture of small modular reactors (SMRs). Advanced technologies including: electron beam welding for thick sections, powder metallurgy-HIP, diode laser cladding, dissimilar metal joining, and cryogenic machining

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are just a few of the examples technologies. Many of these technologies are now mature and can be readily demonstrated from production of SMRs.

In early 2016, EPRI and Nuclear-AMRC began assembly of a large project wherein the two organizations planned to demonstrate several of these advanced technologies aimed at the manufacture and fabrication of a 2/3rds scale SMR vessel. Their efforts were met with tremendous interest from industry and with co-sponsorship by the US Department of Energy (DOE) through its Advanced Methods for Manufacturing (AMM) program. The collaborative project began in earnest in early 2017 and is focused on developing/demonstrating three key advanced manufacturing technologies: electron beam welding for thick section components, powder metallurgy-HIP, and diode laser cladding, among a number of other manufacturing/fabrication technologies. The technologies are being demonstrated using NuScale Power's 50MWe (160MWth) SMR design.

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Project Objectives

Three key objectives were identified for this project. These include:

- Develop and demonstrate advanced manufacturing and fabrication technologies to rapidly accelerate the deployment of SMRs
- Develop/demonstrate new methods for manufacture/fabrication of a Reactor Pressure Vessel (RPV) which could lead to production of a vessel in under 12 months.
- Eliminate 40% of the costs of production of an SMR RPV, while reducing the overall schedule by up to 18 months.

These three objectives formed the basis formed for the entire project.

Large Component Manufacture

As described above, the NuScale Power reactor pressure vessel design, a 50MWe (160MWth), was selected for demonstration of various advanced manufacturing technologies at a 2/3rds scale. The NuScale Power RPV design was selected based upon its size and on the basis that it appears to be very near production. The RPV is shown in Figure 1 and consists of 8 major sections. In the current project, two assemblies, upper and lower (Figures 2 and 3), will be demonstrated. These two assemblies were selected based on the premise that the two assemblies would demonstrate many of the advanced manufacturing/fabrication technologies required for construction of an SMR and that assembly of the middle section would simply be redundant with regards to demonstrating these technologies.

Manufacture of the key components for the reactor vessel includes both conventional forging and PM-HIP. The breakdown of the key A508 low alloy steel components are as follows:

<u>PM-HIP (A508, Grade 3, Class 1)</u>

- Lower reactor head
- Upper reactor head
- Steam plenum
- Steam plenum access ports/covers

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- Upper transition shell (in four sections)

Forgings (SA508, Grade 3, Class 1)

- Lower transition shell
- Upper flange
- Lower flange
- PZR (pressurizer) shell

For the purpose of this paper, the discussion will only focus on manufacture of components using the PM-HIP process since forging is already a mature process. The forgings used in this project will be used for the upper and lower assemblies primarily for the purpose of demonstrating the joining and cladding technologies.

PM-HIP was considered for this project for a number of reason. The investigators believed PM-HIP provides a ready means to produce the upper and lower reactor heads in a near-net shaped condition minimizing hundreds of hours of machining from the manufacturing process, 2) it provides excellent properties often better than those that may be produced via forging, 3) the process can significantly reduce the time/schedule to produce a reactor head, and 4) the process provides excellent inspection characteristics. PM-HIP coupled with EB welding and heat treatment also provides an avenue to produce reactor components in sections, thereby eliminating the need for very large forgings such as those used in LWRs and ALWRs for the past 3 decades.

It should also be pointed out that PM-HIP is not currently accepted for production of A508 materials by ASTM or ASME Boiler and Pressure Vessel Code presently. One of the goals of the project is to develop sufficient mechanical, microstructural, and heat treatment data to support the development of an ASTM specification for A508 PM-HIP components and an ASME Code Case for A508 materials. Considerable work will be required to generate this supporting data and information. Preliminary research by the investigators has demonstrated excellent tensile and toughness properties can be readily achieved with the process however.

