NRC Technical Assessment of Electron Beam Welding

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 electron beam welding (EBW) 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 "Review of Advanced Manufacturing Techniques and Qualification Processes for Light Water Reactors—Electron Beam Welding," (Agencywide Documents Access and Management System (ADAMS) Accession No. ML22143A928) (hereafter referred to as the "ORNL TLR"). This assessment, combined with the ORNL TLR, highlights key technical information related to the application of EBW in nuclear facilities and fulfills the deliverable for EBW 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 the EBW process and conventional arc welding, assesses the impact that the identified difference has on the performance of welded assemblies, and identifies specific technical considerations related to EBW assemblies. This assessment was conducted on the EBW process in general; however, it identified relevant material-specific impacts and considerations. The overall impact on plant safety (e.g., safety significance) is a function of component or assembly performance and the specific component or assembly application, such as its intended safety function. This report does not include the impact on plant safety, as such an assessment would not be possible without considering a specific component or assembly application.

The staff identified the differences between the EBW and conventional arc welding processes by reviewing the information and gap analysis rankings from the ORNL TLR and other relevant technical information (e.g., 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 of or gaps in the EBW process or component or assembly performance, as defined here:

- important aspect: part of the AMT fabrication process or component or assembly performance that needs to be considered and carefully controlled during the process

- gap: part of the AMT fabrication process or component or assembly 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 contains the EBW process considerations. Table 2 compares the material properties and performance characteristics of an EBW assembly with those associated with a conventionally arc welded pressure vessel steel assembly. The results in Tables 1 and 2 are based on a generic EBW assembly; however, relevant material-specific technical information is also included. In general, any nuclear EBW assembly needs to have material-specific data for the proposed processing and post-processing parameters to ensure adequate component or assembly performance in its environment, including applicable properties (e.g., fracture toughness) and aging mechanisms (e.g., irradiation effects and stress corrosion cracking (SCC)).

The following columns in Tables 1 and 2 identify and provide technical information for the EBW process and the properties and performance characteristics for EBW assembly:

- **Difference:** Identification of the corresponding gaps from Section 3.4 of the ORNL TLR.
- **Definition:** Brief description of the difference with the EBW process.
- **NRC Ranking of Significance:** Discussion of two considerations:
    - **Importance:** Impact on final weld 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 EBW for use in nuclear power plants.

Discussion of the corresponding gaps can be found in Section 3.1 of the ORNL TLR.

3. Codes and Standards

Section 3.2 of the ORNL TLR provides an overview of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (ASME Code) pertaining to EBW of nuclear components, including an analysis to identify any gaps. EBW is generally accepted across the ASME Code, given that the prescribed post weld heat treatment (PWHT), non-destructive testing, and destructive testing of weld joints requirements are followed. The ORNL TLR does note a few cases for which EBW is prohibited, such as the welding of instrument tubing, which is restricted to only gas-tungsten arc welding, as stated in ASME Code, Section III. For EBW, ASME Code, Section III, requires an ultrasonic examination in addition to radiographic examination. Therefore, the analysis found that there are no significant gaps in the codes and standards for EBW use, although there are a few current limitations.

4. Summary and Conclusion

In Tables 1 and 2 of this report, the staff identified and assessed the process considerations and differences associated with using EBW for nuclear applications, as well as the properties and performance characteristics of EBW assemblies. The staff also assessed existing codes and standards pertaining to EBW use in nuclear applications and found that there are no significant gaps for EBW use.

