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United States Nuclear Manufacturing Infrastructure Assessment

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MPR

United States Nuclear Manufacturing Infrastructure Assessment

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Executive Summary

This report provides a review and assessment of the existing U.S. infrastructure capabilities to manufacture on a commercial scale, the major components and unique materials required by the various U.S. designs for advanced nuclear reactors and small modular reactors (SMRs).

The approach was to compare the needs of SMRs and advanced reactors against the capability of U.S. manufacturers to ascertain gaps that could inhibit U.S. industrial support for deployment of SMRs or advanced reactors. This report focused on the reactor plant designs being developed by NuScale Power (the NuScale Power Module), TerraPower (both the Traveling Wave Reactor and the Molten Chloride Fast Reactor to a limited extent), and X-energy (the Xe-100). To gather the information, MPR visited each of these companies and selected candidate suppliers to tour their facilities and conduct in-person interviews. Information was also obtained by telephone interviews, internet research, and literature review of technical reports.

The overarching conclusion from this study is that the U.S. has existing capability or can readily develop capability to support and sustain most, but not all, aspects of commercial deployment of advanced reactors and SMRs.

- The greatest concerns for capability gaps in the U.S. infrastructure for supply of components for SMRs and advanced reactors are associated with reactor pressure vessels, steam generators, and fuel fabrication. Foreign vendors can supply reactor pressure vessels and steam generators. Issues with fuel fabrication are associated with uranium enrichment and development of fabrication methods for the innovative fuel concepts planned for advanced reactors.
- The technical capabilities of U.S. manufacturers appear satisfactory with the possible exceptions noted above. However, the capacity of the existing U.S. manufacturing infrastructure may be insufficient for a high rate of construction. Manufacturers contacted as part of this study indicated a willingness to expand capacity if sufficient orders are in place.

The review of U.S. infrastructure included a detailed review of capabilities in many different processes including forging, tube drawing, machining, fabrication, and testing. In addition, MPR researched the advanced manufacturing processes for additive manufacturing (i.e., 3D printing) and powder metallurgy - hot isostatic pressing. Reactor plant designers and candidate suppliers are planning to rely on traditional processes for the initial plants. If advanced manufacturing processes are developed and accepted by the nuclear industry, these processes may be used in the future. In the immediate term, ongoing research (much of which is funded by DOE) is necessary to develop and refine advanced manufacturing methods.

This report includes several recommendations for DOE that will advance deployment of SMRs and advanced reactors from a manufacturing perspective and other areas identified during the course of this project.

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1 Introduction

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1.1 BACKGROUND

1.1.1 Nuclear Power Generation in the United States

The United States is currently the largest producer of nuclear energy in the world with 99 reactors used for power generation across 60 sites having a total baseload capacity of 99.6 GW. Nuclear energy provides approximately 20% of the electricity generation in the United States. (Reference 1-1)

The vast majority of U.S. nuclear power plants are older facilities, with the average age being about 38 years. The newest reactor to enter service began operation in 2016, but it was a resumption of a project started in 1973. The next newest entered service in 1996. Most reactors in the United States started operation before 1980. The U.S. Nuclear Regulatory Commission (NRC) issues licenses for 40-year periods, which can be renewed in 20-year intervals. Most of the currently-operating commercial nuclear plants in the United States have applied for and received an initial license renewal. The first application for a second license renewal was submitted to the NRC in 2018, and similar applications from other plants are expected in the near future.

The Energy Information Agency publishes an Annual Energy Outlook (Reference 1-2) that includes a forecast of electricity generation in the United States. For nuclear power, Reference 1-2 projects a steady decline in generation, down to 79.1 GW of electric capacity in 2050, due to plant closures without replacement by new construction after 2020.

Nuclear energy plays an important role in the energy portfolio of the United States since it offers a unique combination of features that cannot be achieved by other forms of generation. Nuclear energy provides 56.1% of emissions-free generation in the United States, and is an essential element of national goals for reducing emissions of carbon dioxide and other pollutants (i.e., nitrogen oxides (NO_x) and sulfur oxides (SO_x)). In addition, nuclear energy provides a reliable baseload generation capability, as demonstrated by a capacity factor of 92.2% in 2017. (Reference 1-1)

1.1.2 Nuclear Construction

Due to changes in demand for electricity and following the accident at Three Mile Island (TMI) in 1979, construction of new commercial nuclear power plants in the United States declined with projects wrapping up in the 1990s. In the 2000s, the U.S. power generation industry had renewed interest in constructing nuclear power plants using new designs (Generation III+) for baseload electricity demand. This apparent revival of the nuclear industry was touted as a "Nuclear Renaissance" and many companies made substantial investments in anticipation of the associated business opportunities.

However, in the ensuing decade, the cost of power has been low due to the abundance of natural gas from use of horizontal drilling and hydraulic fracking and subsidies for renewable energy sources (Reference 1-3). At the same time, estimated (and actual) cost of new nuclear plant construction has continually risen, with project schedules also being extended. A longer project schedule is a significant disincentive because it results in higher financing charges, longer time until initial revenue generation, and a longer payback period to recover the construction investment. As a result of unfavorable economics, most of the plans for new construction of nuclear plants in the U.S. were cancelled or suspended.

Only two new nuclear construction projects proceeded to groundbreaking: (1) a two-unit expansion at the A.W. Vogtle site in Georgia using the AP1000 reactor design, and (2) a two-unit expansion at the V.C. Summer site in South Carolina also using the AP1000 reactor design. These projects have experienced schedule delays and cost overruns caused by a variety of factors, such as incomplete design at the start of construction, poor productivity and quality assurance deficiencies during fabrication, and inadequate project controls including project management. The consequences of these factors led to further complications affecting project progress, including bankruptcy of Westinghouse, who was responsible for construction (originally as part of a consortium with Shaw Stone & Webster). These factors ultimately led to cancellation of the V.C. Summer expansion project. Despite the increasing cost, the A.W. Vogtle project has continued, but has been reorganized with construction now under management of Southern Nuclear Operating Company.

Going forward, there are currently no firm plans to construct large nuclear power plants in the U.S. The cost of natural gas is expected to remain relatively low, and the Vogtle and V.C. Summer projects have demonstrated a high and uncertain cost for construction of large nuclear plants.

1.1.3 Legacy Nuclear Plants

The existing nuclear fleet in the United States is comprised entirely of light water reactors (LWRs), which use normal water (as opposed to heavy water, with deuterium hydrogen atoms) as its primary coolant and neutron moderator. LWRs are categorized into two types: Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs).

The PWR concept was an outgrowth of the U.S. Navy Nuclear Propulsion Program and its Shippingport Atomic Power Station, which went into operation in 1957. The developers of the PWR technology in the U.S. were Westinghouse, Babcock & Wilcox, and Combustion Engineering. General Electric developed the BWR concept with the objective to simplify the plant and reduce cost, primarily by eliminating steam generators.

In the early days of the U.S. nuclear industry, reactor designs other than LWRs were built and operated including the Peach Bottom Atomic Power Station Unit 1 high-temperature gas-cooled reactor (HTGR), the Fort St. Vrain HTGR, and the Dresden Unit 1 sodium fast reactor (SFR). These and other non-LWR designs were driven by perceived advantages in one or more areas, such as construction simplification, operating cost, or thermal efficiency. However, none of these designs were operated for more than a few years because of operating costs and reliability inferior to LWRs, and they were not developed further. Ultimately, the U.S. nuclear industry focused on LWR designs because they offered the highest level of confidence as a successful business investment.

1.1.4 Current Development Areas

Since the advent of nuclear power in the 1950s, a wide variety of nuclear technologies have been built and demonstrated in some form, proving that they are technically feasible. However, these designs have not demonstrated that they are sufficiently economical, implementable, and reliable to be competitive in the power generation marketplace.

The nuclear industry is currently revisiting alternative concepts to large LWRs that may be able to demonstrate a compelling business case for new construction. These technologies can be grouped into two categories: Small Modular Reactors and Advanced Reactors (Generation IV).

Small Modular Reactors

The primary distinction between traditional nuclear power plants and SMRs is the construction and fabrication approach. Traditional LWR designs are constructed at the site, while SMR designs are intended to be predominantly fabricated in a factory environment and are shipped to the site as fully assembled as practical. Whereas many traditional plants, including the Generation III and III+ designs[1], produce over 1,000 MW of electric power per reactor, the design outputs of SMRs range from a few MW to hundreds of MW. Developers believe that SMRs can be a more attractive business option than a traditional, large nuclear plant for several reasons, including the following:

- The smaller plant size will reduce capital investment and construction schedule, although some economy of scale will be lost.
- The smaller reactor size allows a simpler design and safety approach. Use of fewer and less complex components can reduce the cost of the plant, which would offset the loss in economy of scale.
- The ability to manufacture SMR modules in a factory simplifies delivery and may achieve considerable cost savings.

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[1] Generation I designs were prototype and power reactors from the 1950s and 1960s that were the first applications of civil nuclear power. Generation II designs were reactors that were intended for commercial use, many of which remain in service in the U.S. today. Generation III and III+ designs include evolutionary changes from Generation II designs in safety systems, fuel, thermal efficiency, modular construction, and standardization. (Reference 1-5)

- SMRs can be sited in locations where large plants are not necessary or the infrastructure is insufficient to support a traditional large plant, thereby opening new markets to nuclear energy.
- The smaller power output of these designs allow them to better match incremental grid needs, as opposed to the very large static baseload outputs of traditional LWRs. This feature is increasingly advantageous as more renewable sources (i.e., wind and solar) are brought online whose output changes significantly throughout the day and throughout the year.

There are many SMR designs that are intended for commercial use, and these designs are in various stages of development. The furthest along in the U.S. is the NuScale Power Module (NPM) design, currently being reviewed by the NRC as part of its Design Certification Application (DCA) (Reference 1-4).

Advanced Reactors

Advanced reactors (i.e., Generation IV) differ from traditional nuclear power plants and SMRs because the coolant is a substance other than light water. Advanced reactors are generally categorized in the following three groups:

- Fast reactors (i.e., liquid metal cooled)
- High-temperature gas-cooled reactors
- Molten-salt reactors

There are many advanced reactor designs that are intended for commercial use, and these designs are in various stages of development, although none have a DCA submitted to the NRC for review.

As previously discussed, the high-level approach for power generation used by most advanced reactor designs has been developed in the past. These designs are now being reconsidered because of the business challenges for large LWRs such as high capital cost and reduced growth in demand for electricity. More recent innovation with one or more aspects of the advanced reactor concepts (e.g., fuel design) may result in a workable business case that was not available when the advanced reactor design was first considered. Outside the U.S., much of advanced reactor development is government-funded because of the high cost, long duration, and business risk of undertaking design of a new reactor.

1.1.5 Department of Energy Projects

The U.S. Department of Energy (DOE) is a primary driver for developing and deploying nuclear reactor technologies for commercial power generation. One area of interest for DOE is whether sufficient infrastructure exists to support manufacture and deployment of new nuclear reactors in the U.S. Previous DOE projects that addressed this topic are summarized below.

Construction Infrastructure Assessment

In 2005, MPR Associates (MPR) completed an assessment (Reference 1-6) for the DOE to identify weaknesses in the domestic and global infrastructures for manufacturing, fabrication, or construction (including labor and equipment) associated with startup of new U.S. Generation III+ nuclear power plants (e.g., AP1000).

This assessment concluded that the necessary manufacturing, fabrication, labor, and construction equipment infrastructure was available in 2005 or could be easily developed to support the construction and commissioning of up to eight U.S. nuclear units during the period from 2010 to 2017. MPR concluded that the main challenge for the U.S. nuclear power industry to support new construction of the first Generation III+ units would be to have the right resources available at the right place and the right time. Shortfalls were identified in four general areas: codes and standards, manufacturing capability, qualified personnel, and material procurement.

With respect to manufacturing capability, the primary concern was for reactor pressure vessel (RPV) fabrication, because nuclear-grade large ring forgings were only available from one Japanese supplier in 2005. Another concern was capacity of the manufacturing infrastructure, which would have needed to be increased to support widespread deployment of Generation III+ reactors, although manufacturers indicated that they could increase their capacity in time to support such construction.

The assessment concluded that major equipment (RPVs, steam generators, and moisture separator reheaters) for near-term deployment of Generation III+ reactors would be from international manufacturers, because U.S. manufacturers did not have the capability for components of the necessary size. Smaller equipment could be provided by U.S. suppliers.

Study on Developing U.S. Ultra-Large Forging Capability

In 2010, MPR completed a study (Reference 1-7) for the DOE to analyze the costs and benefits of developing a domestic capability for ultra-large forgings that would support manufacture of large components (e.g., RPVs, steam generators) for Generation III+ nuclear plants. As part of this study, MPR reviewed international capacity for manufacturing large forgings and current and planned domestic and foreign demand.

The study concluded that the cost/benefit trade-off for building and operating an ultra-large forging facility in the U.S. was unfavorable, even with optimistic assumptions for demand. The study identified that there would be surplus international manufacturing capacity, and it would be difficult for a U.S. ultra-large forge to capture sufficient market share to justify the very large capital investment (over $2 billion). Furthermore, a large proportion (estimated at one third) of this capital investment would be to procure specialty equipment from foreign vendors, so only a fraction of the investment would go to U.S. suppliers.

The study recommended that the DOE explore other alternatives to support the nuclear industry, such as initiatives to develop reactor vessel designs and manufacturing approaches that eliminate the need for very large forgings.

1.2 SCOPE

Developments over the last decade have driven the U.S. away from new construction of large generating plants such as Generation III and III+ LWRs, making SMRs and advanced reactors more credible candidates for a future nuclear renaissance. Accordingly, the scope of this report is focused on SMRs and advanced reactors, rather than large LWRs. Reactor designs for large LWRs are considered in this report to the extent that their supply chain and lessons learned can inform the assessment of manufacturing and fabrication of future SMRs and advanced reactors.

This report focuses on the manufacturing aspects of deploying new reactors, rather than construction. This focus reflects the continued decline of the U.S. manufacturing infrastructure for traditional processes and the significant research and development that is ongoing for advanced manufacturing. Furthermore, the designs considered will most likely include more modular manufacturing and fabrication and less on-site construction. Challenges with construction played a significant role in the delays and associated cost increases for the new construction projects at the V.C. Summer and A.W. Vogtle plants. However, a study of U.S. construction capability is beyond this scope of work.

SMR and advanced reactor designs are still in development, so the manufacturing capabilities needed to support deployment of these designs are not fully known at this time. In addition, there is considerable variability in the supply chain needs among the various advanced reactor designs. Therefore, this assessment focused on the manufacturing needs for plant designs that appear to be more complete and more credible for future deployment. Specifically, this report focused on the reactor plant designs being developed by NuScale Power (the NPM), TerraPower (the Traveling Wave Reactor or TWR and the Molten Chloride Fast Reactor or MCFR), and X-energy (the Xe-100).

1.3 APPROACH

The fundamental approach for this project is to compare the needs of SMRs and advanced reactors against the capability of U.S. manufacturers to ascertain gaps that could inhibit U.S. industrial support for deployment of SMRs or advanced reactors.

The report is organized to present information in a sequence that develops this comparison. In addition, the content of the report is presented such that information can be readily maintained and re-evaluated in the future, as SMR and advanced reactor designs mature. The following list provides a high-level overview of the sections in the main body of the report.

- Industry Requirements – Summarizes selected SMR and advanced reactor designs and identifies the key technical requirements for manufacturing.
- Supply Chain – Reviews the supply chain for the AP1000 plants in the U.S. to capture the most recent experience with manufacturing support and discusses supply chain plans for SMRs and advanced reactors (to the extent that such plans are available).
- Raw Materials – Discusses selected raw materials and inputs for manufacturing processes that are of particular interest to delivery of SMRs and advanced reactors.

- Manufacturing – Discusses selected processes that are of particular interest to manufacturing and delivery of SMRs and advanced reactors.
- Assessment of U.S. Capabilities for SMRs and Advanced Reactors – Evaluates the information presented in the preceding chapters to identify gaps in the U.S. manufacturing infrastructure that need to be addressed to support domestic manufacturing of SMRs and advanced reactors.

MPR obtained the information to populate the chapters on industry requirements, supply chain, raw materials, and manufacturing by several different means. This project included site visits for selected reactor plant designers and candidate suppliers to tour their facilities and conduct in-person interviews. Information was also obtained by telephone interviews, internet research, and literature review of technical reports.

This report also includes several appendices, including a List of Acronyms (Appendix A), a list of U.S.-based ASME Stamp Holders (Appendix B), and a Contact List (Appendix C) that provides information on the individuals that provided information for this report.

This report is part of a broader DOE effort to evaluate the supply chain for SMRs and advanced reactors that could be deployed in the U.S. While the scope of this report is a high-level review of U.S. manufacturing infrastructure, subsequent DOE efforts may include a more detailed review of selected aspects of domestic supply capabilities and/or a review of the international infrastructure to support SMRs and advanced reactors in the U.S.

2 Summary

2.1 CONCLUSIONS

The overarching conclusion from this study is that the U.S. has existing capability or can readily develop capability to support and sustain most, but not all, aspects of commercial deployment of advanced reactors and SMRs. Based on discussions with selected reactor plant designers, suppliers, and national laboratories, and extensive literature review, MPR identified gaps in the U.S. infrastructure, as summarized in the discussions below.

In support of this assessment, MPR reviewed the SMR and advanced reactor designs and their plans for supply chain and deployment. MPR also investigated advanced manufacturing methods that could be leveraged for deployment of advanced reactors and SMRs. Conclusions from these aspects of the scope of work are also summarized below.

2.1.1 Manufacturing Needs for Advanced Reactors and SMRs

As part of this project, MPR visited NuScale Power, TerraPower, and X-energy to discuss their plant designs and understand the manufacturing needs for key components. The scope of the review included numerous components such as RPVs, steam generators, heat exchangers, control rods and drive mechanisms, fuel elements, pumps, valves, fuel handling systems, control equipment, and balance of plant components. The designs being advanced by the companies in the scope of this study vary widely and, therefore, have significant differences in their supply chain needs. Additionally, design work is ongoing, so the specific parameters and materials for many components are still changing. Accordingly, the content of this report reflects the best information available to date.

The details on weight, size, and materials identified during this investigation of component design parameters were compared against the capabilities of the U.S. infrastructure for various manufacturing processes. In summary, most of the components needed for reactor plant designs considered in this study are within the capability of the U.S. manufacturing infrastructure. The principal capability gaps are associated with reactor pressure vessels, steam generators, and fuel fabrication. Further discussion of selected components is included below for the applicable manufacturing processes.

There are many components for SMRs or advanced reactor designs that will be first-of-a-kind (FOAK), first-in-a-while (FIAW), or customized for the parameters of a particular design. Examples include control rod drive mechanisms, primary coolant pumps, helium circulators, fuel handling systems, and components for use with a molten salt/sodium working fluid. While FOAK, FIAW, or customized components are subject to the typical challenges for manufacturing unique items, they are generally expected to be within the capability of the U.S. infrastructure.

Depending on the construction rate of SMRs and advanced reactors, the capacity of the existing U.S. manufacturing infrastructure may be insufficient, but manufacturing companies all indicated a willingness to expand capacity when sufficient orders are placed to justify investment.

2.1.2 Commercial Deployment Schedules for SMRs and Advanced Reactors

Commercial deployment of an SMR or advanced reactor depends on finalizing the technical design, obtaining NRC approval, and having a customer to build a plant. The list below provides a brief summary of the near term commercial deployment plans for each of the main designs addressed in this report.

- NuScale has submitted its DCA to the NRC for approval and is proceeding with plans to deliver the first NuScale plant (consisting of 12 modules) in 2027, with the first module operational in 2026. NuScale is actively engaged with other potential customers, but does not have any firm orders at this time.
- TerraPower plans to deploy a half-power demonstration reactor of their TWR design in China within the next 10 years, and potentially a larger demonstration plant 5 years thereafter. Global commercialization would follow initial implementation in China. There are no current plans to build a TWR plant in the U.S. or current deployment plans for the TerraPower MCFR design.
- X-energy has a timeline for a Xe-100 reactor to be operational by the late 2020s. However, the final Xe-100 design is not complete, so a DCA has not been submitted to the NRC for approval, and there are currently no firm plans for siting a Xe-100 plant.

Although there are currently no contracts for building new nuclear plants in the U.S. aside from completing the Vogtle project, an intermediate term demand is expected to exist for new nuclear power generation. Legislation in several U.S. states has acknowledged that the current market conditions do not properly value the benefits of nuclear power in terms of grid reliability and emissions of carbon dioxide and pollutants. Further recognition of the value of nuclear power in the future may provide a basis for construction of new nuclear plants, particularly as existing plants age and ultimately retire. International demand for new construction of nuclear power plants is strong and also provides a potential market for U.S. SMRs and advanced reactors when they become commercially available. Studies that consider the need for reduced carbon emissions and improved air quality suggest a global campaign for new nuclear generation of about 30 GW per year, which is equivalent to construction of 50 NuScale SMR plants (of 12 modules each) per year. There is clearly an opportunity for SMRs and advanced reactors to provide at least some of this new generation capacity.

The number of nuclear suppliers in the U.S. has declined. The lack of nuclear projects in the U.S. in the immediate term will continue to erode U.S. capabilities and capacities for supporting construction of new nuclear plants. By the time SMRs and advanced reactors are ready to be widely deployed in the U.S., the capability and capacity of the U.S. manufacturing infrastructure may be different than at the time this report was prepared.

2.1.3 Supply Chain

Generation III+ reactors (i.e., AP1000) are currently under construction and have an established supply chain for manufactured components. For the ongoing Vogtle expansion project and the cancelled V.C. Summer expansion project, the supply chain consisted of an international group of vendors. Many of the components were provided by U.S. suppliers, including the control rod drive mechanisms, fuel elements, reactor coolant pumps, many of the valves, and the station batteries. International suppliers were used for other components, including the reactor vessel, steam generator, condenser, and turbine generator. Key considerations for using international suppliers were the capability of overseas suppliers relative to U.S. suppliers (e.g., for large forgings) and business considerations for Westinghouse, who was responsible for the supply chain and was owned by a foreign company that wanted to supply components from its manufacturing base.

MPR identified the following three observations regarding AP1000 supply chain experience:

- A number of vendors had to build new or expand existing facilities in order to supply AP1000 needs, and they struggled to recapture or develop nuclear fabrication capability and knowhow. The most successful suppliers were those who maintained nuclear capability by supporting the U.S. Naval Nuclear Propulsion Program or by supplying foreign nuclear projects.
- The four lead AP1000 plants are in China. Starting with the second unit, increasing portions of the AP1000 units in China have been supplied with components fabricated in the country, decreasing the opportunity for U.S. industry to become more proficient and cost effective.
- Following Vogtle equipment sourcing, which should be largely complete in the next year, no near term orders are likely to occur to sustain the U.S. capability and the recently redeveloped knowhow.

For SMRs and advanced reactors, the horizon for commercial deployment is several years in the future, so the supply chain has not yet been fully developed.

- NuScale plans to use U.S. suppliers for the majority of the first NuScale plant, but will turn to foreign suppliers where components cannot be made by a U.S. supplier (e.g., potentially for selected forgings).
- For the TWR, Chinese manufacturing capability may not be adequate for some components, and an international supplier (potentially from the U.S.) may be needed in such cases. If a TWR plant were built in the U.S., suppliers from the U.S. would be considered.
- X-energy plans to procure as much of its equipment from U.S. sources as possible, and is developing its supply chain using that strategy. X-energy will use foreign suppliers to provide components that are either not available from U.S. suppliers or are considerably more expensive from U.S. suppliers.

2.1.4 Raw Materials

As part of the review of the supply chain for advanced reactors and SMRs, MPR considered availability of raw materials from domestic sources. In most cases, the raw materials for manufacturing were not a concern, but MPR identified the following key areas where domestic production was not sufficient:

- Uranium oxide concentrate ("yellow cake") for fuel fabrication and subsequent processing and enrichment capacity.
- Uranium trichloride and uranium tetrachloride for the molten fuel for TerraPower's MCFR.
- Nickel for production of stainless steel and alloy steel products. Domestic mining of nickel is minimal, and U.S. industries are heavily dependent on foreign suppliers.
- Chromium for production of stainless steel and heat resistant steel. Chromium is not currently mined in the U.S., so the U.S. manufacturing base is entirely dependent on foreign suppliers.
- Graphite moderator for Xe-100 plants. Raw graphite materials are currently available primarily from international sources. Domestic manufacturing capability currently exists for the production of pebble matrix graphite required for advanced reactor moderation applications. Domestic manufacturers are also pursuing the development of new, domestic sources of raw graphite.

2.1.5 Forging

As part of this project, MPR visited Lehigh Heavy Forge in Bethlehem, PA for a review of state-of-the-art manufacturing capabilities and to interview personnel. MPR also contacted personnel from several other domestic forges as part of this study. U.S. forges have the capability to supply most of the forgings for the SMR and advanced reactor designs that were part of this study. While the forgings planned for SMRs and advanced reactors are smaller than for Generation III+ plants, there are still some forgings in the NuScale design that narrowly exceed the capability of U.S. forges. Discussions between NuScale and the forges have identified that design changes would allow U.S. forges to produce all of the forgings. However, such changes would have a functional impact on the design; NuScale would have to choose a foreign supplier to maintain the existing design.

U.S. forges have made capital investments to increase their capability in the recent past. Investment to increase capability for larger forgings would be very expensive, but could be justified if there were sufficient demand.

2.1.6 Tube Drawing

All three of the designs included in this study plan to use a helical coil steam generator (HCSG), which is a departure from existing commercially deployed designs. This component selection requires longer steam generator tubes than for traditional nuclear plants. MPR contacted several tube manufacturers and identified that these suppliers have adequate technical capabilities in terms of process fundamentals, but none of the domestic suppliers possessed sufficient capabilities to meet all of the specifications for the NuScale HCSG. Gaps from various vendors included ability to draw and straighten tubes of high nickel alloy of sufficient length, precision of tube geometry (e.g., size, wall thickness, circularity), and non-destructive inspection capabilities. Foreign suppliers are capable of satisfying all of the specifications for the NuScale HCSG tubes.

2.1.7 Machining

Similar to traditional nuclear plants, production of components for SMRs and advanced reactors will continue to rely on machining to shape pieces into the final desired shape to support the design. As part of this project, MPR visited Vigor Works LLC and contacted several other facilities that perform machining. MPR also toured machining capabilities at Lehigh Heavy Forge as part of the visit to their facility. All machining centers routinely use computer numerical control (CNC) on large machines and use some form of computer-based inspection system. The capability to machine components of the size required for SMRs or advanced reactor components currently exists, and numerous U.S. suppliers maintain certificates for supplying nuclear-grade components (e.g., N-Stamp). While the existing capacity may not be sufficient if there were a large increase in orders, suppliers stated that they would consider increasing their production capacity if there were orders to warrant such an investment.

2.1.8 Component Fabrication

Fabrication capabilities will be needed for SMRs and advanced reactors for many components. Based on MPR's visit to Vigor Works LLC and discussions with other fabricators, the U.S. manufacturing infrastructure includes many facilities that are capable of supporting SMRs and advanced reactors, and currently possess certificates for supplying nuclear-grade components.

The HCSGs used in all of the three plant designs considered in this study pose new fabrication challenges associated with tube bending, tube support manufacturing, and assembly. Plant designers are currently working with suppliers to address these issues with fabrication, although foreign suppliers have been selected for this work due to their experience and capabilities.

The TWR, MCFR, and Xe-100 all have unique fuel designs that will require fabrication that depart to a varying extent from existing methodologies. The fuel for each uses high-assay low-enriched uranium (HALEU), for which there is not an existing commercial domestic facility for providing enrichment. In addition, the designs for these fuels are unique, and will require development of the fabrication process to produce high quality fuel at a high yield. TerraPower and X-energy are actively researching and developing the fuel design and fabrication process. By contrast, NuScale uses fuel that is very similar to fuel that is used in operating commercial nuclear plants (e.g., similar enrichment, fuel rod diameter, and fuel assembly concept), and does not require development.

2.1.9 Component Testing

Testing programs will be required for SMRs and advanced reactors for design certification, equipment qualification, and plant commissioning. U.S. companies maintain strong capabilities for equipment testing and qualification for nuclear power applications to support the existing fleet of commercial nuclear power plants. While the specific testing required for SMR and advanced reactor components is not firmly known, requirements are expected to be comparable to existing designs. Companies that perform testing expect that they will be able to support such testing, particularly for the NuScale design, which is similar to existing PWRs. An exception is for the helical coil steam generators, which are significantly different from existing components. NuScale is performing testing overseas due to lack of U.S. experience and capability for these test programs.

TerraPower considers that water can be used in lieu of sodium for many component tests, but those tests that do require sodium will pose an additional challenge. TerraPower is considering development of its own test facility to support such testing.

Irradiation testing for particular materials is a potential challenge. Testing facilities in the U.S. (e.g., the Advanced Test Reactor) have limited capacity and availability, so designers are considering use of international irradiation testing capabilities as an alternative.

2.1.10 Powder Metallurgy - Hot Isostatic Pressing

Powder Metallurgy - Hot Isostatic Pressing (PM-HIP) is a manufacturing method for making large, complex shaped parts near net shape with high quality material properties. Accordingly, PM-HIP is a process that could replace forging for components like RPV heads. As part of this project, MPR met with the Electric Power Research Institute (EPRI), which is a leading developer for PM-HIP and is currently working with the DOE on a project exploring its use for the NuScale reactor vessel head. MPR also researched companies that have or are pursuing PM-HIP capabilities.

PM-HIP is currently used in the U.S. and abroad for industrial applications. However, the largest vessel in the U.S. for PM-HIP is only 66 inches in diameter, which is not sufficient for the NuScale RPV top or bottom head. A potential alternative is to use electron beam welding to join parts that have been manufactured by PM-HIP to produce a final product that exceeds the capability for manufacture of a single piece.

There are several limitations with the PM-HIP process that researchers and developers are currently working to overcome, including:

- High effort required to produce a “can” (i.e., the mold for the PM-HIP process), and to remove the can from a complex geometry once the part is manufactured.
- Control of shrinkage during production of the part, which is inherent to the PM-HIP process but requires simulation and modeling to predict.
- Formal acceptance of the methodology by the nuclear regulatory and codes and standards organizations, including ASME and the NRC.

In discussions with MPR, reactor plant designers and component suppliers acknowledged the potential benefits of PM-HIP, but considered that it was too far from commercial deployment to affect current plans for supply chain.

2.1.11 Additive Manufacturing

Additive manufacturing (AM), also referred to as 3D printing, is a process by which a digital design is used to build up a component in layers by precisely depositing material. AM provides the capability to more easily manufacture geometries that are challenging (or impossible) to produce using traditional processes, which allows designs with greater complexity. In addition, AM allows placement of specific constituents at very high precision, which can optimize designs where such precision is important (e.g., fuel, bimetallic joints). Another potential advantage of AM is "born-qualified" products that do not require the same post-production qualification as a traditional process, because the input parameters for AM are precisely controlled. As part of this project, MPR visited Oak Ridge National Laboratory (ORNL) to review state-of-the-art technology for AM and to interview personnel.

AM is a relatively new process that is largely in the research phase in terms of applicability for nuclear power plants. Successful production of parts by AM has primarily been for small components, as larger parts have exhibited anisotropic material properties and incomplete densification. Ongoing research at the national laboratories and selected suppliers aims to address these issues. Additionally, AM still requires review and acceptance by nuclear regulatory and codes and standards organizations, including the NRC and ASME.

In discussions with MPR, designers and suppliers acknowledged the potential benefits of AM, but considered that it was too far from commercial deployment to affect current plans for supply chain.

2.2 RECOMMENDATIONS

Based on the results of this study, MPR developed recommendations to address gaps in U.S. manufacturing infrastructure and other issues related to deployment of SMRs and advanced reactors. These recommendations are summarized in the discussions below.

2.2.1 Support for Manufacturing Complex Components

SMR and advanced reactor designs include many FOAK or FIAW components that will require development for manufacturing. Although the U.S. manufacturing infrastructure has or could develop the capability for such components, reactor designers may select foreign suppliers who have more experience (e.g., helical coil steam generators). To incentivize selection of U.S. suppliers, DOE could fund manufacturing demonstrations to be performed at U.S. facilities. Mechanisms for supporting such efforts already exist (e.g., the DOE Funding Opportunity Announcement for Advanced Nuclear Technology), but appear to be leveraged more for longer-term research (e.g., additive manufacturing). MPR recommends that DOE provide funding for nearer-term applications that would engage the existing U.S. manufacturing infrastructure (e.g., proof of manufacturability demonstrations).

2.2.2 HALEU Fuel Enrichment and Shipping

Advanced reactor designs rely on HALEU fuel, for which there is not currently a commercial enrichment capability in the U.S. Even if such an enrichment capability existed, there is not a capability for shipping HALEU fuel throughout the fuel cycle that has been approved by the NRC. To facilitate use of HALEU fuel in advanced reactor designs, MPR recommends that DOE support commercial uranium enrichment and development of associated shipping containers. While there are fuel design specific aspects, some needs are generically applicable; U.S. competitiveness would be enhanced by avoiding the need for each new reactor vendor to independently develop the capabilities.

2.2.3 Risk Mitigation for Manufacturers Supporting Nuclear Projects

U.S. manufacturers interviewed for this study typically expressed concern about making capital investments intended for the sole purpose of supplying new construction nuclear projects. The nuclear industry in the U.S. has demonstrated over recent decades that plans for projects are often cancelled or suspended, and even projects in the midst of construction can be cancelled. Therefore, manufacturers are leery of making investments for the nuclear industry without orders being placed and reasonable assurance that those orders will be carried through to completion. MPR recommends that DOE investigate and promote avenues to mitigate the risks for U.S. manufacturers supporting nuclear projects, akin to the measures that have been provided to utilities for constructing nuclear plants (i.e., loan guarantees).

2.2.4 Continued Investment in Advanced Manufacturing

Although advanced manufacturing techniques have the potential to provide significant benefit to the nuclear industry, U.S. manufacturers interviewed for this study expressed relatively low interest in advanced manufacturing techniques such as PM-HIP and AM. This position was echoed by the reactor plant designers who were amenable to using advanced manufacturing techniques if they were available and proven, but were not interested in absorbing the risk to their projects involved with driving such innovation. MPR recommends that DOE continue to invest in advanced manufacturing methods, because incentive to industry to achieve a potential technological breakthrough in advanced manufacturing appears to be low. Funding is needed both to support research and development of the technology and also for development of associated codes and standards. AM will require review and acceptance by the nuclear community (e.g., ASME, NRC, utilities) before commercial deployment. No ASME code cases have been accepted for AM processes or parts.

