



Advanced Reactor Supply Chain Assessment

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GAIN Report

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EXECUTIVE SUMMARY

Several net-zero scenario evaluations predict a rapid ramp up of nuclear energy in the coming decades. If this materializes, it will most likely strain the supply chains associated with the potential advanced reactor concepts awaiting deployment. To help assess the current and potential capacities of the various advanced reactor supply chains, the Gateway for Accelerated Innovation in Nuclear (GAIN) conducted a survey of companies able to produce components for advanced reactors in the near future (namely for sodium, gas-cooled, and molten salt reactors). Using an aggressive nuclear deployment scenario, the objective was to assess the ability of the various supply chains to meet the considerable demand projections for certain key components (vessels, heat exchangers, pumps, graphite, and sensors) and identify potential challenges. While individual companies were unable to meet the most optimistic nuclear deployment rate projections, it was found that on aggregate, a United States-based supply chain projected that expansion could be ramped up to meet a larger future demand of these components. However, meeting projected demand for several more complex items (namely gas or salt heat exchangers) was found to be more challenging.

Deploying new reactors at scale necessitates the production of more and more supply chain components, requiring a ramp up in production. Supply chain companies were surveyed, and respondents appeared less able to meet short term demand (next year) versus longer-term demand projections (5 and 10 years). This reflects the need to obtain orders with adequate lead times (can range from 3 to 30 months). Future demand will need to be met by expanding existing capacity. These expansions will require suppliers to raise capital or secure other types of support (federal loans or grants) to invest in facilities, equipment, and workforce. Individual suppliers indicated financial investments could be in the range of \$100 million to \$1 billion for their own facilities (depending on the type of facility). The biggest risk, according to respondents, related to general uncertainties surrounding the future nuclear industry and whether the potential demand projections will materialize into real demand that is actionable from a business perspective. Businesses do not seem willing to take investments risks without clear orders. If businesses are not able to invest to expand the supply, it will either delay the deployment of advanced nuclear technology, or the supply chain will be met by suppliers outside of the United States.

This report only focuses on the domestic supply chain's ability to meet the various projections stipulated here for the specific assessed components (vessels, heat exchangers, pumps, graphite, and sensors). The report does not cover all reactor designs or all components that may ultimately be needed for any one reactor design. It also does not address whether any specific aspect of the supply chain will be cost competitive in the global market, nor how potential state-backed entities could affect the expansion of a United States-based supply chain. The largest challenges in ramping up capacity among respondents appear to be workforce related. This includes workforce availability, experience, training, and turnover. In addition to facility investment,

suppliers will also need to invest heavily in long-term workforce training to meet production goals. This issue is not nuclear-specific, and the expansion of any supply chain will likely face similar challenges. While suppliers evaluated expected normal business demand from other markets outside of nuclear, it is possible that other market segments could expand more than predicted and compete for the same suppliers. One potential market that may compete for the same supplier resources is the United States military, as many of these suppliers support both the commercial nuclear sector as well as the Navy with reactors and components.

In summary, suppliers in the United States believe that there is a way to increase production in order to begin meeting the demand which will exist for advanced reactors—as long as appropriate investments can be made in the supply chain in an appropriate timeframe. Based on the capacity projections and lead times, investment will be needed to meet the 5-year and 10-year production targets. Therefore, if significant nuclear deployment is to occur in the 2030s, investment and ramp up of the advanced nuclear supply chain will need to begin in the near future for the United States to successfully deploy these advanced reactors with domestic supply chains.

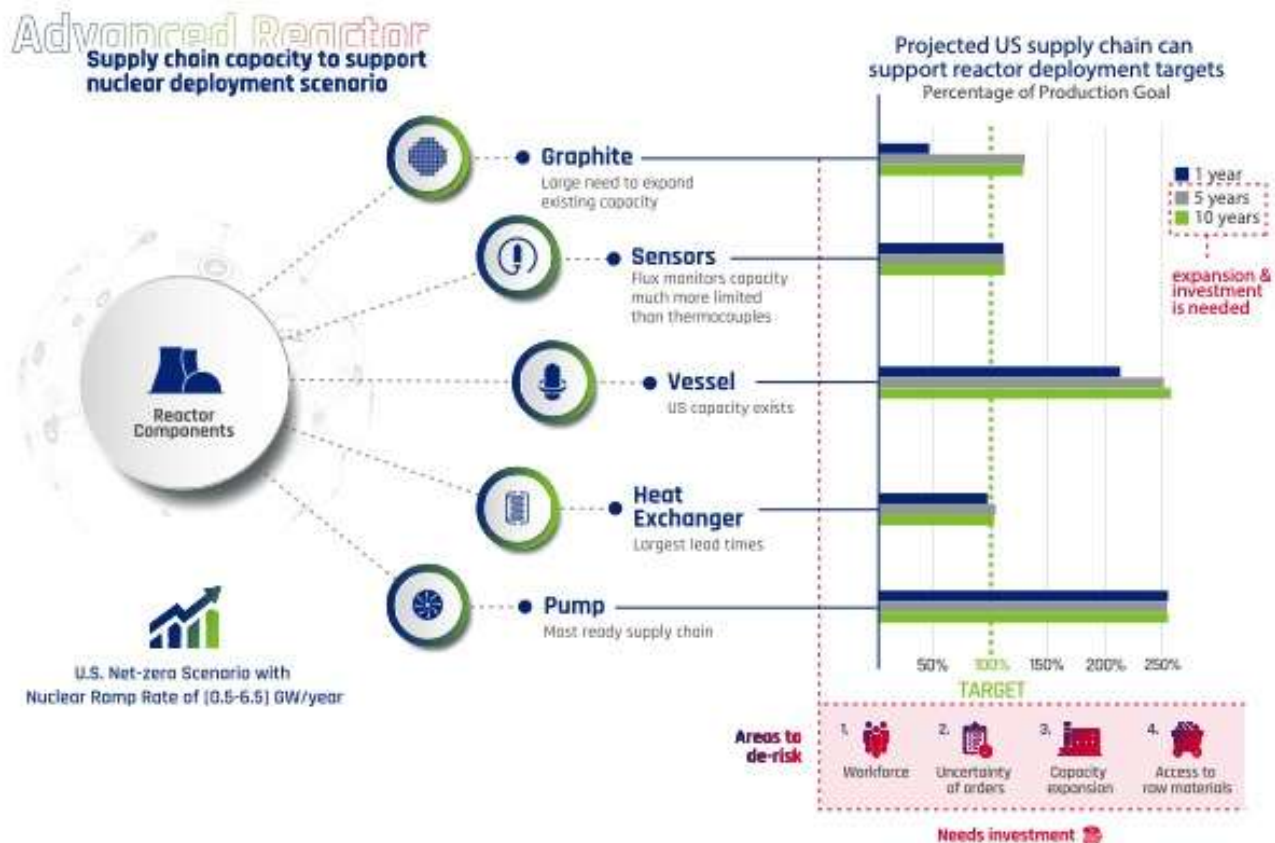


Figure 1. Overview of the advanced reactor supply chain assessment for the various components considered in this study.

