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PM-HIP for Nuclear: Outlook, Technology and Applications

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Abstract. Significant reductions in CO_2 greenhouse gas emissions must be realized to meet the US goal of a 50% overall decrease by 2030. To further meet the net-zero emission goal by 2050, substantial reductions across three primary sectors (electricity, transportation, and industrial/buildings) must also be realized. Within the electricity sector, these significant reductions can only be accomplished through the replacement of much of the existing power generation infrastructure with renewables, hydrogen, natural gas, storage and new nuclear. It is anticipated that by 2050, the US will have to replace nearly 800GW of fossil and nuclear power generation assets (Note: 1GW = ~750,000 homes or 2 coal-fired power plants). This paper highlights several planned nuclear units (40 units) that are slated for production by the 2030 timeframe. If the PM-HIP community wants to be a part of this transition and support new nuclear, it too must begin work immediately to both qualify new materials/components and further develop its infrastructure for new component manufacturing and fabrication. This paper provides an overview of the current materials that are accepted within the ASME Boiler and Pressure Vessel Code and highlights recent changes which will allow PM-HIP materials/components to be more easily integrated and accepted into the Code. Additionally, this paper identifies many of the key needs for PM-HIP to be considered part of the new build equation including two enabling technologies: PM-HIP modeling & design and large PM-HIP capabilities, along with three additional supporting needs: powder production, scaling of components, and engagement of the end-user community.

Pathway to Net-Zero

From 2005-2018, the US reduced overall CO_2 greenhouse gas emissions by ~12 percent. From 2018-2030, the US expects to reduce emissions by another 38 percent which would bring the overall reductions to 50 percent over a 25-year period. To date, much of this reduction can be attributed to the electricity industry where many coal burning fossil units have been displaced with cleaner and more efficient gas units or renewables (wind, solar, etc.). To achieve the 50% reductions by 2030 however, other industry sectors must become more deeply involved along with the electricity sector. Specifically, the transportation and industrial/buildings sectors must also reduce their emissions substantially. Hence, the big drive by industry to electrify the automotive industry and to work with industrial/building owners to significantly improve energy efficiencies. To approach net-zero applications, even further reductions will be required along all 3 sectors. Figure 1 provides a view of some of the modeling efforts by EPRI to more clearly show the reductions that will be required [1].

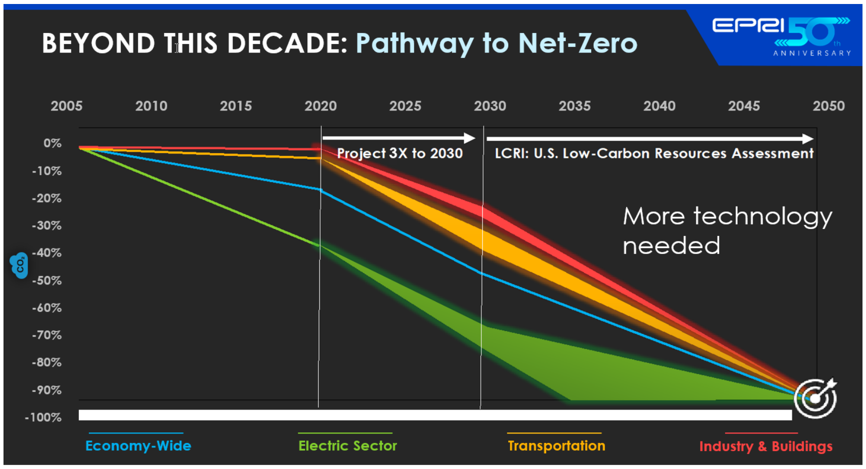

Figure 1. Pathway to Net-Zero [1].

The transformation of the electricity sector will be immense over the next four decades and will include renewables, hydrogen, natural gas, storage, and of course—nuclear (Fig. 2). It is anticipated that by 2050, the US will have to replace almost all its 800GW of fossil and nuclear generation assets. That is a huge amount of electrical capacity that will require replacement and certainly nuclear will play a large part in this replacement. Consistently over the past several decades, nuclear has made up roughly 20% (100GW) of the domestic production and is anticipated to remain around those levels. Furthermore, the 800GW does not include "new nuclear" applications that will also be added to the mix. As one can imagine, the supply chain will have to significantly ramp upwards to accommodate the demand that is expected over the next several decades. More on this topic can be found in References 1 and 2.