In 2017, two PM-HIP components are being manufactured: the upper head at 40% of full size and one-half of the lower head at 2/3rds size. The 50-inch (1.27m) in diameter upper head consists of 27 penetrations and weighs almost 2400lbs (1088kgs), is shown schematically in Figure 4. It is being manufactured at Synertech-PM at ~40% of its full size to demonstrate that it can be produced to near-net shape with today's HIP vessel technology. Only the size of the HIP vessel limits our ability to produce a larger component. Later in the project, the upper head will be produced in two one-half sections at a 2/3rds scale and EB welded together (more on this topic in the next section).

The lower head is also being produced via PM-HIP. At 2/3rds scale, the head is roughly 8ft (2.44m) in diameter and will be produced in two half sections and welded together as shown in Figure 5. The lower head upon completion will weigh approximately 4300lbs (1950kgs). Further discussion on EB welding of the head will be provided in the following section.

Other key 2/3rds-scale components that will be produced from PM-HIP include the steam plenum which will weigh almost 13,000lbs (5900kgs) and the upper transition shell which will weigh approximately 20,000lbs (9072kgs). The latter will be described in the following Fabrication section. The former will consist of five major sections that are produced via PM-HIP and welded together via EB welding (not covered in this paper however).

Additionally, the authors would like to point out that a full size steam plenum access port was produced under EPRI's Advanced Nuclear Technology (ANT) program in 2016. The 1200lb

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(544kg) access port is shown in Figure 6 (still in the HIP capsule) and was produced from A508 powder. An access port will also be produced at 2/3rds scale for the upper assembly later in the project.

Component Fabrication

Two advanced fabrication technologies, electron beam welding (EBW) and diode laser cladding (DLC) are being developed/demonstrated in this project. EBW will be used to join half sections of the reactor heads, to perform major girth welds around the diameter of the vessel, and to join PM-HIP sections of the steam plenum and sections of the upper transition shell together. DLC, which will not be discussed herein, is being employed to apply the cladding to both the ID and OD surfaces of the reactor vessel.

EBW was selected as the joining process for this project due to three key attributes: 1) no filler wire is used with the process (eliminates the potential of weld embrittlement later in reactor service), 2) welds can be completed in a single pass, and 3) the investigators believe the technology can eliminate 80-90% of the welding time necessary for completion of the reactor vessel assembly.

As mentioned earlier, the lower and upper heads for the 2/3rds scale assembly will be produced using one-half sections (produced by PM-HIP) and welded together via EBW. Figure 5 provides a pictorial view of the lower head, while Figure 7 provides a view of the upper head. Each weld will be performed in the horizontal welding position as shown in Figure 8. Following welding, the assembly will be annealed, quenched, normalized and then tempered to produce final properties and to remove any evidence of the weld.

Assembly of the entire SMR vessel would require 10 major girth welds. Since the middle RPV assembly is not being considered in this project, only 5 girth welds will be demonstrated. The first girth weld will be performed to attach the lower flange to the lower flange shell (Figure 9). This is performed in the upside down position. Next, the lower reactor head will be attached to the lower flange as shown in Figure 10 (again shown in the upside down position). This completes one-half of the lower reactor assembly.

The upper one-half of the lower reactor assembly is comprised of an upper transition shell and a large flange. The upper transition shell consists of four individual sections which will be joined using vertical EB welding (Figure 11). Next, the upper transition shell will be welded to the upper flange once again using a horizontal girth weld (Figure 12). This completes the second-half of the lower assembly. At this point, both halves of the lower assembly will be heat treated, final machining will be performed, and the two flanges are ready to be bolted together. This will complete the first phase of the project.

The upper assembly, which is the more difficult of the two assemblies, will be produced and assembled in Phase 2 of the project which is slated to begin in late 2018. For the purpose of this discussion, individual girth welds will be applied to join the steam plenum to the PZR shell and the PZR shell to the upper head. There are a number of other EB welds which will be performed to assemble the steam plenum, but they will not be covered in this paper. Approximately 20 EB welds will be performed on thick section components ranging from 75-110mm in this project

Project Status

Much of 2017 has focused on detailed planning of various work packages to support the project in the areas of machining, EBW, DLC, NDE, PM-HIP, etc. The work packages have been completed and development of mockups/test pieces is currently in progress to support each of these technologies. Additionally, forgings for the project have also been ordered from Sheffield Forgemasters and are anticipated during Q1-2018.