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ACRONYMS

ABTR	Advanced Burner Test Reactor
ANL	Argonne National Laboratory
ARDP	Advanced Reactor Demonstration Program
ASME	American Society of Mechanical Engineers
DOE	Department of Energy
EM	Electromagnetic
EPRI	Electric Power Research Institute
FFTF	Fast Flux Test Facility
FHR	Fluoride salt-cooled high-temperature reactor
FSV	Fort St. Vrain
GAIN	Gateway for Accelerated Innovation in Nuclear
GCAM	Global Change Assessment Model
GenIV	Generation IV
GW	Gigawatt
HALEU	High-assay low-enriched uranium
HCSG	Helical Coil Steam Generator
IFR	Integral Fast Reactor
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
LWR	Light water reactor
MCFR	Molten Chloride Fast Reactor
MSRE	Molten Salt Reactor Experiment
NEI	Nuclear Energy Institute
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
PRISM	Power Reactor Innovative Small Module
RPV	Reactor Pressure Vessel
PWR	Pressurized Water Reactor
SA&I	Systems Analysis & Integration

SPND	Self-powered neutron detectors
TRISO	Tri-structural ISOtropic
U.S.	United States
VTR	Versatile Test Reactor

INTRODUCTION

Nuclear power plants (NPPs) currently produce 20% of the total electricity in the United States and are the largest source of carbon-free energy (EIA 2022a). As the world looks to decarbonize, there are targets for the United States to move to a net-zero carbon emission economy by 2050. One potential way to decrease carbon emissions is to deploy additional NPPs as highlighted by the Department of Energy ‘Liftoff’ Report (DOE 2023). Advanced reactors are being developed with the intent to deploy them to support a clean (net-zero) economy. The Department of Energy Office of Nuclear Energy (DOE-NE) is already working with advanced reactor developers to demonstrate advanced reactor designs this decade through the Advanced Reactor Demonstration Program (ARDP). The ARDP also includes investment in many other technologies that could be ready to be deployed in the early to mid-2030s (DOE 2022a). Recognizing that the deployment of advanced nuclear reactors could meaningfully decarbonize the economy, there exists a critical need to identify gaps or constraints along these complex and nascent advanced nuclear supply chains.

The DOE recently issued several reports in response to Executive Order 14017 which required an assessment of America’s Supply Chains. The DOE Office of Policy issued a deep dive assessment on the nuclear energy supply chain (DOE 2022b). The report reviewed the current and advanced reactor supply chain but did not assess the capacity of the nuclear energy supply chain to support an increased advanced nuclear build out.

Most of the American NPPs were built in the 1970s. During the prior nuclear build out, deployment was an average of 4.5 GW per year with peaks exceeding 10 GW per year (MPR 2018). Recent models show that as we move to a decarbonized economy, significant building of zero carbon energy infrastructure will be required that will include all generation types. Of interest to this report is the scale of nuclear deployment that will be required over time to meet the net-zero targets. Studies were performed that show that the nuclear deployment could be over 6 GW per year in the 2030s (see Table 4). Therefore, the average build rate could be larger than what was previously accomplished and since the reactors are smaller, more concurrent construction activities will be ongoing. Additionally, other countries are also considering large expansions of their nuclear fleets as well which would add to the global demands on the supply chains. With the potential for large amounts of nuclear fabrication and construction, the supply chain must be able to expand to support this increased demand.

This report performs an assessment of the American supply chain capacity of select components (vessels, heat exchangers, graphite, pumps, and sensors) to help obtain an initial understanding of where gaps may exist in the ability to increase the deployment rate of nuclear plants. Various advanced reactor technologies are reviewed, and certain significant components listed. A down selection of components is made to then assess capacity. Outreach was performed to various companies to help understand the capacity for various parts and components. This capacity was then compared to the potential nuclear demand for a net-zero economy transition.

High-Assay Low-Enrichment Uranium (HALEU) is one of the most critical items for most advanced reactors that rely on uranium enriched above 5%. The DOE Office of Policy deep dive covered the need for HALEU and the current production levels in the United States (DOE 2022b). As a result, this report does not consider the question of uranium enrichment needs, as they are being covered by multiple organizations, with several DOE-NE efforts to address this item. Similarly, fuel fabrication and other fuel related items are not considered in this work. This report focused primarily on more complex, large structural components for advanced reactors and does not cover the entire advanced reactor supply chain.

NPPs require a significant number of unique components that involve various sectors of the supply chain. This report did not perform a complete supply chain mapping, but rather looked at various nuclear-centric components present across reactor designs. A selection of only a few components was made to intentionally limit the overall scope of this assessment. Even so, this report does cover several large, fabricated components that involve many unique facilities and additional certifications/requirements. There is still a need for follow-up work to study the supply chain for nuclear components more broadly than was possible in this single report. This will help identify any additional areas that need attention or that may be limiting.

Based on the assessed components in this report, the capacity to start initial builds of advanced nuclear plants seems to exist. However, given the potential increased rate of deployment, significant expansion and growth of the supply chain would be required. Depending on the timing of that investment, it may be possible to meet demand for the components assessed in this report. There may be some large/complex components that would hinder the deployment of advanced reactors.

OVERVIEW OF ADVANCED REACTOR COMPONENTS

For new, advanced reactors to quickly decarbonize domestic energy supply, vast amounts of coordination among the public, policymakers, regulators, researchers, developers, and suppliers must occur on a national scale. Among the various reactor designs, this report focuses primarily on non-Light-Water Reactors (non-LWRs): sodium fast, high-temperature gas, and molten salt reactors. Various significant components were considered, and their specifications were tabulated to perform a supply chain assessment for these reactor types. The sections below provide some background on the various components considered in this study.

