NRC Technical Assessment of Powder Metallurgy—Hot Isostatic Pressing

1. Introduction and Purpose

This document provides a U.S. Nuclear Regulatory Commission (NRC) technical assessment of the process considerations and knowledge gaps related to the application of powder metallurgy—hot isostatic pressing (PM-HIP) in the nuclear power industry. This assessment is primarily based upon the technical information and gap analysis developed by Oak Ridge National Laboratory (ORNL) in technical letter report (TLR) entitled "The Use of Powder Metallurgy (PM) and Hot Isostatic Pressing (HIP) for Fabricating Components of Nuclear Power Plants (NPPs)," (Agencywide Documents Access & Management System (ADAMS) Accession No. ML22164A438) (hereafter referred to as the "ORNL TLR"). This assessment, combined with the ORNL TLR, highlights key technical information related to the implementation of PM-HIP in nuclear facilities and fulfills the deliverable for PM-HIP under Subtask 1A of the "Action Plan for Advanced Manufacturing Technologies (AMTs), Revision 1," dated June 23, 2020 (ADAMS Accession No. ML19333B973).

2. NRC Identification and Assessment of Differences

This section describes the differences between PM-HIP and traditionally manufactured heavy section large components, assesses the impact that the identified differences have on component performance, and identifies specific technical considerations related to PM-HIP components. The overall impact to plant safety (e.g., safety significance) of these identified differences is a function of component performance and the specific component application (e.g., its intended safety function). This report does not include impact on plant safety, as such an assessment would not be possible without considering a specific component application.

The staff identified the differences between PM-HIP and traditional manufacturing processes by reviewing the information and gap analysis rankings from the ORNL TLR, as well as other relevant technical information (e.g., from NRC regulatory and research experience, technical meetings and conferences, codes and standards activities, Electric Power Research Institute and U.S. Department of Energy products and activities). The identified differences and their significance originated either as important aspects or gaps of the PM-HIP process or component performance as defined here:

- <u>important aspect</u>: part of the AMT fabrication process or component performance that needs to be considered and carefully controlled during manufacturing

- <u>gap</u>: part of the AMT fabrication process or component performance that is not well known or understood due to limited information and data

The results of this technical assessment are provided in two tables. Table 1 includes the powder production and PM-HIP process considerations. Table 2 includes additional material-specific considerations for producing PM-HIP components using American Society for Testing Materials (ASTM) A508, "Standard Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels," Grade 3, Class 1 low-alloy steel (A508), which is the alloy of primary interest from the nuclear industry for producing heavy section large components. Components produced by PM-HIP using 316L stainless steel are generally smaller in size and weight and have undergone an extensive development effort that has led to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (ASME Code), Section III, “Rules for Construction of Nuclear Facility Components,” Division 1, Code Case N-834, “ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components Section III, Division 1,” for Class 1 components. While Table 2 is based on the available information in the open literature for A508-type low-alloy steels, the differences identified in Table 2 involving material-specific properties and performance would likely need to be considered for any new material to be fabricated using PM-HIP. In general, an important need for any nuclear PM-HIP component is material-specific data for the proposed processing and post-processing parameters to ensure adequate component performance in its environment, including applicable properties (e.g., fracture toughness, tensile strength) and aging mechanisms (e.g., thermal aging, irradiation effects, and stress corrosion cracking (SCC)).

The following columns in Tables 1 and 2 identify and provide technical information for the PM-HIP process and component performance:

- **Difference:** Identification of corresponding gaps from Section 3.2 of the ORNL TLR.
- **Definition:** Brief description of the difference with the PM-HIP process.
- **NRC Ranking of Significance:** Discussion of two considerations:
    - **Importance:** Impact on final component integrity considering the likelihood of occurrence or magnitude of degradation in conjunction with the ease of detection or ability to mitigate.
        - A *high* ranking signifies that the difference has a significant impact on component performance.
        - A *medium* ranking signifies that the difference has a moderate impact on component performance.
        - A *low* ranking signifies that the difference has a minimal impact on component performance.
    - **Knowledge/Manageability:** Description of how well understood and manageable the difference is.
- **Key Technical Information:** Technical information for the consideration of PM-HIP for use in nuclear power plants.

Discussion of the corresponding ORNL gaps can be found in Section 3.2 of the ORNL TLR.