2.2.5 Irradiation Testing

SMR and advanced reactor designs require or may benefit from use of materials that do not presently have sufficient irradiation test data. Discussions with plant designers indicated that U.S. facilities do not have the capacity to supply the necessary data. Accordingly, plant designers are currently looking to international testing facilities to provide this irradiation testing capacity. MPR recommends that DOE review prioritization of irradiation tests and determine if there is an opportunity to improve support of SMR and advanced reactor needs.

2.2.6 Identify and Implement Lessons Learned and Good Practices

During the course of this project, vendors provided information on lessons learned and good practices for supporting nuclear construction projects. Although the following examples may be obvious, they were identified as important by multiple organizations interviewed for this study.

- Engaging candidate suppliers early in the design process to solicit feedback on the manufacturability of components. Manufacturers have a different perspective than designers, and obtaining feedback from suppliers as part of the design process will ultimately produce a less expensive component that is simpler to manufacture.
- Development of new infrastructure for component testing can require a long lead time due to the associated quality requirements. To ensure that component testing is not in the critical path for deployment, early preparation of testing specifications and associated discussions with testing vendors would be prudent.
- The AP1000 projects in the U.S. have demonstrated the high importance of having a completed design in advance of finalizing an order from a customer and moving forward with manufacturing and construction activities. The long NRC approval process requires a tremendous investment with a distant payback period, so designers have financial incentive to proceed at risk, in advance of obtaining final NRC approval. Manufacturing and construction from a more complete design would allow greater certainty of cost and schedule for new build projects.
- The AP1000 projects were hindered by the lack of nuclear experience among some manufacturing and fabrication suppliers. The lack of a "nuclear culture" at such suppliers was a reason for delays associated with workmanship, documentation, or other areas of product quality.

MPR recommends that DOE fund a study to gather and publish good practices and lessons learned for supporting new nuclear construction in the U.S. A study by DOE at this time to document good practices would help with knowledge management and ensure that lessons learned from the Watts Bar 2, Vogtle, and V.C. Summer projects are appropriately captured.

2.2.7 Construction

A major cause for the schedule and budget challenges for the V.C. Summer and Vogtle projects was difficulties with construction. Lack of nuclear experience among the stakeholders for the V.C. Summer and Vogtle projects, including the constructor, the owner, and the regulator, was an important factor faced by these projects. Based on the fact that no other nuclear construction projects are planned in the U.S. in the near term, SMR and advanced reactor construction projects will be faced with a similar challenge in terms of lack of recent experience. MPR recommends that DOE consider a study on construction capabilities in the U.S. for nuclear projects and capturing lessons learned from the AP1000 projects.

2.2.8 Strategic Need for Building Multiple Plants

Manufacturing and construction of an SMR or advanced reactor design plant will be a FOAK effort that will result in higher cost and schedule for the first plant than for subsequent plants. This factor will be exacerbated by the limited experience in the U.S. for building nuclear plants over the last several decades. Recent history with the Vogtle and Summer projects exemplifies these issues. The extremely high cost of these FOAK projects has dissuaded U.S. utilities from pursuing additional AP1000 plants, so the experience gained on these first units will not be leveraged to make future AP1000 plants more efficient and cost effective to build. For SMRs and advanced reactors, DOE support may be necessary to offset the high cost for initial builds and allow SMRs and advanced reactors an opportunity to demonstrate their potential for cost effectiveness over multiple projects. MPR recommends that DOE incentivize construction of multiple plants by commercial entities and seek opportunities for construction of SMRs or advanced reactors among the complex of U.S. government assets (e.g., military, laboratory, Tennessee Valley Authority).

3 SMR and Advanced Reactor Designs

This chapter provides a high-level discussion of the current designs for the NuScale Power Module (NPM), the TerraPower TWR, the X-energy Xe-100, and the concept of molten salt fuel for the TerraPower MCFR. The discussions focus on parameters of the design (e.g., weight, size, and material) that dictate requirements to support manufacturing SMRs and advanced reactors.

An overview of each design being considered in this report (i.e., NuScale, TerraPower, and X-energy) is provided in Section 3.1. The selected reactor designs are representative of three reactor types (SMRs, LMFRs, HTGRs) being considered for future applications and are sufficiently developed to allow for an assessment of their industry requirements. A more detailed discussion of the design features of major components is provided in Section 3.2. The information presented in these sections reflects information available at the time this report was published.

Development of SMRs and advanced reactor designs is ongoing with the first expected units operating no earlier than 2026. Accordingly, there is not an urgent demand for U.S. manufacturing capabilities to align with industry requirements. To provide perspective on the timing and potential capacity needs to support commercial deployment of SMRs and advanced reactors, Section 3.3 discusses current plans for the designs within the scope of this report and the potential future demand for nuclear power.

3.1 Overview of Reactor Designs and Unique Features

The NuScale SMR design is the most mature of the designs evaluated in this assessment and is the furthest along in the licensing process. Therefore, more information about its design and supply chain is accessible and could be shared in this report. The other designs (TerraPower TWR, and X-energy Xe-100) are less mature and have less publically available information; therefore, the information provided in this report for these designs is less specific. Summaries of each of the designs are provided in the following subsections.

Additionally, a brief summary of a molten salt reactor (MSR) design is included to facilitate the discussion of MSR fuel.

3.1.1 NuScale Power Module

The NPM is a 50 MWe advanced PWR that utilizes both integral and modular design. The modules initially will be licensed at 50 MWe with a future goal of 60 MWe. Each plant can operate up to 12 modules, with one module consisting of a reactor and steam generator, housed within a containment vessel (Reference 3-1). A model of the NPM is shown in Figure 3-1.

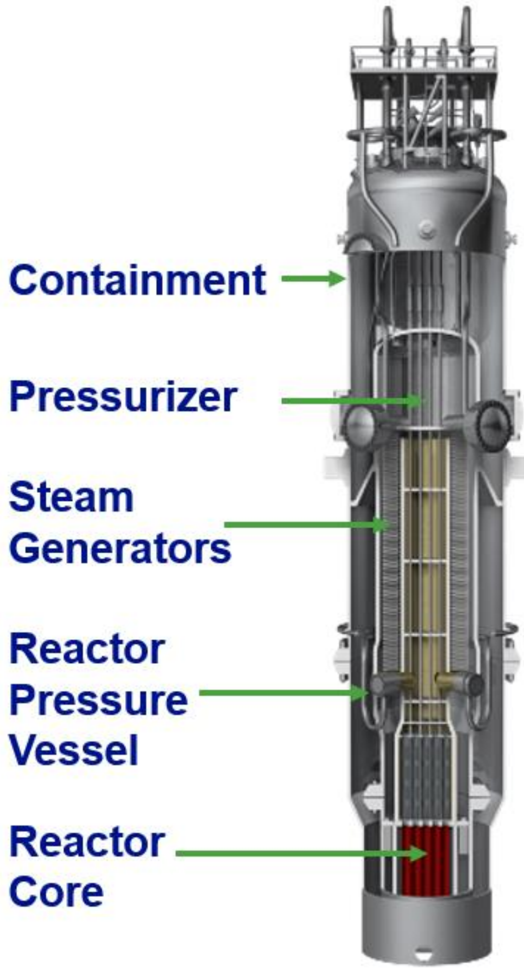

Figure 3-1. Model of the NuScale Power Module (Reference 3-1)

The overall technology underlying the NuScale SMR is comparable to the technology of currently licensed LWRs (Reference 3-2). There are however, significant design differences. The main differences are no reactor coolant pumps, external steam generator vessels, or large-bore coolant piping, which reduces the complexity and associated costs (Reference 3-3).

The NPM design contains two independent safety-related helical coil steam generators (HCSGs). The HCSGs are contained inside the reactor vessel above the reactor in the annular space between a central hot leg riser and the reactor vessel inner wall. The reactor coolant flows up from the reactor located near the bottom of the integral vessel through a central riser. The reactor coolant is turned above the steam generators by a baffle plate and flows downward across the outside of the HCSG tubes, transferring heat to the fluid inside the tubes. The motive force for reactor coolant flow is buoyancy driven flow (i.e., natural convection) by the differences in temperature and elevation between the reactor (heat source) and the steam generator (heat sink). Hence, reactor coolant flow velocity is very low in comparison to traditional forced flow LWR designs.

Each module is designed for off-site fabrication and assembly, and can be delivered to the site ready to install (Reference 3-3). The module is sized to permit transport from a central fabrication and assembly facility.

Key technical features of the NuScale design are:

- Integral reactor pressure vessel containing core, reactor coolant system, steam generators, and pressurizer.
- Buoyancy driven reactor coolant flow with no use of pumps.
- Full passive safety without reliance on safety-related electrical power, motor-operated valves, or pumps.
- Disconnection, relocation, and disassembly of each NPM for refueling and maintenance.
- A module weight of approximately 760 tons.

Special manufacturing considerations for NuScale include:

- Long seamless Alloy 690 tubes for the HCSG.
- Assembly of the HCSG.
- Some forgings for the RPV and containment vessel (CNV) are large.

3.1.2 TerraPower Traveling Wave Reactor

The TerraPower TWR design is a pool-type, liquid sodium-cooled fast reactor (SFR) with two sodium intermediate loops that transfer heat to steam generators. This design allows for a low pressure primary coolant system (Reference 3-4). TerraPower plans to construct a 300 MWe demonstration plant (TWR-300) and potentially a larger demonstration plant, which will be predecessors to the plants that are ultimately envisioned for commercial deployment (Reference 3-5). A model of the TWR design is shown in Figure 3-2.

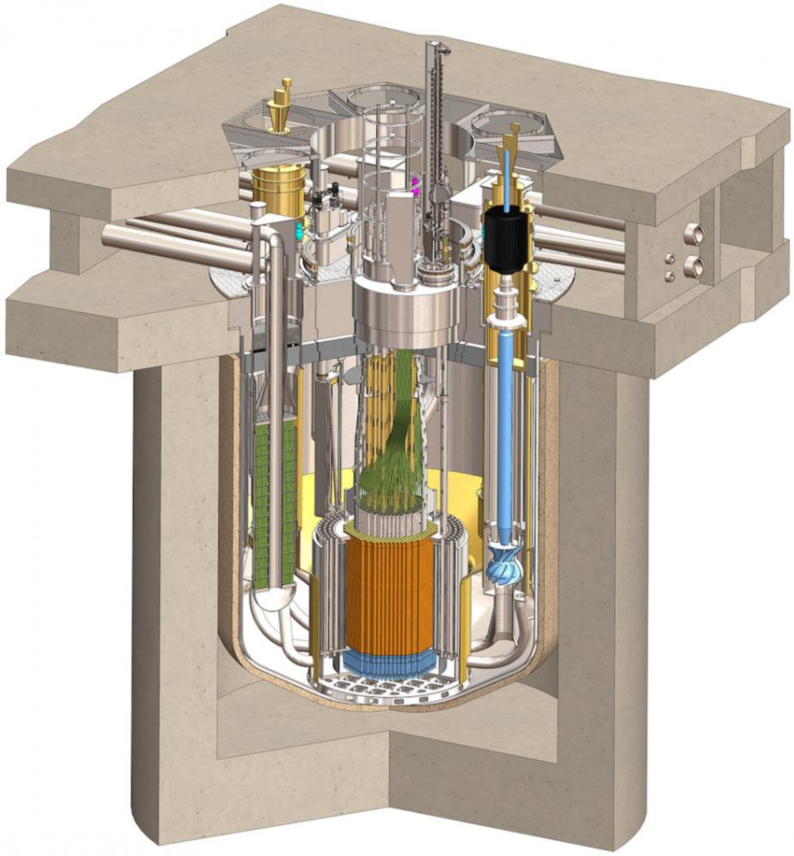

Figure 3-2. Model of the TerraPower Traveling Wave Reactor (Reference 3-6)

Unlike LWR or HTGR reactor designs, the reactor vessel does not experience high pressure conditions, but it is a larger size. The TWR design will rely heavily on HT9 steel, which is a 12Cr-1Mo-VW steel, for fuel cladding and duct material. HT9 is not commercially available, and fabrication of HT9 tube and duct components presents unique manufacturing considerations due to the size and tolerance requirements, thin wall for cladding tubes, and the material's higher mechanical properties (as compared to other common stainless steels) (Reference 3-7).

Key technical features of the TWR design are:

- Similarity to Fast Flux Test Facility outside of the core design,
- Absence of high pressure reactor vessels due to low pressure of the pool design,
- Need for high temperature materials and ASME Code components made of them, and
- Refueling is performed in the sodium pool, requiring refueling equipment not dependent on vision.

Special manufacturing considerations for the TerraPower TWR design include:

- Need for high temperature materials (i.e., HT9),

- Need for high-assay low enriched uranium for the fuel for the demonstration plant and small quantities for the ultimate commercial TWR design, and
- Lack of recent experience with sodium reactor component production or testing.

3.1.3 X-energy High Temperature Gas Reactor

The X-energy Xe-100 reactor is an HTGR utilizing pebble bed fuel with graphite as the moderator and high temperature helium coolant. Each reactor module can generate 76 MWe, with a standard plant layout having 4 reactor modules. The Xe-100 plant will use modular construction with most components to be constructed off-site and transported to the project site for installation. A model of the Xe-100 reactor and steam generator is shown in Figure 3-3.

The Xe-100 design includes a single steam generator vessel that connects to the RPV via a crossover pipe. The reactor primary coolant is helium gas, which is circulated through the RPV and steam generator by circulators installed on the top head of an HCSG.

An innovative aspect of the Xe-100 design is the pebble fuel. Each reactor uses about 220,000 pebbles with TRISO particles containing uranium oxycarbide (UCO) kernels encased in carbon and ceramic layers and embedded in a graphite matrix. Each pebble contains about 18,000 TRISO particles. The reactor makes use of a multi-pass online fueling system which measures burnup each time a pebble passes through the core. Once spent, pebbles are placed into dry storage casks for onsite storage. Because the reactor is gas-cooled, helium circulators, rather than pumps, are used to circulate the coolant. The HCSG operates at very high temperature and high secondary side pressure. The HCSG has very long coiled tubes with much greater wall thickness than PWR SGs, making it a first-of-a-kind design. (References 3-20 and 3-22)

Key technical features of the Xe-100 design are:

- Use of an HCSG.
- Helium circulators are used to move the helium.
- Need for high temperature materials and ASME Code components made of them.

All components other than those exposed to the high temperature helium will be made of materials commonly used in the nuclear industry at conditions covered by codes and standards. The materials exposed to high temperature are also covered by codes and standards (e.g., ASME Boiler and Pressure Vessel (B&PV) Code, Section III, Division 5) but are not in common use in the LWR fleet.

Special manufacturing considerations for the Xe-100 design include:

- HCGS with very complex tube configurations.
- Procurement of nuclear grade graphite.
- Need for high-assay low enriched uranium for the fuel.
- Lack of recent experience with gas reactor component production or testing facilities.

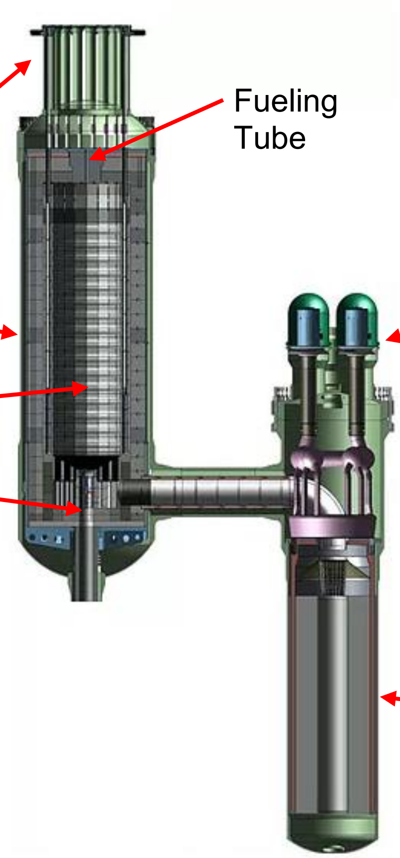

Figure 3-3. Model of the X-energy Xe-100 Design (References 3-8 and 3-9)

3.1.4 TerraPower Molten Chloride Fast Reactor

Development of MSR designs is in a very early stage, so there is limited available detail compared to the information on other designs addressed in this report. However, the molten salt fuel is vastly different than that of the existing commercial reactors and other advanced reactor designs, so the fuel is included in the scope of this report. The TerraPower Molten Chloride Fast Reactor (MCFR) design is briefly described here.

The MCFR design uses molten chloride salts at very high temperature as a coolant and fuel. The molten salt flows through the "reactor core," which is a large volume which has a geometry allowing criticality to be achieved so fission will directly heat the salts. The mixture is then circulated through a heat exchanger in a second loop that can be used for process heat, thermal storage or electricity generation (Reference 3-10). The simplicity of the reactor concept design can be seen in Figure 3-4 below.

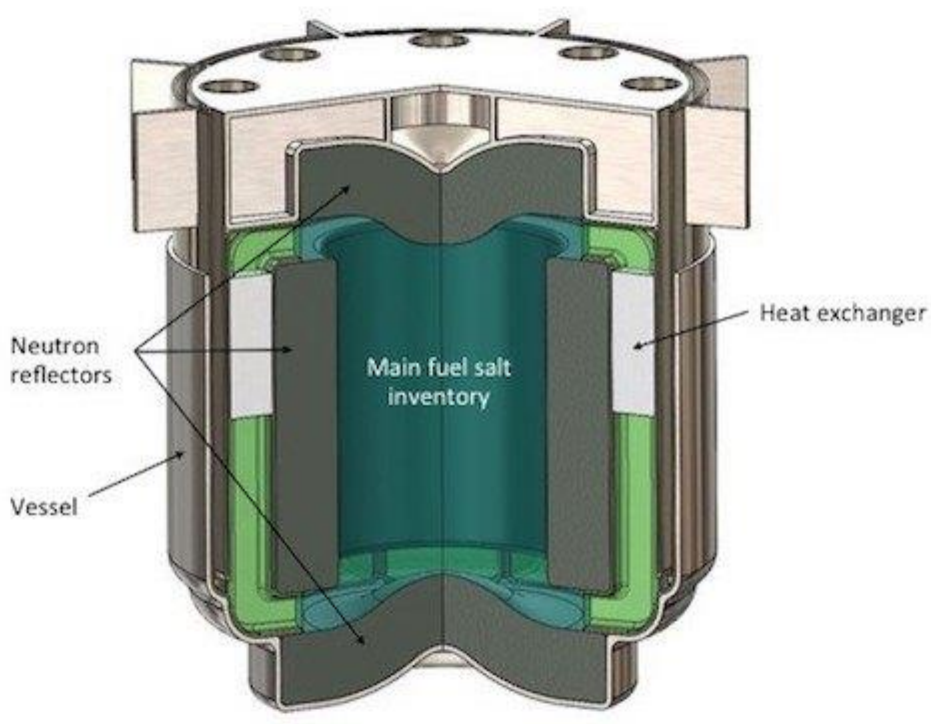

Figure 3-4. Conceptual Drawing of the TerraPower Molten Chloride Fast Reactor (Reference 3-11)

As a fast reactor, the TerraPower MCFR can use U-238, actinides and thorium as well as used LWR fuel, requiring no enrichment apart from the initial fuel load (Reference 3-12).

There are many challenges associated with the MCFR design such as high radiation dose outside the core volume and material resistance to corrosion (Reference 3-13).

For the MCFR, this report focuses on the challenge of obtaining qualified fuel, which is a unique aspect of the MCFR design that is not discussed for the other designs. Other aspects of the MCFR are not addressed because of the low level of design details compared to other designs.

3.2 COMPONENT CHARACTERISTICS

This section identifies and catalogs the defining characteristics (e.g., size, weight, configuration, or material type) of the main components in the plant designs within the scope of this report that could affect processes and locations of manufacturing and testing.

3.2.1 Reactor and Containment Vessels

Overview

Characteristics of vessels for some of the reactor designs result in challenges associated with lack of material irradiation data and with forging sizes. Unlike large LWRs where the containment is a building, these designs each take a substantially different approach to containment.

NuScale NPM

The NuScale NPM reactor pressure vessel (RPV) consists of an approximately cylindrical steel vessel with an inside diameter of approximately 10 feet and an overall height of approximately 58 feet that is designed for an operating pressure of approximately 1,850 psia. It is ASME Code Class 1. The upper and lower heads are torispherical, and the lower portion of the vessel has a flange to provide access for refueling. The RPV consists of three sections: the RPV head section, the upper section made of five parts, and the lower section made of two parts. The RPV head is welded to the top of the upper section, and the upper and lower sections are flanged together using bolts (Reference 3-14).

The RPV is housed within a cylindrical steel CNV with dimensions approximately 76 feet by 15 feet. The CNV is fabricated to ASME Code Class 1. The CNV consists of an upper CNV section with a welded torispherical top head and a lower CNV section with a welded head. The CNV is almost fully immersed in the reactor pool, which provides a passive heat sink for containment heat removal. The upper and lower CNV sections are flanged together using bolts. The flange connection permits the CNV to be separated to provide access to the RPV for refueling and maintenance (Reference 3-14). The CNV is designed to withstand the external environment of the reactor pool as well as the internal pressure and temperature of a design-basis accident.

The RPV will weigh about 340 tons (not including the core, inner vessel structures, and fuel) (Reference 3-15). The containment vessel will weigh approximately 325 tons not including the integral RPV and piping (Reference 3-16).

The RPV and CNV materials will be forged using low alloy steels and austenitic stainless steels. The preliminary designs of the RPV and CNV require about 10 forgings each (Reference 3-15).

SA-508 will likely be used for these vessels, although martensitic steel is being researched as well. An issue with both SA-508 and martensitic stainless steel for the CNV is the lack of irradiation data for the conditions experienced at the bottom of the CNV, which is subject to substantial neutron fluence and which is exposed to low temperature water on its external surface (Reference 3-5).

The Upper Reactor Pressure Vessel components are listed in Table 3-1 and illustrated in Figure 3-5. The Lower Reactor Pressure Vessel components are listed in Table 3-2 and illustrated in Figure 3-6. The Upper Containment Vessel components are listed in Table 3-3 and illustrated in Figure 3-7. The Lower Containment Vessel components are listed in Table 3-4 and illustrated in Figure 3-8.

Table 3-1. Overview of Upper Pressure Vessel Forged Components (Reference 3-15)

Upper RPV/ Head Forgings	Approximate Dimensions		Material
RPV Top Head	10' x 10' x 3'	13 ton	Clad Low Alloy Steel
RPV PZR Shell	10' x 10' x 4'	10 ton	
Integral Steam Plenum	10' x 10' x 5.5'	40 ton	
Upper SG Shell	10' x 10' x 16.5'	45 ton	
Lower SG Shell	10' x 10' x 7'	33 tons	
Upper RPV Flange	12' x 12' x 8.5'	47 tons	

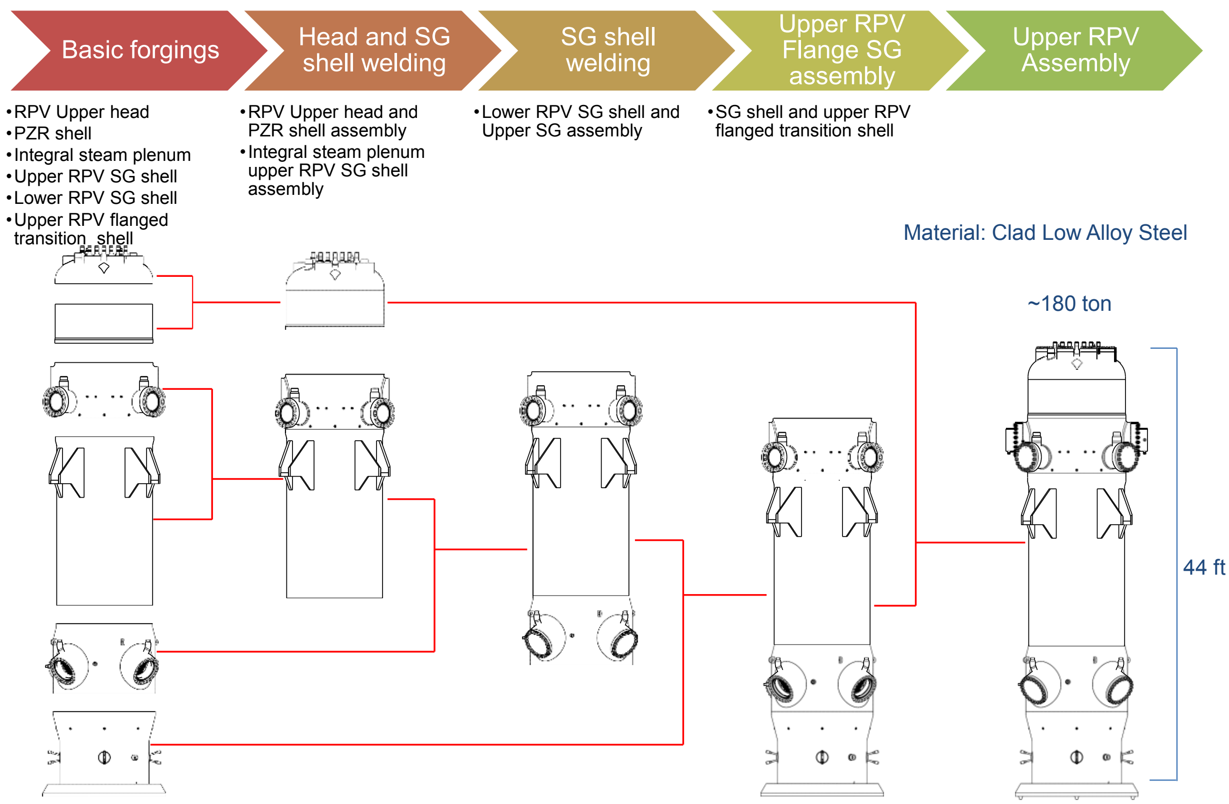

Figure 3-5. Upper Reactor Pressure Vessel Assembly (Reference 3-15)

Table 3-2. Overview of Lower Pressure Vessel Forged Components (Reference 3-15)

Lower RPV Forgings	Approximate Dimensions		Material
Lower RPV Flange Shell	~12' x 12' x 10'	24 ton	Clad Low Alloy Steel
RPV Bottom Head	~9' x 9' x 4'	9 ton	

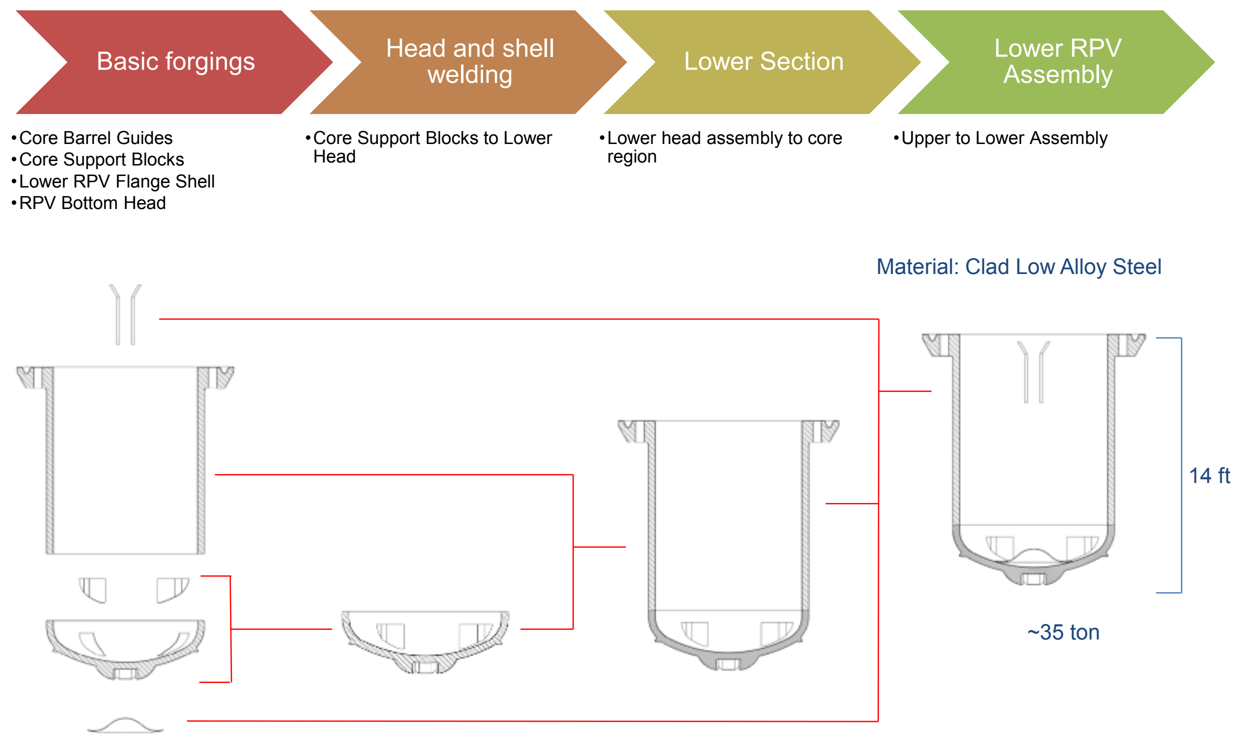

Figure 3-6. Lower Reactor Pressure Vessel Assembly (Reference 3-15)

Table 3-3. Overview of Upper Containment Vessel Forged Components (Reference 3-15)

Upper CNV / Head Forgings	Approximate Dimensions		Material
CNV Head	15' x 15' x 4.5'	81 ton	Clad Low Alloy Steel
CNV Upper Shell	15'x 15' x 14'	50 ton	
CNV Steam Plenum Access Shell	15' x 15' x 14'	65 ton	
CNV RPV Support Ledge Shell	15'x 15' x 5'	16 ton	
CNV Upper Flange	18'x 18' x 10'	35 ton	

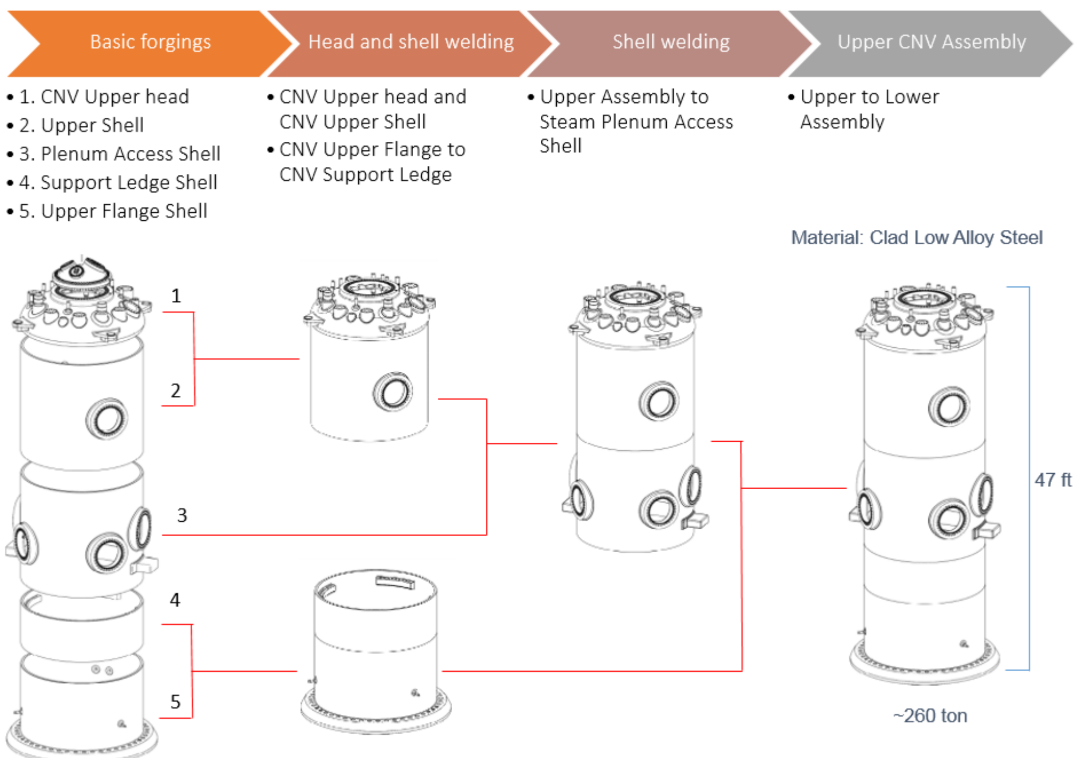

Figure 3-7. Upper Containment Vessel Assembly (Reference 3-15)

Table 3-4. Overview of Lower Containment Vessel Forged Components (Reference 3-15)

Lower CNV Forgings	Approximate Dimensions		Material
CNV Lower Flange	18’ x 18’ x 12’	35 ton	SA-508 or Stainless Steel
CNV Lower Transition Shell	15’ x 15’ x 5’	10 ton	
CNV Core Region Shell	15’ x 15’ x 7’	18 ton	
CNV Bottom Head	15’ x 15’ x 4’	16 ton	
CNV Support Skirt	15’ x 15’ x 1’	-	
CNV Support Skirt Ring	15’ x 15’ x 0.5’	-	
Passive Skirt Support	15’ x 15’ x 0.5’	-	

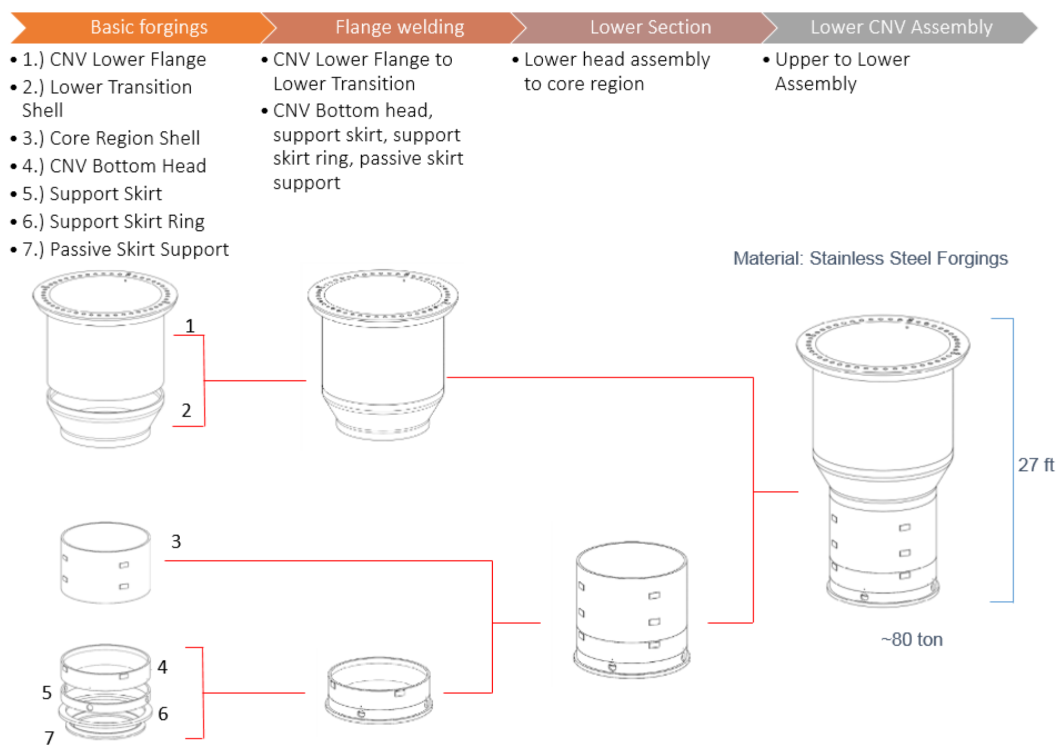

Figure 3-8. Lower Containment Vessel Assembly (Reference 3-15)

TerraPower TWR

The TerraPower TWR reactor vessel (RV) is a stainless steel cylinder over 35 feet in diameter with walls that are much thinner than an LWR, because of the low operating pressure. The reactor vessel will be designed and fabricated as a Class A vessel in accordance with the ASME B&PV Code, Section III, Division 5 and is expected to be acceptable to the regulator (Reference 3-17).