Sodium Fast Reactors

Sodium Fast Reactors (SFRs) use liquid sodium or a sodium-potassium eutectic as the coolant either in pool or loop type configurations. There have only been a few SFRs built across the

world. Notable domestic examples include Experimental Breeder Reactors I and II (EBR-I and EBR-II) and the Fast Flux Test Facility (FFTF). Many of today's SFR designs trace their origins to the Integral Fast Reactor (IFR). IFR was a 1980s initiative to design and build a full scale SFR power plant, based on the successful loss-of-power safety demonstrations performed by the EBR-II (Chang 1986). Plans to develop a full scale IFR plant were undertaken by Argonne National Laboratory (ANL) but were ultimately cancelled in 1994 (ANL 2017). Since then, there have been several attempts to develop new U.S.-based SFR designs and prototypes, namely the Power Reactor Innovative Small Module (PRISM) reactor (Triplett 2012), the Advanced Burner Test Reactor (ABTR) (Chang 2006) and the more recent Versatile Test Reactor (VTR) (Roglans-Ribas 2022), but thus far none of these concepts have been deployed.

The two primary SFR designs being developed are TerraPower's Natrium Design and GE-Hitachi's PRISM design. The Natrium consortium is currently planning the deployment of an SFR unit at a site in Wyoming with an agreement signed to consider up to five additional deployments in the state (terrapower.com). The level of potential deployment rates underlines the need for a supply chain assessment for advanced reactors. Figure 2 provides an overview of an SFR plant. In the pool-type system shown, the active core region is submerged in a pool of sodium along with pumps and heat exchangers. This enables the manufacturing of a self-contained guard vessel, reducing the risk of leakage. The secondary sodium system extracts heat from the primary loop and provides it to a tertiary Rankine cycle (or other power conversion system) to generate electricity.

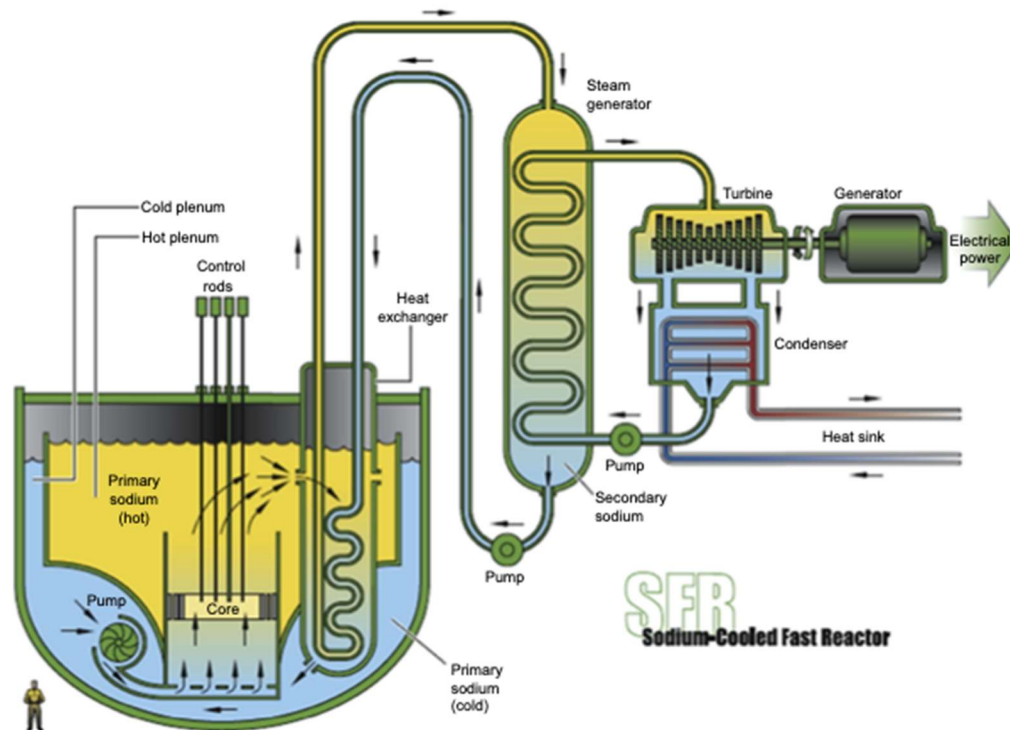


Figure 2. Layout of a Sodium Fast Reactor. Taken from GenIV International Forum (Ohshima 2016).

For this study, the GE-Hitachi PRISM design was taken as the reference SFR use-case (Triplett 2012) as Sodium includes many features of this design (NRC 2022). The reactor is a pool-type concept generating a power output of 300 MWe. This section will provide some background information on the various subcomponents in this reactor that will be considered in the supply chain assessment. A summary of the various specifications used as a reference is provided in Table 1. Additional information on each item considered (and some not included in the survey) is included in the Appendix.

Table 1. Overview of standard SFR components used to guide the supply chain assessment. The data was primarily based on the PRISM reactor specifications.

Component	Specs	Reference
Sodium Pump	86,000 gpm flow rate	(Sulzer 2010)
Sodium Heat Exchanger	500°C (930°F)	(Triplett 2012)
Reactor Vessel built with Rings and Heads	10 m (33ft) dia x 17.5 m (57.5ft) high, 20 mm (0.75 in.) thick Material–SS316	(Triplett 2012, Paredes 2020)
Reactor Vessel Ring	2.5 -3 m (8.5 -10 ft) Height Material–SS316	(Tanaka 2015)
Reactor Vessel Head	1 m (3.25 ft) Height Material–SS316	(Tanaka 2015)

High-Temperature Gas-cooled Reactors

Gas-cooled reactors come in many variants as well. They tend to be graphite-moderated, helium cooled, and able to reach very high outlet temperatures of 700–850°C (with even higher values considered in the past). This allows for greater thermal conversion efficiencies as well as suitability for high-temperature industrial applications. High-Temperature Gas-Cooled Reactors (HTGRs) can be broadly divided into the prismatic design or the pebble-bed design. The prismatic HTGR consists of vertical arrays of fuel blocks (or Tri-structural ISOtropic [TRISO] compacts), reflectors, and control rods assembled hexagonally within its core. The pebble-bed design consists of an open fuel core centered within the Reactor Pressure Vessel (RPV) where fuel pebbles collect and funnel down the reactor core. Each pebble (or prismatic fuel block) contains thousands of millimeter-sized coated uranium fuel particles known as TRISO fuel (the same fuel can also be used in compacts within prismatic HTGRs). This report will focus on the X-energy pebble-bed HTGR. Figure 3 provides an overview of an HTGR plant with a more detailed look of the reactor vessel and steam generator in Figure 4.