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For the PM-HIP portion of this project, the focus has been on production of a one-half section of the lower head and production of the 40% upper head section. Both of these components will provide valuable insight into production of full sections of these components to support the overall project moving forward.

Project Summary

Several advanced manufacturing and fabrication technologies have been covered in the subject Advanced Manufacturing and Fabrication project. Two key technologies: PM-HIP and electron beam welding (EBW) have been covered in this paper. Both technologies have the potential to completely change the way industry fabricates reactor vessels today, to rapidly accelerate deployment of SMRs, and to significantly reduced costs and time toward production of a SMR.
PM-HIP is being used to manufacture/demonstrate five major sections of the reactor vessel including:

- Lower reactor head
- Upper reactor head
- Steam plenum (in five sections)
- Steam plenum access ports/covers
- Upper transition shell (in four sections)

It is believed that PM-HIP can offer dramatic improvements in both properties and in time-delivery schedule for reactor parts.

EBW is being employed to join reactor head sections, produce vertical welds to join shell sections, and to perform major girth welds to join sections of the reactor. The EBW technology is being considered in this project for the following reasons: 1) it eliminates the need for welding filler material, 2) it can be performed in a single weld pass, and 3) it has the potential to eliminate 80-90% of the welding time required for reactor vessel fabrication.
Together these two advanced manufacturing/fabrication technologies have the potential of making SMRs competitive with other lower cost energy production methods such as natural gas.

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Figure 1. NuScale Power Reactor Pressure Vessel (Courtesy of NuScale Power).

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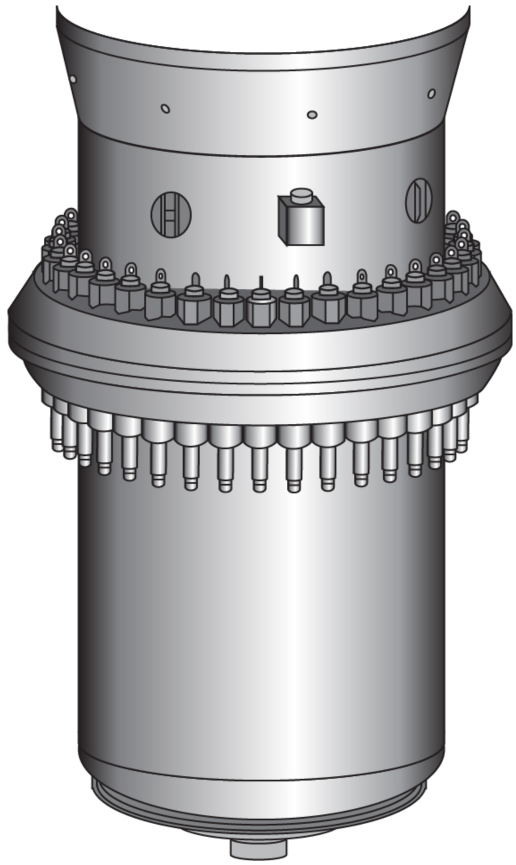

Figure 2. Lower Reactor Assembly (Courtesy of NuScale Power).