Table 1 Technical Information—EBW Process Considerations

Difference	Definition	NRC Ranking of Significance	Key Technical Information
Weld Repairs	The addressing of defects that occur during the EBW process to prevent them from impacting the performance and integrity of the weld.	**High** Defects formed during EBW are typically not near the surface of the weld when discovered. Weld repairs can be difficult to complete successfully and may require additional machining or grinding or both to reach the defect depth. Weld repairs may also require the use of filler metals, which can negate some of the advantages of using EBW (e.g., removing sources of trace elements, which can result in improved materials properties).	• Because the welding process is typically used for deep single-pass welds, defects that occur are typically not near the surface of the weld when discovered. This may require additional machining or grinding or both to reach the defect depth. • A re-weld may be required that consists of the repeated use of the fusion pass weld schedule over the previously welded section. This is often done in its entirety, re-welding the entire weld joint, not just the section with the defect. • More difficult repairs may require the use of a qualified procedure. Because qualifications are very expensive, the fabricator may be limited to certain repair procedures or may need to request a deviation to a procedure to best serve the product. • Arc welding is typically used for weld repairs. Repairing an electron beam weld with an arc weld using filler metals requires careful consideration of the filler metal permitted and subsequent inspections.
Unexpected Arc Shut Down / Faults During Welding	Unintended interruptions of the electron beam and weld that occur mid-process.	**Medium** Although EBW is a highly reliable process, arc faults or shutdowns can occur for various reasons, which can lead to termination of the weld and defects in the weld. These occurrences can be minimized through quality assurance (e.g., thorough cleanliness activities). Repairing electron beam welds can be difficult if it is needed.	• The EBW process is a highly reliable process. However, arc faults or shutdowns do occur for various reasons. Arc faults are known to scrap small components due to the runaway energy that is sometimes produced. • Welding amperage can spike suddenly, causing a large increase in heat input at the location of the weld. This is often followed by a fault and termination of the weld, which may leave a hole in the weld. • Dirtier materials, such as plain carbon steels, may release entrapped gases in the material due to the lower vapor pressure of the substance and vacuum during welding. This release of entrapped gases can cause momentary spikes in the gun, which can terminate the weld. • A repair to address defects can be attempted in large components; however, it may be difficult to address a

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			loss of material at the joint through expulsion at the weld top surface or at the root of the weld. • The addition of filler metal can be used to repair the weld, using either EBW or traditional arc welding.
Addition of Filler Metal using Conventional or Electron Beam Methods	Addition of metal in the making of a joint through welding, in EBW through wire-fed or preplaced filler material between the parts to be welded.	**Medium** EBW with filler metal additions has had limited historical use. Filler metal can be used to address certain issues related to EBW (e.g., porosity, excessive loss of material, difficulty of weld repair). However, careful consideration is needed to determine the use of filler, as adding filler may also negate some of the advantages of using EBW (e.g., removing sources of trace elements, which can result in improved materials properties).	• Advanced beam controls and additive manufacturing have revitalized the use of wire for EBW to the point of practical use for certain applications. – However, wire addition is still likely to remain in limited use. • Wire-fed EBW is completed by adding an alloy to improve the alloy composition of the weld. However, this can be difficult or impossible to implement, depending on the geometry of the part and access to the weld pool. • Adding a wire feeder to the electron beam welder allows for gaps in the mating materials to be filled, thus reducing the amount of residual stress on the completed weld. This may be of particular interest for very thick welds or welds where a preferential filler alloy is beneficial because of its metallurgical or corrosion resistance properties. • Adding filler metal may reduce porosity levels in the weld. • Utilizing filler metal should be carefully decided upon as the addition of filler metals introduces a source of copper, which can impact fracture toughness of the weld, especially if the component is irradiated.
Vendor/ Equipment Capability	The availability and reliability of systems that can perform EBW for girth welds, which are necessary for full-size reactor pressure vessels.	**High** EBW systems large enough to perform girth welds for full-size reactor pressure vessels do not exist in the United States. Therefore, there are no current vendors that can perform all of the electron beam welds for a fully assembled reactor pressure vessel.	• In traditional EBW, the size of the welded assembly is limited by the size of the vacuum chamber. • A reduced-pressure electron beam system has been developed for large component fabrication, eliminating the need for a large vacuum chamber. However, this technology is not currently being pursued in the U.S. nuclear industry. • Development of welding systems to accommodate the welding of small modular reactor pressure vessels is