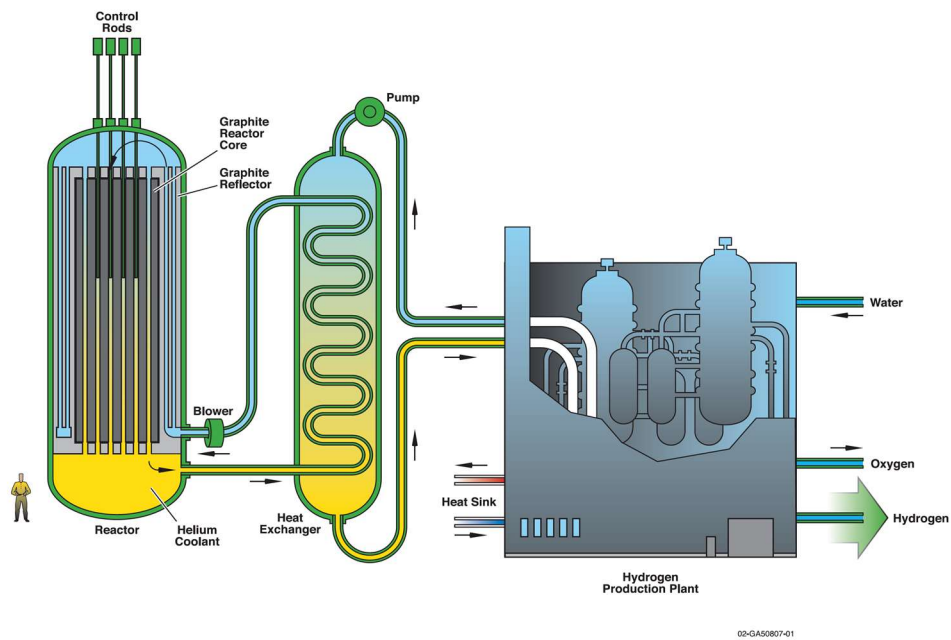


Figure 3. Layout of a HTGR Plan (GIF 2002).

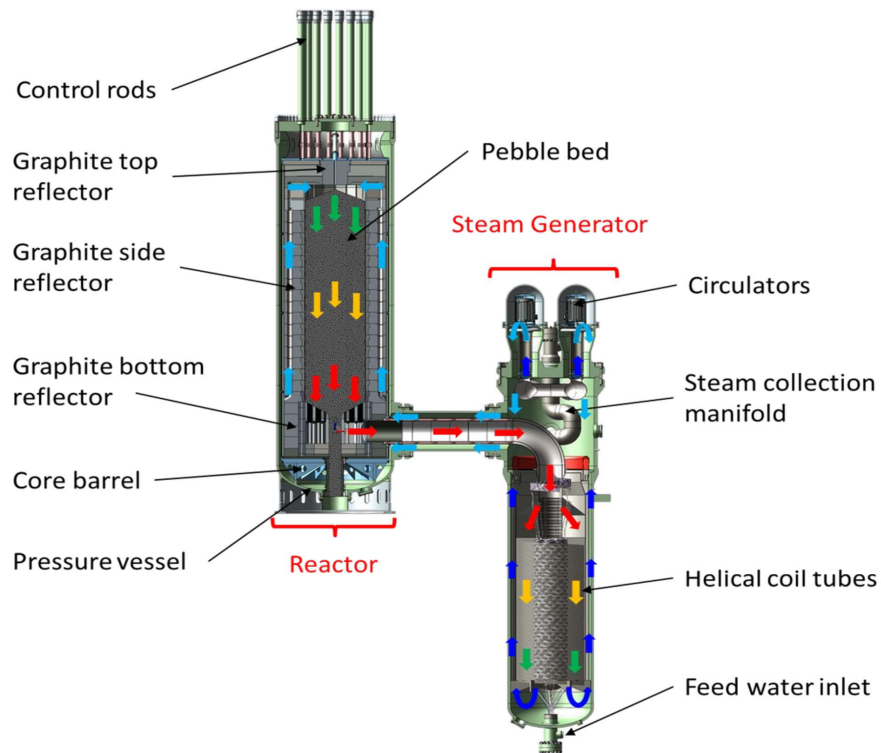


Figure 4. X-energy Pebble-Bed HTGR: The Xe-100 Reactor (X-energy 2022).

A total of eight HTGR plants have been built and operated throughout the world (Beck, Pincock 2011, WNN 2021). These plants have provided valuable lessons when examining the materials and components used within HTGRs. A summary of the components and specifications used in this study is provided in Table 2.

Table 2. Overview of the reference HTGR component specifications used in the study. The specifications are primarily based on the Xe-100 design.

Component	Specs	Reference
Helium Compressor/ Circulator	3.2 m (10.5 ft) high x 1.4 m (4.5 ft) dia Rate—71.1 kg/s (155 lbs/s)	(Burton 2022)
Steam Generator (Helical coil)	20.1 m (66 ft) high x 4.6 m (15 ft) dia Shell/Head—Carbon Steel Tubes—Alloy 800H 400,000 kg	(Hoffer 2011)
Reactor Vessel built with Rings and Heads	16.9 m (55 ft) high x 4.9 m (16 ft) dia, thickness 3.5 in SA-508 Low Alloy Steel	(X-energy 2022)
Reactor Vessel Ring	1.5–2.3 m (5–7.5ft) high, SA-508, thickness 89 mm (3.5 in.)	(X-energy 2022)
Reactor Vessel Head	0.75 m (2.5 ft) high, SA-508. thickness 89 mm (3.5 in.)	(X-energy 2022)
Poison Rod	Diameter ~285 mm (11.2 in.) Height 4881 mm (192 in.)	
Nuclear Shaped Graphite	~50 kg blocks	(X-energy 2022)
High Purity Helium	99.997% He	(X-energy 2022)

Molten Salt Reactors

Molten salt reactors (MSRs) have more design options, with MSRs typically having their fuel dissolved in a molten salt coolant, but some variants use solid fuel cooled by a molten salt. Most MSRs have high outlet temperatures of around 600–750°C, which like HTGRs can allow for greater thermal efficiencies as well as broader industrial heat applications. MSRs are broadly divided into thermal and fast spectrum reactors. Most thermal spectrum reactors use fluoride salts (FliBe, FliNaK), while fast spectrum reactors use primarily chloride salts (although fluoride salts were considered for fast variants as well). Neutron moderation for thermal spectrum MSRs comes from channels of solid graphite within the reactor core. Figure 5 provides an overview of a liquid-fuel MSR plant.