The bottom of the vessel houses the core support structure. The overall height is over 50 feet. The reactor head is also over 40 feet in diameter and over 8 feet thick, and is made of stainless steel filled with a layer of shielding. (Reference 3-5)

The Guard Vessel (GV) is a cylindrical vessel attached to the Reactor Vessel Head (RVH). The GV is sealed to the RV (Reference 3-5). The annular region between these two vessels is filled with argon gas. The inert gas ensures that in the unlikely event of a leak of primary sodium from the RV a sodium fire is precluded. The GV will not be not safety-related, but will be classified as augmented quality (Reference 3-5).

X-energy Xe-100

The reactor vessel (RV) will be designed for high temperature helium gas heat transport fluid with a feature that during normal operation the RV is not exposed to temperatures greater than normal in a LWR (Reference 3-19). The size of the X-energy Xe-100 reactor, including the pressure vessel, is about 16 feet wide and 75 feet tall (Reference 3-9). X-energy expects that the RV will be made of SA-508 steel and another martensitic material. The only welds in the RV are horizontal and these ring welds will be located in low-fluence areas. There will be two pieces comprising the bottom of the RV (Reference 3-19). The Xe-100 design does not have a traditional containment building due to the concept of "functional containment" provided by the tri-isotropic (TRISO) fuel design with several layers of containment material around the fuel, the helium pressure boundary (i.e., RV, cross vessel, and steam generator), and the reactor building (Reference 3-9).

3.2.2 Steam Generators

Overview

The steam generators for the SMRs and advanced reactors described in this report are fundamentally different than conventional PWR steam generators in that they are all helical coil designs with boiling occurring inside the tubes. In addition, some will operate at high temperatures and thus require use of materials qualified for high temperature use. What limited fabrication experience there is for steam generators with these design characteristics is decades old.

NuScale NPM

The steam generators are once-through helical coil design, with secondary fluid inside the tubes and reactor coolant outside the tubes. The tubes of the two steam generators are intertwined in the helical heat exchanger to achieve uniform performance. Feed water enters through feed nozzles and tube sheets located in forged inserts welded to the vessel wall just below the helical tube bundle and steam with superheat exits through tube sheets and steam plenums that are integral to the pressurizer baffle plate and vessel above the steam generator.

The steam generator tubes are supported by structures that extend vertically between the helical tube columns and by the steam and feed tubesheets to which they are attached. Consistent with conventional PWR steam generators, the steam generators contain single-piece tubes which are less than 100 feet in length (Reference 3-14).

Materials are consistent with conventional PWRs: tubes are NiCrFe Alloy 690, tube supports are stainless steel, and the integral vessel is low alloy steel.

There are substantial fabrication challenges associated with the unique characteristics of the NuScale design which are addressed later in this report. In addition, several types of qualification testing are necessary to validate predicted performance, including:

- Thermal performance
- Pressure drop
- Secondary side flow stability
- Flow induced vibration
- Inspectability
- Manufacturability

TerraPower TWR

Two sodium-filled intermediate heat transfer loops accept heat from the reactor coolant and transport the heat to the steam generators which are located outside of containment. The steam generators are not safety-related (Reference 3-5).

Although the TWR steam generator design is in development, the steam generators are currently envisioned to be a once-through helical coil design with sodium outside the tubes and water/steam inside the tubes, consistent with the steam generator design concept developed for the U.S. Advanced Liquid Metal Reactor (ALMR) program. Hot sodium from the intermediate heat transfer loop (~500°C) enters each steam generator via a nozzle on the top of the component, is discharged into the steam generator below an argon blanket that is maintained in the upper head, flows down across the helical heat exchanger, and is discharged via a single flow nozzle near the bottom of the component. Feed water enters the bottom of the steam generator via several feed nozzles, flows upward through the helical tubes where it is heated by the sodium coolant, and superheated steam is discharged via several steam nozzles on the top of the SG.

Steam generator size will depend on the number of steam generators selected for the plant (e.g., 1 to 4 steam generators per intermediate loop). To accommodate the sodium operating temperature, the steam generator tubes, pressure vessel and internals will be fabricated from chrome-moly material. Each steam generator contains a relatively small number (several hundred) of long tubes (several hundred feet long) which is typical of steam generators designed for liquid sodium coolant. To accommodate the effects of high temperature and internal water/steam pressure, the tubes are very thick, compared to LWR steam generator tubes. Because of tube length, tubes must be fabricated from several individual straight lengths that are butt welded together. Installed tube geometry includes the helical region in the heat exchanger and transition bends from the feed nozzles to the heat exchanger and from the heat exchanger to the steam nozzles.

Manufacturing challenges are anticipated for the unique aspects of this design, and are discussed later in this report. Testing may be appropriate in the following areas to confirm design predictions:

- Thermal performance
- Secondary side flow stability
- Flow induced vibration
- Sodium flow striping
- Inspectability
- Manufacturability

X-energy Xe-100

The Xe-100 steam generator is not safety-related. The X-energy reactor employs a single steam generator per module. The steam generator is a pressure vessel containing a once-through helical heat exchanger with helium flow outside the tubes and water/steam flow inside the tubes. The steam generator heat exchanger consists of two independent but intertwined flow circuits on the water/steam side. Heat is transferred from the helium to the water/steam that is flowing upward through the helical heat transfer tubes, and steam with significant superheat exits via the two steam nozzles on the upper head (Reference 3-19).

The heat exchanger is surrounded by an insulated shroud to maintain a relatively cool vessel temperature (i.e., slightly greater than the feedwater temperature). Above the shroud, the helium is routed to two circulators mounted on the top head. The circulators discharge the helium into the upper region of the steam generator and helium is returned to the reactor via the outer annulus in the crossover pipe.

Consistent with typical high temperature helium steam generators, the Xe-100 steam generator contains a small number (less than 200) of very long tubes. The tube length requires that tubes be fabricated from several individual straight lengths that are butt welded together. The tube routing is complex in order to accommodate thermal growth. The tubes are fabricated of NiCrFe Alloy 800H and are very thick compared to LWR steam generator tubes to accommodate the effects of high temperature and pressure.

Internals exposed to the hot helium are likewise fabricated of materials qualified for high temperature application. Most of the vessel is maintained below about 250°C and is fabricated of low alloy steel. Regions of the vessel which experience higher temperature are fabricated from materials qualified for the higher temperatures. Vessel thickness is comparable to typical LWR steam generator vessels.

Several manufacturing challenges are anticipated for the unique aspects of the Xe-100 steam generator design and are discussed later in this report. Testing may be appropriate in some of the following areas to validate the Xe-100 SG performance predicted by analysis:

- Thermal performance
- Pressure drop
- Secondary side flow stability
- Flow induced vibration
- Helium flow distribution
- Acoustic resonance
- Inspectability
- Material tribology
- Manufacturability

3.2.3 Intermediate Heat Exchangers

The TerraPower TWR design incorporates intermediate heat exchangers (IHX) into its heat transport process, whereas the NuScale and X-energy reactor designs do not. The intermediate loops isolate radioactive sodium from the sodium-to-water interface in the steam generators. The TWR IHXs transfer heat out of the sodium pool to the Intermediate Heat Transfer Loops. Hot sodium issues from the reactor and is collected in the "hot pool." This sodium is then drawn through the primary side of the IHX, which moves the sodium below the redan structure to the "cold pool" where it is drawn into the pump suction (Reference 3-5).

The TWR IHXs are a shell and tube design. The piping and materials of the IHTS will be selected to comply with ASME B&PV Code, Class A requirements under design basis normal and transient conditions. The IHX tubes, tubesheets and coaxial piping are part of the reactor coolant boundary. The IHX is approximately 2 meters in diameter at the shell, 2.7 meters in maximum diameter and 17.5 meters in overall height. The IHXs are expected to be fabricated from austenitic stainless steel (Reference 3-5).

3.2.4 Control Rods and Drive Mechanisms

Overview

A control rod drive mechanism (CRDM) is a complex electromechanical device that is exposed to thousands of continuous operating hours between plant outages and demanding environmental and operating conditions (e.g., high cycles, high internal temperatures, and high temperature gradients). These characteristics necessitate extensive qualification.

Control rods also operate in a challenging environment and must be an effective neutron absorber with limited burnout during an operating cycle, be corrosion resistant, not distort (e.g., bow or swell) significantly, and be capable of inserting while subjected to differential pressures that may occur during a loss of coolant event.

NuScale NPM

Standard control rods and drive mechanisms are to be used, but the control rod shaft is far longer than in existing reactors. Each of the sixteen NuScale control rod assemblies (CRA) consists of a group of 24 individual control rods fastened to a spider assembly and is similar to CRAs for traditional nuclear plants except for the length which is approximately half length.

The CRA contains twenty-four individual control rods with boron carbide (B4C) pellets in the upper portion of the rod, and silver-indium-cadmium (AIC) absorber in the tip of the rod. The rod internals are sealed within a 304 stainless steel cladding tube to protect the absorber from the coolant. The tube is plugged and welded at each end. The top ends of the control rods are fastened to a spider using a threaded and pinned joint.

The CRDMs are mounted on the RPV head above the pressurizer section of the RPV, and the CRDM pressure housings are safety related ASME Class 1 pressure boundaries. The CRDMs are typical designs that are made with standard materials used in LWRs. Their operating environment will differ, though, because of exposure to the higher temperature steam and gas from the pressurizer steam space.

The pre-operational and initial startup tests are performed to verify the proper function of the CRDMs. They include insertion, withdrawal and drop time testing, and hydrostatic tests. In-service tests are conducted to verify the operability of the CRDMs on a periodic basis. Tests are also performed to confirm the operability of the control rod drive shafts for a range of potential component conditions and distortions (Reference 3-21).

TerraPower TWR

In the TWR design, there are two control rod drive systems. One is the Reactivity Control System, which controls the movement of control rods via the CRDMs. The Reactivity Control System employs 15 control rods to control the power levels in the core and provides SCRAM insertion capability with sufficient reactivity worth to shut down the reactor (Reference 3-5).

The other control rod drive system is the Standby Shutdown System that releases three high-worth control rods. These control rods (safety rods) are positioned above the core during reactor operation and are used for secondary shutdown capability and to provide protection for beyond-design-basis accidents. These control rods are positioned by the shutdown rod drive mechanisms (SRDMs).

The control rods are tubes containing pellets of absorber. The difference between the control and safety rods is that the absorber bundle of the safety rods has enriched material versus the natural material in control rods (Reference 3-5).

TerraPower's fast reactor design requires fine control of rod position. The CRDMs are planned to be the same design as the SRDMs with the only difference being in their settings.

The CRDMs and SRDMs in the TWR design will be similar to the CRDMs used for traditional LWR nuclear plants. A difference is that the TWR CRDM internals are exposed to the sodium coolant and cover gas with little pressure differential across the pressure boundary. This design is similar in basic approach to the FFTF design. All the tests required for the NuScale CRDMs will likely be required for the TerraPower CRDMs and SRDMs.

X-energy Xe-100

Like the TWR design, the Xe-100 has two types of neutron controlling rods, control rods which make adjustments to the power level during operation and shutdown rods to scram the reactor. These sit on top of the RV and form part of the pressure boundary.

While the CRDMs and SRDMs are likely to be similar to traditional nuclear plants, they will have to operate in a high-temperature gas environment, making them FOAK or FIAW. Further design details are proprietary, so little detail is available. All the tests required for the NuScale CRDMs will be required for the X-energy CRDMs (Reference 3-23).

3.2.5 Fuel

Overview

Each of the fuel designs for the SMR and advanced reactor designs considered in this report is fundamentally different and introduces unique manufacturing considerations. While the NuScale fuel is consistent with traditional PWR fuel, the TWR, Xe-100, and MCFR use innovative designs that require further development for manufacturing. In addition, these three designs require HALEU fuel, which requires more enrichment than traditional fuel.

NuScale NPM

The NuScale fuel assembly is a 17x17 pressurized water reactor (PWR) design that is approximately one-half the length of typical PWR nuclear plant fuel. Other than the shortened length, the assembly contains design features similar to those of proven LWR fuel designs. All components of the fuel assembly have relevant operating experience that demonstrates their suitability for use in reactor cores. The assembly is supported by five spacer grids, 24 guide tubes, and a top and bottom nozzle that together provide the structural skeleton for the 264 fuel rods and centrally located instrument tube. The fuel rod consists of M5 alloy cladding (a proprietary variant of zirconium alloy with 1% niobium developed by Framatome) and uranium dioxide (UO_2) pellets with gadolinium oxide (Gd_2O_3) as a burnable absorber homogeneously mixed within the fuel pellets in select rod locations.

The fuel is expected to be enriched to no more than 5% ^{235}U, which is commercially available and will support up to a 24-month refueling cycle for each NuScale NPM (Reference 3-5).

TerraPower

Traveling Wave Reactor

The fuel for the TerraPower TWR design is a metallic uranium alloyed with 10 w.t. % zirconium (U-10Zr) and will be enriched up to HALEU for the driver fuel (< 19.75%). Each fuel assembly has over 200 fuel pins in a triangular pitch spacing, and the assembly housing itself, which is termed the HT9 Duct, has a hexagonal shape as shown below in Figure 3-9. A sodium bond is employed between the U-10Zr fuel and cladding (Reference 3-24).

TerraPower selected the ferritic martensitic stainless steel (HT9) as the cladding for the TWR fuel element as well as the fuel assembly duct material. TerraPower noted that variability issues in swelling performance have historically been witnessed with HT9. An optimized type of HT9 was developed by TerraPower in order to withstand higher fluences with minimal swelling, while reducing the variability of swelling data. There is no current commercially available source for fuel utilizing the HT9 ducting and cladding.

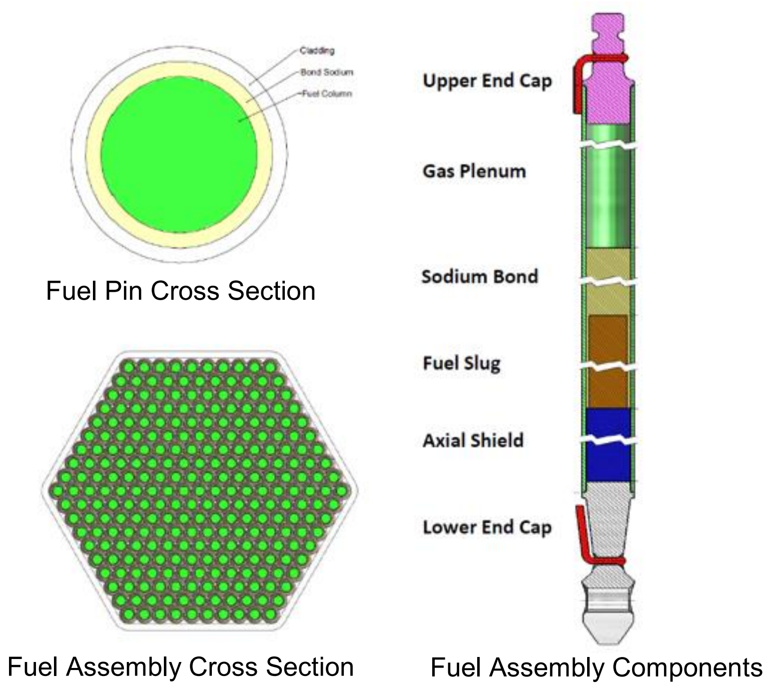

Figure 3-9. TerraPower TWR Fuel

Molten Chloride Fast Reactor

The MCFR will employ fuel in the form of uranium salts of chloride. While the MCFR is in the early stages of design, the concept may use ternary fuel salts of UCl_3, UCl_4, and NaCl, with a melting point of roughly 500ºC (Reference 3-25). The use of chloride-based salts is intended to maintain a fast neutron spectrum in order to allow for breed-and-burn cycles. The molten fuel salt is driven through the core at a velocity high enough to control reactor performance and optimize the breeding process while also attempting to preclude degradation of the fuel-facing components and liners in the reactor core and primary loop. TerraPower is considering HALEU fuel for the MCFR.

X-energy Xe-100

The X-energy Xe-100 design uses pebble fuel elements with TRISO particle fuel. The pebble bed of each reactor consists of 220,000 fuel pebbles, each roughly 60mm in diameter and made of uranium oxycarbide (UCO) encased in carbon and ceramic layers (TRISO particles). Each pebble is made up of roughly 18,000 TRISO particles embedded in a graphite matrix. Manufacturing challenges will arise from finding a large quantity of nuclear grade graphite to use in the fabrication of the fuel and the reflector around the core. The pebble fuel will use high assay LEU of roughly 15% enrichment, which is not currently available.

The benefits of the pebble fuel include additional barriers to release of radioactivity. The pyrolytic carbon and ceramic layers of the UCO TRISO particles act like pressure vessels to retain fission products within the particle (Reference 3-26). The graphite surrounding the TRISO particles moderates the nuclear reactions. The constituent parts of the X-energy Xe-100 pebble fuel are shown below in Figure 3-10. X-energy has already established a fuel manufacturing facility and is producing fuel with surrogate TRISO particles at a fuel facility at ORNL.

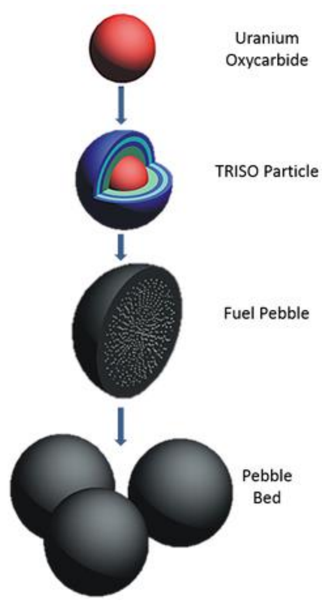

Figure 3-10. X-energy Xe-100 Pebble Fuel

3.2.6 Primary and Intermediate Coolant Pumps and Circulators

Overview

The primary coolant pumps in a nuclear plant typically are designed specifically for each plant. Common concerns include seal leakage, bearing wear, corrosion, limitations on use of cobalt in bearings because of neutron activation of cobalt in the reactor core, need for large rotating inertia (e.g., heavy flywheels), and high starting electrical current. Changes to existing designs, even if only scaling or size, historically have not avoided such problems. Challenges include long lead times and FOAK design challenges.

All of the coolant pumps and circulators for SMRs and advanced reactors will need standard tests performed (e.g., NPSH and head-flow curves), however, these tests will have to be performed in specialized coolant loops (sodium for the TWR and helium for the Xe-100).

NuScale NPM

The NuScale Power Module does not have any primary coolant pumps.

TerraPower TWR

Like the FFTF, the TWR design uses primary and intermediate sodium pumps to transport the sodium in the primary and intermediate loops. The two primary sodium pumps are large, electrical motor driven centrifugal pumps, approximately 6 feet in diameter and operate at about 635 rpm. They will be submerged in the sodium pool. The two intermediate sodium pumps are also mechanical pumps. Both types of pumps use Alloy 304H material (Reference 3-5).

X-energy Xe-100

The Xe-100 design uses two helium circulators with impeller diameter of about 4 feet. The circulators each require approximately 1.5 MW mechanical power, likely provided by electrical motors.

Circulators are not currently made for helium, and the Xe-100 design is larger than typical circulator design and has a unique blade profile, making them FOAK. The use of electromagnetic bearings rather than hydraulic lubricated bearings is another departure from typical circulator designs (Reference 3-19).

3.2.7 Valves

Overview

Plants have hundreds of nuclear system valves of up to a dozen different types. It is unlikely that a single manufacturer can supply all of them. Isolation valves need to be paired with a suitable actuator. Even when an existing design is suitable, nuclear specific requirements on corrosion resistance, closing/opening time, interlocks, environmental qualification, avoidance of cobalt on wear surfaces of primary valves, and leak tightness usually require special manufacturing.

NuScale NPM

NuScale's only "active" safety-related components are valves. The NuScale design relies on entirely passive systems including the valves; however, the valves must change alignment to perform their safety function. The valves assume their safety position without external motive force either using system pressure or passive hydraulic actuators. Each module requires the following set of safety-related valves:

- Five hydraulic and 10 solenoid valves in the Emergency Core Cooling System
- Two safety relief valves
- Eighteen hydraulic containment isolation valves ranging from 2 to 12 inch diameter
- Four decay heat removal actuation valves
- Four check valves
- Two excess flow check valves

Some of these valves will need to be customized from typical LWR valve designs. Testing requirements for the valves are typical of those in current LWRs.

TerraPower TWR

The TWR design needs a variety of valves (a few dozen) due to the use of sodium coolant and cover gas (Reference 3-5). As examples, the TWR design will need small isolation valves for auxiliary sodium systems and large sodium isolation valves outside containment to isolate the steam generator.

These sodium and cover gas valves are not all FOAK, but many are the first-in-a-long-time and many will likely be a size larger than previously manufactured (Reference 3-5).

X-energy Xe-100

The Xe-100 design may require the following safety related valves: primary coolant (helium) isolation valves and SG relief valves. Little other information is available on the material, size, or other design features of these valves at this time (Reference 3-23).

Existing designs are likely not suitable without modification. In addition, a valve-like device will be needed for the fuel pebble sorting system for used fuel (Reference 3-19). The valves will require tests similar to those needed for LWRs, with some to be performed in helium.

3.2.8 Fuel Handling Systems

Overview

SMRs and advanced reactors alike have unique fuel handling that is significantly different than those systems used in the current LWR fleet. The contrast is particularly stark for the SFRs due to limitations with the opacity of the sodium coolant. Much of this equipment is FOAK and will require custom fabrication, and fabricators will have little to no experience with manufacturing these devices. The equipment requires complex electrical control capability as well as specific quality controls so as to not drop or damage the core, fuel, or other associated components.

NuScale NPM

Opening (and reassembling) the module requires development of underwater, remote-controlled stud/nut removal and tightening equipment.

The fuel handling equipment (FHE) consists of the components and equipment used to handle fuel upon receipt on site, during refueling operations, and for loading into a spent fuel shipping cask: fuel handling machine (FHM), new fuel jib crane (NFJC), new fuel elevator (NFE).

The FHM is designed to be single-failure-proof per ASME NOG-1 criteria. The FHM consists of the bridge, trolley, mast, and grapple and has a capacity of 1200 pounds.

The NFJC is used to remove new fuel assemblies (NFAs) from their shipping containers, support the NFAs during inspection, and move the NFAs to the NFE. The NFJC is comprised of a jib beam with an underhung trolley and hoist. The NFJC jib beam is an engineered welded composite. It has a capacity of 1000 lbs.

The NFE elevator track structure is welded 304 stainless steel and is secured to the pool wall via bolted connection to permanently welded pads. The NFE fuel carriage and basket assembly is welded stainless steel construction. It has a capacity of 1200 pounds (Reference 3-14).

The NFJC and NFE are unique FOAK designs that will require customization but are within the capability of existing suppliers. Testing involves simulation of fuel loading and unloading with dummy fuel, but should not be an issue to set up in the plant.

Even where FOAK, the refueling components will not require expansion or development of fabrication capabilities not already available.

TerraPower TWR

The Fuel Handling System consists of in-vessel and ex-vessel core component handling equipment. The In-Vessel Handling Machines (IVHM) move and rotate core assemblies within the reactor vessel. This equipment will handle all types of core assemblies. The IVHM interfaces with the Ex-Vessel Handling Machine (EVHM) which is used to transfer unirradiated and irradiated fuel assemblies into and out of the reactor vessel. Support systems are included for receipt of new components, interfacing the reactor with the EVHM and discharging irradiated core components removed from the reactor (Reference 3-5).

Some of the FHE for the TWR plant is expected to be based on designs used in previous facilities. Other FHE are FOAK designs that will require customization. The most challenging aspect is the need for ensuring proper fuel handling without visual access, but this was satisfactorily accomplished in FFTF. (Reference 3-5)

X-energy Xe-100

The fuel handling system consists of multiple subsystems which are all custom, FOAK designs and are planned to be made out of austenitic stainless steel. These designs will require special consideration of the neutron activation of the fuel handling component materials.

The sub-systems include:

- The fuel unloading device (i.e., an auger that rotates the fuel pebbles 3-4 times and checks size to evaluate whether or not to remove the pebble)
- Pebble pneumatic transport moves fuel pebbles from the bottom of the reactor to the top
- Fresh fuel supply system
- Spent fuel system
- Burn-up measurement device

The fuel handling system is augmented quality, thus no nuclear quality assurance testing is required and the level of testing and qualification needed is being determined. The safety concerns for this system are geared towards protecting personnel and limiting dose (Reference 3-19).

3.2.9 Balance of Plant Components

The balance of plant components include steam turbine-generators, condensers, cooling towers, feedwater and other pumps and valves that are not nuclear-unique or safety-related. The reactor plant designs in the scope of this report plan to use existing and readily available commercial technology for the balance of plant components. Accordingly, these components were not individually reviewed for this scope of work.

3.2.10 Additional Unique Equipment

NuScale NPM

NuScale Power Module refueling and maintenance entails disconnecting the module from systems, lifting it slightly, and transiting it from its operating position to the refueling and maintenance area. Lifting the module requires a single-failure-proof building bridge crane with a very large capacity: approximately 800 tons, with a 44 foot lift, and a 69 foot span, but will not require new manufacturing capability.

TerraPower TWR

The TWR design requires a sodium fire protection system that includes catch pans and fire protection pans, which do not appear to pose any manufacturing challenges.

Inside containment, pipes carrying sodium will be surrounded by an argon-inerted guard pipe or be located inside an inerted cell. Additional instrumentation is needed to ensure detection of sodium leaks. Also related to the use of sodium as a coolant are the sodium processing system and ex-vessel storage tank subsystem. These include primarily various cold traps that filter the sodium as well as electromagnetic pumps for circulation.

X-energy Xe-100

Because the Xe-100 design uses helium as a heat transport fluid, a helium purification system is necessary to maintain the chemical composition to limit graphite oxidation, carbon deposition, and deterioration of structural alloys. Designs for previous high temperature gas reactors include a precharcoal bed, copper oxide fixed bed, molecular sieve bed, and a cold charcoal bed (Reference 3-28).

3.3 COMMERCIAL DEPLOYMENT

This section reviews plans for commercial deployment of SMRs and advanced reactors. This section also includes a broader look at long-term demand for nuclear generation, which could be filled by SMRs and advanced reactors.

3.3.1 Demand for Domestic Nuclear Generation

Demand for new nuclear construction in the U.S. in the immediate term is low for several reasons: (1) demand for total generation remains flat, (2) the adverse experience with the AP1000 projects in Georgia and South Carolina, and (3) the more favorable economics for other types of generation (e.g., natural gas). The only active nuclear construction project in the U.S. is the Vogtle 3 & 4 expansion project in Georgia, which is in the process of building two new Generation III+ reactor plants. While new construction of plants in the U.S. has been low, increased utilization of existing plants has resulted in higher nuclear power generation. Power uprates and higher capacity factors have enabled existing U.S. nuclear plants to produce more power annually than in years past. In addition, license extensions of existing plants through 60 years has allowed older plants to continue operating, and an additional round of life extension for many existing plants may extend their service life to 80 years.

The potential for future construction of nuclear reactors in the near term (i.e., the next few years) can be ascertained from the presence of regulatory submittals to the NRC that are needed to proceed with construction. Specifically, utilities initially apply for an Early Site Permit (ESP) to gain NRC approval for locating a nuclear facility and this process is independent of specific reactor designs. Obtaining an ESP does not necessarily indicate that a facility will be built, as evidenced by the numerous ESPs that were sought and obtained in the 2000s for projects that were subsequently cancelled or suspended (e.g., Clinton, Grand Gulf, North Anna). The only ESP currently under review is for the Tennessee Valley Authority (TVA) at the Clinch River Site in Oak Ridge, Tennessee. This ESP is for multiple SMR units at this site. The review process is projected to be complete in late 2019 to early 2020 (References 3-29 and 3-30).

Although there are no firm plans for building new nuclear plants in the U.S. in the near term aside from completing the Vogtle project, an intermediate term demand (i.e., beyond the next few years) is expected to develop. Legislation in several U.S. states has acknowledged that the current market conditions do not properly value the benefits of nuclear power in terms of grid reliability and lack of carbon dioxide and pollutant emissions. Further recognition of the value of nuclear power in the future could strengthen the basis for construction of new nuclear plants, particularly as existing plants age and ultimately retire.

The factors that influence demand for new construction of nuclear power plants in the U.S. in the intermediate term are unpredictable and wide-ranging. This demand will depend on implementation of changes to the market environment, likely through legislation, to reflect the value of nuclear power. Demand for nuclear construction will also depend on factors including: pricing of alternative generation sources (e.g. natural gas); the presence of a definitive spent fuel storage solution; changes in demand for electric generation (e.g., for electric cars); and public perception of nuclear power (e.g., lack of nuclear accidents like Fukushima). For these reasons, a quantitative projection for future U.S. SMR or advanced reactor demand in the intermediate term would be speculative and very uncertain. However, as a basis for comparison, when U.S. nuclear construction was at its peak in the 1970s, nuclear power generation went from 7 GW in 1970 to 52 GW in 1980, which is an average rate of 4.5 GW per year (Reference 3-35). A full NuScale plant with twelve modules has a capacity of ~600 MW, so more than seven NuScale plants per year would be needed to achieve the nuclear build rate experienced in the 1970s. As another point for comparison, NuScale is planning its supply chain for a capacity to support deployment of three NuScale plants per year.

3.3.2 International and Long-Term Demand for Nuclear Power

Internationally, demand for new nuclear construction is surging. At the start of 2018 there were 58 reactors under construction around the world, 20 of which were in China. Electricity demand is rising in developing countries, and there is a need to replace aging fossil fuel units by generating capacity with lower emissions of pollutants and carbon dioxide. Several studies have been published that evaluate global carbon emissions and recommend plans for reducing such emissions to sustainable levels. One study from the Organization for Economic Cooperation and Development (OECD) International Energy Agency describes a "Sustainable Development Scenario" whereby global electricity generation from nuclear power more than doubles by 2040 with capacity growing to 720 GW. Another study from the World Nuclear Association calls for providing 25% of global electricity demand from nuclear power, which would add 1,000 GW of nuclear generation capacity. The annualized build rate for such a campaign would be approximately 30 GW per year, which would be equivalent to fifty NuScale plants. Accordingly, the potential for intermediate-term and long-term demand for SMRs and advanced reactors is present, both in the U.S. and abroad. (Reference 3-31)

<u>NuScale NPM</u>

NuScale Power submitted a design certification application (DCA) for its NPM design to the NRC in January 2017. The NRC completed its Preliminary Safety Evaluation Report (SER) in April 2018 and issued Requests for Additional Information (RAIs) as part of its ongoing review process. The NRC is targeting issuance of the final SER with no open items in September 2020. (Reference 3-32)

NuScale is currently working with Utah Associated Municipal Power Systems (UAMPS) on the Carbon Free Power Project (CFPP) (Reference 3-33), which is a project to construct a plant consisting of 12 NuScale modules at a location within the Idaho National Laboratory (INL) site.

DOE has awarded cost sharing to NuScale to support progress on this project. Site preparation for this project is planned to commence in 2021 (Reference 3-34), with the first safety-related concrete pour in 2023. The first module may be operational by 2026 with the full 12-module plant operational in 2027.

NuScale considers that construction of its 12-module plants can be completed within a 3-year schedule, which reduces the impact of compounding interest for financing and improves the timeline to reach a return on investment.

TerraPower TWR

TerraPower has launched a joint venture with the China National Nuclear Corporation (CNNC) to form the Global Innovation Nuclear Energy Technology Company, which will facilitate a collaboration towards completing the TWR design and commercializing the technology.

As an initial step, the TerraPower-CNNC joint venture plans to build and operate a demonstration reactor with less than half of the power output of the full TWR design. This demonstration reactor, the TWR-300, will be located in China and is envisioned to be operating within the next 10 years. Approximately 5 years thereafter, the joint venture may build and operate a larger demonstration reactor, also in China. Global commercialization of the TWR technology would follow initial implementation in China. There are no current plans to build a TWR plant in the U.S. (Reference 3-5)

The TerraPower-CNNC joint venture recognizes that Chinese manufacturing cannot produce all of the components necessary for the plant, so international suppliers will be utilized where necessary. TerraPower is working with U.S. companies to develop its supply chain where necessary, and U.S. national laboratories are performing research that could be applied for the TWR design.

X-energy Xe-100

The Xe-100 program has completed its basic design and is now in the conceptual design phase. X-energy is currently targeting the late 2020s for a Xe-100 reactor to be operational (Reference 3-19).

As the Xe-100 design is still relatively immature, there are no firm plans for commercial deployment with specific utilities at this time. X-energy has entered a memorandum of understanding (MOU) with the Jordan Atomic Energy Commission for assessing the Xe-100 design and its potential for deployment in Jordan (Reference 3-36).

It is noted that the DOE provided X-energy with a cooperative agreement award in 2015 to manufacture TRISO fuel at Oak Ridge National Laboratory and more recently provided an additional cooperative agreement award to develop the design and license application for a high assay low enriched uranium fuel fabrication facility (Reference 3-37).

4

Supply Chain

Procuring equipment to support new nuclear projects is a capital intensive endeavor that presents unique challenges for prospective project owners and operators due to the relatively small number of suppliers capable of manufacturing the highly-specialized equipment required for nuclear service. The OECD notes that equipment costs can make up 48% of the overall overnight cost of a new nuclear power plant project (Reference 4-1). This chapter discusses supply chain experience from Generation III+ construction projects and supply chain plans for the reactor plant designs within the scope of this report.