Difference	Definition	NRC Ranking of Significance	Key Technical Information
			currently underway. Modular in-chamber EBW is being investigated for this effort.
Electron-Beam-Specific Material Specifications	The selection of alloys to construct reactor pressure vessels or other components using EBW.	**Medium** Unlike many materials where a general understanding of weldability is sufficient, EBW requires more attention to the selection of base metals due to the unique aspects of EBW and because cleaner steels are needed for EBW. However, materials that are more optimal for EBW may not have been previously evaluated for environments and degradation mechanisms applicable to nuclear power plant operation, such as neutron degradation or SCC resistance.	• The application of EBW to pressure vessel girth welds may benefit from the use of supplemental chemistry requirements within existing specification limits, such as specifying limits of tramp elements. • Materials selected for EBW typically have fewer impurities and are selected for their fast cooling rate morphology upon welding. – New materials may be sought to take advantage of EBW microstructure and process aspects. • A cleaner steel with lower amounts of trace element impurities can minimize radiation effects and may improve the fracture toughness of electron beam welds. • Alloys with high thermal expansion coefficients, such as stainless steels and alloys with high solidification shrinkage (e.g., some aluminum alloys) add to the cracking susceptibility. • New material processing techniques such as powder metallurgy-hot isostatic pressing (PM-HIP) introduce higher levels of argon, oxygen, or nitrogen, depending on the technique used. In the case of PM-HIP, it may be beneficial to place limits on the amount of oxygen and nitrogen in the material. – EBW of alloys with high gas content can result in excessive porosity and reduced fracture toughness.
Porosity	The size, distribution, and total volume of voids and pores in the weld.	**Low** Porosity formation has been studied to a great extent in laser welding. Due to the high energy density common in EBW, the two processes share many attributes. Welding in a vacuum environment helps eliminate pores, although they can still occur.	• The vacuum environment used in EBW eliminates uniform porosity in welds when materials are clean and free from entrapped gases. However, porosity can occur due to the process development, material, or loss of cleanliness of the piece parts. • Entrapped oxygen and nitrogen in steels can contribute to porosity formation, which may be an issue, particularly for EBW of PM-HIP components. • Residual magnetisms may cause the beam to deflect unexpectedly and develop root porosity in partial penetration welds.

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			• The weld schedule can be defocused to lessen the sharp intensity of the beam impingement area to reduce root porosity. • The best means of repairing pores is often to grind or machine the pore out of the weld and proceed with a repair procedure. • Adding filler metal may reduce porosity in the weld. • For aluminums, scraping the surfaces to remove the oxide layer before welding is a common technique to minimize porosity formation in the weld.
Magnetism	Can occur in ferromagnetic materials containing iron, nickel, or cobalt and can impact the EBW process.	**Low** Magnetism is a property that is normally not measured or noticed until it is a problem. However, it can be addressed appropriately through process qualification, including developing a procedure that involves measuring the magnetization during setup to determine whether the levels need to be addressed.	• A magnetic field generated by the parts to be welded, fixturing, or nearby sources can influence the beam and have a deleterious effect on the weld. • A thermoelectric effect, in which a magnetic field is generated by the interaction of the beam with materials of different thermal potentials, can cause a lack of bonding in the electron beam weld. • When welding new components, magnetism can be difficult due to the material chemistry effects, installed ferritic components, or the magnetization of tooling components. • Steels are generally avoided in tooling for EBW because of the eventual magnetization of the tooling. – aluminum, stainless steel, and copper or brass are often used to avoid magnetization • Demagnetization techniques currently used for EBW include the following: – use of a slowly decreasing alternating current magnetic field – use of a magnetic shield – preheating above the curie temperature (i.e., the temperature above which certain materials lose their permanent magnetic properties)
Undercut	Defects resulting from grooves in the base metal along	**Medium**	• EBW of thick materials commonly have issues with undercutting on the top surface. • Undercutting can have a significant effect on fatigue life.