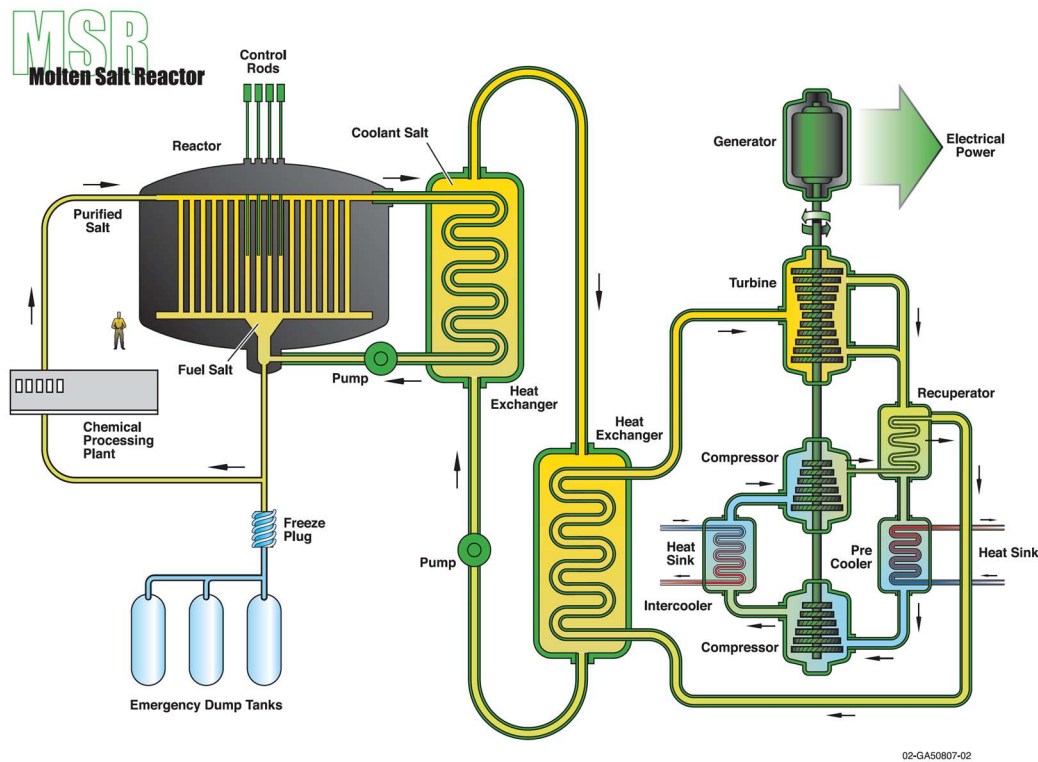


Figure 5. Overview of MSR Design (GIF 2002).

Liquid-fuel MSRs require more complicated chemical processing techniques than any of the other reactor designs. The chemical processing system is dependent on the specific MSR design. Because the fuel is dissolved in the coolant, online systems are often needed to separate the fission products, transuranic, corrosion products, and other transmuted material. The Aircraft Reactor Experiment in 1954 and the Molten Salt Reactor Experiment (MSRE) of the 1960s are the only salt reactor prototypes to have operated (ORNL 1973).

There are currently many different vendors that are looking at various molten salt reactor designs. At this point, most MSR designs are not as mature as either the SFR or HTGR designs. Because of this, there is no real generic design variant that can be considered nominally representative of the class of MSRs. Therefore, the components chosen for the MSR are from many different various public sources of what may be representative. Thus, each component may have a different size or other performance characteristic that may not be fully representative of all options under commercial development today. Table 3 provides an overview of the main specifications for the MSR components leveraged in this study.

Table 3. Overview of the reference MSR components used in this study. The specifications are based on a range of different reactor designs (MSRE, Mk1-FHR, etc.).

Component	Specs	Reference
Salt Pump	1,250 gpm flow rate	(ORNL 1973)
Heat Exchanger	750°C (1375°F)	Private Comm. ¹
Reactor Vessel built with Rings and Heads	12–18 m (39–59 ft) high, 3.6–4.2 m (12–14 ft) dia, 4–6 cm (1.6–2.7 in.) thick Material–Stainless Steel	Private Comm. ¹
Reactor Vessel Ring	2.5–3 m (8.5–10 ft) Material–Stainless Steel	Private Comm. ¹
Reactor Vessel Head	0.75 m (2.5 ft) high Material–Stainless Steel	Private Comm. ¹

Other Reactors and Components

While several other advanced reactors are under consideration (e.g., lead cooled), these are not included in the scope of the study due to time constraints. It is expected that the three reactors selected here (SFR, HTGR, and MSR) are representative enough of the full spectrum of advanced reactors. In addition, advanced LWRs—namely SMR-variants—are not considered here as they are expected to be able to lean heavily on the existing supply chain for the large Pressurized Water Reactors (PWRs) across the United States (if similar in size, the advanced reactor supply chain would be utilized). Microreactors were also not considered in this study but may contribute to the demand for some key advanced reactor components (including graphite, heat exchangers, etc.). Nevertheless, the findings in this report are still expected to be relevant to potential microreactor deployments. These reactors are smaller in size, and their components are expected to be less complex than their larger counterparts. However, build rates in the hundreds of units by 2040 and thousands by 2050 for microreactor deployments are possible under the right conditions (Shropshire 2021), which could bring added challenges for the advanced reactor supply chain as a whole.

Several items included in the survey and not discussed in previous sections include several ‘cross-cutting’ components that would likely be used in all advanced reactor types. This mainly consists of reactor sensors technology, namely thermocouples and neutron flux monitors. Other electronics like semiconductors are not addressed in this work as they are used across several industries and thus have much larger markets outside of the nuclear energy landscape.

¹ Private communication with MSR vendor.

COMPONENT DEMAND PROJECTION

Nuclear Deployment Future Scenario Modeling

Global efforts are underway to reduce CO₂ production in the energy sector. A recent study attempted to predict the share of nuclear electrical capacity as a function of net-zero carbon emission targets and carbon pricing schemes (Kim 2022). This study builds on a prior study to understand the amount of HALEU that would be needed to support advanced reactors. In the prior study, it only included one price scenario and a net-zero date of 2050 and the model predicted a total of 250 GW of nuclear capacity by the 2050 timeframe (Dixon 2021). The current study also leveraged the Global Change Assessment Model (GCAM) software (JGCRI 2022) to evaluate and compare various scenarios. The tool can simulate long-term projections of energy use, agriculture production, land-use, and greenhouse gas emissions. GCAM has been used extensively to quantify the impact of technologies or new policies in alternative scenarios of the future and in the context of global climate change. In the (Kim 2022) study, GCAM was leveraged primarily to investigate the potential role for nuclear energy in addressing climate change. Unsurprisingly, the rate of new nuclear deployment was found to be strongly correlated with the normalized price of energy and the relative aggressiveness of the net-zero targets.