4.1 Supply Chain Background

Many of the supply chain challenges encountered by new nuclear projects in the U.S. can be attributed to the slowdown in nuclear plant construction that began in the late 1970s. This slowdown resulted in a dramatic decrease in the number of suppliers for nuclear plant equipment as manufacturers could no longer justify maintaining strict quality assurance (QA) programs necessary for manufacturing this equipment in a shrinking market. As an example of this drop in capacity, the OECD reported in 2015 that the number of U.S. companies supplying nuclear components has decreased by over 80% since the late 1980s. Similarly, the number of ASME N-type certificate holders had dropped by more than 78% in the same time period, significantly limiting the domestic capacity for manufacturing pressure-retaining components designed for nuclear service (Reference 4-1).

New nuclear projects involving advanced and SMR designs may require procurement of FOAK equipment from a global network of suppliers, not unlike the supply chains associated with Generation III+ reactors currently under construction around the world.

4.2 Experience from Generation III+ Construction

Generation III+ reactor designs are distinguished from Generation II reactors by their use of evolutionary passive safety systems and smaller footprints. However, many Generation III+ designs continue to make use of the general nuclear steam supply system (NSSS) and balance-of-plant (BOP) designs of Generation II reactors. Combined with higher net electrical outputs requiring even larger components than those used in Generation II reactors, the manufacturing demands associated with Generation III+ reactor designs present a unique challenge for equipment and component vendors and engineering, procurement, and construction (EPC) contractors. To address these challenges, Generation III+ projects may be driven to use the international market, particularly for components necessitating heavy forging capabilities.

The domestic AP1000 projects at the V. C. Summer and Vogtle plant sites offer significant insight into the challenges associated with equipment procurement and fabrication for

Generation III+ reactor designs. These challenges are largely a product of the evolving nuclear power plant technology market over the last three decades discussed above. Recommendations from these experiences can be used to inform future procurement and component fabrication efforts associated with SMRs and advanced reactors.

4.2.1 AP1000 Supply Chain

The supply chain associated with the domestic AP1000 projects at the V.C. Summer and Vogtle plant sites are essentially identical as a result of both plant owners signing EPC contracts with Westinghouse and the Shaw Group at the outset of each project. While construction of V.C. Summer 2 and 3 was terminated in July 2017, many of the major components that define the AP1000 supply chain were delivered to the site prior to the cancellation of the project. A majority of the major components associated with the Vogtle project have also been delivered to the site with many already installed. A global overview of the domestic AP1000 supply chain is presented in Figure 4-1, which shows the various domestic and international companies engaged in equipment and component procurement for both projects.

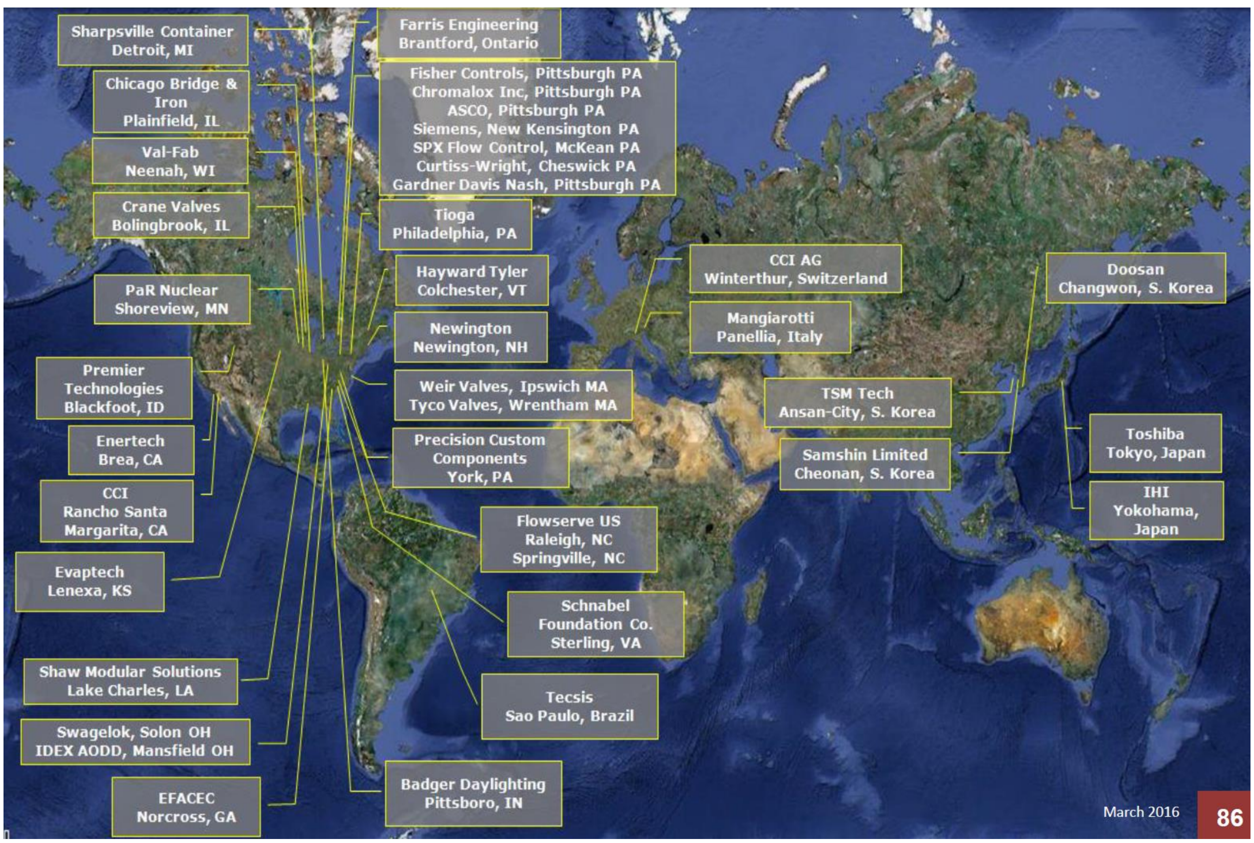

Figure 4-1. AP1000 Global Supply Chain (Reference 4-2)

The major components associated with the domestic AP1000 projects were largely procured from international vendors due primarily to domestic heavy forging limitations.

The discussions below focus on the supply chain elements for the major components, including information regarding the vendor and relevant details regarding their manufacturing capabilities.

Reactor Pressure Vessel and Steam Generators

The reactor pressure vessels and steam generators for V.C. Summer and Vogtle were manufactured by Doosan Heavy Industries and Construction (Doosan) located in Changwon, South Korea. Doosan has upgraded their forging capabilities within the last decade to take advantage of the increased global interest in heavy forgings associated with new nuclear projects, particularly in Asia and the Middle East. Doosan has also provided reactor pressure vessels and steam generators for some of the AP1000 projects at Sanmen and Haiyang sites in China with the balance being manufactured by China First Heavy Industries (Reference 4-3).

Containment Vessel

The steel plates comprising the containment vessels for V.C. Summer Units 2 and 3 and Vogtle Units 3 and 4 were manufactured by IHI Corporation in Yokohama, Japan and assembled at the respective plant sites. IHI Corporation is one of Japan's leading heavy machinery manufacturers and has the capability of supplying boilers, gas turbines, nuclear reactor pressure vessels for PWR and BWR reactors, and containment vessels. The company also maintains a three-way agreement with Toshiba and Doosan Heavy Industries in South Korea that makes Doosan's expertise available to IHI (Reference 4-3).

Control Rod Drives

The control rod drive mechanisms used for both the V.C. Summer and Vogtle projects were manufactured at Westinghouse's Newington, NH facility. This facility is also responsible for producing various AP1000 reactor vessel internal components and supports the currently operating fleet of nuclear power plants.

Fuel Elements

The AP1000 fuel element supply chain involves multiple Westinghouse facilities across three U.S. states. Westinghouse subsidiary Western Zirconium in Ogden, UT produces zirconium metal from zircon sand. Fuel tubing is manufactured at Westinghouse's specialty metals plant in Blairsville, PA. Final fuel assembly fabrication takes place at Westinghouse's Columbia, SC fuel facility. The Columbia, SC facility is also responsible for manufacturing the fuel pellets utilized in the AP1000 fuel assemblies through UF_6 conversion to UO_2 powder. In addition to providing fuel assemblies for the eventual Vogtle core load, this facility also provided the fuel elements currently loaded in the Sanmen and Haiyang AP1000 reactors in China (Reference 4-4).

Steam Turbine Generators and Condensers

The turbine generators associated with the V.C. Summer and Vogtle projects were manufactured by Toshiba America Energy Systems (Toshiba) in Tokyo, Japan. Toshiba is a well-known vendor of power plant technology and was the majority owner of Westinghouse until April 2018 when Toshiba completed the sale of its stake in the company to Brookfield Business Partners.

The condensers used for both projects were designed by Toshiba, but manufactured by BHI Company in Sacheon, South Korea. BHI is a well-known manufacturer of conventional power plant equipment including boilers, feedwater heaters, and condensers.

Reactor Coolant Pumps

The reactor coolant pumps (RCPs) for the V.C. Summer and Vogtle AP1000 projects were manufactured by Curtiss-Wright at the company's Electro-Mechanical Division (EMD) facility in Cheswick, PA. Curtiss-Wright is an established domestic manufacturer of nuclear power plant equipment that also maintains significant service capabilities, including equipment qualification services through its product and service brand QualTech NP. Curtiss-Wright also provided the RCPs for all of the Sanmen and Haiyang AP1000 projects in China.

Valves

Multiple manufacturers have been contracted to supply valves for the AP1000 reactors at V.C. Summer and Vogtle. A majority of the valve manufacturers are domestic, including SPX in McKean, PA (automatic depressurization system squib valves), Fisher Controls in Marshalltown, IA (pressurizer spray valves) and Flowserve in Raleigh, NC (main steam isolation valves). International valve manufacturers include CCI AG in Balterswil, Switzerland (main steam power operated relief valves and feedwater control valves) and Samshin in Cheonan, South Korea (miscellaneous safety- and non-safety-related valves).

Class 1E Switchgear and Equipment

The AP1000 design does not rely on AC power to maintain core cooling and containment cooling in the event of a design basis accident. As such, the Class 1E electrical equipment requirements are limited almost exclusively to DC power systems and no safety-related diesel generators are used in the design. Class 1E batteries for the domestic AP1000 projects are being supplied by EnerSys of Hays, KS. Class 1E battery chargers are being supplied by Schneider Electric subsidiary Gutor Electronic from Wettingen, Switzerland. The limited amount of Class 1E AC power equipment is being supplied by Westinghouse's New Stanton, PA manufacturing facility.

AP1000 Supply Chain Summary

A comprehensive table outlining the key elements of the domestic AP1000 supply chain is presented in Table 4-1. This table is organized by continent to demonstrate the international reach of the AP1000 supply chain. Differences between the V.C. Summer and Vogtle procurement processes and equipment are included as necessary.

Table 4-1. Domestic AP1000 Supply Chain

AP1000 Component	City and State	Country	Continent	Company
Condenser	Sacheon	Korea	Asia	BHI Company
Containment vessel	Yokohoma	Japan	Asia	IHI
Core Barrel	Yokohoma	Japan	Asia	Toshiba
Demineralizer	Ansan City	Korea	Asia	TSM Tech Co.
Heat Exchanger	Ansan City	Korea	Asia	TSM Tech Co.
Main Step-Up Transformers	Tokyo	Japan	Asia	Toshiba
Reactor Vessel	Changwon	Korea	Asia	Doosan
Steam Generators	Changwon	Korea	Asia	Doosan
Turbine Generator	Tokyo	Japan	Asia	Toshiba
Valves	Cheonan	Korea	Asia	Samshin
Accumulators	Panellia	Italy	Europe	Mangiarottia SpA(2)
Class 1E Battery Chargers	Wettingen	Switzerland	Europe	Gutor Electronic
Containment Recirculation Screens	Winterthur	Switzerland	Europe	CCI AG
Core make-up tanks	Panellia	Italy	Europe	Mangiarottia SpA(2)
In-containment Refueling Water Storage Tank	Winterthur	Switzerland	Europe	CCI AG
Pressurizer	Panellia	Italy	Europe	Mangiarottia SpA(2)
Passive RHR Heat Exchanger	Panellia	Italy	Europe	Mangiarottia SpA(2)
Valves	Balterswil	Switzerland	Europe	CCI AG
AP1000 Modules	Cambridge, ON	Canada	North America	Aecon
	Lake Charles, LA	USA	North America	Chicago Bridge & Iron
	Corvallis, OR	USA	North America	Greenberry
	Lakeland, FL	USA	North America	Specialty Maintenance and Construction
	Clackamas, OR	USA	North America	Vigor Works
Automatic Depressurization System Squib Valves	McKean, PA	USA	North America	SPX Flow Control
Auxiliary Relief Valves	Brantford, ON	Canada	North America	Farris Engineering
Class 1E Batteries	Hays, KS	USA	North America	EnerSys
Class 1E Switchgear	New Stanton, PA	USA	North America	Westinghouse
Control Rod Drive Mechanisms	Newington, NH	USA	North America	Westinghouse
Cranes	Shoreview, MN	USA	North America	PaR Nuclear
Degasifiers	Neenah, WI	USA	North America	Val-Fab
Fuel Assemblies	Columbia, SC	USA	North America	Westinghouse
Instrumentation Valves	Solon, OH	USA	North America	Swagelok
Integrated Head Package	Blackfoot, ID	USA	North America	Premier Technologies

Table 4-1. Domestic AP1000 Supply Chain

AP1000 Component	City and State	Country	Continent	Company
Liquid Ring Vacuum Pump	Pittsburgh, PA	USA	North America	Gardner Denver
Radiation Monitoring Systems	San Diego, CA	USA	North America	General Atomics Electromagnetic Systems Group
Reactor Coolant Loop Piping	Philadelphia, PA	USA	North America	Tioga
Reactor Coolant Pumps	Cheswick, PA	USA	North America	Curtiss-Wright
Reactor Vessel Flowskirt	York, PA	USA	North America	Precision Custom Components
Reactor Vessel Internal Lifting Rig	Blackfoot, ID	USA	North America	Premier Technologies
Recirculation Heaters	Pittsburgh, PA	USA	North America	Chromalox
Solenoid Valves	Pittsburgh, PA	USA	North America	ASCO
Steam Generator Recirculation and Drain Pumps	Colchester, VT	USA	North America	Hayward Tyler
Shield Building Panels	Newport News, VA	USA	North America	Newport News Industrial
Spent Resin Tank	Neenah, WI	USA	North America	Val-Fab
Tank demineralizers	Detroit, MI	USA	North America	Sharpsville Container
Unit Auxiliary Transformers	Rincon, GA	USA	North America	Efacec Power Transformers
Valves	Bolingbrook, IL	USA	North America	Crane Valves
	Rancho Santa Margarita, CA	USA	North America	CCI
	Marshalltown, IA	USA	North America	Fisher Controls
	Ipswich, MA	USA	North America	Weir Valves
	Winchester, MA	USA	North America	Tyco Valves
	Raleigh, NC	USA	North America	Flowserve US
	Springville, NC	USA	North America	Flowserve US
Variable Frequency Drives	New Kensington, PA	USA	North America	Siemens
Cooling Tower Fans (V.C. Summer only)	Sao Paulo	Brazil	South America	Tecsis

Notes:

(1) The domestic AP1000 supply chain information is based on information provided from the OCED (Reference 4-1), SCANA (Reference 4-2), and Georgia Power in their August 2017 Georgia Public Service Commission filing (Reference 4-5)

(2) Mangiarottia SpA is a Westinghouse subsidiary.

4.2.2 Supply Chain and Fabrication Challenges

Procurement and fabrication experience gained from domestic AP1000 projects offers significant learning opportunities for new nuclear project supply chains. The challenges associated with the manufacturing and assembly of the modules integral to the AP1000 design offer insight into the difficulties associated with implementing QA programs for new nuclear projects. The following discussion is a summary of information gathered from various sources regarding this topic as it relates to the impact of this experience on domestic manufacturing capabilities.

The modular construction of the AP1000 reactor was structured to expedite the overall construction times for the Generation III+ plant by allowing offsite module fabrication and onsite construction activities to progress in parallel. Offsite module manufacturing allows onsite construction activities to be unimpeded by assembly of components that would traditionally take place onsite. Following module fabrication, the modules would be shipped and assembled at the site. This concept has been successfully implemented in many industries.

Shaw Modular Solutions (SMS) was initially subcontracted by Westinghouse to fabricate the AP1000 modules for the V.C. Summer and Vogtle projects at the SMS facility in Lake Charles, LA. Personnel at the facility did not have significant experience in performing manufacturing work for the nuclear industry. Following significant lapses in QA program implementation at the SMS facility, Shaw Nuclear Services issued a stop work order at the facility on July 23, 2010, that halted manufacturing activities until the QA-related issues were corrected. Lapses included welds that did not comply with design specifications and programmatic weaknesses in correcting non-conformances and carrying out the facility's corrective action program. This stop work order was lifted on August 6, 2010 (Reference 4-6).

Some of the fabrication issues were attributed to overly prescriptive specifications which resulted in unnecessary physical re-work of non-critical component characteristics and processing of specification changes (Reference 4-7). Other notable delays associated with module construction included those due to NRC questions regarding rebar designs used for some structural modules that interface with the shield building. In a quarterly report to the South Carolina Public Utilities Commission, SCE&G stated that extended holds on structural module fabrication remained in place during the fourth quarter of 2010 due to NRC concerns regarding the rebar design and continued lapses in SMS QA program implementation. These delays combined to effect a six-month delay in the production of structural module CA01 for the V.C. Summer project (Reference 4-8). The CA01 module is the primary structural module for the AP1000 containment and its delay resulted in multiple downstream schedule delays to items logically tied to its completion.

In a February 22, 2011, letter to the NRC, SMS acknowledged multiple challenges in the areas of QA, Training, Corrective Action, Management Oversight, Welding, and Material and Nonconforming Material Control (Reference 4-9). As a result of these challenges, the manufacturing responsibility for domestic AP1000 modules was transferred to other subcontractors around the country with Chicago Bridge & Iron (formerly SMS) continuing to perform limited work at the Lake Charles, LA facility in support of the Vogtle project. In a 2014 presentation at the NRC's Regulatory Information Conference, Westinghouse acknowledged additional AP1000 supply chain challenges beyond those regarding module construction

(Reference 4-10). Challenges identified by Westinghouse included the use of sub-tier suppliers and new vendors with no QA program experience, reintroduction of vendors to the nuclear supply chain, and establishing an oversight mechanism for a supply chain involving over 600 suppliers.

The module manufacturing experience associated with the domestic AP1000 projects represents one prominent example of the difficulties in executing QA programs where new nuclear construction has not been undertaken in many decades. The ability to effectively define and implement satisfactory QA programs poses a significant risk to initial commercial deployment of advanced reactors and SMRs, particularly in those areas where such capabilities have not been maintained. This risk is primarily the result of a long domestic nuclear construction hiatus which has limited the collective ability of the industry to gain and retain experience with nuclear QA requirements. New entrants to the nuclear supply chain will face a steep learning curve in this area. Even experienced suppliers may have relatively few personnel with significant nuclear QA experience. As a result, it should be anticipated that the supply chain for new nuclear technology will experience challenges in the area of QA program development and execution. These challenges will be further exacerbated with time.

4.2.3 Evolution of the AP1000 Supply Chain

A prior MPR assessment in 2005 determined gaps in domestic or global manufacturing, fabrication, or construction infrastructures supporting Generation III+ reactor development (Reference 1-6). For the current project, the prior MPR assessment was reviewed to compare the predicted gaps in Generation III+ manufacturing, fabrication, and construction to the current state of the domestic AP1000 supply chain. This enabled an assessment of prior gaps that no longer present a risk to future manufacturing capabilities and gaps that persist and continue to represent development and manufacturing risk.

At the time of the 2005 report, Japan Steel Works was the only supplier of nuclear-grade large ring forgings. This represented a significant risk to the manufacture of Generation III+ reactor pressure vessels. However, as noted above, Doosan's expansion has allowed them to capture a significant portion of the global market for large forgings and reactor pressure vessel manufacturing. This is a significant evolution in the global supply chain that has provided competition for large ring forgings and mitigated the potential for a manufacturing bottleneck.

In addition to large ring forgings, the 2005 assessment indicated that insufficient capacity may exist for supplying digital control systems, plant simulators, castings for pumps and valves, and piping. Required capacity was based on the NP2010 program-driven base case of eight new Generation III+ reactors. To date, there have been essentially no procurement constraints related to this equipment. This can be attributed to a number of factors. These include manufacturer preparation for larger orders and also delays associated with other aspects of the AP1000 projects (i.e., modular construction) that limited the impact of delays caused by procurement of other equipment.

One notable gap identified in the 2005 assessment that has remained relevant to the current review of the AP1000 supply chain is the potential for QA and QC programmatic deficiencies to adversely impact the development of Generation III+ projects. The prior report stated the following:

> *The NRC, nuclear utilities, NSSS vendors, component suppliers, material suppliers, and EPC contractors should ensure that appropriate Quality Assurance (QA) and Quality Control (QC) programs are in place and are properly implemented for the design, fabrication, construction, and inspection of GEN III+ units.*

Inadequate implementation of these programs has had a significant impact on the schedule and cost of ongoing domestic AP1000 projects. This represents a potentially significant gap that is applicable to the success of new nuclear projects.

The current structures of the supply chains for domestic and international AP1000 projects also offer insights into the future prospects for new nuclear technology vendors. Domestic vendors were able to supply a majority of the components not requiring large forging capabilities for the domestic AP1000 projects. This required vendors to expand or construct new facilities to support this effort and attempt to develop or recapture knowledge regarding nuclear technology supply chains. Domestic vendors that had maintained nuclear experience through support of the U.S. Naval Nuclear Propulsion Program did not face a learning curve as steep as others new to the market or who had not supplied equipment to the industry for a long period of time.

The impending completion of the Vogtle project represents the end of near-term sourcing opportunities for domestic vendors in the area of new nuclear technology. This is likely to challenge retention of experience recently gained in this area. Current and upcoming international AP1000 projects present an opportunity for domestic suppliers to maintain their capabilities by supporting these projects. However, China's insistence on access to intellectual property for the projects has allowed it to increase its ability to develop its own sourcing capabilities. This has limited the ability of U.S. suppliers to gain a share of the AP1000 sourcing market in China which, subsequently, limits additional opportunities to maintain domestic sourcing capabilities.

4.2.4 Status of Domestic AP1000 Projects

The Vogtle project is the only new nuclear construction project currently ongoing in the U.S. A summary of the major component status at Vogtle is presented below.

Table 4-2. Vogtle Project Status

Component	Unit 3	Unit 4
Accumulator Tanks	Installed	On-site
Core Makeup Tanks	Installed	On-site
Deaerators	Installed	Installed
Diesel Generators	On-site	On-site
Integrated Head Package	On-site	On-site
Main Step-up Transformers	Installed	Installed
Main Turbine Generator	In Process	In-Process

Table 4-2. Vogtle Project Status

Component	Unit 3	Unit 4
Moisture Separator Reheater	Installed	Installed
Passive Residual Heat Removal Heat Exchanger	Installed	On-site
Polar crane	On-site	In Fabrication
Pressurizer	Installed	On-site
Reactor Coolant Loop Piping	Installed	In Process
Reactor Coolant Pumps	On-Site	On-site
Reactor Vessel	Installed	Installed
Reactor Vessel Internals	On-site	On-site
Reserve Auxiliary Transformers	Installed	Installed
Squib Valves (8")	On-site	On-site
Squib Valves (14")	On-site	On-site
Steam Generators	Installed	1 of 2 Installed

Notes: Information obtained from Georgia Power Nineteenth Semi-annual Vogtle Construction Monitoring Report (Reference 4-11)

4.2.5 Conclusions

Manufacturing and delivery of most key components for domestic AP1000 projects are complete. Components requiring heavy forging capability were largely procured from international manufacturers. However, for many other key components such as pumps, valves, and electrical equipment, sufficient domestic suppliers were able to manufacture equipment to satisfy the needs of domestic AP1000 projects. This required domestic vendors to expand or construct new facilities to support AP1000 projects along with developing or recapturing the capability to operate in the nuclear technology supply chain. Retention of this recent experience is likely to be challenged by the impending completion of the Vogtle project and the increasing focus of other countries on indigenous sourcing.

Rigorous application of lessons learned from Generation III+ construction activities will be vital to the success of new nuclear projects, particularly in the area of QA program implementation. As the domestic market for nuclear technology declines, vendors may determine that maintenance of a nuclear QA program is cost-prohibitive. This will result in the continuing loss of valuable experience in an area with a very small knowledge base. It will therefore be essential to emphasize the need for rigorous preparation and implementation of appropriate QA programs at manufacturing vendors. Manufacturing vendors must likewise ensure that subcontractors are well versed and prepared to properly implement the QA requirements associated with working in the nuclear power industry.

The potential for design changes to occur during the licensing process that affect fabrication, as occurred with the V. C. Summer project, is a risk that must be better managed to avoid delays in future projects. Early and frequent interaction between the design agency and the NRC is essential, especially associated with key design aspects that represent the greatest risk for manufacturing delays.

4.3 SUPPLY CHAIN PLANS FOR NUSCALE NPM

NuScale's NPM is likely to be the first SMR to enter commercial service in the U.S. Accordingly, NuScale has established relationships with equipment manufacturers and fabricators to develop a supply chain for the NPM. NuScale estimates that its approved supplier list for safety related components will include only 30 to 40 suppliers compared to those of Generation III+ designs which were estimated to exceed 600 suppliers. This drastic reduction in the number of approved suppliers is a result of the NPM's reduced number of safety-related components.

NuScale believes that the existing domestic infrastructure will be sufficient to substantially support fabrication and construction of NPMs, particularly for the first few plants. Its supply chain estimates currently consider a base case of three plants being constructed per year, each with twelve modules. This is an important consideration for the NuScale supply chain due to the fact that while many companies are capable of manufacturing NPM components, the quantity required may challenge the overall supply chain capacity.

MPR investigated the supply chain plans for NuScale's SMR design by interviewing the NuScale team. NuScale has already performed evaluations of its supply chain and has reached conclusions about supplier capabilities. The following discussion is primarily based on interviews with NuScale in support of this project (References 3-5).

Fuel

NuScale has selected Framatome as its fuel assembly fabricator. Framatome will be manufacturing the fuel assemblies domestically at its Richland, WA facility. NuScale noted that this is not a challenging procurement activity due to the fact that the design utilizes below 5% enriched uranium with geometry and specifications similar to those employed in current LWRs (Reference 3-5).

Major Components

The module design requires approximately one hundred large forgings (e.g., approximately 20 for the shells of the vessels and the remainder for RPV and CNV internals). However, due to ingot size limitations, the company indicated that at least seven of the forgings may need to be sourced from international manufacturers. This limitation, unless design changes are implemented that reduce the size of the largest forgings, is most relevant to the NuScale RPV and CNV as the vessel ring forgings in the existing design cannot be handled by domestic manufacturers. NuScale noted that they have investigated the use of PM-HIP to manufacture the RPV head, but the economics and risk associated with a novel manufacturing method make its implementation unlikely; at least until the approach is more proven.

Similarly, the company is still evaluating manufacturing options for the SG that is integral to the NPM design. There are no domestic manufacturers currently capable of forging the entire upper RPV SG shell. As a result, additional fabrication will be required to support welding of the upper shell. With respect to the helical SG tube bundles, the design requires four bundles per module of Alloy 690 tube material. The helical design requires longer tube lengths than can be sourced domestically with this material. NuScale has identified four international suppliers capable of manufacturing the required length of straight tube.

Safety-Related Equipment

The key safety-related elements of the NPM design are the CRDMs, emergency core cooling system (ECCS) valves, and containment isolation valves. With respect to the CRDMs, NuScale notes that these will likely be sourced domestically and they have two suppliers under consideration. The CRDMs could challenge the NuScale supply chain due to the number required per module (sixteen) and the total needed for a plant. This will require the manufacture of close to 600 CRDMs per year to support three, twelve-module plants. NuScale noted that they are interested in exploring additive manufacturing techniques for the CRDM guide cards, but such techniques are not sufficiently developed for this application at this time.

NuScale has already selected domestic suppliers for the safety-related valves used in the design which are not unlike those currently used for operating reactors.

Instrumentation and Controls

NuScale has selected suppliers for its safety-related instrumentation and controls (I&C) systems that will be employed in the NPM design. For the safety-related I&C platforms, U.K.-based Ultra Nuclear Control Systems will serve as the primary supplier. However, NuScale indicated that Ultra intends on manufacturing the NuScale-related I&C equipment in the U.S at its Texas based facility, formerly known as Weed Electronics. Weed Electronics was an established supplier of safety-related instrumentation for the domestic nuclear market. Non-safety-related I&C platforms are likely to be provided by domestic suppliers. NuScale has noted that it is currently evaluating suppliers for its in-core instrumentation needs and its wave-guide level transmitters, the latter of which represents a FOAK design.

Auxiliary and BOP Equipment

One of the unique requirements of the NuScale NPM plants is the need for a large capacity (i.e., approximately 800 tons) bridge crane with clearances sufficient to support module refueling and maintenance. NuScale indicated that it has engaged various vendors for procuring this equipment, but has not yet selected a supplier. Similarly, the pools utilized at each plant will require the use of underwater fuel handling and maintenance equipment similar to current equipment utilized in operating reactors. The NPM pools are deeper than the spent fuel pools and refueling cavities found at currently operating reactors. This consideration has required additional design and development effort in this area. NuScale believes that suppliers will ultimately rely on existing equipment designs to support NPM refueling efforts.

The turbine-generator sets utilized at NuScale plants will be similar to those employed at conventional power generating stations. However, no supplier for this equipment has been announced. With respect to the BOP valves used at each NPM, NuScale intends on procuring the balance of these valves from domestic suppliers and they are not considered supply chain constraints.

Virtual Design and Construction Tools

NuScale plans to make use of virtual design and construction tools to minimize disruptions in its supply chain. As a part of this modernized method of manufacturing, NuScale indicated that it intends to make use of the minimally toleranced design principles of ASME Y-14.5-2009, Dimensioning and Tolerancing. This practice allows designers to focus on critical design characteristics and works to prevent over-specification of drawings. Over-specification has been recognized as a major factor in delays in the construction of domestic AP1000 projects. NuScale is hopeful that their use of minimally toleranced designs will mitigate the administrative burdens associated with inevitable design changes realized during fabrication (Reference 3-5).

4.4 PLANS FOR ADVANCED REACTORS

Advanced reactor designs include some components that are significantly different than those currently used in the operating fleet. A new supply chain may be needed for such components.

MPR investigated the supply chain plans for the deployment of the TerraPower TWR, TerraPower MCFR, and X-energy Xe-100 by interviewing personnel from these companies. The following discussions are primarily based on those interviews (References 3-5 and 3-19).

4.4.1 TerraPower

The supply chain plans for TerraPower's TWR design will be influenced by the joint venture and plans to build and operate the first plant in China.

The generic challenges associated with the TWR supply chain are a result of the company's initial demonstration intentions as part of the path to commercialization. This point-design approach requires suppliers to develop potentially new manufacturing capabilities for one reactor. Where existing Chinese capabilities are inadequate, TerraPower intends to engage international suppliers for the first few plants, but expects a subsequent transition of these manufacturing operations to China.

Fuel

Similar to other advanced reactor developers, the use of HALEU presents a challenge for TerraPower as fuel requiring near 20% enrichment cannot be commercially produced in the U.S. without facility and license modifications. TerraPower is therefore exploring international options for fuel supply.

The fuel will also make extensive use of HT9 martensitic steel for the cladding and ducting. There is currently no raw material constraint associated with manufacturing HT9. However, there is limited capacity for fabrication of this material, particularly on the scale required for the TWR. Notably, the fuel will require fabrication of five meter long HT9 ducts, which requires re-establishment of, and advancements to, former fabrication capabilities. TerraPower also has tested advanced manufacturing techniques for its HT9 applications, including the production of a three-inch duct section by additive manufacturing and a one-meter long section produced by HIP. The TerraPower reactor internals also will make use of HT9.

Major Components

TerraPower has indicated that its reactor vessel likely will be fabricated at the operation site due to the size. The current design will use welded rolled plates, although the company indicated it has considered the use of forgings to minimize welds and subsequent inspection requirements. Fabrication of the guard vessel currently is planned to be performed on-site and likely will use rolled plate. TerraPower has not indicated who will provide the manufacturing capability for these components.

TerraPower indicated that the forgings required for steam generator components such as the head will likely be sourced from international manufacturers. Although the TWR design includes heat exchangers that are different than typical nuclear plants, TerraPower does not expect manufacturing challenges due to the fact that the designs are similar to typical heat exchangers.

The TWR design will make use of many isolation valves that are in contact with sodium; these include some larger valves used for SG isolation. TerraPower indicated that these can be manufactured domestically and does not see a supply chain constraint for these components.

The primary sodium pumps are a concern to TerraPower due to the small number of potential manufacturers for these components. TerraPower has considered both domestic (Curtiss-Wright) and international (SPX) suppliers, but indicated that eight year lead times are possible due to the liquid sodium as the pumped fluid and the long pump shafts in the current design. Procuring the TWR intermediate sodium pumps poses challenges similar to the procurement of the primary sodium pumps. However, TerraPower believes that existing technology associated with other free surface pumps may reduce the lead times for these pumps as this experience can be applied to the TWR design.

Instrumentation and Controls

The I&C platforms used for the TWR design will likely be procured initially from non-Chinese sources with the responsibility ultimately being transitioned to Chinese manufacturers. TerraPower indicated that it intends to draw on Chinese experience associated with AP1000 implementation to support design, development, and manufacturing of the TWR I&C platforms. With respect to the individual instruments utilized in the TWR design, TerraPower indicated that it expects challenges in procuring instrumentation that will be able to withstand the harsh environments involved in the liquid-sodium environment.

Fuel Handling Equipment

The TWR design makes use of many different types of fuel handling equipment. Components include an Offset Arm In-Vessel Handling Machine, Straight Pull In-Vessel Handling Machine, Ex-Vessel Handling Machine and Bottom Loading Transfer Cask. TerraPower indicated that it intends to leverage the domestic experience from fuel handling equipment used at the FFTF liquid sodium-cooled research reactor that operated at the DOE Hanford site in Washington. TerraPower indicated there is a risk that much of the knowledge and experience associated with the FFTF fuel handling applications may be outdated or no longer available.

Balance of Plant

TerraPower indicated that most BOP equipment will be manufactured in China, including TWR turbine generator sets. However, the company also suggested that it would attempt to establish domestic sourcing for this equipment if sufficient domestic interest in the design and procurement aspects of the TWR design increased.