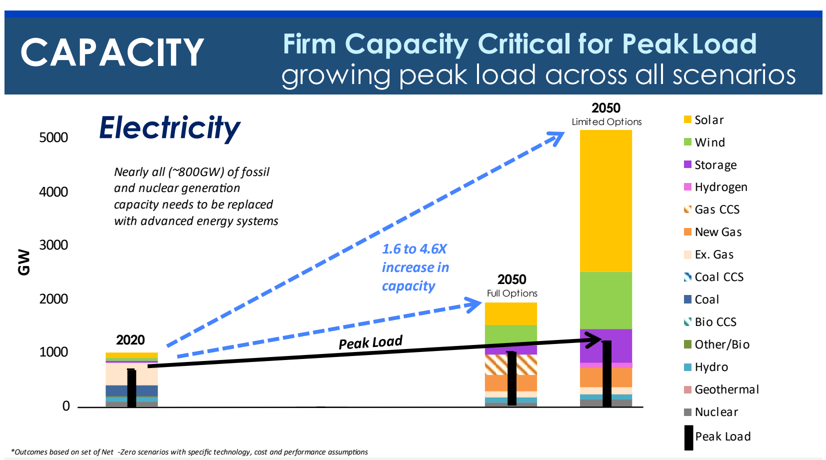

Figure 2. Project electricity capacities within North America through 2050 [1].

Advanced Nuclear Deployment Plans

The Nuclear Energy Institute (NEI) recently highlighted several planned or under construction projects in the US and Europe (note, this doesn't include China and Russia where significant investments are also being made) [3]. Table 1 provides a snapshot of ~40 reactors (~7500MW total) that are planned to be operational by 2030-32. These units include grid-scale reactors and represent only the tip of the iceberg in terms of new builds over the next decade. A similar list can also be found for micro-reactors (reactors below ~10MW) [3]. Even at this level, it is anticipated that the supply chain will be strained to meet the demand as much of the manufacturing/fabrication capabilities in the USA have now moved overseas, NEI suggests that as many as 300 reactors generating 90GW of "new capacity" might represent the low end of commissioning over the next three decades [4].

Table 1. Advanced reactor deployment plans [3].

Developer	Utility / User	Location	Size	Target Online
NuScale	UAMPS	Idaho, USA	6 @ 77MW	2029
	KGHM Polska Miedz	Poland	6 @ 77MW	2029
	Nuclearelectrica	Romania	6 @ 77MW	2028
GEH BWR X-300	OPG	ON, Canada	300 MW	2028
	TVA	TN, USA	300 MW	2032
	Synthos & Orlen	Poland	300 MW (>10 plants)	Early 2030s
	SaskPower	Sask., Canada	~300 MW (4 plants)	2032 to 2042
Holtec SMR-160	TBD	NJ, USA	160 MW	2030
X-energy Xe-100	Grant County PUD	WA, USA	4 @ 80MW	2027
TerraPower	Pacific Corp.	Wyoming	345 - 500MW	2028
ARC	NB Power	NB, Canada	100 MW	2030
Moltex	NB Power	NB, Canada	300 MW	2032
TBD	Purdue/Duke Energy	Indiana, USA	TBD	TBD

So as one can see, "WE'RE GOING TO BUILD A LOT OF POWER PLANTS AND COMPONENTS OVER THE NEXT SEVERAL DECADES!"
Even if these projections are under by 50%, there is still ample space for the PM-HIP community to be deeply involved. Later in this paper, some "key needs" and common areas that the HIP community can begin working on collaboratively will be presented.

Approved Alloys Added to 2021 Edition of ASME Code

The ASME Boiler and Pressure Vessel Code has been developed over many decades by industry to provide standard rules for the construction of steam boilers and other pressure retaining components. Section I of the Code provides rules governing Power Boiler applications, Section II provides rules for Materials, and Section III provides rules for Construction of Nuclear Facility Components, while Section VIII provides rules for Pressure Vessels. Until recently, PM-HIP was only acknowledged within the ASME Code through a handful of Code Cases. In 2021, Section II-Materials recognized ~30 HIP materials for the first time by incorporating several ASTM specifications as SA/SB standards:

- SA988/SA988M -- Specification for Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service
- SA989/SA989M -- Specification For Hot Isostatically-pressed Alloy Steel Flanges, Fittings, Valves, And Parts For High Temperature Service
- SB834/SB834M -- Specification for Pressure Consolidated Powder Metallurgy Iron-Nickel Chromium-Molybdenum (UNS N08367), Nickel-Chromium- Molybdenum Columbium (Nb) (UNS N06625), Nickel- Chromium-Iron Alloys (UNS N06600 and N06690), and Nickel-Chromium-Iron-Columbium Molybdenum (UNS N07718) Alloy Pipe Flanges, Fittings, Valves, and Parts

This recognition is very significant in that several austenitic stainless steels, ferritic steels, and nickel-based alloys are now available for use in pressure retaining applications.
Additionally, and equally important, new guidance was provided to industry for qualification and acceptance of PM-HIP. This permits PM-HIP to be used for the manufacture of components in a

similar manner to that applied for forged, cast, or other wrought product forms as long as one can qualify the material. The guidance is provided under the following:

- BPV-II, Part D, Mandatory Appendix 5 -- Guidelines on the Approval of New Materials Under the ASME Boiler and Pressure Vessel Code

For materials accepted under Section II-Materials to be used in pressure retaining applications, one of the three Book Sections (Section I, III, VIII) must also recognize the material. For nuclear applications, Section III has recently incorporated/recognized 316L stainless steel (UNS S31603) under a Mandatory Appendix (Record No. 21-2331) that permits its use for component manufacture. Prior to this, 316L SS was only recognized under Code Case N-834. The incorporation of 316L SS now provides a blueprint for recognition of additional alloys under Section III. Priority alloys which may be incorporated over the next several years include: SA508 low alloy steel and several nickel-based alloys: 600, 617, 625, 690 and 800H.

Approved Alloys & New Alloys Needed

Many of the alloys found within nuclear applications to date have been manufactured using product forms such as forgings, castings, extrusions, etc. Applications have been for the most part at reasonably lower temperatures (<400C) to date. As industry moves toward higher temperature (550-750C) Advanced Reactor applications, additional alloys qualifications will be required. To date, only six alloys have been recognized for high temperature nuclear applications:

- 2-1/4Cr-1Mo
- A508 Grade 3 Class 1 and SA533 Type B Class1
- 9Cr-1M-V (Grade 91)
- 304/304H and 316/316H
- Alloy 800H
- Alloy 617

Many additional alloys are currently being considered for nuclear applications or actual qualification of various product forms of these alloys is underway. EPRI has developed an Advanced Reactor Materials Development Roadmap that highlights many of these alloys. (5). Several of these are highlighted below:

- Stainless Steels
- 316LN, 316H, 316FR, 15-15Ti, D9, Alumina forming SS
- Ferritic or Ferritic-Martensitic Alloys
- 508 Grade 3, Classes 1 and 2
- F/M-9Cr and 12Cr
- Nickel Alloys
- 625, 690, 617, 800H
- Cladding applications
- Mo, W, Hastelloy N

As one might anticipate, many of these alloys can be readily produced by the PM-HIP process based on current industry experience. It's simply a matter of qualifying the alloys for Section III, Division 5 applications. The PM-HIP industry is encouraged to work with EPRI and various OEMs to bring these alloys forward for higher temperature service.

What's Required for PM-HIP to Be Part of the Plans for Advanced Nuclear Deployment – Key Needs

As noted earlier, the nuclear industry plans to deploy ~40 SMRs and ARs by the 2030 timeframe. To accomplish this, many have elected to use conventional product forms for first-of-a-kind (FOAK) applications. However, as new manufacturing methods and alloys are qualified, OEMs will look toward more advanced manufacturing methods such as PM-HIP and Additive Manufacturing to produce components. To be part of the overall plans for advanced nuclear deployment, the PM-HIP community must begin qualification of components/materials now as it can often take 3-5 years to gain acceptance within the Code. Furthermore, there are several other key needs that must be addressed over the next few years if PM-HIP is to become mainstream for nuclear applications:

- PM-HIP Modeling & Design
- Powder Production (quality & quantity)
- Large HIP
- Scaling of Components
- Engagement of End-User Community

Each of these needs will be discussed further below. However, before beginning that discussion, let's look a bit more deeply at what the cost drivers are for PM-HIP applications. Figure 3 provides a good overview of both the cost drivers and the commercial availability for each step in the overall PM-HIP process. As can be seen from the figure, modeling/design of the capsule and powder costs are the two most significant influencers from a cost perspective, while model/design and capsule filling are the two steps that are currently very limited in terms of commercial availability. Each of these elements play a large role in acceptance of PM-HIP technology for the production of large parts and require further focus by industry.