3. Codes and Standards

Section 3.3 of the ORNL TLR provides an overview of the ASME Code, including an analysis to identify any gaps pertaining to using PM-HIP to fabricate heavy section, low-alloy-steel components. For heavy section, low-alloy-steel components, there is a need to develop an ASTM specification for PM-HIP low-alloy steel to use as a basis for an ASME Code, Section III, Code Case and eventual inclusion in ASME Code, Section II, “Materials,” Part A, “Ferrous Material Specifications,” and Part D, “Properties.” Key challenges include consistently fabricating materials with sufficient starting and irradiated fracture toughness as described in Tables 1 and 2.

4. Summary and Conclusion

In Tables 1 and 2 of this report, the staff has identified and assessed the material-generic differences for the PM-HIP process and component performance as well as the material-specific differences for A508 low-alloy steel compared to conventional manufacturing. The staff has also discussed gaps in existing codes and standards that should be addressed to support PM-HIP use in nuclear applications, including the need to develop an ASTM specification and ASME Code Case for PM-HIP of low-alloy steel to support eventual inclusion of this material in ASME Section II.

Table 1 Technical Information—PM-HIP Generic

Difference	Definition	NRC Ranking of Significance	Key Technical Information
Metal Powder Composition and Particle Size Distribution[1]	Metal powder composition and particle size distribution covers the production and management of the important physical characteristics of the powder before the build process.	**Low** The composition and particle size distribution of gas atomized metal powders must be carefully controlled within specifications to ensure adequate properties and performance of the final product. However, commercial production of gas atomized metal powders is very mature and well established.	• Producing metal powders by atomization is the preferred method since any composition can be produced accurately to specifications. – Depending on the reactivity of the metal powders, the proper choice of atomization process must be considered since an increase in reactivity will potentially lead to an increase in contamination of the metal powder. • Optimal particle size should balance densification with the likelihood of contamination. – Generally, smaller particle sizes help to achieve higher packing density and greater densification after HIP but can also increase the likelihood of contamination due to their higher percentage of surface area to volume. • The particle size and size distribution characteristics of metal powders are influenced by the atomization method and the associated process parameters used in powder production. • Sieving is an essential activity to effectively control the particle size and size distribution. – Sieving also ensures a proper size range for filling and packing the inside of the steel can, which improves the densification and microstructure of consolidated component after HIP.
Metal Powder Production by Gas Atomization	This covers the important considerations of using gas atomization for the commercial production of high-quality metal powder for manufacturing PM-HIP components.	**Low** The method of melting the elemental constituents of stainless steels and low-alloy steels and the atomization environment can significantly affect the quality of the powder and resulting component properties and performance. However, these powder production methods have been studied carefully and are well established.	• Inert gas atomization methods are superior to air and water atomization methods since the surface of the molten metal droplets are protected by the inert gas atmosphere during solidification to form powder with varying sizes with low oxygen content. – Water atomization produces irregular-shaped particles with higher oxygen levels compared to gas atomization. • Gas atomization using primarily argon and nitrogen has emerged as the most popular method for producing high-quality powders that have spherical morphology and accurate and reproducible compositions of a wide range of stainless steels, low-alloy steels, and nickel-based alloys. • Important gas atomization parameters that are optimized in order to produce desirable particle size and size distribution include high gas-to-metal ratio, melt superheat, and gas recirculation.