While the study conducted a wide range of analyses looking at different approaches to incentivize carbon emission reductions, the net-zero evaluations were selected for this report. In these analyses, sensitivity studies on two fundamental variables were conducted: (a) the overnight cost of the nuclear power plant in 2050 (ranging from \$6,600/kW to \$2,600/kW); and (b) the target end-date for the net-zero policy (ranging from 2050 to 2080). In all but the \$6,600/kW case, the initial overnight costs of new NPPs were assumed to be \$6,200/kW. These initializing costs are representative of current, conventional gigawatt scale deployment. Costs are assumed to drop linearly until the 2050 value is reached. Essentially, the scenario assumes that nuclear power deployment is initially expensive, but costs drop as more units are deployed and benefit from learning. Each model predicts the advanced nuclear generating capacity, measured in GWs, in intervals of 5 years. The resulting scenarios based on these different conditions are shown in Figure 6. ‘Nz’ corresponds to a given net-zero scenario (e.g., Nz50 means net-zero emissions by 2050), while ‘Nuc’ corresponds to the overnight price of new nuclear deployment at 2050 (e.g., Nuc26 means overnight cost of \$2,600/kW in 2050).

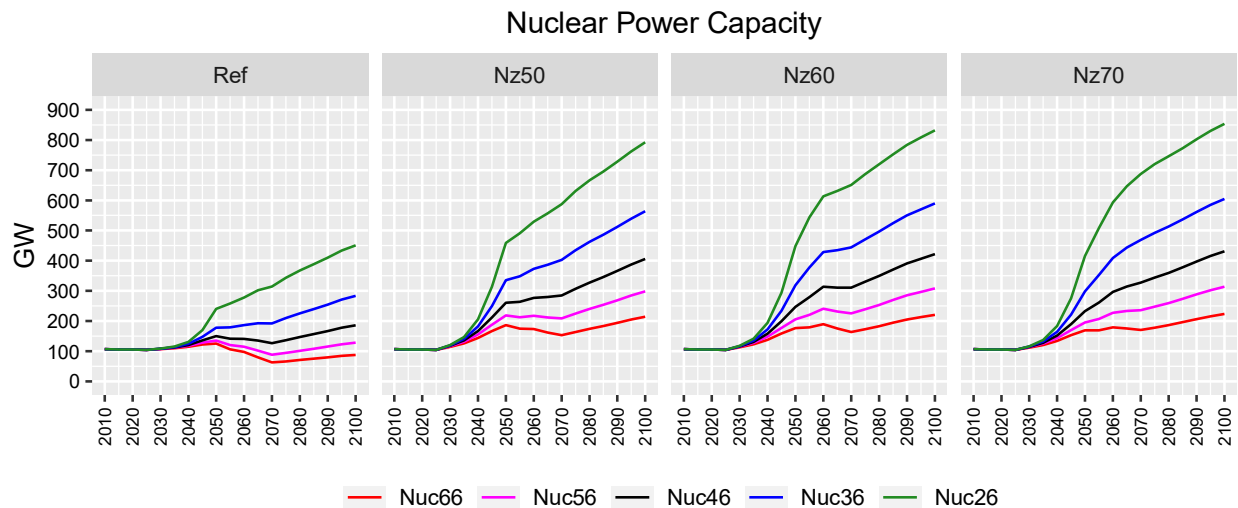


Figure 6. New nuclear power capacity deployment under various cost and net-zero scenarios. Taken from (Kim 2022).

Bounding Case: Optimistic Nuclear Deployment

For the purposes of this report, the most optimistic case for nuclear deployment (highest rate) is selected as it will be the most challenging for the supply chain. This corresponds to a net-zero target by 2050, and nuclear power overnight costs decreasing precipitously from \$6,200/kW in 2025 to \$2,600/kW in 2050. This corresponds to the curve labeled ‘Nuc26’ in the ‘Nz50’ plot. It is important to note that the Nuc26 deployment rate can be considered to be very optimistic from a deployment scenario. Relative to the Nuc66 case (where nuclear energy costs stay at \$6,600/kW), the total new capacity deployed by 2050 is approximately four times larger. This constitutes a wide range of uncertainty that depends on the eventual nuclear deployment costs (and net-zero policy). Nevertheless, the Nuc26 case was deemed to be a bounding analysis for the purpose of this report.

On the other hand, it is important to note that these simulations do not account for international demand nor leveraging nuclear capacity for industrial, heat-generation, or other types of applications. Therefore, in each curve shown in Figure 6, it remains possible that the total capacity deployment could be higher.

Leveraging this bounding scenario, three demand targets were extracted and summarized in Table 4. These represent the various demand targets that were provided to surveyed suppliers to assess their ability to meet aggressive nuclear deployment rates. The three targets loosely correspond to different timesteps in the GCAM simulation. Since the initial deployment rate is relatively flat between 2010–2030, the first data point is taken when demand starts picking up, then another 5 years later, and then 10 years after that. Because demand is expected to be

continually ramping up, the targets are defined in terms of yearly rate of production (GW/year) rather than the total capacity deployed in a single given year. Surveyed suppliers were therefore asked how readily they can meet the corresponding production rates assuming they had firm orders 1, 5, and 10 years ahead of time. This is expected to provide insight into the nuclear supply chain's ability to meet various scenarios and an expectation of the lead time required for these aggressive timelines. The DOE, in a separate study, determined an even higher rate of buildout may be required of up to 13 GW/year by 2035 to reach deployment of 200 GW of advanced nuclear by 2050 (DOE 2023). As the advanced nuclear supply chain is not established, understanding timelines for ramping up that deployment will inform the ultimate build of the supply chain.

Table 4. Selected bounding scenario: new deployment rates and demand targets.

	Capacity installed around that timestep in the simulation	Average rate of deployment used in survey
1-year target	0–4 GW	0.79 GW/year
5-year target	4–16 GW	3.17 GW/year
10-year target	27–59 GW	6.40 GW/year

Bounding Component Demand Targets

For the purposes of this analysis, the entire demand will be assumed to be taken up by a single reactor type. This is a conservative assumption and avoids the need to predict which reactor type will prove to be dominant. As such, each surveyed company will respond to their ability to meet demand targets assuming the entire demand is fulfilled by the reactor they are supporting. This is likely an overprediction of the exact reactor type being deployed, however even if a variety of reactor types are deployed, this may still strain the supply chain in a similar fashion (e.g., a single vendor might supply both sodium and salt pumps). As a result of this assumption, the quantity of components needed for each reactor type is overestimated.