4.4.2 Molten Chloride Fast Reactor

The TerraPower MCFR is currently in the early stages of development and many elements of the supply chain have not been established. With respect to the molten salt fuel, TerraPower indicated that it is likely to pursue development of its own method for producing molten salt coolant utilizing uranium chlorides, particularly for the initial testing phases. There is currently no market for nuclear grade molten salt with dissolved fuel.

4.4.3 X-energy

X-energy is in the early stages of developing the details of the Xe-100 pebble bed reactor supply chain. As additional design details are finalized and manufacturing and fabrication constraints are determined, X-energy will be able to identify more specific suppliers of the various components that will make up its Xe-100 reactor. X-energy has stated that it intends to procure as much of its equipment from domestic sources as possible.

Fuel

The pebble fuel for the X-energy reactor design is significantly different from existing reactor fuels. As a result, many of the supply chain challenges that X-energy has encountered are associated with the fuel. These challenges are primarily related to obtaining and creating HALEU (~10-20% enriched) TRISO fuel and procuring and fabricating nuclear grade, qualified graphite. There is currently no domestic commercial HALEU fuel supply and X-energy believes this is the greatest risk to their design being completed on time.

The TRISO particles are formed by coating a small spherical "kernel" of uranium oxycarbide (UCO) in five carbon and ceramic layers. Based on their 2015 collaboration at ORNL to develop TRISO fuel with depleted uranium (in lieu of enriched uranium), X-energy has made a decision to design and supply their own HALEU TRISO fuel (not the HALEU itself). X-energy recently applied for and won an award through a DOE funding opportunity announcement (FOA) to design and build a commercial scale HALEU fuel fabrication facility at ORNL (Reference 3-37). X-energy is now working on the design for the fuel production facility. This facility will also produce HALEU-based fuels and TRISO fuel for other reactor designs.

In addition to the challenges associated with the TRISO particles noted above, X-energy acknowledged supply chain constraints associated with the pebble matrix graphite in which the TRISO particles are embedded. Pebble matrix graphite development and production are identified as the second longest lead time item behind TRISO fuel fabrication. Discussions with X-energy indicate that they have identified at least two potential domestic manufacturers of the pebble matrix graphite. Uncertainty associated with graphite supply is driven by inherent inconsistencies in graphite quality and, in the case of the Xe-100 reflector, the need for a graphite type that will survive 30 to 60 years of reactor operation. However, X-energy is confident that it will be able to domestically procure the machined graphite necessary for the reflector. Procurement of nuclear-grade graphite is currently reliant on an international supply chain for raw graphite.

Use of nuclear-grade graphite is complicated by the fact that there are limited codes and standards available to design, procure, and manufacture this material. Irradiation test data will need to be obtained for all types of graphite used in the plant. To support these efforts, X-energy obtained funding through DOE ARC 2015 cost share program to conduct graphite irradiation and selected SGL Group as their partner for graphite production. SGL is a German graphite supplier that has had a U.S. presence for many years.

Major Components

With respect to the vessel components making up the Xe-100 design, X-energy intends to use forging as much as possible to reduce the number of welds in the design. The company stated that they have selected fabrication partners to support the design and production of most of their NSSS components.

X-energy has not announced a specific fabricator for its reactor vessel. The Xe-100 steam generator shell will also make use of forged components. X-energy has spoken with a number of suppliers for its helical coil tube bundles, including domestic suppliers Joseph Oat Corporation and Lehigh Heavy Forge Corporation but has not announced a fabricator for these components. The helium crossover pipe that connects the reactor vessel and steam generator will be forged. X-energy also noted that it may consider using additive manufacturing to produce the ribbed core barrel used in the design.

The two helium circulators integral to the Xe-100 design have garnered much X-energy attention from a supply chain perspective. X-energy has identified Howden (UK-based) and GE as potential manufacturers of the circulators. If Howden was selected as the supplier, X-energy has indicated that it would request that they establish manufacturing capabilities in the U.S. Due to the complexities associated with the circulators, X-energy has also discussed potentially employing additive manufacturing techniques for these components. Use of electromagnetic bearings (EM) rather than hydrodynamic journal bearings is a departure from typical circulator designs. X-energy is developing EM technology with manufacturers experienced in EM bearing production.

Fuel Handling Equipment

The Xe-100 fuel design requires the fabrication and manufacturing of a custom, FOAK fuel handling system. X-energy considers this task to be the second-most challenging manufacturing issue behind the Xe-100 fuel. The fuel handling system is comprised of three subsystems. These include a fuel unloading device, a pebble pneumatic transport device, and a burn-up measurement device. These systems are not available in the U.S. and therefore, X-energy intends to design these subsystems in-house and have their fabrication partners perform manufacturing. X-energy's fabrication partners believe that they have the capability to construct these subsystems. X-energy also plans to leverage the experience of domestic and international manufacturers involved the in development of fuel handling equipment for the PBMR in South Africa to support the Xe-100 fuel handling equipment.

Balance of Plant

X-energy plans to use commercially available BOP equipment. The company is likely to procure turbine generators from international suppliers initially due to cost considerations. X-energy did indicate that if a domestic X-energy owner/operator desired a U.S.-manufactured turbine-generator, X-energy would support sourcing this equipment.

Helium Coolant

With respect to procurement of the helium used as coolant, X-energy indicated that it has not identified a supplier of high-purity helium, but that it intends on addressing this as part of its conceptual design activities in 2019.

5 Raw Materials

The unique designs and operational characteristics of small modular and advanced reactors require serious consideration of the materials involved in these undertakings. In addition to the manufacturing aspects involved in fabricating materials for new nuclear technology, stakeholders in the supply chains for these projects must evaluate potential raw material constraints at the front end of these processes. Raw materials for equipment and components such as fuel, fuel cladding, reactor vessel internals, and primary coolant have been identified as potentially limiting project attributes and are addressed in this chapter.

5.1 FUELS

5.1.1 Uranium Supply and Production of Uranium Concentrate

Uranium mines supply enough yellow cake uranium oxide concentrate (U_3O_8) to make up almost all of the utilities' annual requirements. The remaining balance is made up from secondary sources which include utilities' stockpiled uranium. The U.S. does not currently supply its own demand for uranium concentrate (Reference 5-2).

Besides existing and future uranium mines, commercial nuclear fuel supply may be from secondary sources including: (1) recycled uranium and plutonium from used fuel as mixed oxide (MOX) fuel, (2) re-enriched depleted uranium tails, (3) ex-military weapons-grade uranium (blended down), (4) civil stockpiles, and (5) ex-military weapons-grade plutonium, as MOX fuel. Fuel re-processing plants for commercial purposes are operational in both France and UK, some reprocessing occurs in Russia, another reprocessing plant is due to start up in Japan. The product from these facilities re-enters the fuel cycle and is fabricated into fresh MOX fuel elements.

5.1.2 UF_6 Conversion Capability

After milling, yellow cake requires further processing to convert it to uranium dioxide (UO_2) powder or uranium hexafluoride (UF_6) gas, which is required for subsequent enrichment. All commercial conversion companies that are currently providing services for the nuclear industry are located outside the U.S.

The sole U.S. conversion supplier Converdyn (General Atomics and Honeywell) located in Metropolis, IL was shut down in 2017 due to prolonged depressed prices for conversion services. Converdyn has the potential to reopen, but it is noted that there is already excess capacity in world conversion services without the Converdyn facility. Converdyn is in the process of extending the operating license, with a decision by the company due by the end of 2019. Therefore, the shutdown raises the possibility of permanent closure (Reference 5-3).

5.1.3 Uranium Dioxide Powder Production

Uranium arrives at a fuel manufacturing plant in one of two forms, uranium hexafluoride (UF_6) or uranium trioxide (UO_3), depending on whether it has been enriched or not. It needs to be converted to uranium dioxide (UO_2) prior to pellet fabrication. Most fabrication plants have their own facilities for effecting this chemical conversion (some do not, and acquire UO_2 from plants with excess conversion capacity). Chemical conversion to and from UF_6 are distinct processes, but both involve the handling of aggressive fluorine compounds and plants may be set up to do both. The U.S. has several facilities for conversion that support fuel fabrication (Reference 6-13).

5.1.4 Uranium Enrichment Capability

There are currently six primary suppliers of LEU (uranium with less than 20% ^{235}U), one of which is based in the U.S. (USEC) (Reference 5-4).

Two methods are currently employed to enrich uranium: gas centrifuge and gaseous diffusion. Gaseous diffusion is considered a legacy approach due to the large capital outlay for facilities and the very high consumption rate of electrical energy required. Gas centrifuge technology involves relatively high capital costs for the specialized equipment required, but it uses much less electricity than the gas diffusion method, and is therefore leading to the gradual replacement of gas diffusion technology.

Two laser-based enrichment technologies are currently under investigation for future deployment: atomic vapor laser isotope separation (AVLIS) and molecular laser isotope separation (MLIS).

The U.S. and international commercial enrichers have no capability to enrich uranium to assays above five percent ^{235}U. At present, uranium needed for fuel above this enrichment comes from down-blending HEU to the desired ^{235}U assay. The number of reactors that will depend on a reliable supply of HALEU (uranium enriched to at least five percent, but not more than 20% ^{235}U) is expected to increase as the conversion of research reactors continues and as new HALEU-fueled advanced reactors and research reactors are built.

The U.S. does not maintain a stockpile of HALEU. The U.S. DOE does maintain a small working inventory of about 1 MTU of 19.75% enriched material that it uses to supply fuel for approved research, space, and isotope production reactors (Reference 5-5). This working inventory is maintained by down-blending HEU that has been declared excess to U.S. national security needs. When the supply of available excess HEU is exhausted, an alternate source will be required.

Current allocations of HEU for non-national-security-related interests show that the supply designated for this purpose is projected to be exhausted by around 2030. After this date, additional supplies of HALEU will have to be available for research and isotope production reactors, as well as for advanced reactor designs that may use high assay fuels. In addition, HEU for reactors that are still in the process of conversion may be needed (Reference 5-5).

5.1.5 Transport of Nuclear Materials

Transporting uranium hexafluoride enriched above 5% from the enrichment facility to the HALEU fuel fabrication facility presents a challenge. Although the uranium hexafluoride feed can be transported from the conversion facility to the enrichment facility using approved cylinders, just as is done today, at the moment there is no U.S. Department of Transportation (DOT) approved, commercially viable cylinder or packages for material that is enriched to greater than 5% uranium-235 (Reference 5-6). Currently, shipments of uranium hexafluoride are made in the 30B cylinder, which is limited to material of up to 5% enrichment.

To ensure that HALEU is available for advanced reactor commercialization, effort is needed to develop a new shipping package, certified for safe transport of uranium hexafluoride with enrichments from 5% to less than 20% uranium-235. In addition, shipping packages will need to be designed, tested, and certified for deconverted HALEU forms, such as oxides or metals, as well as the manufactured fuel being transported from the manufacturer to the reactor site. This effort will require cooperation and coordination between the DOE, the NRC, the DOT, and the industry.

5.2 GRAPHITE

Graphite is primarily employed in advanced reactor designs for moderation. With respect to new nuclear reactor designs, the use of graphite appears prominently in the design of X-Energy's Xe-100 advanced reactor design. The Xe-100's fuel pebbles are based on the use of a graphitized matrix for the TRISO fuel particles. The Xe-100 design also relies on the use of graphite for the internal reflector.

The domestic capability for the production of graphite is extremely limited. Natural graphite is currently not produced in the U.S., and the U.S. Geological Survey (USGS) 2018 Mineral Commodity Summaries notes that the U.S. is 100% reliant on imports for all domestic consumption activities (Reference 5-7). China is currently the world's leading graphite producer, providing 67% of the world's production supply in 2017. Mexico, Canada, Brazil, and Madagascar, along with China, combined to provide 99% of the graphite imported to the U.S. in 2017. The USGS notes that there are new natural graphite deposits being developed in multiple African countries. Additionally, worldwide resources are estimated at greater than 800 million tons of recoverable graphite, signifying that international supply is sufficient to meet domestic demands in the absence of domestic production.

Domestically, two companies are currently in the process of developing natural graphite production operations in Alabama and Alaska. Domestic consumption has steadily declined from 2014 when 57,000 tons of natural graphite was consumed in the U.S. to 2017 when apparent consumption was reported as 24,000 tons. However, the USGS expects this number to rise significantly in the next two years due to the use of graphite in lithium-ion battery production and the impending completion of a battery production plant that is expected to require 93,000 tons of flake graphite per year.

While the worldwide supply of natural graphite is likely sufficient to meet the demands of new nuclear technology, the current reliance on imported graphite for domestic applications and expected rise in domestic consumption may complicate the use of this material in advanced reactor technologies.

5.3 Molten Salts

Some advanced reactor designs may use various salts as a cooling medium and for liquid fuel, where fuel is dissolved in the primary salt coolant.

TerraPower's Traveling Wave Reactor (TWR) utilizes sodium in both its primary sodium pool and intermediate sodium loop. Pure sodium is not found freely in nature due to its high reactivity and propensity to form ionic salts. As a result, sodium is generally found in the form of sodium chloride (NaCl or "salt"). Sodium chloride decomposition can be performed using electrolysis or other methods to produce pure sodium. Based on the USGS 2018 Mineral Commodity Summaries, domestic sodium chloride production totaled 43 million pounds in 2017, a 2.4% increase over 2016 production levels. Sodium chloride was produced by 28 different companies at 63 facilities across the U.S. and reserves are considered inexhaustible. A supplier for large quantities of nuclear grade sodium does not currently exist and will be needed to support commercial deployment of SFRs like the TWR design.

TerraPower's Molten Chloride Fast Reactor (MCFR) will utilize a uranium chloride-type fuel salt. While the chemical processes associated with producing uranium chlorides are well established, commercial capabilities for the production of uranium chloride fuel salts, including UCl_3 and UCl_4, do not currently exist. TerraPower may develop its own method for fuel salt development, particularly in early test stages.

The primary challenge associated with the production and use of salts for advanced and small modular reactor designs is the purification and production of primary salt coolants for MSRs. Purification is critical to reliable plant operation due to the fact that any impurities can result in undesired corrosion or unexpected chemical reactions. Data from the Oak Ridge National Laboratory (ORNL) Molten Salt Reactor Experiment (MSRE) provides insights into methods used for developing fuel salts, particularly for fluoride salt-cooled reactors (Reference 5-8).

Lithium, in particular Li-7, is recognized as the most limiting element utilized in fluoride salt-cooled reactors. The element's low neutron cross-section and excellent heat transfer capabilities make it ideal for a primary coolant medium. Lithium as a raw material constraint poses two challenges: 1) enrichment of Li-7 to very high levels of purity and 2) domestic and global production. The USGS 2018 Mineral Commodity Summaries notes that worldwide lithium consumption increased 13% last year, largely from an increased interest in lithium batteries. Domestic production capability is limited to one brine operation in Nevada with most of the world's lithium supply being imported from South America. Global lithium resources are estimated at more than 53 million tons (compared to an estimated consumption of 41,500 tons in 2017) and are expected to rise as continued exploration is actively being pursued. Security of lithium supplies is also recognized by the USGS as being a top priority for technology companies in the U.S. and Asia.

5.4 HELIUM (GAS REACTOR COOLANT)

The X-energy and other gas reactor designs use high purity helium as coolant. Current helium supplies are sufficient but not generous for the present uses (e.g., scientific and diagnostic equipment, semiconductor manufacturing). However, one major source of helium is embargoed (i.e., Qatar) while others have declining capabilities (e.g., U.S. Bureau of Land Management production wells) (References 5-10 and 5-11). As a result, industries that rely on helium are concerned with the potential for shortages of helium supply for their expected demands. Such market and production challenges raise questions about the potential impact of helium scarcity on gas reactor designs that require helium.

Over the last few years, several international summits have been held for discussion and approaches to helium use and supply. The most recent summit was held in Houston, Texas in October 2018 (Reference 5-10). In summary, conference presenters indicated that the supply of helium will continue to be a challenge for the near term, but there are many ongoing projects to develop additional sources. Many of these projects are outside of the U.S. Another potential avenue for mitigating the current short supply is helium capture and recycling equipment, which some users implemented following a previous helium shortage (Reference 5-11).

5.5 HIGH-ALLOY METALS

High-alloy metals will be utilized extensively in the construction of SMRs and advanced reactors. As a result, the success and feasibility of these designs is contingent on a reliable supply of alloying elements. The most limiting alloying metals for new nuclear applications are commonly recognized as nickel and chromium.

5.5.1 Nickel

The USGS reports that the manufacture of stainless and alloy steel products represents the most common use of nickel in the U.S. (48% of all domestic nickel consumption). Domestic nickel concentrate production is limited to the underground Eagle Mine in Michigan. Eagle Mine produced 23,000 tons of nickel concentrate in 2017. Additional domestic production sources include byproduct and refining operations in Montana that produce nickel in crystalline sulfate form (production totals unknown). Domestic nickel consumption was estimated at 230,000 tons with an overall net import reliance percentage of 59%. The USGS notes that 90,000 tons of nickel was recovered from purchased scrap in 2017, representing 39% of total domestic consumption. Domestic nickel reserves are estimated at 130,000 tons against a global reserve estimate of 74 million tons. Global production of nickel was essentially unchanged in 2017 with additional exploration in new locations currently taking place in east-central Africa and the subarctic.

5.5.2 Chromium

Stainless steel and heat-resisting steel production are the highest chromium-consuming (ferrochromium) activities in the U.S., by percentage. The U.S. currently has no mining operations that produce chromite ore, although the Stillwater Complex in Montana is known to contain these deposits. Domestic production of chromium is therefore currently limited to recycling of stainless steel scrap. Recycling resulted in the domestic production of 160,000 tons of chromium in 2017. The USGS reported that the apparent U.S. consumption of chromium in 2017 was 510,000 tons. Combined, the U.S. had a net import reliance percentage of 69% in 2017 for chromium consumption.

While U.S. production of chromium is currently limited, the USGS reports that global resources of shipping-grade chromite total greater than 12 billion tons and are sufficient to meet known demand for centuries. Kazakhstan and southern Africa contain 95% of the world's chromium resources. The USGS noted that a significant price spike in chromium took place between October 2016 and July 2017 due to low inventory and Chinese demand for stainless steel. Stainless steel and heat-resisting steel production require ferrochromium. Recent commissioning of ferrochromium furnaces in South Africa and China have the potential to significantly boost ferrochromium production for these activities and reduce inventory and price burdens.

5.6 Powdered Metal

Powdered metal is the base material used in HIP and AM. The HIP process utilizes high temperatures and pressures along with an inert gas environment to apply uniform pressure to a powdered specimen and develop a solid component with isotropic properties. Additive manufacturing, also known as three-dimensional printing, utilizes metal powders to manufacture components in a layered fashion as opposed to conventional machining ("subtractive manufacturing"). In the future, advanced and small modular reactor designs may utilize these advanced manufacturing techniques to support development of FOAK components used in the designs. The Metal Powder Industries Federation (MPIF) currently lists 21 domestic suppliers of metal powders and raw materials for use in HIP and AM applications. Due to their extensive use in traditional nuclear-related manufacturing applications, the most limiting powdered metals for new nuclear applications using HIP or AM techniques will likely be iron, steel, stainless steel, and nickel.

Powdered metal production statistics for North America show a steady growth in shipments of iron and steel (2%), stainless steel (3%) and nickel (2%) from 2016 to 2017 (Reference 5-9). Notably, shipments of powdered iron and steel totaled 428,978 tons in 2017; this is significantly more than the 2017 shipments of powdered stainless steel (8,750 tons) and powdered nickel (6,325 tons). The MPIF indicated that the U.S. market for powdered metals has stabilized and expects flat growth in 2018. Not considering the raw material constraints associated with producing metal powder, there appear to be no risks associated with procuring adequate supplies of powdered metals for new nuclear applications.

5.7 Conclusions

The immature state of advanced and small reactor designs and the uncertainty on extent of deployment limits the ability to assess the potential impact of raw materials constraints on domestic manufacturing capabilities. Material constraints will ultimately be a function of final reactor designs and the number of reactors manufactured.

Developing the needed fuel cycle infrastructure to support the deployment of advanced reactors that utilize HALEU fuels will require government involvement and support by DOE and NRC in cooperation with the U.S. nuclear industry. DOE, NRC, and DOT involvement will be necessary to support the design and certification of packages and transporters that can be used to economically transport HALEU. To maintain the viability of the U.S. nuclear industry and to ensure ongoing international competitiveness, the U.S. Government should provide assistance for the domestic industry to design, license and construct a HALEU enrichment facility and HALEU fuel fabrication facilities. There appears to be no limitation associated with the domestic supply of uranium concentrate available to support the front end of new reactor fuel cycles.

Procurement of natural graphite to support new nuclear technology will likely be reliant on an international market for immediate-term applications, although new U.S. suppliers may provide an adequate supply by the time the first Xe-100 plant needs material.

While there appear to be no raw materials constraints associated with commercial salt procurement, there are currently a limited number of commercial methods that would support the use of molten salts in new nuclear designs. This includes commercial capabilities for the decomposition of sodium chloride and manufacturing of uranium chlorides. Initial testing of molten sodium reactors will likely rely on novel techniques developed for the reactor plant technology.

There is currently a shortage of helium supplies, which is a concern for a potential future fleet of gas-cooled reactors. However, because these reactors are years away from deployment, ongoing projects to develop new helium sources (many of which are outside the U.S.) may alleviate supply concerns. Cost-effective helium management may be important for future gas reactor designs, but helium supply is not expected to be a controlling limitation for their deployment.

For high-alloy metals, there is a limited domestic supply of nickel and chromium to support manufacturing needs. However, international supplies will likely support continued reactor development. Reliance on international supply chains for raw materials may increase the risks associated with material costs as the international market for raw materials has proven more volatile due to emerging market growth and region-specific issues (e.g., environmental concerns). If vendors or suppliers decide to employ advanced manufacturing techniques using powdered metals, there will likely be a sufficient supply of powdered metals to support this need.

6 Manufacturing and Testing

The current capabilities and capacity of vendors of manufacturing services to the nuclear industry must be understood to provide an accurate assessment of the ability of the current domestic infrastructure to support deployment of SMRs and advanced reactors. This chapter describes, for selected manufacturing areas, the current state of the domestic capabilities, plans for further development, anticipated timing and cost of that development, and major challenges experienced in each area. The manufacturing areas selected are both traditional and advanced manufacturing techniques that are essential, of special interest, or may be beneficial to the deployment of new nuclear assets. The selected manufacturing areas are:

- Forgings
- Tube Drawing
- Large Component Machining
- Component Fabrication
- Powdered Metal Hot Isostatic Pressing
- Additive Manufacturing

This chapter also addresses key testing programs required to support design development and certification, equipment qualification, licensing, and plant commissioning.

6.1 Forging

6.1.1 Technology Overview

Forging is a process which uses compressive forces to shape a metal block, or ingot, into a desired shape. It is widely used for large nuclear components since forged pieces offer mechanical and material properties superior to the properties of components that are produced using other traditional methods (e.g., castings). Forgings have higher tensile, yield and fatigue strengths, with fewer smaller internal flaws, making them the highest quality components for nuclear applications (Reference 6-1). While there are many different forging techniques, the forging technique used most commonly for creating large nuclear forgings is called "open die forging" which is illustrated in Figure 6-1.

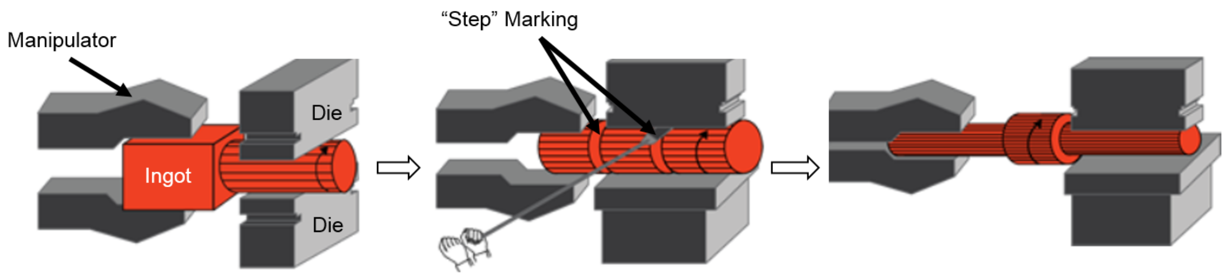

Figure 6-1. Overview of the Open Die Forging Process for Making a Spindle (Reference 6-2)

Nuclear power plants contain many forged parts, ranging in size and geometry. The U.S. has multiple forging facilities capable of making the smaller forgings required by the nuclear industry. These smaller forgings are used for components such as nozzles, valve bodies, flanges, and shafts. However, only a handful of vendors are capable of providing the forgings required for larger components. These larger components include rings, shells, and formed heads for reactor pressure vessels and steam generators, and large rotor shafts for turbines. Following the final forging step, the forged piece is sent to a machine shop for final machining and non-destructive evaluation (NDE). Once machining and non-destructive evaluation of the piece is finished, it is ready to be delivered to a fabricator for assembly.

There are a few variables that determine how large of a forging a given facility can make. One factor is the overall size of the press in terms of pressing force, overhead clearance (sometimes referred to as vertical daylight), size of the die, and the capacity of the manipulators and cranes used to move the ingot. A second limiting factor is the actual size of the ingot that a facility can produce; larger forgings need to start from larger ingots. Lastly, a forging facility's transportation infrastructure can limit the size of a forging. Larger forgings require larger means of transportation, such as a barge. Therefore, a landlocked facility would be at a strategic disadvantage compared to a forging facility that has access to a waterway.

Forgings are typically discussed by three size categories: small, large, and ultra-large. There is no exact definition in terms of size for these categories. Small forgings are those required for components such as nozzles, valve bodies, flanges, and shafts. Large forgings are those required for larger components such as SMR reactor pressure vessels and steam generators, and large rotor shafts for turbines. Ultra-large forgings are those required for Generation III+ reactor pressure vessels (typically forgings greater than 350 tonnes are considered ultra-large).

Small forgings are not a challenge for the domestic U.S. forging infrastructure; there are numerous facilities that can produce forgings of these sizes. The U.S. capabilities to produce ultra-large, and large forgings are discussed below.

6.1.2 U.S. Ultra-Large Forging Capability

In 2010, MPR prepared a report for the DOE evaluating the domestic infastructure to supply ultra-large forgings for Generation III+ RPVs (Reference 1-7). Ultra-large forging is not a technical term; and is coloquially used to refer to forgings made by presses with a pressing capacity greater than 10,000 tonnes and ingots weighing more than 350 tonnes. This report concluded that the capability does not exist domestically to produce these ultra-large forgings, however, there is surplus capacity internationally. The report also concluded to procure the capability to prodcue ultra-large forgings domestically the cost would be approximately $2 billion. The forging companies contacted for the current scope of work considered that these conclusions are still valid.

Japan Steel Works (JSW), located in Muroran, Hokkaido, Japan, has been responsible for the majority of ultra-large nuclear forgings throughout the world. JSW claims 80% of the world market for large and forged components and has supplied at least 130 reactor vessels around the world, including some in the U.S. JSW has two 14,000 tonne presses, each capable of handling ingots up to 650 tonnes. It is estimated that JSW can manufacture up to 12 RPV sets, or other major components per year.

Doosan Heavy Industries and Construction has also supplied ultra-large forgings for U.S. nuclear plants. Doosan's newest forge, a 13,000 tonne press which can handle ingots up to 540 tonnes, went online in 2010 (Reference 4-3). It is estimated that Doosan can manufacture up to 5 RPV sets, or other major components, per year. Doosan supplied four RPVs and eight steam generators for the Vogtle and now defunct V.C. Summer AP1000s in the U.S. (Reference 6-5), and also supplied two Chinese AP1000s with steam generators and RPVs.

Worldwide demand for ultra-large forgings primarily resides in China, where many forges are increasing capacity to keep up with demand. Given the increase in international capacity for ultra-large forgings, it is unlikely that market forces in the U.S. will spur the expansion of facilities to create ultra-large forgings.

6.1.3 U.S. Large Forging Capability

The SMR and advanced reactor designs discussed in Chapter 3, as currently designed, do not require any ultra-large forgings. The largest forgings required fall into the large forgings category. There are a handful of domestic forges that are capable of producing these size forgings. A summary of some of the largest U.S. forging facilities is shown in Table 6-1 below.

As part of this scope of work, MPR visited Lehigh Heavy Forge to tour their facilities and conduct interviews with personnel. For other forges, MPR conducted telephone interviews and reviewed available literature.

Table 6-1. Large U.S. Forging Facility Overview

Forge Name	Location	Pressing Size (ton)	Max Ingot Size (ton)
Lehigh Heavy Forge	Bethlehem, PA	10,000	300
North American Forgemasters[1]	New Castle, PA	10,120	185
Scot Forge	Spring Grove, IL	16,500	52
Jorgenson Forging	Tukwila, WA	5,000	N/A
ATI (Allegheny Technologies)[1]	Cudhay, WI	15,000	185

[1]Pressing size and max ingot size found in Reference 6-6
[2]Pressing size and max ingot size found in Reference 6-7

ATI Metals

ATI is a global manufacturer of technically advanced specialty materials and complex components. Of their many facilities around the world, ATI has one major forging facility in Wisconsin, called ATI Forged Products. This facility is capable of producing and shaping large forgings. At the facility in Cudahy, Wisconsin, ATI operates one of the largest ring rolling operations in the world which can produce rings from 60 inches to 336 inches in outside diameter. This ring mill can accommodate heights up to 120 inches and weights up to 350,000 lbs. ATI has experience using this ring mill with titanium alloys, aluminum alloys, and specialty steels. ATI also has a variety of hammers and presses that can produce other forgings beyond rings including large ellipsoidal and hemispherical heads. ATI also has the capability at this facility to do all heat treating, rough machining, NDE, and testing.

Jorgenson Forge

Jorgenson Forge is located in Tukwila, WA and is an ISO9001:2008 specialty metals forge (Reference 6-8). Jorgenson has business in the aerospace, defense, and commercial nuclear industry. Jorgenson has four open die presses, the largest of which is a 5,000 ton press. Jorgenson also has two ring rolling mills, capable of rolling rings up to 180 inches in diameter, a 2,400 ton ring expander capable of stretching rings to a maximum 225 inch diameter, and a horizontal 2,500 ton straightening press, with 72 inch maximum diameter flange capability. Jorgenson is capable of forging stainless steel alloys, low carbon/low alloy steels, aluminum, titanium, and nickel-based alloys. While Jorgenson cannot make forgings as large as other domestic facilities, Jorgenson is unique in the types of alloys they can work with.

Lehigh Heavy Forge

Lehigh Heavy Forge (Reference 6-9) is a subsidiary of WHEMCO Holdings Inc. WHEMCO supplies several industries, including commercial nuclear, power generation, and national defense. LHF supplies heavy forgings for the US Navy and industry. In an effort to improve their capabilities, LHF has invested in expanding their suppliers' capabilities. In 2014, LHF invested over $10.5 million dollars in expanding ArcelorMittal's Steelton (AMS) facility, which is approximately 90 miles away from LHF and supplies ingots by rail. AMS supplies large ingots to LHF using the Vacuum Stream Degassing (VSD) process coupled with ladle degassing.

VSD significantly reduces the risk of delayed hydrogen flaking by reducing the amount of dissolved gas (i.e., hydrogen, nitrogen) in the steel. VSD ingots produced at AMS are made exclusively for LHF. LHF does not have the ability to cast forging ingots on site.

LHF has two large forging presses. The larger press has a pressing capacity of 10,000 tons which can handle ingots weighing up to 300 tons. Two hydraulic cranes and a rail-bound manipulator are used to move the ingot during pressing. The smaller press has a pressing capacity of 4,000 tons, and is used on smaller products. The LHF forging facility has multiple furnaces, the largest of which has a length of over 70 feet and a cross-sectional area of 15 feet by 15.75 feet. These furnaces are used for reheating ingots that are being pressed, and for heat treatments.

There are multiple horizontal and circular quenching tanks in the facility that provide a capability for quenching in either oil or water. Spray quench capabilities are also available, as are large open areas for air cooling of components. A new horizontal water tank for longer products is planned for the facility and is currently in the design phase. Clearances in this area of the facility potentially could be a limiting factor, especially when moving large pieces, such as reactor pressure vessel components.

North American Forgemasters

North American Forgemasters (NAF) is located in New Castle, PA. NAF was formed as a joint venture between Scot Forge, and Ellwood Group, Inc. NAF is at the same complex as its sister division Ellwood Quality Steels (EQS), which produces NAF's ingots which are moved hot a few hundred yards to NAF where they are forged. EQS supplies low-cost carbon, alloy, and tool steel ingots up to 185 tons (Reference 6-10). Elwood National Steel (ENS), a division of EQS, has the capability to produce large, low-carbon stainless steel ingots (e.g., martensitic stainless steel F6NM).

NAF has a new open-die forging press with a pressing capacity of 10,120 tons and can work with ingots weighing up to 185 tons. The press became operational in February of 2016. The press has 236 inches of vertical daylight and 197 inches between the columns. This press was privately funded and installed at a cost of roughly $95 million. One of the many markets that factored into the justification for building the press was large forgings for SMR and advanced reactors. The press is serviced by a 220-ton rail bound manipulator, a 110-ton mobile manipulator, and a 205-ton overhead crane. The facility also has a 4,500-ton open-die forging press which was installed in 1997 and fully rebuilt in 2012. At NAF there are three furnaces – two are box type and one is a car bottom type. There is also a moving hood heat treat furnace capable of annealing, normalizing, tempering, stress relieving, and slow cooling the largest forgings that NAF can produce.

Scot Forge

Scot Forge (Reference 6-11), a 50% owner in NAF, is a manufacturer of custom open die forgings and seamless rolled rings. Scot Forge has over 125 years of experience and the capability to open die forge parts weighing up to 80,000 pounds. Scot Forge can also ring roll up to 240 inches in diameter and 48,000 pounds in weight. They have eight open die hydraulic presses. The largest, at 16,500 tons, coupled with supporting modern mobile manipulators, became operational in 2017. The high tonnage press with heavy weight material manipulator allows for the successful production of heavy “near net” forgings, such as reactor vessel heads. In addition to working with all low carbon, alloy steel, and stainless grades Scot Forge has extensive experience forging non-ferrous material grades and specialty steels.

6.1.4 Plans for Future Development

The forges contacted for input to this report did not disclose any plans to fund additional near term major facility upgrades. The privately funded investments referenced at EQS, ENS, NAF, and Scot Forge made within the last couple years exceed $200M. In general, most of the companies seemed willing to make additional major modifications to their facilities, if there were a business case that justified such an investment (e.g., a large order for SMR forgings).