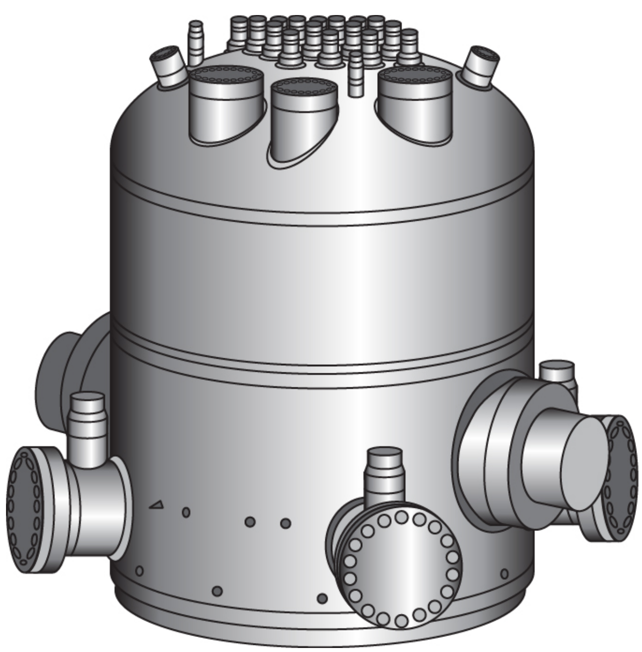

Figure 3. Upper Reactor Assembly (Courtesy of NuScale Power).

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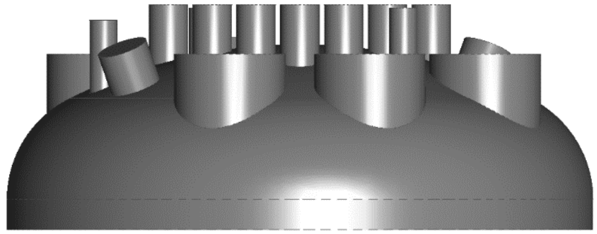

Figure 4. Schematic of the upper reactor head at 40% size

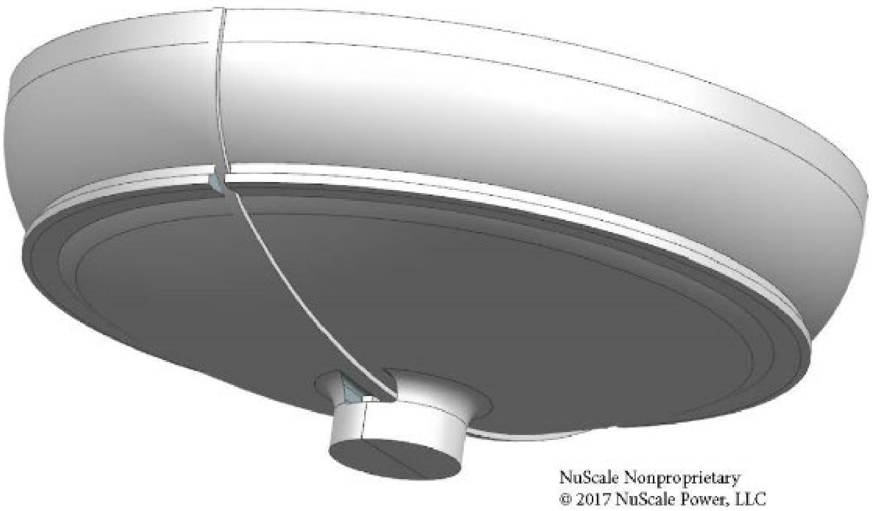

Figure 5. Lower reactor head produced in 2 halves.

Figure 6. A508 SMR Steam Access Port produced via PM-HIP.

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Figure 7. Schematic of the upper reactor head produced in 2 halves.