Difference	Definition	NRC Ranking of Significance	Key Technical Information
Design and Fabrication of Heavy Section Large Steel Cans[2]	The can serves as the pressure vessel containing the metal powder and must form an impenetrable seal between the metal powder and pressurized gas during HIP. Producing heavy section large steel requires fabricating cans of corresponding size. This covers the important considerations of designing and fabricating these cans, including the use of modeling to predict the densification of the can and metal powders during HIP to achieve the dimensional tolerances required for a component.	**Medium** Scaling up the fabrication of steel cans from design specifications for producing heavy section large components by PM-HIP has been successfully demonstrated in initial applications. Design models for predicting the volume shrinkage of heavy section large steel cans have been successfully demonstrated to be accurate with low or no distortions. However, the design and fabrication of large cans is dependent on component-specific properties and characteristics (e.g., complexity of the component geometry).	• ASTM PM-HIP specifications require that the can material be selected to ensure that it has no deleterious effect on the final product. • The materials used for fabricating the can must have high strength for dimensional stability and ductility for plastic deformation during the dimensional reduction of the can to the fully dense product. – The materials typically used for fabricating the can are stainless steel and low-carbon steels due to the combination of strength and ductility properties. • The wall thickness of the can is important to consider. The can must be thick enough not to crack or fail during the HIP process but not too thick since a thick wall will resist plastic deformation compared to a thinner wall. • The steel can must also be weldable to ensure mechanical integrity of the can during volumetric shrinkage associated with HIP. • The design and geometric dimensions of the component are important factors that need to be optimized for predicting the volume shrinkage and minimizing post-HIP machining of the can from the product. – For example, differences in the thickness of sections should be considered in the design and fabrication of the cans as they will impact the densification of the can and powder due to uneven cooling rates. • For the complex can designs, models are required for predicting the volumetric shrinkage. – This especially applies to very large can designs since less experience and knowledge are available due to the limited number of large products that are typically produced by PM-HIP. • The accuracy of modeling to predict the volume shrinkage of the large can will influence the can design, including selection of material, complexity of the component geometry, and HIP parameters. • Large complex-shaped components will likely need a demonstration run to verify the HIP procedure, including shrinkage prediction and achievement of dimensional tolerances.

Difference	Definition	NRC Ranking of Significance	Key Technical Information
			• Dimensions of the steel can may be intentionally oversized due to uncertainties in precisely predicting the volume shrinkage of the powder and deformation behavior of the steel can during HIP. • Most models that have been developed are based on continuum mechanics, such as micromechanical simulations and constitutive relations, using the finite element method for calculating the distributions of stress and density of the metal powder enclosed can. These approaches consist of plasticity models to understand the mechanical properties, such as yielding and hardening of the metal powder during compaction and continuum models for predicting the effects of sintering on changes in grain size, densification, and plastic deformation of the metal powders.
Filling, Degassing, and Vacuum Annealing of Metal Powders[3]	This covers the important considerations related to the process for filling, degassing, and vacuum annealing of metal powders before HIP.	**High** Improper filling, degassing, and vacuum annealing can cause contamination of the metal powder and can adversely affect densification. This can have a significant impact on final product performance. There is limited industry experience with properly filling large cans for PM-HIP, especially for components with complex shapes. Also, vacuum degassing has not been effectively demonstrated on the large cans needed for heavy section PM-HIP components, and degassing will be more challenging as the component size increases.	• Proper degassing conditions must be used for successful desorption of all adsorb molecules associated with contamination. – Degassing effectiveness is influenced by the combination of the vacuum pump properties (pressure, flow rate, etc.) and the design and placement of the degassing ports and lines connecting to the pump. – The temperature during degassing is an important consideration to prevent contaminant gases from forming stronger bonds (e.g., oxides and nitrides) with the metal powder particles. – Air is the most common contributor to contamination of metal powder. • Improper filling may result in non-uniform packing of stainless steel and low-alloy-steel powders, particularly in large, complex-shaped steel cans. – This may result in different local tap densities of the powder inside and cause non-uniform consolidation and local density variations of the HIP component. These issues may subsequently impact component properties and performance. • Scaling up the HIP process to larger components makes degassing more challenging due to the greater volume of gas to remove.

Difference	Definition	NRC Ranking of Significance	Key Technical Information
HIP Parameters for Heavy Section Large Components	This covers the important considerations regarding the HIP process parameters that are used specifically to manufacture heavy section large components.	**Medium** Improper HIP parameters may affect the densification and microstructure and can impact mechanical properties of the large component. Although optimized HIP parameters have been developed for various other applications, optimization for producing heavy section large components has not been consistently demonstrated. Post-HIP heat treatment can help obtain the required microstructure and properties.	• Understanding and optimizing HIP process parameters (e.g., time, temperature, pressure) is important for producing components with the required microstructure and mechanical properties. For example, the HIP process parameters should be optimized to reduce and eliminate pores to achieve high theoretical density of the metal. • Non-uniform densification can occur, depending on the HIP parameters for applied pressure, temperature, heating rate, and component size. Rapid heating rate combined with large component sizes can cause preferential densification of the metal powder, especially near the surface of the can, which can result in distortions. • For cans with complex geometries, differences in the thickness of sections will enhance the distortions due to uneven cooling rates caused by gas flow disturbances on the surface of the component. – Reducing the cooling rate can reduce the temperature differences but will add time to the cooling cycle and may affect the resulting mechanical properties. • Proper HIP parameters combined with rapid cooling rates through the use of argon cooling systems can eliminate the need for post-process heat treatment.
Witness Specimens and Protrusions	Witness specimens and protrusions are test specimens that are fabricated concurrently with end-use components and used to provide confirmation of build quality and product performance.	**High** Protrusions and witness specimens can be used to measure the density and mechanical properties of heavy section large components to demonstrate process control. However, it has not been demonstrated that protrusions or witness specimens can be acceptably relied upon to verify material properties that are representative or bounding of the entire component, or at least	• The use of witness specimens and protrusions may be the only practical method to measure the density of heavy section large components. • Material for conducting microstructure, mechanical properties, and corrosion tests can be machined directly from a separately produced witness specimen or from a protrusion on the component(s) that have undergone HIP. • Use of witness specimens and protrusions should demonstrate that they are representative of the component's performance. – Dimension and size relative to the component are two important factors for witness specimens. – The dimension, size, number, location, and orientation relative to the steel can are important factors for protrusions. – For producing heavy section large components by PM-HIP, the dimensions of the witness specimens and protrusions may need to match the largest thickness of the component. This can