Additional upgrades beyond steelmaking, open die forging, and ring rolling such as heat treatment and machining may be needed for large forgings depending on the specifics of the final reactor designs. Worth noting is the potential need for a large face (i.e., >120”) tall ring roller which would reduce the amount of circumferential welds subject to in service inspection for the life of the reactor. Such upgrades would be significantly less expensive than what would be needed to support production of ultra-large forgings.

6.1.5 Conclusion

The U.S. has numerous forgers capable of producing small forgings, but has no viable capability to produce Generation III ultra-large forgings. The open die, near net, and seamless rolled rings large forgings required for SMR and Advanced Reactors can be produced by a small handful of domestic vendors. Additional upgrades may be needed depending on the specifics of the final reactor designs, but those upgrades would be significantly less expensive than what would be needed to support production of ultra-large forgings. In discussions with MPR, most forges stated that they would be willing to upgrade their facilities to support these large forgings if there were a business reason that justified such an investment.

6.2 TUBE DRAWING

NuScale Power, TerraPower, and X-energy informed MPR that they intend to use helical coil steam generators in their plant designs. This is a departure from typical existing light water civilian reactor designs in the U.S. and around the world. The length of tubes in a steam generator for the AP1000 (a Gen III+ plant) is approximately 70 feet. The length of the helical tubes in the NuScale helical tube steam generator is approximately 90 feet. Tube for TerraPower and X-energy steam generators are much longer (several hundred feet). NuScale steam generator tubes must be single-piece tubes, but tubes for TerraPower and X-energy steam generators can be multi-piece tubes welded together.

MPR contacted Plymouth Tube, Superior Tube, and TechTube/Tube Methods. Plymouth can draw and straighten high nickel alloy tubes to 130 feet long. However, it no longer has a nuclear quality assurance program that meets ASME NQA-1 or 10 CFR 50, Appendix B requirements. Plymouth disclosed that they have an NDA with NuScale Power and are in the process of establishing an NDA with TerraPower. Plymouth indicated that they further said they can meet the NuScale Power Module requirements only by significant capital investment. TechTube can draw tubes of high nickel alloy but have not disclosed the maximum length that they can draw and straighten. They do not have a nuclear quality assurance program.

Superior Tube can and does draw and straighten high nickel and other alloy tubes to 45 feet and can draw and coil tubes to 2000 feet long. Superior disclosed that the bulk of their nuclear tube manufacture are Alloy 690 tubes approximately 20 feet long; however, they also draw Alloy 600 tubes to 44 feet long. They noted that the NuScale Power Module specification required close control of tube geometry (i.e., size, wall thickness, and circularity) and specific non-destructive inspection of the drawn tubes. Those specifications require the tubes be straightened prior to inspection. The NuScale Power tubes would be subsequently coiled for the helical steam generator fabrication. Superior has an active nuclear quality assurance program that meets the requirements of ASME NQA-1 and 10 CFR 50, Appendix B. They have no current plans to increase their capability to draw and straighten longer tubes due to a lack of orders.

The technical capabilities of these three tubing manufacturers currently are not sufficient to supply tubes for the SMR and advanced designs discussed, with limitations on length and quality assurance requirements. If these capability issues were resolved, current capacity is adequate to supply the early plant construction. None of these companies have firm plans to increase capabilities or capacity to support new nuclear builds at this time.

6.3 MACHINING

Machining in the U.S. continues to be readily available. Numerous facilities have nuclear QA programs. The pressure vessel machining and fabrication facilities already in the nuclear supply chains also have ASME N Stamp certification which indicates they can provide machining operations for pressure vessels designed and built to ASME B&PV Code Section III requirements. Large machining capabilities including for large pressure vessels (e.g., reactor pressure vessel segments and steam generator shell segments) are available. Pressure vessels up to hundreds of feet long are fabricated from machined segments and components in the USA, although not in the nuclear supply chain.

All machining centers identified or contacted routinely use computer numerical control on most of their large machines. This is no longer an advanced capability. Most or all use some form of computer-based inspection system, which also is no longer considered an advanced capability.

To supply pressure-retaining components for the nuclear island to the U.S. nuclear industry, an ASME certification is needed. The following are the main forms of certification in the nuclear supply industry in the U.S.

- N — Nuclear vessels, pumps, valves, piping systems, storage tanks, core support structures, concrete containments, and transport packaging
- NA — Nuclear installation and shop assembly of all items
- NPT — Nuclear Partials (e.g., parts, appurtenances, welded tubular products, and piping subassemblies)
- NS — Nuclear Components (e.g., supports)

NV Nuclear Safety and Safety Relief Valves

In the U.S., there are more than 50 N Certificate holders, about 30 NA Certificate holders, more than 70 NPT Certificate holders, about 35 NS Certificate holders, and 4 (four) NV Certificate holders (See Appendix B). Many certificate holders have more than one type in their portfolio. As is readily apparent, some of the certificates are properly fabrication only (e.g., NA) while others are manufacturing (e.g., N allows casting, forging, machining, and fabrication).

In addition, numerous foreign sites and entities hold ASME certificates and can supply nuclear island components to the U.S. nuclear industry.

Some manufacturers indicated they already have some advanced processes in regular use. For example, Curtiss-Wright currently uses electron beam welding in their production of valves. Most firms contacted currently have no firm plans to increase production capability (i.e., use of advanced processes or larger components) or capacity. There is insufficient new business to justify the investments needed. However, many firms noted that they would consider increased production capacity if orders were in the offing.

6.4 Component Fabrication

The U.S. has significant fabrication facilities in the nuclear supply chain, as was noted in the preceding section on machining. There are more than 50 firms that have ASME N or NA certificates indicating the capability to provide pressure vessels, components, and assemblies to the U.S. nuclear fleet, specifically to the nuclear island. Not all fabricators can work with the largest vessels (i.e., Generation III+ reactor pressure vessel or steam generators). Since there is no forging capability in the U.S. sufficient to produce forgings needed for those vessels, the machining and fabrication of such large vessels falls outside the normal scope of work for U.S. firms in the nuclear supply chain. However, several firms have the capability and capacity to machine and fabricate vessels for a NuScale Power-sized reactor and containment vessel. Firms contacted or investigated with fabrication capabilities sized for NuScale Power vessels include Vigor Works LLC, Premier Technology Inc, Precision Custom Components LLC, Westinghouse Electric Company LLC (and its many subsidiaries and acquisitions), and Newport News Industrial Corporation.

Outside of the nuclear supply chain, most fabricators of large pressure vessels work with much thinner materials (perhaps up to 3 inches thick rather than the approximately 10-inch thick vessels needed for Generation III+ reactors or the approximately 6-inch thick NuScale Power reactor pressure vessel). Few pressure vessels needed in U.S. industrial sector address the requirements of temperature and pressure common to nuclear reactors. It is clear that this capability has diminished in the U.S. in the last 30 years.

Vigor Works LLC

MPR visited Vigor Works LLC in Clackamas, OR in July 2018 as part of this assessment (Reference 6-12). Vigor is one fabricator which produced modules for the AP1000 sites in Georgia and South Carolina. Vigor obtained this work after Shaw Modular Solutions struggled with nuclear quality assurance and quality control issues. They maintain the following ASME certifications: N, NA, NPT, and NS.

Vigor has very significant capabilities and capacity but much is allocated to commercial and shipping businesses. For example, the firm has very large fabrication bays at their Swan Island facility including one bay dedicated to large application robotic welding. They have large machining capabilities (e.g., a 5-axis position large part CNC machining unit that can handle parts up to 27.6' long × 14.7' wide × 6.8' high; a 110' traveling floor mill that can handle material 105' long × 144" wide × 8' high; and a 40' open-sided planer mill) in their Clackamas facility.

During the site visit, Vigor mentioned a concern about qualified skilled craft workers. Welders and iron workers who have nuclear quality and safety consciousness and have the requisite skills are in short supply and the workforce appears to be decreasing.

6.4.1 Reactor Vessels

NuScale NPM

The NuScale vessels (i.e., reactor pressure vessel and integral containment vessel) are at the current capability limits or slightly exceed the capabilities of U.S. forges. However, capabilities exist in the U.S. to fabricate the vessels if forged components are sourced offshore. For example, Premier Technology, Inc. in Idaho has a 60 ton crane capacity and 28 feet clearance. These are greater than any of the forgings for the NuScale RPV. They would have to fabricate (i.e., weld) the vessel in a horizontal orientation but have the capability to do so. Similarly, Precision Custom Components in York, PA has 350 ton lifting capability with 42 feet clearance. They also would fabricate in the horizontal orientation but have the lifting capability to handle the entire RPV as a unit. Both firms also have the capability to fabricate the NuScale containment vessel.

The NuScale design has the upper reactor pressure vessel and the upper containment vessel assembled together in the factory. Neither firm noted above can currently lift the fully assembled system. Final assembly, which certainly will include weld fabrication techniques, represents a manufacturing challenge and no demonstrated capability exists today.

TerraPower TWR

The TerraPower TWR vessel is designed to be low pressure (approximately atmospheric pressure) and may be fabricated by joining rolled plate. The main concerns for the vessel and fabrication techniques will be neutron damage, corrosion, and pressure integrity. This design concept is akin to a welded steel oil storage tank commonly found in petroleum refineries and distribution hubs. Fabrication and erection firms across the U.S. routinely erect such tanks for oil or water storage today. The technology would require upgrading to nuclear service (e.g., QA requirements and neutron resistant materials) but does not present technical challenges.

X-energy Xe-100

As noted in Chapter 3, X-energy's reactor vessel for the Xe-100 design is not well defined at this time, so fabrication capabilities needed to support the RPV cannot be fully assessed. However, MPR considers that few corrosion issues exist with helium as the circulating heat transport fluid. The existing LWR reactor vessel capabilities should be sufficient with the caveat that some forgings may be larger than can be handled by U.S. forges.

6.4.2 Steam Generators

All steam generator designs for SMRs and advanced reactor designs addressed above are once through helical designs with boiling inside the tubes. Domestic suppliers have not qualified or fabricated steam generators with these characteristics for many decades (Fort St. Vrain HTGR used a helical steam generator which was fabricated in the late 1960s – about 50 years ago). The three designs share a number of qualification and fabrication challenges associated with these common design characteristics which could be addressed to some extent with generic development work. Currently, fabrication of helical steam generators is not a manufacturing capability in the U.S.

6.4.3 Fuel Elements

Fabrication of High-Assay LEU Fuel

LWR Fuel

Low-enriched uranium fuel is fabricated at the U.S. facilities that sell to the commercial LWR community world-wide: Global Nuclear Fuel Americas facility (Wilmington, North Carolina), Westinghouse Columbia Fuel Fabrication Facility (Columbia, South Carolina), and AREVA Inc., facility (Richland, Washington).

There are also two U.S. facilities (the Nuclear Fuel Services facility in Erwin, TN, and the BWXT Nuclear Operations Group plant in Lynchburg, VA) licensed to fabricate highly enriched fuel from existing HEU inventories, primarily for the U.S. defense industry. These two facilities have produced fuel for reactors requiring greater than 5% uranium-235 (e.g., test, medical isotope and research reactors). The higher enriched fuel is produced from HEU, which is down-blended to the required enrichment.

U.S. LWR commercial reactor fuel production facilities convert uranium hexafluoride to uranium dioxide and use a dry process to convert that into a uranium dioxide powder and subsequently into uranium pellets and then fuel assemblies. Manufacturing HALEU fuel for a new generation of reactors which require higher uranium-235 enrichments would likely necessitate the deconversion of uranium hexafluoride into uranium metal or oxide, in order to simplify the design process for an HALEU shipping container, and more conservative criticality design considerations. It should be noted that material in different forms may introduce the need to consider other safety issues related to fire protection, chemical safety, and radiological controls. Additional regulatory guidance may be needed in these areas.

High Temperature Reactor Fuel

The main high-temperature reactor (HTR) fuel fabrication plant is at Baotou in China, the Northern Branch of China Nuclear Fuel Element Co Ltd. This facility produced fuel pebbles for the HTR-PM under construction at Shidaowan, China. Previous production has been on a small scale in Germany. In the U.S., BWXT is making TRISO fuel on an engineering scale, funded by the DOE which is aiming to take it to commercial scale. In September 2017, X-energy signed an agreement with Centrus Energy to develop a TRISO fabrication technology for uranium carbide fuel. The DOE awarded X-energy a funding award in 2018 to bolster the development of a commercial-scale TRISO fabrication facility. In Japan, NFI at Tokai has 400 kgU/yr HTR fuel capacity (Reference 6-13).

Secondary Supply from Recycle and Mixed-Oxide Blending

The U.S. currently does not have the ability to generate reprocessed uranium (RepU). Nearly all RepU is produced at MSZ in Russia (capacity of 250 t/yr) and AREVA in France (licensed to fabricate 150 t/yr) (Reference 6-13).

At present, nearly all commercial mixed-oxide (MOX) fuel is fabricated at MELOX by AREVA in France (capacity of 195 t/yr). The U.S. is nearly 70% complete in constructing the MOX Fuel Fabrication Facility (MFFF) at the Savannah River National Laboratory (SRNL). This project was terminated in 2018 due to increased cost as well as a shifting geopolitical landscape.

Criticality Challenges

A significant factor in the licensing of any HALEU facility or equipment is criticality safety, for which there is less benchmark data for enrichments above 5 percent. Therefore, there is need for reliance on computer software and the importance of bounding considerations becomes greater.

Licensing a HALEU facility or transportation package for enrichments closer to 20% may be challenging due to the limited availability of applicable benchmark data. In these cases, there are methods developed by the nuclear industry and accepted by the NRC to define sensitivity and uncertainty information, to help designers establish adequately large margins to cover the lack of benchmark validation. NRC guidance to the NRC staff clarifies the minimum margin of subcriticality for safety relative to a license application or an amendment request under 10 CFR Part 70, Subpart H and Fuel Cycle Safety and Safeguards-Interim Staff Guidance-10. The problem is that, at higher enrichments, a designer may be unable to apply the needed margin and still achieve the design objectives for the process in a cost effective manner.

To facilitate the development of HALEU technology, industry and regulators need to develop criticality benchmark data, to allow the safe and effective use of HALEU fuels. Criticality benchmark data would be needed to support the licensing of an enrichment facility producing material between 11% and 20%. Developing this data would need government financial support. The data could be developed by the Department of Energy or the private sector in cooperation with the NRC. As a part of this effort it is important to identify the range of material forms that will potentially be needed as it will impact the experiments.

Design-specific Details

NuScale Power

The NuScale NPM fuel elements will be supplied domestically and fabricated by Framatome (formerly AREVA) (France). The uranium in the fuel is standard LWR fuel, enriched to less than 5%. The fuel is a current standard fuel geometry, thus standard transport devices, methods, and fuel supports can be used. It is expected that there will be little to no more effort to procure this fuel than is already expended to procure fuel for the current commercial nuclear fleet. Some small scale prototypes have already been fabricated by Framatome. Off-the-shelf components have been utilized to allow full reliance on existing operating experience to minimize fuel performance uncertainties.

TerraPower

TerraPower is restarting U.S.-based development of fast reactor fuel in preparation for the TWR demonstration reactor. Currently, fuel materials are being tested in the Advanced Test Reactor at Idaho National Laboratory (INL) (Reference 6-15). TerraPower is also working with INL to commission a lab-scale fuel fabrication facility, which is expected to produce the first extrusions of metallic nuclear fuel in the U.S. since the 1980s (Reference 6-45).

In partnership with AREVA Federal Services, TerraPower manufactured the first full-size test assembly for the TWR technology (Reference 6-15). Additionally, the company is now receiving and analyzing results from its first irradiation experiments, conducted in partnership with the BOR-60 fast reactor in Russia (Reference 6-15).

One of TerraPower's current key goals is to establish a commercial supply of HT9 for fuel cladding, assembly ducts, end caps, wires, etc., as well as developing an optimized HT9 relative to historical material in order to enhance irradiation performance. HT9 ingots have been made for process optimization and to support fuels and materials irradiation programs and duct/cladding/end cap fabrication. TerraPower has identified that the critical processes identified for fabricating the HT9 microstructure include: (1) thermo-mechanical processing and final heat treatment, and (2) changes in HT9 specification for improved uniformity. Successful fabrication of billets, bars, cladding, and plates have been demonstrated with fabricators Kobe Special Tube Co., Ltd. (Japan) and Carpenter Technology Corporation (U.S) (Reference 6-15).

TerraPower is also working to develop a commercial HT9 Assembly Duct fabrication process. The HT9 Duct is a key component of the TWR fuel assembly, and there is limited industry experience with high-tonnage HT9 drawing needed to supply the ducts. The company has worked with supplier Veridiam (U.S.) to successfully draw first and final passes of an HT9 Assembly Duct, which has generated a high degree of confidence for commercial scale-up (Reference 6-15).

To set up the HT9 cladding tube supply chain, TerraPower is working with two vendors: (1) Veridiam (U.S.), and (2) Kobe Special Tube Co., Ltd. (Japan) to fabricate HT9 cladding tube to TerraPower specifications and drawings. To date, draw sequences, heat treatments, and other process details have been defined, and suppliers are currently working to develop ultrasonic inspection techniques (Reference 6-15).

TerraPower has established a laboratory-scale TWR metal fuel fabrication facility to develop and demonstrate the commercial fuel methods (from metal feedstock to wire-wrapped pins) as well as support irradiation testing and fabrication of test pins. This facility is located at the INL Experimental Fuels Facility (EFF) (Reference 6-15).

Extrusion has been selected as the fuel slug fabrication method, which represents an advancement over historic manufacturing methods used for the FFTF and Experimental Breeder Reactor II (EBR-II). The billet casting technique has been developed at the INL and the 1st uranium extrusion was performed in July 2015 (Reference 6-15).

The Babcock and Wilcox Company (B&W) (U.S.) has been selected for developing commercial methods for fuel pin assembly, which includes HT9 end cap welding, sodium bonding techniques, and wire wrapping. The Resistance Pressure Welding (RPW) technique has been developed for the end cap welding which uses proven LWR technology and allows for higher throughput, quality, and reliability with minimal inspections (Reference 6-15).

Fuel assembly proof-of-fabrication and testing is supplied by AREVA Federal Services (France), as well as knowledgeable experts from FFTF. Early results have proven the capability to manufacture TWR fuel assemblies. Water flow testing results have confirmed the design correlation and bundle pressure drop. TerraPower is considering larger scale fuel testing using sodium in the future, with the ability to test multiple components at once. The venue for this testing will most likely be Transient Reactor Test Facility (TREAT), which is expected to cover needs (Reference 6-15).

X-energy

The production of pebble fuel is a multi-step process involving kernel fabrication, deposition of several coating layers to form TRISO particles, and finally over coating and pressing of TRISO particles into a spherical fuel pebble. Each of these fabrication steps also requires significant characterization support to determine the quality of the product material and to serve as a critical feedback into process development. Teams in each of the three fabrication steps, as well as characterization, have been formed between X-energy and Oak Ridge National Laboratory (ORNL) at the Pebble Fuel Development project at ORNL in Oak Ridge, TN. This project has made advancements in implementing the pebble bed fabrication capabilities on a laboratory scale as well as improving upon existing methods.

In the first year of the Pebble Fuel Development project, the characterization teams have provided ongoing development of fabrication processes while also developing groundbreaking new characterization methods to address gaps in prior TRISO particle fuel characterization work. The kernel fabrication team has developed recipes for gelsphere feedstock production and kernel conversion and has begun deeper study of relevant thermodynamic mechanisms while also preparing for scale-up of the production process. The TRISO coating team has completed initial tuning of coating parameters and has supplied significant quantities of coated material (with non-uranium surrogate kernels) to support initial pebble pressing development. Finally, the pebble fabrication team has completed initial scoping studies on graphite and resin pebble matrix materials, particle over coating, and pebble pressing methods, and has successfully produced the first surrogate-TRISO particle fuel pebble cores. In all of these endeavors, X-energy detailees at ORNL have been intimately involved and taken lead roles to ensure effective transfer of the relevant knowledge and capabilities necessary for pebble fuel fabrication (Reference 6-16).

X-energy has partnered with Centrus Energy Corporation (U.S.) to support development of a commercial production facility called TRISO-X for advanced reactors within the next 6-7 years.

ORNL is being considered as a location for TRISO-X. The DOE has announced that X-energy has been awarded an $8.99 million cooperative agreement for the design and license application development of a cross-cutting, HALEU fuel fabrication facility (Reference 3-37). The TRISO-X fuel facility is expected to support the X-energy fuel type, other advanced reactor designs, as well as accident-tolerant fuel designs, with the capability to fabricate multiple HALEU fuel forms (Reference 6-17).

Suppliers and plans for commercial-scale fabrication of fuel elements have largely been identified by the NuScale, TerraPower and X-energy for the SMR, TWR, and Xe-100, respectively. The chief issue in the fabrication of HALEU elements (TWR and Xe-100 designs) is the supply of HALEU itself, as previously detailed in Section 6.4.3 above. The DOE and the U.S. nuclear industry, in cooperation with the NRC, should develop the necessary criticality benchmark data, to allow efficient and cost effective licensing of a new generation of HALEU fuel facilities and transportation packages. HALEU licensees likely will need this criticality benchmark data to achieve an efficient cost effective design option.

6.5 COMPONENT TESTING

Testing programs support reactor licensing and design certification, equipment qualification, and plant commissioning. Much of the ongoing testing associated with SMRs and advanced reactors is currently focused on licensing and design, including some proof-of-concept testing. Vendors have identified testing constraints associated with their designs which may drive overall project timelines due to the novelty and complexity of these tests. These are discussed below along with specific areas of concern including steam generators and integrated testing capabilities. From a manufacturing perspective, equipment qualification testing can become a major constraint for reactor development due to the small number of service providers that offer these services in accordance with a quality assurance program that satisfies the requirements of 10 CFR Part 50 Appendix B. As such, this represents a focus area for assessing the domestic infrastructure available to support new nuclear projects.

Equipment qualification test programs include, but are not limited to, thermal, radiation and operational aging testing, harsh environment effects testing (e.g., Loss of Coolant Accident (LOCA) and High Energy Line Break (HELB)), and seismic and dynamic testing. Testing for the impacts of electromagnetic interference (EMI) and radio-frequency interference (RFI) may also be required within the scope of an equipment qualification test program, depending on the equipment service conditions. Active mechanical equipment must undergo functional testing to ensure the equipment will be able to perform under all expected service conditions. Consensus standards from the Institute of Electrical and Electronics Engineers (IEEE) and ASME establish rigorous requirements that must be met to qualify equipment for nuclear service.

In general, testing and qualification activities are performed by equipment manufacturers or third-party entities. Advanced and small modular reactor vendors are likely to develop their own testing capabilities as well due to the cost of performing custom testing for FOAK equipment at third party facilities. Due to their experience and resources, third-party entities are often used when qualifying unique equipment for service or when performing commercial grade dedication of equipment purchased from a non-nuclear supplier. As such, they are likely to be key to successfully qualifying FOAK equipment used in new nuclear plant designs, such as sodium pumps and helical steam generators. Companies known to be involved in qualifying equipment for advanced and small reactor designs were surveyed for input to this report. Vendors of advanced and small modular reactor designs were also surveyed to gain their perspectives on this topic.

6.5.1 Domestic Service Providers

The U.S. maintains a strong market for testing and qualifying equipment for use in nuclear power applications, including commercial grade dedication. This domestic capability has been sustained by the fact that there are still 99 commercial nuclear power plants operating in the U.S. This relatively large fleet requires an equipment supply chain that can support testing and qualification of replacement components, commercial grade dedication due to obsolescence, and testing for various issues identified throughout the life of a plant. The three primary domestic providers of third-party equipment testing and qualification services are NTS Huntsville (formerly Wyle Laboratories), AZZ Nuclear/NLI, and QualTech NP.

NTS Huntsville

NTS is a privately-held testing, inspection, and certification company based in Anaheim, CA. Testing and qualification services provided for the nuclear power industry are primarily performed at the company's NTS Huntsville facility in Huntsville, AL. The company maintains approximately 40% of the market share for testing and qualification services provided to the domestic nuclear power market and provides a wide range of equipment qualification testing services along with the capability to perform commercial grade dedication. Equipment qualification testing services provided by NTS Huntsville include functional testing, thermal aging, radiation aging, harsh environment (i.e., post-LOCA environments), EMI/RFI, and dynamic effects testing, including seismic. The company maintains a quality assurance program that satisfies the requirements of 10 CFR Part 50 Appendix B (Reference 6-38).

Discussions were held with NTS Huntsville to identify their capabilities to provide testing and qualification services for advanced reactors and small modular reactors. The company stated that, while there may be some unique testing involved for advanced and small modular reactor equipment, many of the qualification activities would likely be the same as those required for currently operating reactors. For these types of testing and qualification activities, such as seismic qualification, NTS Huntsville indicated that they maintain sufficient capacity to support the next generation of new nuclear projects and have the capability to expand in this area should the need arise. Any unique testing and qualification requirements necessitated by new nuclear projects will be assessed based on customer proposals and testing specifications consistent with the company's current practice.

AZZ Nuclear/NLI

AZZ is a multi-faceted company that provides services to a variety of industries across its metal coatings and energy segments. AZZ acquired Nuclear Logistics Inc (NLI) in 2012 to expand the company's ability to provide equipment and related services to the nuclear industry. The company's nuclear business unit (AZZ Nuclear) is based out of Fort Worth, TX and is the largest third-party supplier of equipment solely focused on the nuclear industry. The company maintains a quality assurance program that satisfies the requirements of 10 CFR Part 50 Appendix B.

With respect to equipment qualification and testing capabilities, the company reports that it is capable of performing qualification testing requiring any combination of thermal aging, radiation aging, EMI/RFI, seismic, and harsh environment testing for LOCA conditions (Reference 6-39). The company notes that their seismic qualification capabilities are supported by four seismic simulators (shake tables), including a 10-foot by 10-foot triaxial table and a 12-foot by 12-foot biaxial table. All testing activities are capable of being performed at AZZ's Fort Worth, TX facility with the exception of radiation testing. AZZ Nuclear/NLI did not participate in the survey for this report.

QualTech NP

QualTech NP is a service brand of Curtiss-Wright Nuclear with locations in Huntsville, AL and Cincinnati, OH. Curtiss-Wright Nuclear is a service provider and equipment supplier to the global nuclear industry. The company has been involved in the nuclear industry for 55 years and maintains a quality assurance program that satisfies the requirements of 10 CFR Part 50 Appendix B. Through its QualTech NP service brand, Curtiss-Wright is able to offer equipment qualification testing and commercial grade dedication services. Among the company's listed testing capabilities are cyclic, humidity, thermal and vibration aging, EMI/RFI, mild and harsh environment testing, radiation testing and submergence testing. QualTech NP is also capable of performing functional testing for active mechanical equipment. The company's advertised seismic qualification capabilities include four shake tables (two triaxial tables and two uniaxial tables) that can model a wide frequency band with damping ratios up to 10% (Reference 6-40). QualTech NP did not participate in the survey for this report.

6.5.2 International Service Providers

The combination of rising nuclear plant construction outside the U.S. and declining domestic market for nuclear technology has resulted in a growing number of international providers for testing and qualifying nuclear plant equipment for service. Advanced and small modular reactor vendors may seek these services from outside the U.S. for various reasons including lower costs or business partnerships. International testing entities must also ensure that a quality assurance program is in place that satisfies the requirements of 10 CFR Part 50 Appendix B.

Kinectrics

Kinectrics is a Toronto, ON-based private company that provides testing, inspection and certification services to the electric power industry. Kinectrics has a network of 25 independent laboratory and test facilities and over 1100 staff in North America. The company maintains a quality assurance program that satisfies the requirements of 10 CFR Part 50 Appendix B. Kinectrics testing capabilities supporting nuclear power applications include, but are not limited to, thermal and radiation aging tests, harsh environment testing, EMI/RFI, seismic qualification, and functional testing of active components (Reference 6-41).

Kinectrics testing capabilities for LOCA-induced harsh environments include five steam chambers that can test electrical and mechanical equipment survivability at temperatures up to

500°F and pressures up to 150 psig. The company noted that it has recently upgraded its steam testing facilities to accommodate advanced reactor designs. Kinectrics has 14 ovens available to perform thermal and radiation aging testing with temperature ranges from -100°F to 1300°F and humidity ranges from 5% to 95%. Seismic capabilities include one triaxial shaker table and a random input motion (RIM) table. Discussions with Kinectrics indicate that the company invests heavily into research and development to address new challenges that may arise in component and equipment testing. To that end, the company stated that it is prepared to support testing and qualification activities for advanced and small modular reactor designs as those designs mature.

Framatome

Framatome is an international provider of equipment and services for the nuclear power industry with 14,000 employees. Framatome is owned by Électricité de France (EDF) (75.5%), Mitsubishi Heavy Industries (MHI) (19.5%) and Assystem (5%). Framatome provides an extensive number of testing services to the global nuclear power industry and employs 350 personnel for these activities, including 130 personnel dedicated to thermal-hydraulics (TH) and components testing. Framatome's scale provides it with significantly more resources than a standard EQ and testing service provider, particularly in the area of full-scale TH testing for large component qualification. Framatome is also capable of performing a wide range of equipment qualification and commercial grade dedication testing (Reference 6-42). The company maintains a quality assurance program that satisfies many international standards and meets the requirements of 10 CFR Part 50 Appendix B.

According to information provided by NuScale, they have engaged Framatome for a number of testing services to support the development of its Nuclear Power Module (NPM) reactor (Reference 6-43). This includes fuels testing at the Richland Test Facility in Richland, Washington, Critical Heat Flux testing at the KATHY loop in Karlstein, Germany, Control Rod Assembly (CRA) drop / shaft alignment testing at the KOPRA facility in Erlangen, Germany, SG FIV testing at the PETER Loop in Erlangen, Germany and Control Rod Assembly Guide Tube (CRAGT) FIV testing at the MAGALY facility in Le Creusot, France. Framatome testing personnel stated that their size and experience allow them to support almost any testing needs for light water reactor components, including those for new nuclear reactor designs such as the NuScale NPM. Framatome indicated that they are capable of supporting additional testing needs for advanced and small modular light-water reactor designs, should the need arise.

SIET

SIET is an Italian company based in Piacenza that specializes in large-scale TH testing for the global nuclear power industry. The company employs 21 people and conducts operations out of three main test facilities. SIET maintains an active quality assurance program that satisfies many international standards and meets the requirements of 10 CFR Part 50 Appendix B. The facility's location within an operating power station provides it with unique testing capabilities for steam applications. These capabilities include testing at steam pressures up to 10 MPa (1,450 psig) and temperatures up to 500°C (932°F) (Reference 6-44). This enables tests to be conducted across a broad spectrum of operating conditions.

The company is heavily involved in the development and testing of the helical coil steam generators that will be used in the NuScale small modular reactor. SIET's support for NuScale includes prototype development with both heat transfer and flow-induced vibration (FIV) testing. Discussions with SIET indicate that the company has almost 20 years of experience in testing helical coil steam generators including support for nuclear applications and experimental work associated with heat transfer and flow instability for this design. This experience may be particularly valuable for other advanced and small modular reactor designers seeking international testing services. SIET indicated that their capability to take on additional new nuclear projects would be a function of the type of testing required and the time period in which it was requested.

6.5.3 Steam Generator Testing

The advanced and small modular reactors that are the subject of this assessment make use of helical coil steam generators which operate with feedwater and steam on the tube side (i.e., boiling in tubes). Domestic suppliers have not qualified or fabricated steam generators with these characteristics in many decades. As such, the testing infrastructure for these components is a point of emphasis for vendors. NuScale has already undertaken extensive testing activities abroad due to the cost and capability limitations found in the domestic testing market, and it is expected that other vendors may seek the same approach.

From a technical perspective, full scale testing will likely be required to address many aspects of the helical coil steam generator designs. These tests will include thermal performance testing to assess the heat transfer characteristics of boiling inside helical tubes, natural circulation flow over tubes and high velocity helium flow over tubes. For designs that rely on natural circulation, pressure drop testing will be relied upon to ensure that sufficient primary-side flow is maintained during plant operation. FIV testing will also be of high importance to ensure that the helical tube bundle designs are not susceptible to FIV-induced failures. Secondary-side flow stability must also be assessed due to the fact that steam generator designs with boiling inside tubes are susceptible to secondary flow instability unless adequate flow restriction is incorporated at the tube entrance. In addition, inspectability must be demonstrated for the helical tube designs to ensure that owners and operators are capable of locating tubing flaws throughout the service life of the component.

6.5.4 Integrated Testing

Development of integrated testing infrastructure will be vital to the testing and qualification of FOAK reactor designs. NuScale has developed the NuScale Integral System Test (NIST-1) facility at Oregon State University (OSU) in Corvallis, OR for this purpose and appears well-positioned to carry out large-scale integrated effects testing. The NIST-1 facility is largely a product of a DOE grant awarded to OSU to explore natural circulation phenomena in small light water reactor designs. By contracting the services of OSU at this facility and establishing the NIST-1, NuScale's NPM design has benefitted significantly from these circumstances. Integrated testing for FOAK designs utilizing novel heat transfer equipment and fluids (e.g., molten salt) may prove more difficult due to the capital investments required to develop this capability and the minimal operating experience associated with these technologies. Regardless, many designers of advanced and small modular reactors may determine that the most economical option for testing and qualifying their designs is to establish an in-house integrated testing platform. This platform may also provide a mechanism to perform other equipment qualification tests (e.g., functional tests required by ASME QME-1).

6.5.5 Vendor Perspectives

The infancy of advanced and small modular reactor designs limits the amount of information currently known regarding the testing specifications that will be required to qualify this equipment. There are many stages involved in reactor design and test specification development relies upon upstream activities, including the development of operating parameters and component and equipment design details. Vendors expect that most equipment qualification details will be handled by equipment manufacturers and third-party testing entities; this assumption is consistent with the current structure of the nuclear equipment supply chain. The combination of this expectation with undeveloped test specifications may present a risk to advanced and small reactor development timelines. Without testing specifications or purchase orders, testing providers will be limited in their ability to assess how their capabilities match the unique requirements that may be involved in new nuclear projects, particularly those with FOAK features. Vendors were engaged to obtain information regarding specific constraints that they have identified regarding their testing and qualification efforts.

NuScale

The NuScale NPM makes use of many design features that are similar to currently operating LWRs; this will limit the amount of FOAK testing and qualification needed for this design. However, NuScale has indicated that certain components, such as the NPM CRDMs, may require testing beyond that employed for the operating fleet. From a materials testing standpoint, the company indicated that it has explored the use of martensitic stainless steel for the lower containment structure. However, there is little information available for irradiation testing of this material in low temperature, high fluence environments.

TerraPower

Many of the testing constraints for the TerraPower TWR design are material-related. The TWR will make extensive use of HT9 steel. The domestic capabilities to perform testing for HT9 applications are limited, so international options may be needed.