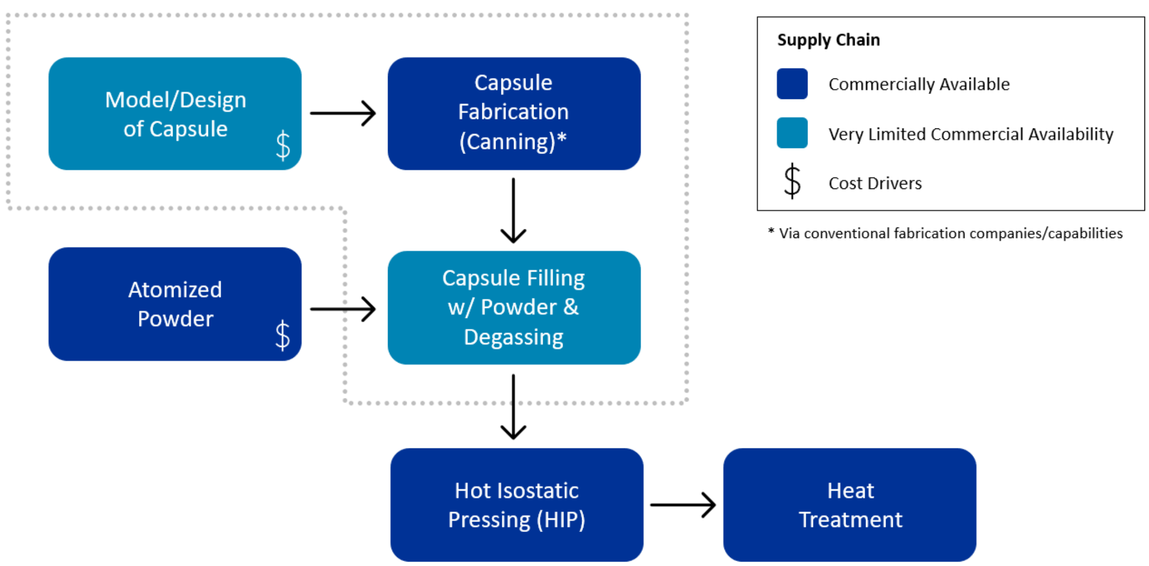

Figure 3. Cost drivers and commercial availability for each step in the overall PM-HIP process.

PM-HIP Modeling & Design. Modeling & capsule design are seen as a key enabler for PM-HIP technology expansion and deployment. Today only a handful of modelers/designers currently exist in this market around the world. This is very limiting if the industry plans to expand into large component production. If industry expects PM-HIP technology to expand further and become "mainstream" to compete (and/or supplement) forging and casting technologies, industry must develop improved modeling capabilities and performance. Other forming industries use advanced tools like DEFORM®, MAGMA®, and PROCAST® to name a few, that enable engineers to predict casting and forging product sizes and movement. A similar capability for modeling/design is sorely needed for the PM-HIP industry if modelers/designers of equipment are expected to consider PM-HIP for various pressure retaining and large structural applications. Constitutive models have been developed for <20 alloys to date. (6-15) Furthermore, constitutive properties are often held by the developer and used as a competitive advantage. Industry should look to come together to share models/properties and to develop new models/properties for alloys that could be used soon. Development of software models/properties are the #1priority for the PM-HIP industry to be a part the advanced nuclear equation.

Powder Production. Over the past decade, many powder manufacturers have moved to support the additive manufacturing community. Unfortunately, this has led to a flat or possibly lower powder production rate for PM-HIP applications, just as the nuclear industry is looking to dramatically expand into new alloys/markets. Powder manufactures are encouraged to work with OEMs and developers to better understand the needs in powder production for nuclear applications and to support development of new alloy powders for this industry.

The following example demonstrates how one organization could use PM-HIP for nuclear applications. Please note, this represents only one OEM, and many others are going to be part of the nuclear market. The NuScale Power reactor is used here only as an example. Table 2 identifies four major components (lower head, upper head, steam plenum, and access ports) that could be produced from PM-HIP, while the rest of the reactor would be manufactured with conventionally forged products. As shown, the total weight for these four components would approach 100,000lbs (45,300kgs) for just one reactor. At full production, NuScale Power hopes to produce as many as 12 reactors annually. This would significantly strain the current powder production capabilities of industry today. It is anticipated that other OEMs would expect similar production capacities.