The data in Table 4 needed to be translated in terms of the component/material quantity for each considered reactor design. While many different types of reactors (even within the same type) are expected to be deployed, their normalized component-need per unit of energy is assumed to be representative. As a result, the SFR components are normalized to 300 MW (corresponding to Sodium/PRISM concept), the HTGR components are normalized to 80 MW (corresponding to X-energy concept), and the MSR components to a range of designs based on the component considered (e.g., MSRE, MSBR, IMSR, Mk-1 PBFHR, and MCFR). Then, taking a particular reference concept, the number of each component per GW of energy could be derived. The resulting values are summarized in Table 5.

For a general perspective in using these component numbers, it is of interest to at least be aware of the number of reactors being deployed in these scenarios. For the HTGR at 80 MW, it

translates to about 40 reactors per year in the 5-year target and 80 reactors per year in the 10-year target. For the SFR design, these numbers correlate to over 10 reactors per year in the 5-year target and over 21 reactors per year in the 10-year target. For a representative MSR design at 195 MW, these numbers correlate to over 16 reactors per year in the 5-year target and over 32 reactors per year in the 10-year target. So, while companies are focused on smaller reactors, and smaller sites, the number of reactors that could be deployed in these scenarios is quite large.

Table 5. Translating the demand targets into yearly component production rates.

Component List/Production rate target	1-year	5-year	10-year
SFR Components			
Sodium Pump (# units/year)	10	40	90
Primary Heat Exchanger (# units/year)	10	20	40
Reactor and guard vessel (# units/year)	10	20	40
HTGR Components			
Reactor pressure vessel (# units/year)	10	40	80
Helium circulator (# units/year)	20	80	160
Helical Coil Steam Generator (# units/year)	10	40	80
MSR Components			
Reactor vessel and guard (# units/year)	1	20	30
Fuel Salt Pump (# units/year)	10	40	80
Heat Exchanger (# units/year)	1	20	30
Cross-Cutting Components			
Shaped Graphite (kg/year)	390,000	1,500,000	3,000,000
Thermocouples (# units/year)	4,000	15,000	30,000
Flux monitor (# units/year)	400	1,590	3,200

The evaluation highlights the variability in the number of components required per reactor, and per unit of energy produced by a specific concept. For instance, at a given target, thousands more thermocouples are needed than pumps or heat exchangers. Note that some of the similarities/discrepancies among components are due to rounding up/down values to simplify the survey questionnaire. These values were then provided in a questionnaire to select companies to evaluate their readiness in meeting these projected demand scenarios.

SUPPLY CHAIN OVERVIEW

The United States nuclear supply chain is directly tied to the operation of the current domestic nuclear fleet of 92 LWRs (EIA 2022b). The most recent new build plants are the two AP1000 designs in Georgia where Vogtle Unit 3 will commence operations in 2023 with Unit 4 shortly thereafter (Georgia Power 2022). Outside of these two new builds, there are no current plans for other large LWRs in the United States. Therefore, the current supply chain is aligned with supporting operations and maintenance of the current fleet. With the current LWR fleet only looking at standard maintenance and repairs, capital projects like steam generator replacement or

other large construction activities are limited. Most steam generators, which have been replaced by the current LWRs, have been fabricated outside of the United States which means the United States lacks recent experience in making larger components that would be similar to large advanced reactor components. Most domestic fabricators have supported the United States military (Navy) with various components that could be comparable in size. While the United States has most capabilities to domestically manufacture all the parts needed for advanced reactors, there is no current established supply chain for advanced reactors. A recent report by the Boston Consulting Group on American competitiveness in emerging clean technologies noted that the United States holds leads in many areas around research and development and intellectual property as well as the original equipment manufacturer space. To capitalize on these leads, a robust pipeline must be established that will drive demand that can build a domestic advantage and cost reductions in manufacturing (BCG 2022).

The components for advanced reactors discussed earlier demonstrate that while there are some new and unique components required for certain advanced reactors, many reactors will still require traditional components of nuclear reactors like: vessels, pumps, heat exchangers, steam generators, etc. These are standard components for many energy installations so fabricators for the oil and gas industry have similar capabilities that could be leveraged. The one unique aspect is that many nuclear components usually require companies to work under a specific nuclear quality assurance program and hold specific “stamps” or “certifications” to produce these components. These specific programs usually add cost and limit the number of suppliers that make these components as it creates a barrier for entry into the market. Many advanced reactor developers and other organizations are looking at ways to reduce the number of specific requirements for components either through specific design choices or changes to regulation. Even with these changes, components that must be procured as safety related will have to be procured with requirements that meet 10CFR50 Appendix B (NRC 2022). For things like piping, vessels, pumps, valves, heat exchangers, etc., these parts will also be procured under an ASME NQA-1 program using rules and requirements from the American Society of Mechanical Engineers (ASME). Since many components are designed to ASME standards, they will also be fabricated to those standards which require certifications and stamps. These stamps are obtained by companies meeting a specific set of criteria and producing demonstration components.

For this supply chain assessment, it is believed that large, complex components would be the most limiting since they would require complicated processes and use a limited set of suppliers that have the appropriate certifications and quality programs. These would include reactor vessels, heat exchangers, and other components that are unique to advanced reactors (like graphite). It is recognized that many organizations (national labs, developers, and other research organizations) are working on advanced manufacturing methods that could have an impact on the nuclear supply chain for some of these components. Advanced manufacturing methods may speed up processes or fabricate parts using entirely new fabrication methods. Currently, there are limited methods that are available to suppliers that are approved for manufacturing nuclear

components. If these methods do become available, they have the potential to support the nuclear supply chain and increase capacity through adoption of new technology (assuming it is cost competitive). For performing this assessment, the team reached out to suppliers that work in the industry or that are aware of the industry, and that also have similar capabilities using current approved fabrication techniques. This started with companies that have known ASME N-Stamps for manufacturing various nuclear components.

Overview of N-Stamp Manufacturers

Many of the components considered here would be considered mostly large, manufactured components that would fall under ASME Code rules and be manufactured with an N-stamp. Since the current supply chain has supported LWRs, many N-stamp holders do not currently have N-stamps that are applicable to manufacture components to ASME Code, Section III, Division 5 which would be needed for high-temperature components (ASME 2021). Additionally, searching the ASME certificate holder database for holders of a certificate for fabrication of graphite components as of December 2022 (ASME 2022) returns zero results. Due to this fact, most suppliers surveyed for this work will need to obtain appropriate certificates before producing any components for reactors that are designed/built to ASME Code, Section III, Division 5. This gap is not seen as a limiting factor in the advanced nuclear supply chain but is something that can be addressed as the supply chain develops. Many vendors that support the current LWR plants will be able to easily obtain the other relevant certifications required for manufacturing high-temperature components.