Difference	Definition	NRC Ranking of Significance	Key Technical Information
		those critical locations that govern the design requirements.	ensure that microstructural inhomogeneities that may occur in the heavy section large component are captured in the witness specimens and protrusions for correlation between mechanical properties measurements. – Microstructural inhomogeneities can be due to variations with tap density of the metal powder and variations in localized densification rates and cooling rates between the surface and internal location.
Can Removal/ Surface Finish/ Processing	This refers to any combination of machining, finish grinding, and other surface treatments that are employed both to remove the can after completing HIP and to meet the final dimensional requirements for the component.	**Low** Post-HIP surface finish can be a potential concern, depending on the can removal method. However, machining to the final dimensions and surface post-processing steps can make surface finish similar to conventionally manufactured components. The machinability of the PM-HIP component would not be expected to differ significantly from conventionally manufactured components.	• Depending on the can removal method, a fairly rough surface may be left. Lack of post-HIP machining or surface processing (such as peening or grinding) may lead to greater susceptibility to SCC, corrosion, and fatigue. • If can removal is done by acid pickling, the effects of the acid on the component surface should be carefully considered and mitigated as needed. • For low-alloy-steel materials, the can removal should be done by machining rather than acid pickling due to the susceptibility of low-alloy steel to acid. • Because machining can be used to meet the final dimensional tolerances for a component, the dimensions of the steel can are sometimes intentionally oversized. Due to uncertainties in precisely predicting the volume shrinkage of the powder and deformation behavior of the steel can during HIP, oversizing and machining may be more practical for producing heavy section large components for nuclear reactors by PM-HIP.

Note 1: Difference combines the “Composition assurance of the gas atomized metal powders” and “Powder particle size distribution” ORNL gaps from Section 3.2 of the ORNL TLR.
Note 2: Difference combines the “Fabrication of heavy section large steel cans” and “Predicting the volume shrinkage of heavy section large components during HIP” ORNL gaps from Section 3.2 of the ORNL TLR.
Note 3: Difference combines the “Filling the large Steel Can with the metal powders,” “Degassing and vacuum annealing of metal powders,“ and “Scale Up of the Vacuum System for Degassing Powders in Heavy Section Large Steel Can” ORNL gaps from Section 3.2 of the ORNL TLR.