Table 2. An example of the projected annual powder requirements for one OEM.

Weights (full-scale) for one reactor:
- Lower Head – 19,000lbs
- Upper Head – 21,000lbs
- Steam Plenum – 39,000lbs
- Access Ports – 5100lbs x 4

→ ★ **~100,000lbs/unit X 12/year**

Large HIP. Two large scale HIP efforts, ATLAS and TITAN, are being considered by industry to produce PM-HIP components that are >3.0m in diameter. Specifically, ATLAS-4.05m and TITAN-~4.6m are both under consideration. ATLAS (Fig. 4) appears to be slightly ahead in terms of design/deployment now, but both appear to be serious considerations. For HIP to be part of the nuclear equation, one or more of these systems must be designed, fabricated, and commissioned. Both will more than likely exceed $200M (if building costs are included) and will more than likely include some level of government funding.

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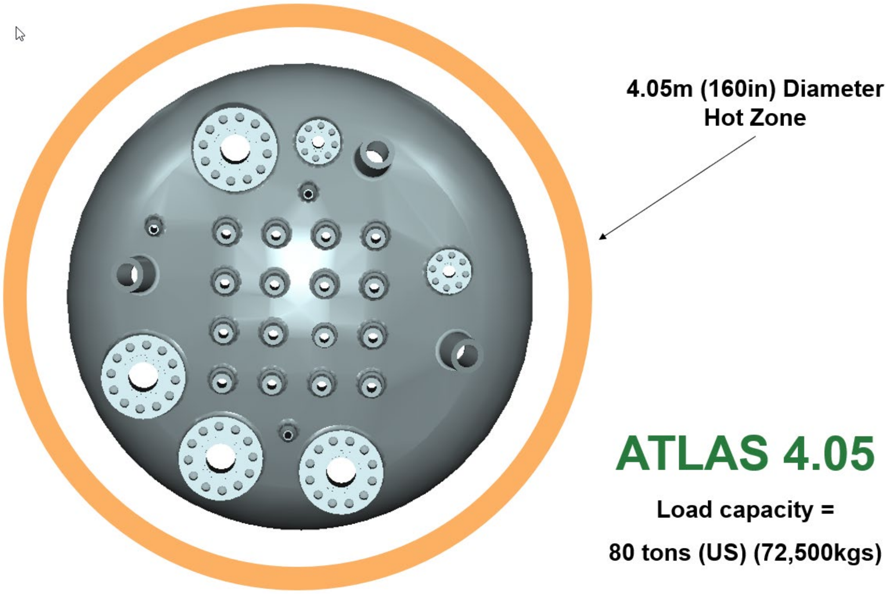

Figure 4. A schematic showing a reactor head within ATLAS 4.05.

Current plans suggest that ATLAS will be funded by a Consortium of industry investors and will be more than likely led by the BWXT, UNNPP, Stack Metallurgical, and EPRI, while the UK effort will be led by Rolls-Royce and other partners. The HIP 2022 conference will hopefully provide some greater clarity around the scope and plans of each "Large HIP" application.

Scaling of Components. Another key and often overlooked need for HIP to be realized for nuclear applications is scaling of the technology for larger components. Many of the components anticipated currently exceed the capacity of today's HIP units. As industry moves to scale beyond ~1.25m (50 inches) in diameter, many of these components will need to be scaled to assure both properties and dimensional conformance. One example that is currently being pursued by the US Department of Energy project on SMRs Manufacture and Fabrication (16) is the production of both an upper and lower head using PM-HIP. Initial research was performed on a 44% scale upper head (which would just fit inside a 65-inch HIP) (see Fig. 5). Next, it is being scaled to a 2/3-scale by producing the head in half sections and then welding it together. Eventually, when ATLAS or TITAN become realities, the heads could be produced in full section. So as one can see, the process requires some progression in scaling. It also requires development of properties at such a large scale.

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Figure 5. Scaling of large components such as a reactor head may take several iterations to reach acceptable dimensional and property requirements. A 44% upper head and one-half of a 67% upper head were manufactured under a large US DOE project [16].