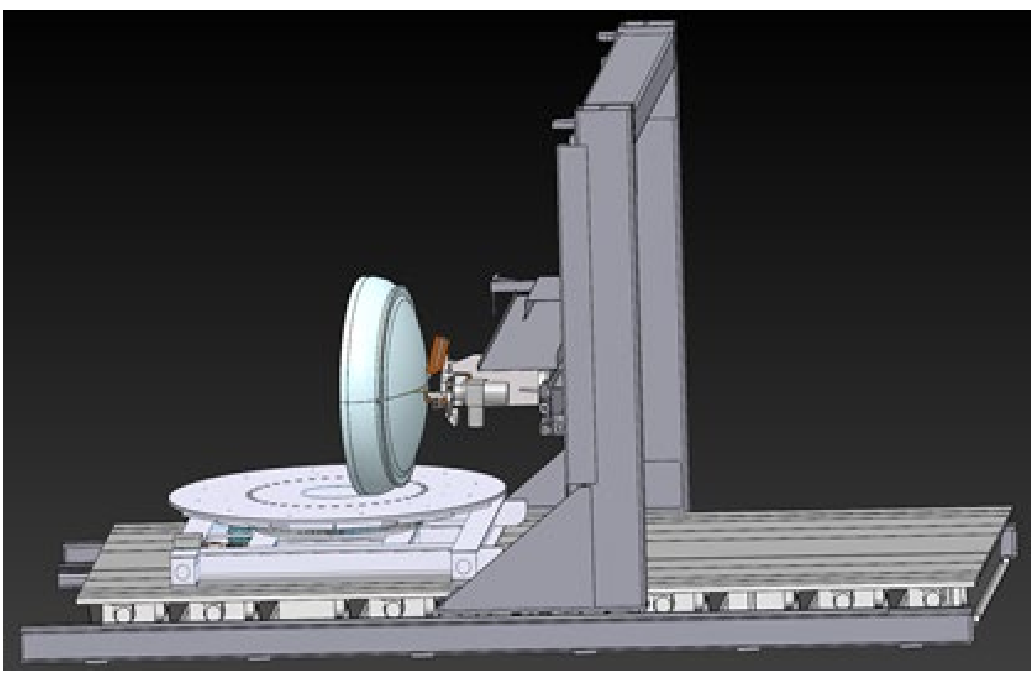

Figure 8. EB welding of the lower and upper heads will be performed in the horizontal position.

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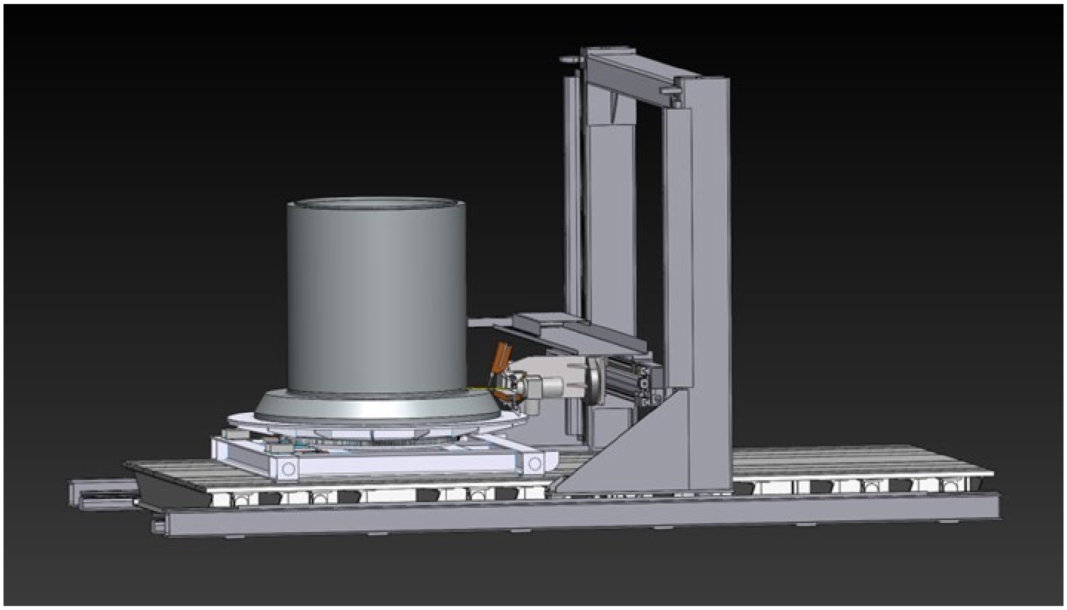