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	edges of the weld that are not completely filled during the welding process.	Undercutting is a common problem in EBW, particularly for deep welds, and can increase the susceptibility for fatigue and solidification cracks. However, undercutting can be addressed through a cosmetic or defocused weld pass placed on top of the penetrating pass.	• Locally to the undercut area, the material is under higher solidification stresses, which can initiate solidification cracks in sensitive materials. • In some cases, the additional heat input needed to reflow the top surface can be undesirable. However, in such instances, the top surface can be ground flush or the joint can be made with increased joint thickness that is later machined or ground off.
Reduced Pressure Electron Beam Welding	Traditional EBW that is conducted using a local vacuum at the location of the weld as opposed to the entire assembly within a vacuum chamber.	**Low (High if pursued in the United States)** The size of some reactor pressure vessels necessitates a large chamber or advanced process to conduct EBW. These large chambers are not commonly available in the United States. Minimal information is available about the reliability of reduced-pressure EBW, as this process has not been widely used in nuclear industry. Current efforts in the United States are focused on large-chamber EBW, which results in a Low NRC Ranking of Significance. If this technology is pursued in the future, the need for demonstration of this technology would be elevated to a High ranking.	• Removal of the large vacuum chamber allows immediate improvements in application to large structures and reduces the size of the pumps needed to provide the local vacuum around the weld area. – The energy and time used to pump down a large chamber can be reduced significantly. • Initial testing has shown that single-pass, reduced-pressure EBW results in higher as-welded hardness through the fusion zone compared to arc welding. However, PWHT was shown to be effective in reducing hardness values. • Initial testing showed that, after PWHT, residual stress magnitudes can be comparable for reduced-pressure EBW and arc welding, but the residual stress distributions were quite different between the welds. Limited information is available on the effect of these different residual stress distributions on weld integrity.
Weld Appearance Including Spatter and Blow Through	Post weld surface conditions of the electron beam weld and surrounding surfaces.	**Low** During full-penetration EBW, spatter can solidify on the inner and outer surfaces. However, this can be successfully removed through mechanically assisted tooling. Spatter and blow-through can also be mitigated through other means, such as sacrificial spatter shields or a beam impingement device that can be inserted on the backside of the weld.	• The weld root in particular can have large amounts of spatter present, although this is not expected to impact the integrity of the weld. • The excess beam power and droplets of material can be expelled from the root of the weld and adhere strongly to the opposite side of a vessel. • The visual appearance of an electron beam weld will be narrower and rougher than a typical arc weld and may include spatter, particularly on the interior of the component. This could increase susceptibility to fatigue and SCC.

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			• For components fabricated using PM-HIP, a high amount of inherent dissolved gas in the components may cause fluctuations in the weld pool, resulting in increased spatter.
Joint Preparation, Fit-Up, and Gaps	The preparation and set up of the EBW joint.	**Low** The machining of weld joints is simplified for EBW; however, the joint preparation for EBW and tolerancing of mating components are critical for EBW without wire additions.	• Most electron beam welds are completed without the addition of filler material. This requires that the mating components are tight fitting with minimal gaps. • Larger gaps reduce the amount of weld reinforcement and may result in a concave weld surface, which can increase solidification cracking susceptibility. • EBW does not have the flexibility that exists in traditional arc welding processes to accommodate variations in the bevel angle or joint gaps.
Fluidity of the Molten Pool	The fluidity and propensity of material to flow away from the weld joint.	**Low** The potential for loss of material in the weld joint should be identified early in the procedure development process. It can be addressed appropriately through process qualification, including adding material to support the molten weld bead during welding.	• Loss of material due to fluid flow is usually more severe on the beam side (hot end) of the weld; therefore, support structures are typically used on the beam side and not the root side of the weld. Very hot, deep, or high-energy welds may also need root-side support. • The effects of using an off-axis weld depend on the material being welded, as molten pool fluidity has a great effect on the surface tension of the pool and the ability to create a weld without losing molten material due to the combination of surface tension, gravity, and fluid flow. Larger welds are therefore more susceptible to fluid material loss. • Material can be tack welded to the weld joint (e.g., support bars) to help resist the fluid puddle from falling out of the joint. These can be used on the outer and inner surfaces of the weld, depending upon internal access and weld parameter settings.
Post Weld Heat Treatment[1]	Methods that involve elevated temperatures to reduce internal residual stresses in the material and improve material	**High** PWHT should make material properties and performance more homogeneous and similar to those of the arc welding process and may significantly impact considerations related to the other EBW	• ASME Code, Section III, requires PWHT of all carbon steel and low-alloy welds. Some exemptions to these requirements are provided in the ASME Code based on material type, carbon content, thickness, and the application of a specified preheat. However, none of these exemptions can be applied to heavy section welds.

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	properties in the weld.	differences presented in Tables 1 and 2. Conversely, weld integrity may be degraded if adequate PWHT is not used. PWHT is required by ASME Code, Section III, for carbon steel and low-alloy welds. The adequacy of these requirements for thick-section EBW is still being demonstrated.	• PWHT may be beneficial in reducing hardness, yield strength, and residual stress and in increasing impact toughness.
			  – In terms of these properties, PWHT can result in electron beam weld properties that are more comparable to conventional arc welds.
			• The use of a solution heat treatment is being investigated specifically for electron beam welds. Because the electron beam weld does not add filler metal, the chemical composition of the weld is nearly identical to the base material. The heat treatment is intended to homogenize the weld and base metal microstructures and return the weld fusion zone to near base metal properties.
			  – Because the heat treatment would be completed on final assemblies after welding and machining, distortion caused by the heat treatment is a concern.