The use of liquid sodium coolant also presents testing and qualification challenges. Many of the flow-related testing activities associated with the fuel design can potentially be accomplished in a water environment due to the similarity of sodium properties at reactor temperatures. A specific challenge is the testing and qualification that will be required for the primary and intermediate sodium pumps employed in the design. A potential solution is an integrated test facility that incorporates a liquid-sodium environment.

X-energy

Due to its use of pebble fuel and the numerous variables in the graphite manufacturing process, X-energy will be performing a significant amount of testing for graphite materials in support of reactor design and development. The company has indicated that it must obtain irradiation test data for all types of graphite that will be utilized in the plant. The mixing and shaping processes used to produce graphite are less standardized than the fabrication methods used to produce typical nuclear plant materials, such as stainless and carbon steels. As a result, a supplier and specific type of graphite must first be chosen prior to obtaining graphite test data.

6.5.6 Conclusions

The current state of SMRs and advanced reactor designs limits the ability to accurately assess whether sufficient testing and qualification capabilities exist for these designs. However, it is likely that the existing domestic testing infrastructure for basic equipment qualification needs will exceed what is required to support new nuclear projects. An example of this basic qualification capability is seismic qualification. Further, it is expected that testing infrastructure will be capable of supporting most other aspects of equipment qualification (e.g., temperature, pressure, radiation levels). However, as indicated above, there is insufficient information known regarding these parameters to determine whether sufficient domestic testing capabilities are available.

Strict QA requirements associated with qualification and testing can result in long lead times for developing new testing infrastructure. As such, there are significant schedule risks for new nuclear projects that have not yet established testing specifications, particularly for FOAK equipment employed in new designs. Therefore, it is recommended that new reactor vendors establish comprehensive testing and qualification plans as early as possible during the design phase to 1) limit schedule impacts and 2) ensure a path to success exists for qualifying equipment that will be employed in a final design. Plan development should involve extensive interactions with equipment manufacturers and third-party testing service providers, even if the designer plans to perform in-house qualification and testing under its own QA program.

For advanced testing needs associated with FOAK equipment, such as helical coil steam generators, liquid sodium pumps, and helium gas circulators, the existing domestic testing infrastructure is unlikely to support qualification of this equipment. This is evident in the fact that most of the NuScale steam generator testing is taking place internationally. Additionally, vendors are seeking out non-traditional qualification and testing entities (e.g., national labs and universities) to address FOAK equipment testing challenges. Without significant upfront investment, manufacturers and traditional third-party testing entities are unlikely to develop new testing infrastructure. This will force vendors to consider performance of their own testing and qualification activities or seeking out additional non-traditional providers. The costs associated with this strategy may prove prohibitive.

Similarly, integrated testing will be critical to completing required qualification and licensure of advanced and small modular reactor designs. Additional investigation may be needed to identify the specific resources that will be necessary to develop integrated testing capabilities for novel reactor designs.

6.6 Powder Metallurgy - Hot Isostatic Pressing

As part of this project, MPR met with the Electric Power Research Institute (EPRI), which is a leading developer for PM-HIP and is currently working with the DOE on a project exploring its use for the NuScale reactor vessel. MPR also researched companies that have or are pursuing PM-HIP capabilities. The discussion below reflects information obtained as part of these activities.

Technology Description

PM-HIP is a process by which atomized powdered metal is heated and compressed at very high pressures to form a fully-dense solid part. The supply chain, current availability, and different types of powdered metals are discussed in detail in Chapter 5. PM-HIP can be used to produce parts directly from powdered metal or can be used to improve the material properties of parts made by other processes (e.g., densification of parts made by additive manufacturing).

To produce a part from powdered metal using PM-HIP the first step is to fabricate a hollow can or capsule (commonly produced from mild steel) in the shape of the desired part. The can is filled with the powder metal and vibrated such that the packing density of the powder is very high. The can is evacuated of any air during this process so that the inside of the can is at vacuum. Once the can is filled, evacuated, and sealed shut via welding it is ready for the HIP process.

The can is placed inside a HIP unit, which is gradually brought up to pressure and temperature. Typical HIP units reach temperatures of approximately 900°F to 2200°F and pressures of 7,000 psi to 45,000 psi, depending on the alloy type of the powder (Reference 6-18). The HIP unit maintains its desired temperature and pressure for a predetermined amount of time to achieve full densification of the part. The pressure is applied uniformly in all directions using an inert gas. The time at elevated temperature and pressure allows plastic deformation, creep, and diffusion to occur, causing the material to change to a "plastic state" in which voids collapse. The clean surfaces of the voids bond together making the components or parts stronger. This process causes shrinkage of the part and corresponding movement of the can. Computational simulation is used to predict this shrinkage so it can be accounted for in the design of the can.

After the HIP process is complete, the can is removed by various means depending on the component. The can may be removed by machining. The can may also be removed by pickling, where an acidic agent is used to remove a mild steel can from a higher alloy steel part.

HIP can be used to improve the material properties of parts manufactured by other processes. Two examples of this are castings and additively manufactured parts. The molten metal used in the casting process may trap and contain gasses causing porosity in the metal castings. Similarly, some additive manufacturing processes result in products that are not fully dense or have anisotropic material properties. In these cases HIP consolidation can be used to reduce the porosity of the part, improving the material properties. No can is needed for these HIP processes; instead the part is inserted directly into the HIP unit. The combination of elevated pressure and temperature and time duration allows the material to flow in the solid state and to bond on an atomic level.

Summary of Potential Benefits

PM-HIP can make large, complex shaped parts near net shape with high quality material properties. The fact that the part can be produced near net shape significantly reduces the need for machining and the amount of scrap material, both of which make the production of the part cheaper. The complex shaped parts can often be made with no welds, also reducing the fabrication cost and eliminating the need for potentially costly future weld inspections leading to possible repair or scrapping of the part. The parts are fully dense with isotropic material properties. HIP can also be used to improve the material properties of parts manufactured by other processes, such as casting or additive manufacturing. PM-HIP can theoretically be used with a wide range of different metals including nickel-based alloys and most types of steel.

Summary of Potential Drawbacks

The most significant limitation with this technology at the present time is the size of the HIP units available, which are not large enough to accommodate larger parts, which would be the most beneficial application of PM-HIP for the nuclear industry (further discussed in Sections 6.6.2 and 6.6.3). It may be possible to work around the size limitations of current PM-HIP units by utilizing advanced welding methods such as Electron Beam Welding, as discussed in Section 6.6.4, but a larger HIP vessel would likely be required to support future reactor vessel applications.

Another limitation of the technology is the ability to make the cans. Complex geometries require complex cans to be produced. These cans may be cumbersome and time consuming to produce, requiring numerous welds. Furthermore, removing the can, especially for a complex shape and if a similar alloy metal is used for the can as the part, may be a challenge. Future work may focus on making the can an integral part of the final piece so removal is not required.

Finally, there is limited acceptance of powdered metal and the associated parts by the nuclear community. An ASME code case and ASTM standard was developed and approved by the NRC for 316L stainless steel. Austenitic steels (A988), ferritic steels (A989 steels) and nickel- based alloys (B834) have been approved by ASME B&PV-II, but have not yet received NRC approval. Appendix V of ASME B&PV-II has been revised to now treat PM-HIP similarly to forgings, castings, and wrought products allowing for the acceptance of new alloys if the material properties can be properly demonstrated.

6.6.2 U.S. Capabilities

The largest currently operating HIP units in the U.S. are shown in Table 6-2 with the operating company and size (Reference 6-19). There are slightly bigger units internationally. It is suspected that there are sufficient HIP units in the U.S. (i.e., the size capability is limiting, not the capacity). PM-HIP has not traditionally been used for major components in the nuclear industry, however, this technology has a proven track record in other power industries and the offshore oil and gas industry. It has been used to produce hubs, manifolds, pump housings, steam chests, turbine rotor shafts, valve bodies, and wye pieces.

Table 6-2. Largest Domestic HIP Unit Sizes

Company	Size (diameter × length) [in.]
BodyCote	66 × 100
ATI	51 × 115
Alcoa Howmet	59 × 80
Alcoa Howmet	42 × 97
Kittyhawk	47 × 79

PM-HIP has also been used extensively in the aerospace industry. For example, it has been used to produce turbine blades and vanes for jet engines. Further, many precision airframe components made from alloys such as titanium, aluminum and steel were formerly made by casting, but are now manufactured by HIP to ensure integrity, optimize mechanical properties and improve fatigue life. There is an increasing prevalence of 3D printed metal parts in the aerospace industry. HIP is commonly performed to strengthen parts, and is often used to reduce the porosity of castings (Reference 6-20).

6.6.3 Plans for Future Development

Numerous entities are actively working to expand their PM-HIP capabilities. Domestic PM-HIP vendors such as BodyCote, ATI, and Kittyhawk are looking to expand their business. The Center for Advanced Nuclear Manufacturing (CANM) is working to improve PM-HIP processes. EPRI is working on several projects to develop this technology specifically for the nuclear industry. In particular, EPRI has a joint project with NuScale and the DOE to produce a 2/3-sized model of the RPV for the NuScale Power Module. The goal of this project is to significantly reduce the cost and time required to manufacture a reactor through the use of advanced manufacturing processes such as PM-HIP. Significant progress on manufacturing certain portions of the vessel including the lower head assembly has already been made. This project is scheduled to run until approximately 2022. Ultimately, use of PM-HIP may reduce the cost of manufacturing the RPV by 40% and reduce the schedule to 12 months.

EPRI is also working with the DOE and industry to deploy a new large scale HIP facility, referred to as ATLAS. ATLAS would be approximately 140 inches in diameter, which is twice as large as the largest current HIP units and would significantly increase the value of this technology to the nuclear industry (Reference 6-19). The estimated cost of the ATLAS HIP unit is approximately $55 million (Reference 6-21). ATLAS is still in need of funding before construction can begin. Analysis is being performed to demonstrate the feasibility of the proposed design.

6.6.4 Electron Beam Welding

Electron Beam Welding (EBW) is an advanced welding technique that complements PM-HIP in addition to other industrial uses. EBW is a fusion welding process in which electrons are accelerated to very high speeds and focused in a beam on the two materials to be joined. The two materials melt and flow together as the as the kinetic energy of the electrons is converted to heat upon impact. EBW generally occurs in a vacuum as the presence of gas molecules can scatter the electron beam (Reference 6-22).

EBW is advantageous over traditional welding techniques because it offers precise control, increased weld depth, a smaller heat affected zone, high strength due to no use of a filler metal, higher purity because it is conducted in a vacuum, and the ability to join dissimilar metals. These advantages are especially attractive when combined with post-process heat treatment. EPRI has conducted research on EBW with parts produced by PM-HIP. The research has demonstrated that if the correct post process heat treatment is applied, then the weld is no longer discernable on a microstructure level from the base material. This result from EBW could theoretically eliminate the need for costly in-service weld inspections. With respect to manufacture of large parts, use of EBW may allow smaller parts manufactured by PM-HIP to be welded together to create parts that otherwise would need to be produced through forging.

6.6.5 Conclusions

PM-HIP is a promising technology that could provide an alternate path for manufacturing numerous components in the nuclear industry. The most significant limitations with PM-HIP are with regard to the size of the HIP units currently available and the qualification of the nuclear grade parts using this technology. Research on PM-HIP to address these limitations is ongoing, so it is not likely to be sufficiently developed to support initial deployment of SMRs and advanced reactors, but could be ready for later commercial deployment on a larger scale. PM-HIP may allow less expensive manufacturing of certain large components than traditional methods, because PM-HIP produces high quality parts near net shape with limited wasted material. These benefits are further increased when this technology is paired with EBW, which can be used to join smaller parts into a larger part that exceeds the capacity of existing HIP facilities. Outside of its value to PM-HIP, EBW provides improved welds in other fabrication processes, including dissimilar metal welding.

6.7 ADDITIVE MANUFACTURING

Additive manufacturing (AM), also referred to as 3D printing, is a process by which a digital design is used to build up a component in layers by precisely depositing material. AM is an active area of research and development with a variety of different applications. This report only discusses AM techniques and capabilities associated with manufacturing metallic components because this is seen as the technology most applicable to the nuclear industry. Substantial work is also being done using polymers, but the application of polymers in nuclear is not considered for this report.

As part of this project, MPR visited ORNL to review of state-of-the-art technology for AM and to interview personnel. MPR also investigated use of AM among industrial companies. The discussion below reflects information obtained as part of these activities.

6.7.1 Technology Overview

<u>Technology Description</u>

This section discusses some of the different additive manufacturing technologies that currently exist and are under development. The processes described herein are a representative sampling, although it is noted that numerous other techniques exist.

The AM process used for each application is selected based on relative strength and weaknesses of each process, specifically regarding size, material, and quality (Reference 6-23). The technologies, their strengths, weaknesses, and currently demonstrated size are listed in Table 6-3. The sizes provided in the table are relative, but as a point of reference, a demonstrated size of "small" is less than one cubic foot in volume.

Table 6-3. Additive Manufacturing Technologies

Technique	Pros	Cons	Demonstrated Size
UAM	• Solid-state • Use of reactive metals • Embedding of sensors and optical fibers	• Poor material properties in accumulation direction	Small
DED	• Fully dense parts • Repairs • High quality parts • Control over microstructure • Coatings	• Slow • Expensive	Versatile (small to large)
EBM	• High temperature materials • In situ monitoring • Complex shapes • Relatively low cost	• Rake powder bed • Slow • High power required • Structural integrity • Size limitations	Small
Large Scale Welding	• Unrestricted footprint • Relatively fast • Low cost	• Limited control over material properties	Large

Ultrasonic Additive Manufacturing (UAM)

UAM is a solid-state process (i.e., no melting) in which layers of metallic tape are vibrated fast enough that extensive plastic deformation occurs, which removes the oxide layer and brings the metals in close contact so they achieve a spontaneous weld (Reference 6-24). A schematic of this process is shown in Figure 6-2. Due to the process being entirely solid state, UAM allows for the embedding of optical fibers, sensors, and other components that are sensitive to high temperatures in the metal matrix (Reference 6-25).

Current UAM systems may result in poor material properties in the accumulation direction, or the direction in which the material is being built up. The poor material properties are due to the different layers of material not fully bonding to one another, but can be corrected by post-process heat treatments (Reference 6-24).

The UAM process has been used at ORNL to fabricate a control plate for HFIR (the High Flux Isotope Reactor located at ORNL). The solid-state process allowed for the embedding and accurate placement of neutron absorbers in the metallic matrix. UAM was also used to embed an optical fiber in a metal plate for HFIR in-core instrumentation (Reference 6-25). One application of this technology has been in the development of copper and aluminum small-scale heat exchangers (Reference 6-26).

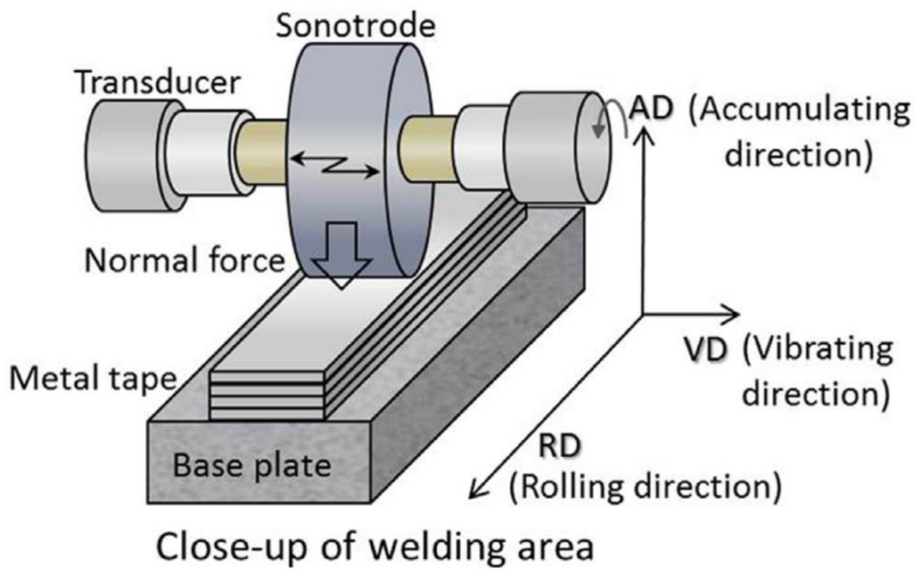

Figure 6-2. Schematic of Ultrasonic Advanced Manufacturing Process (Reference 6-27)

Laser Direct Energy Deposition (DED)

Laser DED (also called laser metal deposition) is a process that uses a nozzle, typically mounted on a multi-axis arm, to spray metallic powder through a laser that melts the powder for deposition onto the target surface. This process produces fully dense parts with strong metallurgical bonds to the base material. Laser DED allows for very precise material addition and is good for repairing large structures with high fidelity. However, current laser DED machines are slow and expensive (Reference 6-25).

Laser DED is currently used for repairs to gas turbines because it requires less time, money, labor, and energy than refabricating entire parts due to minimal cracks or wear. It is used for application of advanced coating material for corrosion and wear resistance onto parts by consolidating the powder into the bulk component (Reference 6-28).

Laser DED also offers the ability to use two different materials and gradually change the relative amount of each that is being added to the structure in order to fuse dissimilar metals while reducing the likelihood of residual stress and cracking within the final component. Figure 6-3 is a diagram for using two different metal powders to produce a component that gradually transitions between the two materials. Welding of dissimilar metals is challenging due to large thermal expansion mismatches potentially resulting in large stresses and eventual component failure. Laser DED has been used to produce a graded material transition joint between ferritic steel and austenitic stainless steel (Reference 6-25).

Laser DED was used at ORNL to produce an ACO-3 Hex Duct for TerraPower using HT9 as the material. The laser DED fabricated pieces of HT9 were shown to have better mechanical strength than traditional HT9 with a limited decrease in ductility (Reference 6-25).

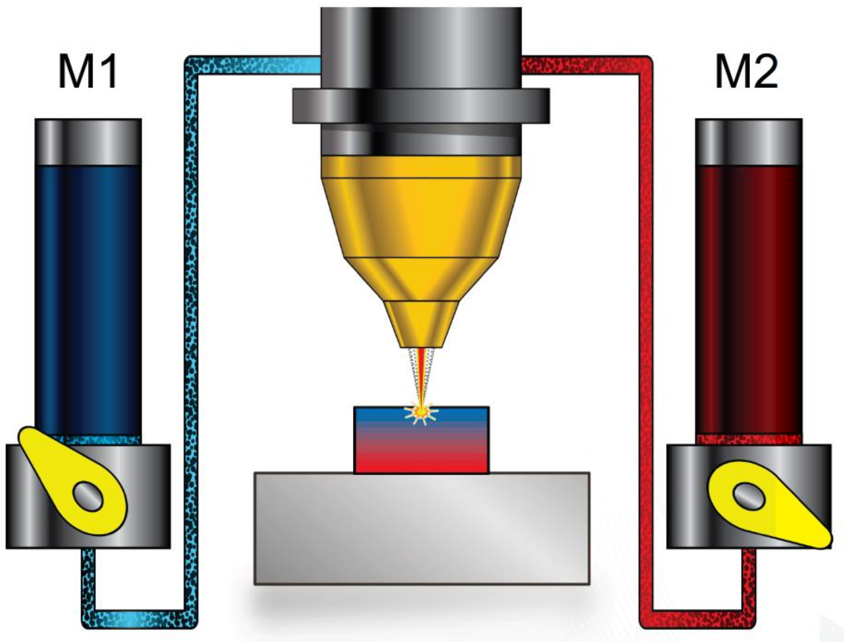

Figure 6-3. Schematic of Building Transition Joint Using DED (Reference 6-29)

Electron Beam Melting (EBM)

EBM uses an electron beam to precisely melt areas of a heated powder metal bed. This process allows for the creation of complex shapes only possible with AM. EBM can be used to manufacture components using high temperature, highly non-weldable materials such as Ni-based superalloys. EBM machines are developing in-situ characterization, feedback, and control for unprecedented microstructure control. For example, a current machine being used by the research community monitors 600+ variables per second and captures images of every printed layer (Reference 6-25).

Large Scale Welding

Large scale welding is a branch of AM that occurs in an open air environment and uses a metal inert gas (MIG) welding arm. Metal wire is fed to the arm and layers of weld material are built up into components. This method is relatively cheap and allows for an unrestricted print size. An example of an application of this technology is the 7 foot tall, 400 pound steel excavator arm built by Wolf Robotics. However, this process does not allow for as much control over material properties as other techniques (Reference 6-25).

Potential Benefits

AM provides the ability to more easily manufacture geometries that are challenging or impossible to produce using traditional processes. AM therefore allows designers the option to use complex geometries, and manufacture the parts with significantly less material than traditional processes (e.g., subtractive manufacturing by machining). Additive manufacturing eliminates scrap metal by building the part in its final shape. This benefit has led to adoption of AM techniques in the aerospace industry where expensive high strength-low weight materials are used so the aerospace manufacturers can improve the 'buy-to-fly' ratio of the material for their parts (i.e., how much material is purchased compared to the amount of material that is in the final part). Finally, the geometric flexibility can allow for new orientations of fissile material in advanced nuclear core designs.

AM also has the benefit of allowing precise placement of material. This ability enables optimum designs that require locating fissile material or neutron absorbing material in specific places in a component. The other process parameters, such as temperature, can be precisely controlled at each location. This capability allows parts produced by AM to have different grain structures at different locations. Grain structure directly affects the material properties of a part. This ability could, for example, be beneficial for modifying the grain structure at a water interface for increased corrosion resistance. As previously discussed, the Direct Energy Deposition technology has been used to create parts with different materials where there is a material gradient through the transition between materials, which eliminates the need for a bimetallic weld.

Potential Drawbacks

AM processes are still relatively new, and as such there are many areas of active research to address technical challenges and optimize the processes. The research needs vary by process, but a common challenge for AM processes is that they must be performed relatively slowly to produce parts with high quality material properties. This limitation reduces the applicability for the nuclear industry which is most in need of options for large scale manufacturing.

AM processes often produce parts that are not fully dense. In other words, the layers of the AM process are not completely bonded together on a molecular level. This leads to anisotropic material properties – i.e., material properties in the accumulation direction are different than those in the other directions. Many AM parts are put in a HIP unit after they have been made, in order to make them fully dense.

AM will require review and acceptance by the nuclear community (i.e., ASME, NRC, utilities) before commercial deployment. No ASME code cases have been accepted for AM processes or parts. Qualification of parts typically is performed by producing multiples of the same part with the same process and performing destructive examinations on a few of the pieces to qualify the others. This makes the process costly and time consuming.

6.7.2 U.S. Capabilities

<u>Oak Ridge National Lab</u>

LAMBDA Facility

ORNL's Low Activation Materials Development and Analysis (LAMDA) laboratory is a dedicated facility containing specialized instruments for the study of irradiation-induced effects on materials properties. LAMDA consists of several interconnected contamination-zone and clean area suites. Originally created as a facility for plutonium studies and then thermophysical properties of graphite for high temperature gas cooled reactors in the 1960s, the role of LAMDA has changed with the emphasis placed on "low activation" materials. Currently, LAMDA is involved in both fundamental and applied research on radiation-induced changes in structural materials, reactor internals, diagnostic materials and sensor components for both current and advanced reactor designs for both fission and fusion systems. LAMDA typically utilizes small, compact samples to allow researchers to leverage cutting-edge characterization and test equipment to study phenomena not possible at a hot cell facility. Researchers at LAMBDA are currently using AM technology to develop metal matrices in which they can precisely place fissile material to demonstrate the potential benefits AM can have in the fuel/core design of advanced reactors.

MDF

ORNL's Manufacturing Demonstration Facility (MDF) leverages ORNL's science capabilities to solve challenges in AM. The MDF teams with industrial partners for cooperative research to develop and demonstrate AM technologies. To date the MDF has teamed with hundreds of companies in a variety of industries. The MDF currently contains numerous EBM machines (~200 mm in height, width, and length) producing components with titanium, Hastelloy X, Inconel 738 and some refractories. The MDF is scheduled to get an additional EBM machine with a 350 mm diameter, 450 mm tall build volume for high temperature Ni materials. It also contains several other laser powder bed systems with build volumes of ~10 inches in height, width and length using aluminum, maraging steels, and stainless steels. The MDF is close to receiving a DED powder system 36 inches in height, width and length for running steels and other materials. The MDF has a large scale welding machine and several other larger systems, including hybrid machines and laser wire systems, which are in an acquisition process.

<u>Idaho National Lab</u>

INL is the home of the Advanced Test Reactor (ATR) which is capable of producing high neutron fluxes and is often used for irradiation experiments. INL has partnered with several other companies developing AM processes to irradiate test items produced using AM to qualify their material properties under irradiation for use in the nuclear industry.

INL is also working with industry partners to develop a unique AM method of making advanced uranium silicide (U_3Si_2) fuels (References 6-30 and 6-31). This effort is called Additive Manufacturing as an Alternative Fabrication Technique (AMAFT). The AMAFT process is a hybrid technique meaning it uses some AM steps and other traditional manufacturing techniques. It uses a hybrid laser engineering shaping technique to make a small, localized melt pool out of multiple powder sources so a pellet of dense U_3Si_2 fuel is directly formed. AM is beneficial for this application because it eliminates the steps of pre-processing of UF_6 to convert it to UO_2.

Siemens

Siemens was the first company to deliver a part produced by additive manufacturing that was placed into a commercial nuclear power plant. Specifically, Siemens produced a mechanical impeller for a plant in Slovenia that was installed in 2017. The impeller was for a fire protection pump and was 4.25 inches in diameter. The part was additively manufactured because the manufacturer of the original impeller was out of business and no replacements were available. A digital twin was reverse engineered, and then the replacement was additively manufactured (Reference 6-32).

Siemens is continuing R&D of AM processes, including in steam turbine component manufacturing and maintenance. Two oil sealing rings have been installed as replacement parts on an industrial steam turbine operating at a customer plant in India. Most of Siemens' AM development to date has been international.

Westinghouse

Westinghouse is researching and developing AM processes focused on producing parts for the nuclear industry. Westinghouse has focused its development on three techniques (Reference 6-33):

1. Laser powder bed fusion (similar to EBM discussed above) which is good for the production of small, complex fuel structural components, prototype components and tooling.
2. Laser DED which can be used to add features such as nozzles, bosses or flanges to existing components, and can reduce cost and lead time when used for weld repair or automatic cladding, as well as to produce larger or more complex components.
3. AM methods (e.g., binder jetting) which can produce smaller, complex components for a lower cost than powder bed fusion.

Westinghouse views impellers and micro-channel heat exchangers as components that can be produced more efficiently through the use of AM. Additionally, Westinghouse is currently demonstrating the use of AM casting molds to produce safety-related castings, including replacement brackets and bearing housings, for electric motors. The process could be used to reduce the cost and lead time of many cast parts including valve bodies and piping sections and connections. It also allows designers to create more complex shapes than is possible using traditional sand casting (Reference 6-34).

Westinghouse is also in the process of completing a DOE funded project to study the neutron radiation effects on zirconium alloys produced through additive manufacturing for light water reactors. The researchers will conduct post-irradiation examination of zirconium material that was irradiated at the MIT reactor (Reference 6-35).

General Electric Hitachi

GE Hitachi recently constructed a new 125,000 square foot facility in Greenville, SC called the GE Power Advanced Manufacturing Works Facility. GE Hitachi has produced metal AM parts in this facility and partnered with INL to understand the effects of irradiation on the material properties of AM parts. GE is performing this DOE funded work in an effort to use AM for the nuclear industry to produce replacement parts for components that are no longer supported by the original equipment manufacturer (OEM) (Reference 6-36).

BWXT

BWXT has partnered with ORNL and the DOE to work on a project for integrating advanced software into AM processes. This project involves using a combination of in-situ process monitoring technologies, modeling, and data analytics to develop the processing conditions for advanced metals used in reactor cores and other primary system components. The researchers are working to demonstrate component-level qualification, leading to certification of nuclear materials configured in complex geometries (Reference 6-37).

Curtiss-Wright

Curtiss-Wright produces a wide range of nuclear grade products including actuators, valves, heat exchangers, cables, snubbers, etc. When contacted about their involvement and interest in developing AM capabilities, Curtiss-Wright expressed that, once the technology is more developed, they would be interested in using it for parts with complicated geometries including pump impellers, hydraulic manifolds, and yokes. They did not share any development activities of their own. This is consistent with the input from multiple other similar vendors in the industry.

6.7.3 Plans for Further Development

Westinghouse, GE Hitachi, BWXT, INL, and ORNL are all expected to continue to develop their AM capabilities. Many efforts discussed above are ongoing and will continue for years to come. The exact nature of certain development efforts are business sensitive and not available publicly. The following are known areas of further development, in addition to those discussed above.

Oak Ridge National Lab

The MDF at ORNL is continuing to work with industry partners on numerous projects in developing new AM technologies and optimizing processes. They have a goal of producing larger, high quality parts, more quickly and cheaply than are currently available.

One of the active areas of research in AM at ORNL that could potentially benefit the nuclear industry is the concept of producing ‘born qualified’ components. This concept involves using in-situ process parameters (e.g., beam power, molten pool temperature) to predict post-process material properties. The hope is that that a connection can be drawn between the in-situ parameters and final material properties such that minimal post-process inspections or testing are needed to qualify a component. This could significantly reduce the cost of producing high quality components that meet necessary requirements for the nuclear industry.

Westinghouse

By fall of 2018, Westinghouse plans to install an additively manufactured fuel component, a thimble plugging device made of 3D printed 316L stainless steel, in a commercial reactor. This part was produced with a laser powder bed system and similar specimens were irradiated at MIT for testing. The part consists of a traditionally cast body piece with additively manufactured rods that plug the thimble tubes. The company selected the thimble plugging device to be their first additively manufactured fuel component for a commercial reactor because consequences of less-than-expected performance are minimal, posing very low risk. In addition, the thimble plugging device provided an opportunity to enhance understanding and refinement of the design-and-build process for a cast and additively manufactured hybrid component.

Over the next year, Westinghouse researchers will focus on reducing the cost and lead times for replacing obsolete and difficult to procure parts, as well as fuel structural components and prototypes for next generation plants. These will include impellers and microchannel heat exchangers.

In the next year, Westinghouse also is prioritizing the material development, testing and support needed for the development of AM codes and standards. According to Westinghouse, the main challenge in qualifying AM materials is the variability of material properties and overall part quality, which depends on feedstock material, AM process parameters, and part geometry. Current qualification of parts requires producing multiple copies of each part and performing destructive testing on some to qualify the others. This makes initially producing parts time consuming and costly. In addition to performing additional materials testing to aid in AM qualification, Westinghouse is working on developing in-process monitoring capabilities and integrated computational materials engineering processes to reduce the amount of post-manufacturing qualification that needs to be performed (Reference 6-34).

Westinghouse has also partnered with the UK Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC) on studies to enhance SMR design efficiencies and cut build times.

6.7.4 Conclusion

Additive manufacturing is currently employed in the nuclear industry for a very narrow range of applications. The flexibility offered by additive manufacturing with regard to geometries and precise placement of materials makes it an attractive future technology for the industry. Additionally, once processes are optimized, it may be cheaper and quicker at producing some of the complex parts required. However, due to the lack of maturity of many of these processes, AM is not a viable alternative to traditional manufacturing methods at this point for large components of new construction SMRs or advanced reactors. Significant challenges still exist in producing components with the size capability, speed, and cost that are needed for most applications. There are also significant regulatory challenges that must be overcome before these processes can be implemented in the industry on a large scale. AM will likely not be mature enough for the FOAK SMR builds, but has potential to be a useful manufacturing capability for later commercial deployment.

7 Assessment of U.S. Manufacturing Capabilities for Selected Plant Components

This section provides an assessment of the U.S. manufacturing capabilities to meet the requirements for key components of SMRs and advanced reactors, as outlined in Chapter 3. The current supply chain plans for Generation III+, SMRs, and advanced reactors are detailed in Chapter 4. Chapter 5 outlines the domestic supply of raw materials required for these reactor designs. Chapter 6 discusses the domestic manufacturing capabilities that can be utilized to meet the reactor design requirements. This section draws on this information to assess if the current domestic manufacturing infrastructure has the capabilities and capacity to meet the demands of the SMR and advanced reactor designs for each major component.

7.1 Reactor Pressure Vessel

7.1.1 NuScale NPM

As presented in Chapter 3, each NuScale Power Module consists of two major ASME B&PV Code Class 1 pressure vessels: the RPV and the CNV.

Several of the forges discussed in Chapter 6 have been in direct contact with NuScale and had detailed discussions about domestic production of the forgings necessary for the NuScale design. Some of the conclusions from these discussions are proprietary and fluid, as details of the NuScale design are still changing, including the size and material of the large forgings required.

In general, most forging facilities agree that it is possible to make a majority of the forgings for the NPM domestically. Limiting components, in terms of size, are the upper and lower flanges. The height requirement on these large rings is of concern because there are no ring mills long enough in the U.S. to support these lengths. It is possible the design could be modified slightly to shorten the length of the forgings required. Alternatively, facility upgrades could be made to support these lengths. The diameter of these ring forgings is considered less challenging than their length.

NuScale may elect to have some forgings made by foreign suppliers because foreign forges have experience and expertise forging much larger commercial nuclear components. However, NuScale also has a strong interest in domestically sourcing as many components as possible.

In addition to the supply of forgings for the vessels, fabrication rate also may be a concern. Based on conversations with domestic forges, they have the capacity necessary to support an initial order from NuScale, but they have concerns that the fabricators will be able to have high enough throughput for long term demand if NuScale were to produce multiple plants of 12 NPMs each per year.

7.1.2 TerraPower TWR

The TerraPower TWR RV walls are much thinner than an RPV for an LWR because of low operating pressure, so TerraPower may fabricate the RV by welding rolled plate at the site. The Guard Vessel may be fabricated by the same means. Rolled plate could be provided by a domestic supplier. However, site fabrication will require significant numbers of nuclear industry qualified welders, the lack of which has been noted as a concern by some fabricators.

7.1.3 X-energy Xe-100

At this time, X-energy has not developed firm plans for manufacturing the reactor pressure vessel. Its dimensions and weight are similar to those of the NuScale CNV, for which there are some concerns with providing the forgings required because of the height of the pieces and the material. The issues will be similar for manufacturing X-energy's design. Design decisions for material of construction and length of each ring forging have not yet been determined. If the limitations of domestic forges are taken into account as the Xe-100 design moves forward, it is likely that the domestic manufacturing capabilities will be able to support the forgings required for the X-Energy reactor vessel. Because the design of the Xe-100 RPV may approach the limits of domestic forges, a design-for-manufacturability approach that includes consultations with the selected vendor on the final design would be appropriate.