Figure 9. Girth weld joining the lower flange to the lower flange shell

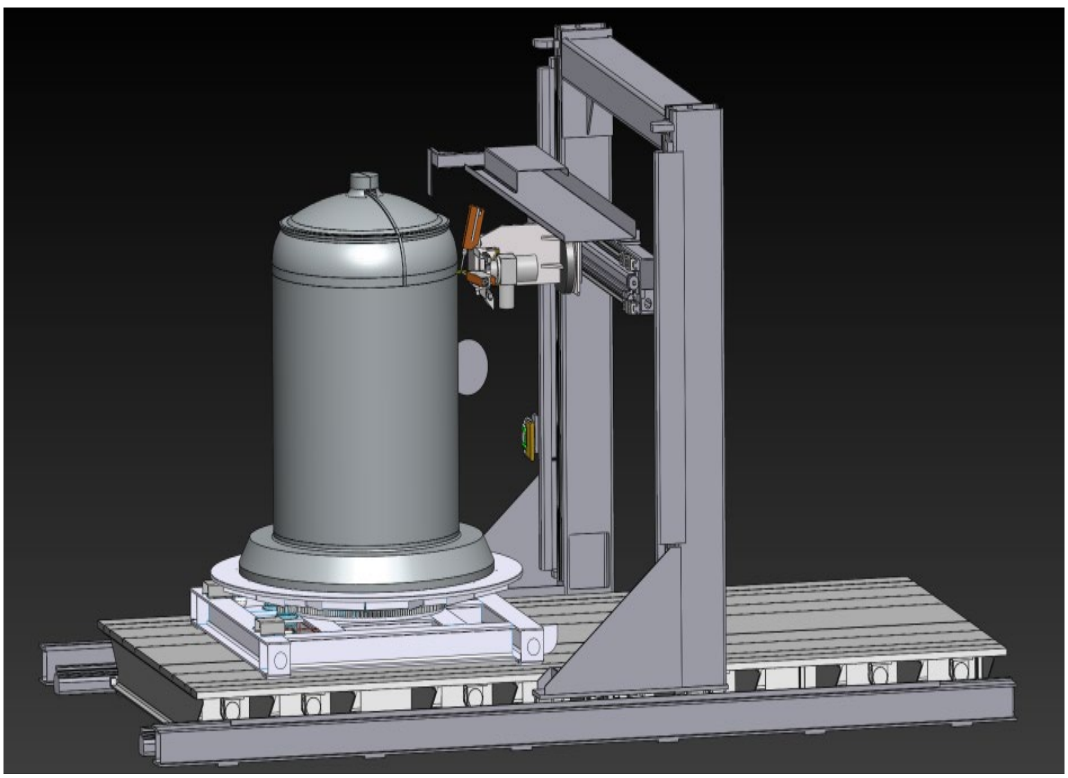

Figure 10. EB welding will also be used to join the lower head to the lower flange shell.