Table 2 Technical Information—PM-HIP A508 Material-Specific

Difference	Definition	NRC Ranking of Significance	Key Technical Information
Impact Toughness[1]	Impact toughness can be correlated to fracture toughness, which is a measure of the material's ability to resist the propagation of flaws.	**High** Producing heavy section large low-alloy-steel components by PM-HIP with consistent and acceptable impact toughness is a significant challenge. Consistent process control through the fabrication process (powder production, handling, storage, degassing, and conducting HIP) is needed to achieve densification, minimize contamination, and produce optimal toughness properties.	• To date, large components produced by PM-HIP have not been able to produce sufficient impact toughness consistently across the component. • A number of microstructural or composition variations may contribute to reduced impact toughness values as well as increased toughness variability. – Oxygen contamination or varying oxygen levels may contribute to reduced impact toughness in PM-HIP low-alloy-steel components. • Control of the oxygen and other contamination in PM-HIP produced large components needs to be managed effectively through the powder production, handling, storage, and degassing stages. • Optimizing HIP process parameters and post-HIP heat treatment would be expected to improve impact toughness values and consistency. • Given that PM-HIP A508 is a new product form that may behave differently from that of forgings, the correlation between acceptable Charpy impact and fracture toughness properties of PM-HIP A508 should be demonstrated.
Stress Corrosion Cracking (SCC)	SCC refers to stress crack initiation and subsequent crack growth of susceptible materials operating under approximately constant stress in a corrosive environment.	**Low** Low-alloy-steel materials generally do not come into contact with the light-water reactor (LWR) environment due to the use of stainless steel cladding, so SCC is not likely to occur.	• PM-HIP is not expected to significantly change the SCC performance in these materials, but test data would be helpful to confirm this expectation. • Lack of post-HIP machining or surface processing may lead to greater susceptibility to SCC. • SCC is a common failure mode in nuclear power plant applications but has generally not been a significant issue in low-alloy-steel components due to the use of stainless steel cladding to separate the low-alloy steel from the coolant. In addition, water chemistry is tightly controlled to reduce the corrosion potential of the system.

Difference	Definition	NRC Ranking of Significance	Key Technical Information
			• SCC in medium-strength unclad low-alloy steels, such as A508, has not been observed in primary pressure boundary LWR environments.
Fatigue	Fatigue refers to the initiation and propagation of cracks due to cyclic loading with or without environmental effects playing a significant role in the process.	**Medium** Fatigue is an important design requirement for some nuclear components. Limited data suggest that fatigue performance may be similar to wrought materials.	• Very few publications were found that discuss fatigue of PM-HIP low-alloy steels. • Lack of post-HIP machining or surface processing may lead to greater susceptibility to fatigue. • Optimizing HIP process parameters, post-HIP heat treatment, and post-HIP surface finish processing would be expected to improve fatigue susceptibility. • PM-HIP materials should demonstrate sufficient strength to mitigate high-cycle fatigue and sufficient ductility to mitigate low-cycle fatigue. • Data in representative environments are important to support fatigue calculations, including environmentally assisted fatigue in PM-HIP materials.
Irradiation Effects	Irradiation effects refer to the impact of neutron irradiation on various aspects of material properties and performance, including, but not limited to, loss of fracture toughness, irradiation assisted SCC, and void swelling.	**High** Irradiation effects are a significant aging effect for low-alloy-steel reactor pressure vessel components. Very limited data are available on neutron-irradiated PM-HIP low-alloy-steel materials.	• Low-alloy steels in the wrought condition are susceptible to irradiation effects, including embrittlement, at LWR-relevant temperatures and neutron doses. • PM-HIP-produced low-alloy steels are expected to exhibit similar irradiation responses to wrought steels having similar chemical compositions and microstructures, but test data are needed to confirm this expectation.

Difference	Definition	NRC Ranking of Significance	Key Technical Information
Other Material Aging (Corrosion, Wear, Thermal Aging)	Other material aging effects include corrosion, wear, and thermal aging. Thermal aging refers to the change in microstructure after significant time at elevated temperature, which can alter mechanical properties, including reductions in fracture toughness and ductility and increases in hardness and strength.	**Medium** There are limited data on these other aging effects that can impact component performance. The applicability and importance of mechanisms will depend on the design requirements and plant-specific application of the component.	• There are limited data on other material aging effects, such as corrosion, wear, and thermal aging on low-alloy-steel PM-HIP materials in LWR environments. • Corrosion and wear are not expected aging mechanisms for stainless-steel-clad low-alloy-steel reactor pressure vessel components but may be important for other low-alloy steel components. • Thermal aging in particular can be highly sensitive to microstructure and chemical composition, which may be different in a PM-HIP material.
Tensile Properties	Tensile properties refer to the material's ultimate tensile and yield strength as well as ductility measures such as percent elongation and percent reduction of area at failure.	**Low** A reasonable body of data to date shows that tensile properties of PM-HIP A508 components should meet or exceed those of forged A508.	• The tensile properties of PM-HIP components have been observed to be comparable to or better than those of components produced by traditional casting, forging, drawing, and rolling methods.

Note 1: Difference corresponds to the "Impact toughness variability of heavy-section large components" ORNL gap from Section 3.2 of the ORNL TLR.

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