7.2 STEAM GENERATORS

All steam generator designs for SMRs and advanced reactor designs addressed above are once through helical designs with boiling inside the tubes. The three designs share a number of qualification and fabrication challenges. However, each of the designs also has a number of unique qualification and fabrication challenges that must be addressed specifically for that design. No helical coil steam generators have been fabricated domestically for many decades. Therefore, fabrication process development will be required to achieve domestic fabrication capability for this type of steam generator.

7.2.1 NuScale SG Fabrication Considerations

Some development of suitable fabrication capabilities is needed to build NuScale steam generators in the U.S. The principal challenges are associated with the tubing, tube supports, and assembly.

1. Tubing: The length, diameter, wall thickness, and material of the NuScale steam generator tubes are within the range of tubing that is currently fabricated for conventional PWR steam generators. However, there currently is no domestic supplier capable of fabricating the tube length required for NuScale steam generator Alloy 690 tubing with the dimensional and inspection characteristics specified by NuScale. All current commercial PWR steam generator tubing is provided by off-shore tube suppliers.
2. Tube bending: The NuScale steam generator tubes must be bent into a helical geometry with complex transition bends at both ends. Current bending capability of existing nuclear steam generator tube suppliers (all international) is limited to single in-plane tube bends of 180 degrees. Bending machinery exists both domestically and internationally to

bend tubes into helical and complex geometries, but these capabilities have never been qualified for unique nuclear steam generator quality requirements. For example, strict limitations apply to lubricants used and bending machine mandrels cannot be fabricated of metal. Such requirements may preclude the use of existing bending machine technology. Tube shape accuracy and precision is also essential to preclude tubes from contacting one another in transition bend regions where there are no tube supports.

3. Bent tube logistics: Once tubes are bent into their final shape, shipment may be difficult because of their bulky configuration and their flexibility which requires considerable support. It may therefore be necessary to collocate tube bending and component assembly facilities, which differs from the current nuclear steam generator tube supply chain wherein tubes are bent by the tube supplier.
4. Tube supports: Tube support design for the helical steam generator will be unique. Manufacturing development is required to achieve affordable methods to manufacture these tubes supports with sufficient accuracy and precision.
5. Assembly: Methods must be developed to sequentially assemble the helical heat exchanger and tube supports inside the reactor pressure vessel. Assembly methods must successfully position the helical tubes in the heat exchanger and fit up the transition bends at both ends to their respective tube sheets.
6. Pressure vessel: The NuScale steam generator heat exchanger is contained within the reactor pressure vessel. The pressure containing feed and steam plenums that are integral with the reactor vessel have some unique design aspects, but do not represent manufacturing challenges outside the current capabilities of domestic suppliers.

7.2.2 TerraPower SG Fabrication Considerations

Key areas that will require effort are:

1. Tubing: There currently is no domestic supplier capable of fabricating chrome-moly tubing of the required thickness with sufficient length to limit the number of tube butt welds to a reasonable number. Therefore, similar to the circumstances for PWR steam generator tubing, only international suppliers currently have the needed tube making capabilities.
2. Tube welding: The TWR steam generator tubes must be joined by butt welding several straight tubes together. These butt welds may be made by an automated welding station. Tube thickness may require several weld passes with filler metal, and weld ID contour must not inhibit the ability to inspect tubes with a bore side probe.
3. Tube bending: The TWR steam generator tubes must be bent into a helical shape with transition bends both above and below the helical region. The helical bends can be made in an automated bending station, but some transition bends may need to be made manually during steam generator assembly. Development of appropriate bending machinery will be required. Dimensional control must be adequate to maintain as-assembled relative tube spacing. Classification of the steam generator as not safety-related may simplify the bending machinery qualification requirements.

It may be desirable to collocate automated tube butt welding equipment with a helical bending station to achieve efficient manufacture of the helical heat portion of the tubes.

4. Bent tube logistics: It may be necessary to collocate the helical tube bending facility with the steam generator manufacturing facility to avoid difficulties associated with transporting very large helical tube assemblies.
5. Heat exchanger assembly: Methods to efficiently assemble the helical heat exchanger must be developed. There is currently insufficient detail available on the design to identify specific heat exchanger assembly fabrication challenges.
6. Steam generator assembly: There currently is insufficient detail available on the design to identify specific steam generator assembly fabrication challenges.
7. Pressure vessel: Although information on the design of the TWR steam generator pressure vessel is limited, there does not appear to be any aspect of the design that is outside existing capabilities of domestic pressure vessel fabricators.

7.2.3 X-energy SG Fabrication Considerations

Similar to the design of all high temperature gas steam generators, the design of the Xe-100 steam generator internals is necessarily complex to accommodate large thermal gradients in the component, and will have manufacturing challenges. Key areas that will require effort are:

1. Tubing: There currently is no domestic supplier capable of fabricating Alloy 800H tubing of the required thickness with sufficient length to limit the number of tube butt welds to a reasonable number. Therefore, similar to the circumstance for PWR steam generator tubing, only international suppliers currently have the needed tube making capabilities.
2. Tube welding: The Xe-100 steam generator tubes must be assembled by butt welding several straight tubes together. Most of these butt welds can be made by an automated welding station but some tube butt welds must be made by portable welding equipment during tube assembly in the steam generator component. Tube thickness may require several weld passes with filler metal, and weld ID contour must not inhibit the ability to inspect tubes with a bore side probe.
3. Tube bending: The Xe-100 steam generator tubes must be bent into a variety of complex shapes. Some of these bends can be made in an automated bending station, but some bends must be made manually during steam generator assembly. Development of appropriate bending machinery will be required. Dimensional control must be adequate to maintain as-assembled relative tube spacing. Classification of the steam generator as not safety-related may simplify the bending machinery qualification requirements.

   It may be desirable to collocate automated tube butt welding equipment with a helical bending station to achieve efficient manufacture of tubes for the helical heat exchanger portion of the steam generator.
4. Bent tube logistics: It may be necessary to collocate the helical tube bending facility with the steam generator manufacturing facility to avoid difficulties associated with transporting very large helical tube assemblies.

5. Heat exchanger assembly: Methods to efficiently assemble the helical heat exchanger must be developed. Existing high temperature gas steam generators utilize three piece tube wear assemblies at every tube-to-support intersection. This adds more than 100,000 parts to the heat exchanger that must be properly assembled and verified as satisfactory. Assembly methods must be developed to improve both the efficiency and quality of this manufacturing process.
6. Steam generator assembly: Steam generator assembly includes many challenging operations that will require manufacturing development. Some of these key assembly aspects include: 1) welding tubes in-place, 2) bending tubes in-place, and 3) insertion and fit-up of large subassemblies inside the vessel.
7. Pressure vessel: There are no aspects of the steam generator pressure vessel that appear to be outside the existing capabilities of domestic pressure vessel fabricators.

7.3 CONTROL ROD DRIVES

7.3.1 NuScale NPM

The NuScale design employs control rods and drive mechanisms that are comparable to traditional nuclear plants, however the control rod shaft is far longer than in existing reactors. The control rod drive mechanisms used for the AP1000 were manufactured domestically at Westinghouse's Newington, NH facility. Based on the similarity to existing designs, the capabilities to manufacture the NuScale CRDMs are not considered a constraint. The larger concern is the capacity of CRDM manufacturers. Currently, the wait time for replacement CRDMs for LWRs is approximately 2 years.

7.3.2 TerraPower TWR

The CRDMs and SRDMs in the TWR design will be similar to the ones used for traditional LWR applications. There are several design challenges for these components. However, based on the similarity to existing design, the capabilities to manufacture the TerraPower CRDMs can likely be developed domestically.

7.3.3 X-energy Xe-100

The Xe-100 design has two types of neutron controlling rods: 1) control rods which make adjustments to the power level during operation and 2) shutdown rods to scram the reactor. The CRDMs are likely to be comparable to traditional designs and identical for both control and shutdown rods. Similar to the TWR CRDMs and SRDMs, it is reasonable to expect that the capability to manufacture the CRDMs domestically could be developed.

7.4 FUEL ELEMENTS

7.4.1 NuScale NPM

The NuScale NPM uses fuel elements that are comparable to existing LWRs, with the exception of reduced size. Domestic sources exist for fabrication of this fuel and NuScale plans to utilize one of these suppliers.

Consistent with the fuel design for existing LWRs, fuel is enriched to less than 5 percent ^{235}U. Therefore, NuScale will utilize existing low-assay LEU supply chains.

7.4.2 TerraPower TWR

Fuel for the TerraPower TWR design will require ^{235}U enrichment up to HALEU levels at the beginning of plant life. A commercial domestic enrichment supplier for HALEU fuel does not exist.

Additionally, the TWR design will rely on HT9 steel for fuel cladding and duct material. HT9 is not commercially available, and fabrication of HT9 tube and duct material is challenging due to the length requirements, tight tolerances, thin wall for fuel pins, and the material's high hardness. A domestic vendor has been identified that has produced prototype HT9 ducting. Further development is in progress, and is needed to enable production at a commercial scale.

ORNL has used AM to produce a section of this duct work with HT9. Work is still on-going to optimize the AM process to produce these parts, but it is a potential solution to manufacture this challenging component.

7.4.3 TerraPower MCFR

The TerraPower MCFR may also require HALEU. As discussed above, a commercial domestic enrichment supplier does not currently exist for this material.

In addition, the process for synthesizing the molten chloride uranium salts that serve as the coolant and the fuel for the MCFR is currently being developed. Facilities for this chemical processing may ultimately be needed at the MCFR plant site.

7.4.4 X-energy Xe-100

The X-energy Xe-100 reactor will employ HALEU in the form of uranium oxycarbide (UCO). As discussed above, a commercial domestic enrichment supplier does not currently exist.

In addition, the pebbles used for Xe-100 fuel are an innovative design that has not been fabricated at a commercial scale. X-energy is currently working with ORNL on a Pebble Fuel Development project that will establish a process for commercial manufacturing of the fuel pebbles needed for the Xe-100 design.

7.5 STEAM TURBINE GENERATORS AND CONDENSERS

The steam turbine generators required for all these designs are not safety related components. Steam turbines have previously been produced domestically for a variety of applications and in a variety of different sizes. However, many suppliers have moved their manufacturing facilities out of the country. The steam turbine and generator sets for the AP1000 were procured from Toshiba in Japan because they were business partners with Westinghouse at the time. There is not a technical challenge for producing this equipment, so the capability to produce these components domestically could be restored and the capacity could be increased if and when required. Business and market factors will likely determine whether domestic companies are interested in producing these components.

7.6 PUMPS

7.6.1 NuScale NPM

The NuScale SMR does not have any primary coolant pumps. Condensate and feedwater pumps and other balance of plant pumps are typical off-the-shelf designs. Based on the numerous vendors capable of supplying these pumps domestically, it is not anticipated that pump production capacity will be a concern. Testing of water pumps can also be performed by numerous vendors or specialty testing suppliers and is not a concern.

7.6.2 TerraPower

The TWR design uses primary and intermediate sodium pumps to transport the sodium in the primary and intermediate loops. The two primary sodium pumps are large, mechanical centrifugal pumps. The two intermediate sodium pumps are also mechanical pumps. Both types of pumps use stainless steel as the primary material of construction.

The U.S. manufacturing infrastructure currently supplies pumps for nuclear power plants, and domestic suppliers could provide the sodium pumps. Such pumps have been produced in the past, but they would be first-in-a-while components, since there is not an existing market for sodium pumps.

7.6.3 X-energy Xe-100

The X-energy reactor design does not use a pump for transporting coolant, but uses helium blowers. The U.S. possesses the capability to supply nuclear grade fans for air movement. The suppliers have sufficient capacity, although at sizes that may be smaller than required for X-energy. X-energy has identified Howden (UK-based) and GE as potential manufacturers of the circulators. If Howden is selected as the supplier, X-energy has indicated that it would request them to establish manufacturing capabilities in the U.S. Circulators are not currently made for helium and the X-energy design has a unique blade profile, making them first of a kind.

7.7 VALVES

7.7.1 NuScale NPM

NuScale's only "active" safety-related components are valves. The NuScale design relies on entirely passive systems including the valves; however, the valves must change alignment to perform their safety function. The valves assume their safety position without external motive force either using system pressure or passive hydraulic actuators.

The design will employ approximately 24 safety-related valves per NPM. NuScale has already selected domestic suppliers for the safety-related valves used in the design which are not unlike those currently used for operating reactors. The capability exists domestically to produce these valves. Due to the large number of valves needed for a 12-module plant, existing capacity may not be sufficient. However, given the number of potential suppliers, it is likely that once orders are in place, valve manufacturers will make any necessary facility upgrades to supply the required number of valves.

7.7.2 TerraPower TWR

The TWR design will make use of many isolation valves for sodium service, including some larger valves used for SG isolation. While the sodium interface will be a FIAW aspect of the valves, it is not expected that this will pose a significant challenge, and TerraPower has identified a domestic manufacturer for these valves.

7.7.3 X-energy Xe-100

The Xe-100 design may require valves for service in high temperature helium. Existing valve designs are likely not suitable without modification, making these valves FOAK. In addition, a valve-like device will be needed for the fuel pebble sorting system for used fuel. Further design and specification for these valves is necessary for a clear assessment on the readiness of U.S. suppliers. At this time, there is no information to suggest that use of domestic suppliers would not be feasible.

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A
List of Acronyms

ALMR	Advanced Liquid Metal Reactor
AM	Additive Manufacturing
ASME	American Society of Mechanical Engineers
AVLIS	Atomic Vapor Laser Isotope Separation
B&PV	Boiler and Pressure Vessel (In reference to ASME B&PV Code)
BOP	Balance of Plant
BWR	Boiling Water Reactor
CFPP	Carbon Free Power Project
CNC	Computer Numerical Control
CNNC	China National Nuclear Corporation
CNV	Containment Vessel
CRD	Control Rod Drive
CRDM	Control Rod Drive Mechanism
DCA	Design Certification Application
DCD	Design Control Document
DED	Direct Energy Deposition
DOE	U.S. Department of Energy
EBM	Electron Beam Melting
EBW	Electron Beam Welding
ECCS	Emergency Core Cooling System
EPC	Engineering Procurement and Construction
EPRI	Electric Power Research Institute
EVHM	Ex-Vessel Handling Machine
FFTF	Fast Flux Test Facility
FHE	Fuel Handling Equipment
FOA	Funding Opportunity Announcement
FOAK	First of a Kind
GV	Guard Vessel

GW	Gigawatt
HALEU	High Assay Low Enriched Uranium
HCSG	Helical Coil Steam Generator
HFIR	High Flux Isotope Reactor
HIP	Hot Isostatic Press
HTGR	High-Temperature Gas-Cooled Reactor
I&C	Instrumentation and Controls
IEEE	Institute of Electrical and Electronics Engineers
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
IVHM	In-Vessel Handling Machine
LEU	Low-Enriched Uranium
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MCFR	Molten Chloride Fast Reactor
MIG	Metal Inert Gas
MOU	Memorandum of Understanding
MPR	MPR Associates
MSR	Molten Salt Reactor
MW	Megawatt
MWe	Megawatt electric
NAF	North American Forgemasters
NDE	Non-destructive Examination
NFA	New Fuel Assembly
NFE	New Fuel Elevator
NFJC	New Fuel Job Crane
NO_x	Nitrogen Oxides
NPM	NuScale Power Module
NRC	U.S. Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory

PM-HIP	Powder Metal Hot Isostatic Press
PWR	Pressurized Water Reactor
QA	Quality Assurance
QC	Quality Control
RAI	Request for Additional Information
RCP	Reactor Coolant Pump
RPV	Reactor Pressure Vessel
RPW	Resistance Pressure Welding
SER	Safety Evaluation Report
SFR	Sodium Fast Reactor
SG	Steam Generator
SMR	Small Modular Reactor
SMS	Shaw Modular Solutions
SO_x	Sulfur Oxides
SWU	Separative Work Units
TH	Thermal-Hydraulics
TMI	Three Mile Island
Ton	US Short ton or 2,000 pounds
Tonne	Metric ton or 1000 kilograms
TRISO	Tri-isotropic
TVA	Tennessee Valley Authority
TWR	Traveling Wave Reactor
UAM	Ultrasonic Additive Manufacturing
UAMPS	Utah Associated Municipal Power System
UCO	Uranium Oxycarbide
VSD	Vacuum Stream Degassing
WNA	World Nuclear Association

B
ASME Stamp Holders

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Aerofin	4621 Murray Place	Lynchburg	VA	N- N-2814		NPT- N-2815	NS- N-3073	
Anvil International, LLC dba Anvil EPS	Precision Park 160 Frenchtown Road	North Kingstown	RI			NPT- N-2802	NS- N-3054	
Atlas Industrial Manufacturing Co.	81 Somerset Place	Clifton	NJ	N- N-3287		NPT- N-3288	NS- N-4011	
AZZ WSI LLC	560 Horizon Drive, Suite 100	Suwanee	GA		NA- N-3912	NPT- N-3911		
AZZ WSI LLC	560 Horizon Drive, Suite 100	Suwanee	GA		NA- N-3912-1	NPT- N-3911-1		
Basic-PSA, Inc.	269 Jari Drive	Johnstown	PA			NPT- N-2952	NS- N-3026	

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Bechtel Power Corporation	12011 Sunset Hills Road	Reston	VA	N- N-4490	NA- N-4491	NPT- N-4492	NS- N-4493	
Bechtel Power Corporation	12011 Sunset Hills Road	Reston	VA	N- N-4514				
BNL Industries, Inc.	30 Industrial Park Road	Vernon	CT	N- N-2882		NPT- N-2883		
Bristol Metals, LLC	390 Bristol Metals Road	Bristol	TN			NPT- N-3104		
Chempump	959 Mearns Road	Warminster	PA	N- N-2057		NPT- N-2058		
Chicago Bridge & Iron Company	14105 S. Route 59	Plainfield	IL	N- N-3267	NA- N-3268	NPT- N-3269	NS- N-3270	
Chicago Bridge & Iron Company	14105 S. Route 59	Plainfield	IL	N- N-3267-2	NA- N-3268-2			
Consolidated Power Supply	1000 Industry Road	McKeesport	PA		NA- N-4477	NPT- N-3341	NS- N-4029	
Control Components Inc.	22591 Avenida Empresa	Rancho Santa Margarita	CA	N- N-2695		NPT- N-2696		

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Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Conval, Inc.	265 Field Road	Somers	CT	N- N-3199		NPT- N-3200		
Crane Nuclear, Inc.	860 Remington Blvd.	Bolingbrook	IL	N- N-2899		NPT- N-2900		
Crosby Valve, LLC	55 Cabot Blvd.	Mansfield	MA	N- N-1876		NPT- N-1877		NV- N-1878
Curtiss-Wright Electro-Mechanical Corporation	1000 Wright Way	Cheswick	PA	N- N-1385		NPT- N-1386	NS- N-3425	
Curtiss-Wright Nuclear Division	125 West Park Loop	Huntsville	AL	N- N-4673	NA- N-4674	NPT- N-3193		
Curtiss-Wright Nuclear Division	2950 E. Birch Street	Brea	CA	N- N-2826		NPT- N-2827	NS- N-3102	
Dieterich Standard, Inc.	5601 North 71st Street	Boulder	CO	NPT- N-1728				
Dragon Valves, Inc.	13457 Excelsior Drive	Norwalk	CA	N- N-1033				
Dresser LLC	12970 Normandy Blvd	Jacksonville	FL	N- N-4536				

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Dresser LLC	12970 Normandy Blvd	Jacksonville	FL	NPT- N-4742				
Dresser LLC	12970 Normandy Blvd	Jacksonville	FL					NV- N-4743
Dresser, Inc.	8011 Shreveport Hwy	Pineville	LA	N- N-1746				
Dresser, Inc.	8011 Shreveport Hwy	Pineville	LA	NPT- N-2434				
Dresser, Inc.	8011 Shreveport Hwy	Pineville	LA					NV- N-1747
Dubose National Energy Services Inc. (DNES)	900 Industrial Drive	Clinton	NC	NA- N-3584		NPT- N-3165	NS- N-3278	
Ellis & Watts Global Industries, Inc.	4400 Glen Willow Lake Lane	Batavia	OH	N- N-3591	NA- N-3709	NPT- N-3813	NS- N-3849	
Energy & Process Corporation	2146 Flintstone Drive	Tucker	GA			NPT- N-3725		
Energy Steel	3123 John Conley Drive	Lapeer	MI	N- N-2994	NA- N-3956	NPT- N-2928	NS- N-3083	

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Fisher Controls International LLC	1700 South 12th Avenue	Marshalltown	IA	N- N-1929		NPT- N-1930		
Flowserve	2300 E. Vernon Avenue	Vernon	CA	N- N-1130		NPT- N-1131		
Flowserve Corporation	1900 South Saunders Street	Raleigh	NC	N- N-1562		NPT- N-1563		
Fluid Handling LLC, Xylem Incorporated	175 Standard Parkway	Cheektowaga	NY	N- N-3464	NA- N-3465	NPT- N-3466		
Fluor Nuclear Power	100 Fluor Daniel Drive	Greenville	SC	N- N-3263	NA- N-3266	NPT- N-3264	NS- N-3265	
Fluor Nuclear Power	100 Fluor Daniel Drive	Greenville	SC	N- N-3263-1	NA- N-3266-1	NPT- N-3264-1	NS- N-3265-1	
Fluor Nuclear Power	100 Fluor Daniel Drive	Greenville	SC	N- N-4375				
Framatome Inc.	3315 Old Forest Road	Lynchburg	VA	N- N-1650	NA- N-3716	NPT- N-2843	NS- N-3362	
Fronek Anchor/Darling Enterprises, Inc.	86 Doris Ray Court	Laconia	NH				NS- N-3015	

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
GE-Hitachi Nuclear Energy Americas LLC	3901 Castle Hayne Road	Wilmington	NC	N- N-1888		NPT- N-1151		
GE-Hitachi Nuclear Energy Americas LLC	3901 Castle Hayne Road	Wilmington	NC	N- N-4388				
Graham Corporation	20 Florence Ave	Batavia	NY	N- N-3663	NA- N-3720	NPT- N-3733	NS- N-3897	
Hayward Tyler Inc.	480 Roosevelt Highway	Colchester	VT	N- N-2884	NA- N-2885	NPT- N-2886	NS- N-3286	
Henry Pratt Company	401 South Highland Avenue	Aurora	IL	N- N-1030		NPT- N-1031		
Holtec Manufacturing Division	Keystone Commons 200 Braddock Avenue	Turtle Creek	PA	N- N-2918		NPT- N-2919	NS- N-4575	
HydroAire Service, Inc.	834 W. Madison	Chicago	IL	N- N-3352		NPT- N-3194		
Instrument & Valve Services Company	757 Old Clemson Road	Columbia	SC			NPT- N-3156		
ISCO Industries, Inc.	100 Witherspoon Street	Louisville	KY		NA- N-3680	NPT- N-3822		

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
ISCO Industries, Inc.	100 Witherspoon Street	Louisville	KY		NA- N-3680-1	NPT- N-3822-1		
ITT Engineered Valves, LLC	33 Centerville Road	Lancaster	PA	N- N-2649		NPT- N-2650		
Joseph Oat Corporation	2500 Broadway	Camden	NJ	N- N-1488	NA- N-1577	NPT- N-1489	NS- N-3014	
Kiewit Power Constructors Co.	9701 Renner Boulevard	Lenexa	KS	N- N-3662	NA- N-3723	NPT- N-3728	NS- N-3903	
Kiewit Power Constructors Co.	9701 Renner Boulevard	Lenexa	KS	N- N-3662-1	NA- N-3723-1	NPT- N-3728-1	NS- N-3903-1	
Lisega, Inc.	370 East Dumplin Valley Road	Kodak	TN			NPT- N-2951	NS- N-3025	
Major Tool & Machine, Inc.	1458 East 19th Street	Indianapolis	IN	N- N-3141	NA- N-4592	NPT- N-3142	NS- N-3228	
Met Weld International, LLC	5727 Ostrander Road	Altamont	NY		NA- N-4343	NPT- N-4344	NS- N-4345	
Mirion Technologies (Conax Nuclear), Inc.	402 Sonwil Drive	Cheektowaga	NY	N- N-1849		NPT- N-1850		

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Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Newport News Industrial Corporation	11850 Jefferson Avenue	Newport News	VA	N- N-3921	NA- N-3274	NPT- N-3275	NS- N-3276	
Newport News Industrial Corporation	11850 Jefferson Avenue	Newport News	VA	N- N-3921-1	NA- N-3274-1	NPT- N-3275-1	NS- N-3276-1	
Newport News Industrial Corporation	11850 Jefferson Avenue	Newport News	VA	N- N-3922				
Nuclear Logistics LLC	7410 Pebble Drive	Fort Worth	TX	N- N-3158		NPT- N-3159	NS- N-3160	
NuSource, LLC	320 King Street	Alexandria	VA	N- N-4306				
OFI Custom Metal Fabrication	10412 Design Road	Ashland	VA			NPT- N-3914	NS- N-3915	
Parker Hannifin Corporation	1005 A Cleaner Way	Huntsville	AL	N- N-3218				
Parker Hannifin Corporation	1005 A Cleaner Way	Huntsville	AL	N- N-3218-1				
Parker Hannifin Corporation	1005 A Cleaner Way	Huntsville	AL	N- N-3218-2				

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
PCI Energy Services, LLC	One Energy Drive	Lake Bluff	IL		NA- N-3173-3	NPT- N-3174-3		
PCI Energy Services, LLC	One Energy Drive	Lake Bluff	IL		NA- N-3173	NPT- N-3174		
PCI Energy Services, LLC	One Energy Drive	Lake Bluff	IL		NA- N-3173-1	NPT- N-3174-1		
PCI Energy Services, LLC	One Energy Drive	Lake Bluff	IL		NA- N-3173-4	NPT- N-3174-4		
Precision Custom Components, LLC	500 Lincoln Street	York	PA	N- N-2995	NA- N-4402	NPT- N-2996	NS- N-3079	
Precision Defense Services, Inc.	1 Quality Way	Irwin	PA			NPT- N-4570		
Premier Technology, Inc.	1858 West Bridge Street	Blackfoot	ID		NA- N-3496	NPT- N-3497	NS- N-3498	
Ranor, Inc.	1 Bella Drive	Westminster	MA		NA- N-3084	NPT- N-3085	NS- N-3086	
Reuter-Stokes, LLC.	8499 Darrow Road	Twinsburg	OH			NPT- N-2703		

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Rotating Equipment Repair, Inc.	W248 N5550 Executive Drive	Sussex	WI			NPT- N-4276		
Ruhrpumpen, Inc	400 Rotary Street	Hampton	VA	N- N-4433		NPT- N-4429		
Senior Operations LLC	2400 Longhorn Industrial Drive	New Braunfels	TX			NPT- N-2778		
SPX FLOW US LLC COPES-VULCAN OPERATION	5620 West Road	McKean	PA	N- N-3052	NA- N-4563	NPT- N-3053		
Stone & Webster, Inc. dbwa Stone & Webster Construction Inc.	3735 Glen Lake Drive	Charlotte	NC	NA- N-1511	NA- N-1511-7	NPT- N-1512		
Stone & Webster, Inc. dbwa Stone & Webster Construction Inc.	3735 Glen Lake Drive	Charlotte	NC			NPT- N-1512-7		
Stone & Webster, Inc. dbwa WECTEC Contractors Inc.	3735 Glen Lake Drive	Charlotte	NC		NA- N-3376	NPT- N-3377		
Sulzer Pumps (US) Inc.	2800 N.W. Front Avenue	Portland	OR	N- N-4619		NPT- N-4620		

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Sulzer Pumps (US) Inc. (Sulzer Nuclear Service Center)	4126 Caine Lane	Chattanooga	TN	N- N-2614		NPT- N-2615		
Super Radiator Coils	104 Peavey Road	Chaska	MN	N- N-3178		NPT- N-3177	NS- N-4265	
Swagelok Company	29500 Solon Road	Solon	OH	N- N-3100	NA- N-3688	NPT- N-3101		
Swepco Tube LLC	1 Clifton Boulevard	Clifton	NJ			NPT- N-2913		
Target Rock	1966 E. Broadhollow Road	E. Farmingdale	NY	N- N-1947		NPT- N-1948		NV- N-1949
Teledyne Brown Engineering, Inc.	300 Sparkman Drive	Huntsville	AL	N- N-2983		NPT- N-2984	NS- N-3874	
Turner Industries Group, L.L.C.	1200 19th St. S.W.	Paris	TX		NA- N-3681	NPT- N-3821	NS- N-3845	
Valcor Engineering Corporation	2 Lawrence Road	Springfield	NJ	N- N-1076				
Valcor Engineering Corporation	2 Lawrence Road	Springfield	NJ			NPT- N-1077	NS- N-3902	
Velan Inc. dba Velan Valve Corp.	94 Avenue C	Williston	VT	N- N-4580		NPT- N-4581		

Table B-1. ASME Stamp Holders

Company Name	Plant Address	City	State	Certificate				
				N-Nuclear Components	**NA-Nuclear Installation and shop assembly**	**NPT-Nuclear Partials**	**NS-Nuclear Components**	NV-Nuclear Safety and Safety Relief Valves
Vigor Works LLC	9700 S.E. Lawnfield Road	Clackamas	OR	N- N-4615	NA- N-4617	NPT- N-4616	NS- N-4618	
Watlow Electric Manufacturing Company	12001 Lackland Road	St. Louis	MO			NPT- N-4222		
WEC Carolina Energy Solutions, LLC	244 E. Mount Gallant Road	Rock Hill	SC		NA- N-3491	NPT- N-3492		
WEC Carolina Energy Solutions, LLC	244 E. Mount Gallant Road	Rock Hill	SC		NA- N-3491-1	NPT- N-3492-1		
WEC Carolina Energy Solutions, LLC	244 E. Mount Gallant Road	Rock Hill	SC		NA- N-3491-2	NPT- N-3492-2		
Weed Instrument Co., Inc.	707 Jeffrey Way	Round Rock	TX	N- N-4235		NPT- N-4236	NS- N-4237	
Weir Valves & Controls USA Inc.	29 Old Right Road	Ipswich	MA	N- N-2606		NPT- N-2607		
Westinghouse Electric Company, LLC	178 Shattuck Way	Newington	NH	N- N-2040	NA- N-2460	NPT- N-2041	NS- N-3070	
Westinghouse Electric Company, LLC	1000 Westinghouse Drive	Cranberry Township	PA	N- N-1149	NA- N-2804	NPT- N-2805		
			Total	70	42	86	39	4

C
Contact List

This Appendix provides a list of contacts developed as part of this nuclear manufacturing infrastructure assessment.

Table C-1. Contact List

Last Name	First Name	Company	Title	Phone	Email
Akans	Robert	CTC Center for Advanced Manufacturing	Senior Director	571-261-9441	akansr@ctc.com
Bailey	Scott	NuScale			sbailey@nuscalepower.com
Baranwal	Rita	INL	Director	208-526-3256	rita.baranwal@inl.gov
Cruse	Jon	Terrapower			jcruse@terrapower.com
Dehoff	Ryan	ORNL, MDF	MDF Facility Leader and Metal Additive Manufacturing Lead	865-946-3114	dehoffrr@ornl.gov
DeWitte	Jacob	OKLO	Co-Founder, CEO	650-550-0127	j@oklo.com
Dunkin	Brad	Vigor (former)			brad.d.dunkin@gmail.com
Field	Greg	Terrapower	Director, Contracts & Supply Management	425-283-4740	gfield@terrapower.com
Frederick	Diane S.	Plymouth Tube Company	Account Executive	872-243-1066	DFrederick@plymouth.com
Gandy	David	EPRI	Technical Executive		davgandy@epri.com
Groome	John	Holtec / SMR, LLC.	Principal Test Engineer		jgroome1320@gmail.com
Hartlage	Bristol	Kinectrics	Director, Nuclear Business Development	619-888-3439	Bristol.Hartlage@kinectrics.com
Hatch	Dana	NuScale	Supply Chain Manager	541-360-0590	dhatch@nuscalepower.com
Heaphy	Kevin	Superior Tube	Director, Defense and Nuclear Products	610-489-5493	kevin.heaphy@ametek.com
Hickman	Tom	Vigor	VP, Marketing and Sales		tom.hickman@vigor.net

Table C-1. Contact List

Last Name	First Name	Company	Title	Phone	Email
Kamnikar	Mike	American Forgemasters	President	724-656-6410	mkamnikar@naforgemasters.com
Landrey	Bruce	Landrey & Co.	Director	503-715-7900	brucel@landreyco.com
Laurendeau	Lee	Holtec	Director Manufacturing Technology	856-797-9000 ext 3993	L.Laurendeau@holtec.com
Liebig	Jan	Framatome	Program Manager	49-9131-90096190	Jan.Liebig@framatme.com
Liskai	Tamas	NuScale	Chief Engineer, Design and Structures	541-360-0520	tliszkai@nuscalepower.com
Marcille	Tom	Holtec / SMR, LLC.	NSSS Design Engineer		T.Marcille@holtec.com
Mason	Greg	NTS Huntsville (Wyle)	Manager, Nuclear Business Development	256-716-4283	Greg.Mason@nts.com
Miller	Tom	DOE	Director	301-903-4517	tom.miller@nuclear.energy.gov
Miller	Jingjing	Terrapower			jmiller@terrapower.com
Morill	Randy	NuScale	Nuclear Engineer	541-360-0724	rmorrill@nuscalepower.com
Patrick	Mattie	DOE, Sandia		505-284-4796	pdmatti@sandia.gov
Pappano	Peter	X-Energy		240-454-1587	ppappano@x-energy.com
Reyes	Jose	NuScale	Founder, CTO	541-360-0503	jreyes@nuscalepower.com
Schmidt	Holger	Framatome	World-Wide Manager Thermal Hydraulics & Components Testing	49-9131-90091980	Holger.Schmidt@framatome.com
Schweiger	Pat	Terrapower			pschweiger@terrapower.com
Stover	Craig	EPRI	Technical Leader	704-595-2990	cstover@epri.com
Terrani	Kurt	ORNL	Program Manager for the Advanced Fuels Campaign	865-576-0264	terranita@ornl.gov
Torosyan	Ararat	Curtiss-Wright / Enertech	VP Enertech Engineering	714-982-1800	atorosyan@curtisswright.com
Van Staden	Martin	X-Energy	VP, Engineering	301-358-5679	martinvs@x-energy.com
Wolbert	Steve	NuScale			swolbert@nuscalepower.com
Wolski	Gary	Curtiss-Wright	VP Market Development	714-982-1822	GWolski@curtisswright.com
Yarwood	David	AST	Project Analyst	301-658-7996	dyarwood@alleghenyst.com
Yraguen	Corey	Vigor			corey.yraguen@vigor.net