Slope Out Parameters	Parameters at the end of a weld cycle to be adjusted to minimize or eliminate defects at the stoppage point in circumferential welds.	**Medium** Improper control of slope out parameters can adversely affect properties and performance of the electron beam weld. However, work has been done to identify and optimize these parameters and can be addressed appropriately through process qualification.	• Slope out parameters need to be developed appropriately to minimize or eliminate defects at the termination of the weld. • Work has been done to identify and optimize parameters such as section length, beam power, welding defocus, and beam oscillation. • Improper slope out parameters can lead to increased root porosity and keyhole collapses at the root of the partially penetrating electron beam weld.

Note 1: Difference does not correspond to an ORNL gap from Section 3.1 of the ORNL TLR.

Table 2 Technical Information—EBW Assembly Properties and Performance Characteristics

Difference	Definition	NRC Ranking of Significance	Key Technical Information
Welding of Forgings to PM-HIP and PM-HIP to PM-HIP	EBW of components that join forged material to PM-HIP fabricated materials and join two PM-HIP fabricated materials.	**High** Differences have been seen in the few tests completed on deep-penetrating electron beam welds on reactor pressure vessel steels when using PM-HIP base materials. The development of EBW of PM-HIP components will need to continue to address these issues in parallel with the development of fabricating PM-HIP reactor pressure vessel components.	• Early testing demonstrated that a forged plate to PM-HIP plate weld behaved similarly to the wrought product with no significant difference in weld fusion zone or heat-affected zone (HAZ) width. • This early testing also showed notable differences in the fusion zone and HAZ width for PM-HIP to PM-HIP welds. • The development of EBW of PM-HIP components is occurring in parallel with the development of the fabrication process of PM-HIP components for the reactor pressure vessel; refinements in both processes may be needed to ensure acceptable weld joint performance.
Solidification Cracking	Formation process of shrinkage cracks during the solidification period of a weld metal.	**Medium** Base metals that are generally considered to be weldable by arc fusion processes may be susceptible to cracking during EBW due to the faster cooling and solidification rates. Austenitic stainless steels such as 304L and 316L are well researched due to crack sensitivity as a result of changes in solidification modes. Work has been done to decrease cooling rates and modify weld pool shapes, but further research is needed to confirm these capabilities.	• The fast welding speeds that are unique to EBW as compared to arc welding processes produce a fast solidification rate that may increase the susceptibility to solidification cracking. • EBW, with its high energy density, results in high temperature gradients and elevated stress levels that may enhance the crack sensitivity of some materials. • The residual stresses on the electron beam weld may be higher than for arc welding depending upon joint configuration, restraint conditions, heat input, and final bead profile. This may increase susceptibility to solidification cracking. • EBW without filler metal may cause a concave weld bead profile, which may be more susceptible to cracking. • Manufacturers have developed multibeam electron optics that raster the beam to multiple positions at extremely fast speeds. This technology has been used to decrease cooling rates, modify weld pool shapes, and deliver

Difference	Definition	NRC Ranking of Significance	Key Technical Information
			PWHT during the completion of the welding pass. Further research is needed to prove its capabilities.
Stress Corrosion Cracking	SCC initiation and growth of susceptible materials under roughly constant stress operating conditions in a corrosive environment.	**Low—Low-Alloy Steels** **Medium—Stainless Steels and Nickel-Based Alloys** SCC can lead to degraded weld integrity if not adequately managed and is one of the most common failure modes in nuclear power plants. Local material characteristics (i.e., grain boundary chemistry and microstructure) may amplify differences with conventional arc welds not apparent in other tests (e.g., tensile). Electron beam welds may be less susceptible to SCC than arc welds, and low-alloy steels are generally resistant to SCC under normal operating conditions. However, there are limited data to demonstrate SCC resistance in electron beam welds of stainless steels and nickel-based alloys.	• Data in representative environments are important to demonstrate that weld integrity will not be degraded due to SCC to a greater degree in electron beam welds than arc welding. • Electron beam welds are generally expected perform better than arc welding due to the inherently clean environment, lower overall heat input, and resulting smaller grain structure of the weld. • PWHT has been shown to reduce hardness values and residual stress levels in the weld metal and HAZ of electron beam welds, largely mitigating SCC susceptibility. • PWHT would be expected to make electron beam weld properties and performance more similar to those of arc welding processes. • Low-alloy steels are generally resistant to SCC under normal operating conditions when sulfur content and hardness levels are appropriately controlled. – SCC susceptibility is more pronounced in austenitic stainless steels and nickel-based alloys than low-alloy steels. • SCC of reactor pressure vessel materials is of higher concern in areas of dissimilar metal combinations, particularly those containing nickel-based alloys.
Fatigue	The initiation and propagation of cracks due to cyclic loading with or without environmental effects playing a	**Low** Fatigue is a common concern in nuclear power plants and can lead to component failure. Fatigue information on the reactor pressure vessel steel electron beam weld metal properties is limited. However, fatigue life is not expected to	• Data in representative environments are important to support fatigue calculations for electron beam welds, including for environmentally assisted fatigue. • PWHT is expected to make electron beam weld properties and performance more similar to those of arc welding processes.