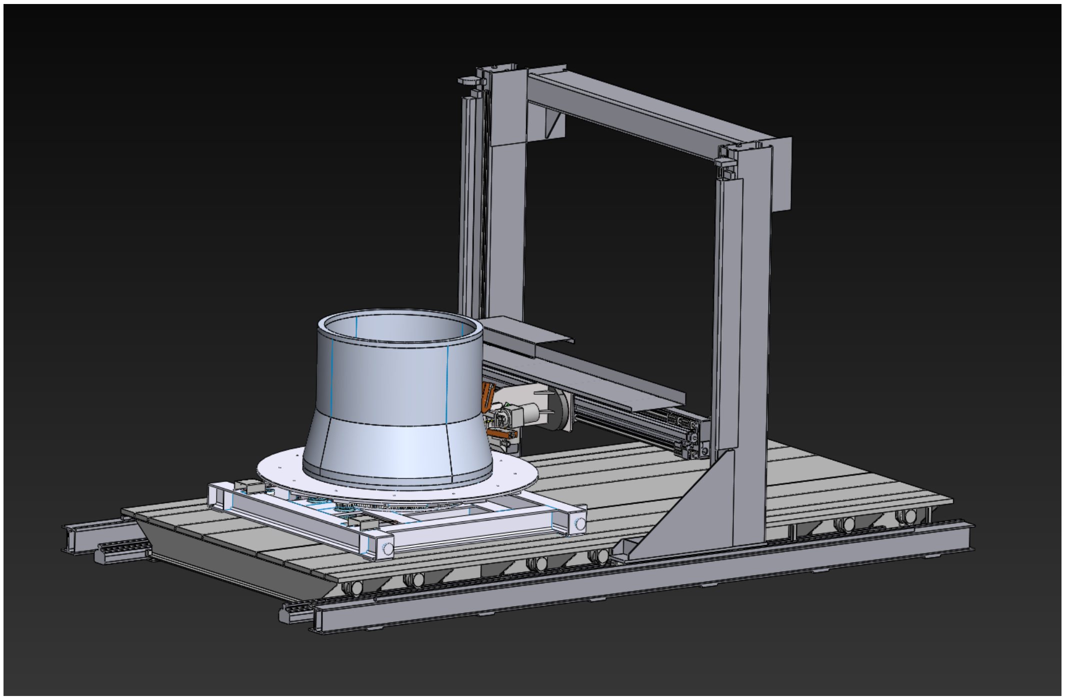

Figure 11. Upper transition shell which consists of 4 individual PM-HIP sections joined via vertical EB welds. EB welds are shown in blue.

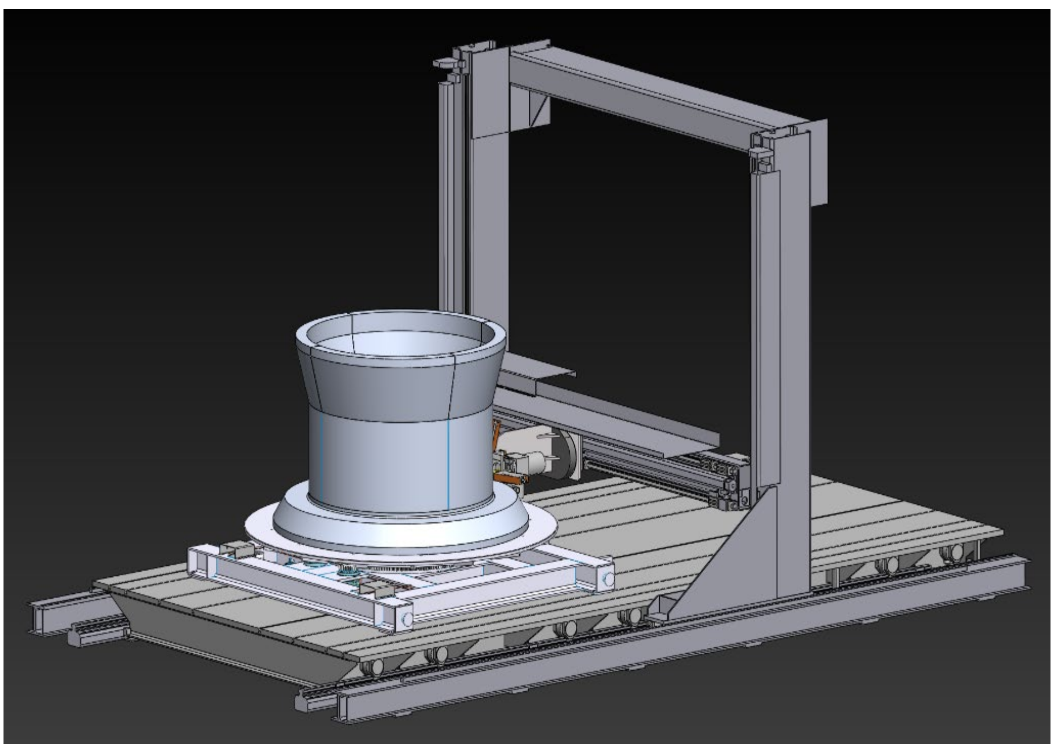

Figure 12. Attachment of the upper transition shell to the upper flange will be completed using the EB process.