Engagement of End-User Community. Lastly, production of large, nuclear components requires engagement from the end-user community as well as power producers, designers, and HIP suppliers. The end-user community is made up of major OEMs and fabricators as well as the utilities that purchase the nuclear units. Engagement is paramount for the technology to be even considered for nuclear applications. EPRI recently conducted a Supply Chain Workshop for Advanced Energy Systems which brought together both end-users and manufacturers, fabricators, etc. (2). A follow up workshop is planned for Q1-2023 to continue bringing interested participants together to address industry needs. Additionally, EPRI is also working with numerous industrial partners and an EPRI Board-funded Initiative to support Advanced Manufacturing, Methods and Materials (AM3) to accelerate qualification and deployment of high temperature materials and manufacturing processes (Fig. 6).

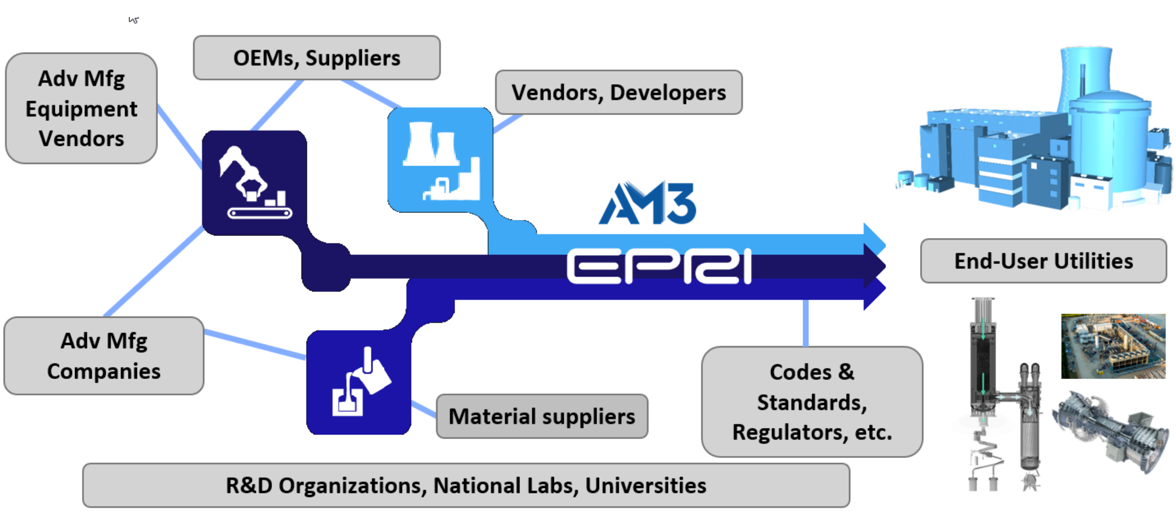

Figure 6. Engaging the entire supply chain will accelerate technology adoption.

Summary

This paper has provided discussion around various needs and activities necessary for PM-HIP to be considered part of the equation for Small Modular Reactor and Advanced Nuclear Reactor applications. Specifically, the paper introduced both a Pathway to Net-Zero (which was based on significant EPRI modeling efforts) and discussed Advanced Nuclear Deployment Plans. From these efforts, it is clear that over the next four decades (by 2050) that approximately 800GW of existing fossil and nuclear production will need to be replaced by renewables, hydrogen, natural gas, storage, and nuclear in North America alone. It is anticipated that nuclear units will account for more than ~100GW or more of this replacement. This doesn't even include new nuclear applications; this only addresses replacement.

The paper also provided a snapshot of many of the alloy qualification needs and highlighted some of the ASME Code changes that have occurred recently to allow production of PM-HIP pressure retaining components. Priority alloys which require qualification and incorporation over the next several years include: SA508 and several nickel-based alloys: 600, 617, 625, 690 and 800H.

Finally, the paper reviewed some of the key needs around what is required for PM-HIP to be part of the plans for advanced nuclear deployment. The five key needs discussed herein include:

- Modeling & Design
- Powder Production
- Large HIP Capability
- Scaling of Components
- Engagement of the End-User Community

The two key enablers include: Modeling & Design and Large HIP Capability. Today only a handful of modelers/designers currently exist within the PM-HIP community around the world. This is very limiting if the industry plans to expand into large component production. If industry expects PM-HIP technology to expand further and become "mainstream" to compete (and/or supplement) forging and casting technologies, industry must develop improved modeling capabilities and performance which allow designers and manufacturers to rapidly model/design capsules for production purposes.

Two large scale HIP efforts, ATLAS and TITAN, are being considered by industry to produce components that are >3.0m in diameter. Specifically, ATLAS-4.05m and TITAN-~4.6m are both under consideration and are highlighted herein.

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