Difference	Definition	NRC Ranking of Significance	Key Technical Information
	significant role in the process.	be detrimentally affected by EBW of the reactor pressure vessel steel if similar microstructures can be achieved. This has been seen in initial (albeit limited) evaluations. Furthermore, activities can be conducted to address issues that adversely affect fatigue life (e.g., undercutting).	• Because fatigue is heavily reliant on the weld microstructure, a significant change in fatigue life is not expected if similar microstructures of conventional arc welds are achieved. • Undercutting, a common problem for EBW, can have a significant effect on fatigue life; however, undercutting of the top surface can be remedied through a cosmetic or defocused weld pass placed on top of the penetrating pass.
Fracture Toughness	A property that describes the ability of a material containing a crack to resist further fracture.	**Medium** Loss of fracture toughness can lead to brittle failure if not adequately managed. Fracture toughness of electron beam welds is expected to be comparable, if not superior, to conventional arc welds for wrought alloys given appropriate PWHT. However, additional data are needed to demonstrate the fracture toughness behavior of electron beam welds such that component integrity will be maintained throughout the design life.	• Data in representative environments are important to demonstrate that fracture toughness does not degrade excessively and will be adequate to meet component design assumptions. • Fracture toughness of electron beam welds for wrought alloys may be comparable to that of conventional arc welds because of the use of cleaner steels with lower trace elements and the reduction of copper due to the absence of filler materials. • PWHT is expected to make electron beam weld properties and performance more similar to those of arc welding processes for wrought alloys. • More information on fracture toughness is needed for PM-HIP steels as the PM-HIP process matures for thick-section, low-alloy steels.
Aging and Irradiation Degradation	Aging, or thermal aging, refers to the reduction in fracture toughness after significant time at elevated temperatures. Irradiation degradation refers	**High** Thermal and irradiation embrittlement, particularly loss of fracture toughness, are concerns in nuclear power plant applications. Local material characteristics (i.e., grain boundary chemistry and microstructure) may amplify differences with conventional arc welds not apparent in other tests (e.g., tensile). PWHT is expected to make	• Data in representative environments are important to demonstrate that thermal aging or irradiation effects will not be significantly greater in electron beam welds than in arc welding. • EBW removes a source of the copper from the filler materials added through arc welding, which can minimize radiation effects in welds.

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	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.	electron beam weld properties and performance more similar to those of arc welding processes. However, no published articles could be found that discuss the effects of long-term exposure to elevated temperatures or radiation-specific electron beam girth welds on reactor pressure vessel steels.	• PWHT is expected to make electron beam weld properties and performance similar to those of arc welding processes.
Residual Stress	Residual stresses that remain in the electron beam weld can affect important properties of the weld.	**Medium** Residual stress in the electron beam weld can negatively impact the mechanical properties of the materials if not properly managed. PWHT has been demonstrated to significantly reduce peak residual stress in electron beam welds. However, no published articles could be found that discuss the effects of residual stress on the structural integrity of large-thickness EBW in reactor pressure vessel materials.	• High residual stress can degrade weld integrity (e.g., increase cracking susceptibility, impact irradiation behavior). • PWHT with appropriate parameters is expected to relieve residual stress in the weld metal and HAZ. • EBW of dissimilar welds results in high residual stresses due to difference in melting temperatures and coefficients of thermal expansion. However, certain process variables can be adjusted to help manage residuals stresses, such as directing more of the beam energy into the material with the higher melting temperatures. • Although the use of wire addition with EBW is limited, the filler metal can reduce the amount of residual stress on the completed weld.

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