The bigger gap will be new manufacturers to the nuclear industry that do not have safety related quality programs and that may not have an NQA-1 and Appendix B program. It can cost more to keep and maintain a safety related quality assurance program, and unless the business case exists to keep that program, many companies may abandon it for overall cost savings. Thus, a safety related quality program can limit the number of potential manufacturers available to the industry. Organizations like the Nuclear Energy Institute (NEI) are working on potential paths to help companies that might only have an ISO9001 program adapt that program to be able to satisfy 10CFR50 Appendix B for safety related work. This could open the market to additional suppliers and reduce the barrier to entry (NEI 2022).

Based on the components selected, the project team reached out to the following types of companies to support understanding of the capacity in the supply chain:

- Forgers
- Large fabricators
- Pump manufacturers
- Graphite vendors (shaped and molded graphite)
- Sensor and instrumentation vendors.

SUPPLY CHAIN READINESS ASSESSMENT

To assess the supply chain, information was gathered directly from suppliers to understand their capacities and their ability to scale production to meet potential market demands. The team was not able to reach all potential suppliers of the various advanced reactor components, and certain companies did not respond to the outreach at all. The information also relies on a company's ability to project potential expansion of operations. It should be noted that most of the information here is based on future projections which may or may not be possible based on any number of factors (known or unknown).

Survey Methodology and Respondent Characteristics

Supply chain outreach efforts began by conducting individual interviews with a sample of potential survey respondents. The interviews were used to discuss potential survey question wording that would yield forecasted production capabilities for the established list of advanced reactor components. Beyond the goal of calculating actual industry production capabilities, the interviews became a source of potential qualitative information regarding general concerns faced by the advanced reactor component suppliers. These qualitative points that surfaced during the interview were aggregated into a list of concerns that was presented to all survey respondents for their review. Survey respondents were asked to indicate the level of concern these qualitative items presented regarding future production barriers.

More than 20 suppliers completed the survey with sufficient answers to fields to be included in the analysis. Near the beginning of the survey, respondents were allowed to select components and commodities their companies could produce. Using display logic, they responded to detailed questions about the items they selected. Survey participants were asked to rate their industry's ability to meet production targets for next year, in 5 years, and in 10 years. In the industry production question, a five-point rating system ranged from unable to meet needs to fully able to meet needs.

The next question in the survey asked participants to estimate the typical lead time, in months, that is required for production of the component or commodities based on the targets in Table 5. Survey responses are assumed to already have production lines and necessary certifications in place prior to an order (in other words, lead time for an Nth unit produced). Respondents were then asked to estimate their company's market share for the items they produce. They were then asked to quantify their ability to meet the market demand targets that were presented previously. Upon completion of the company production questions, additional questions were asked about the investment needed to meet future production goals.

Other information collected from companies was used to evaluate company characteristics such as size, number of locations, time in business, nuclear related certifications, and share of work

performed by the company that is nuclear related. The following charts provide results related to that portion of the survey. The question wording used in the survey is used as chart titles.

Figure 7 indicates that most of the companies responding appear to have recent experience producing some components for the nuclear sector. More than three quarters of respondents produced nuclear grade products within the last year. Only 14% had gone longer than 10 years without making nuclear grade products. This shows that most of the companies in the survey are familiar with the nuclear requirements and the market in general.

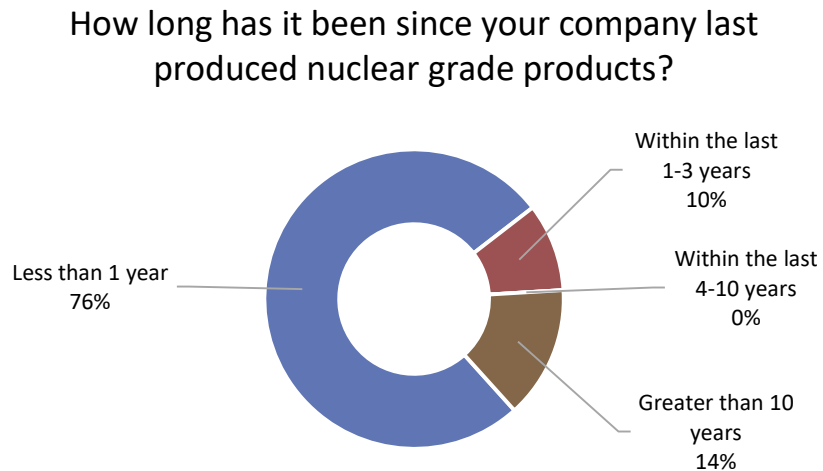


Figure 7. Breakdown of surveyed company experience in the dedicated nuclear supply chain.

Figure 8 reinforces the conclusion that experience working on nuclear grade products was commonplace among the survey participants. Nuclear related projects made up at least half of total production for more than 40% of the respondents.

What share of your production work is on commercial nuclear related projects?

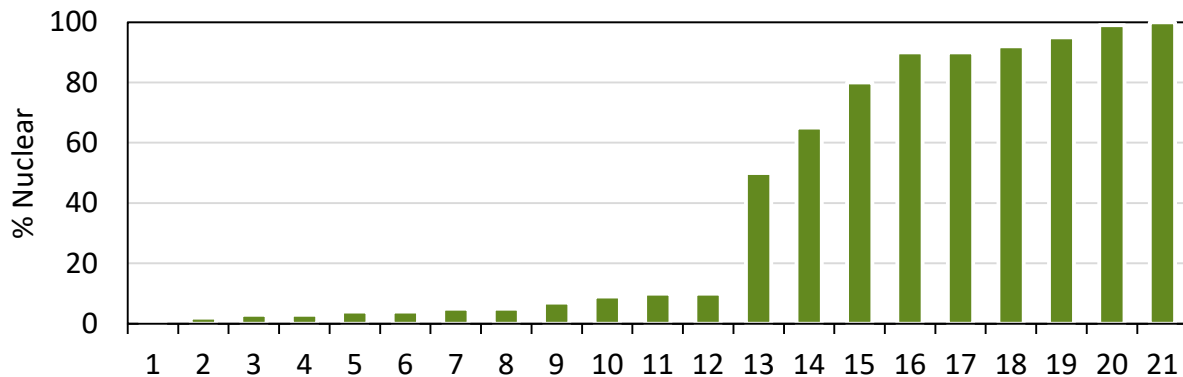
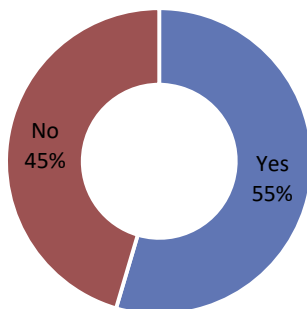


Figure 8. Breakdown of surveyed company production work for commercial nuclear projects.

Figure 9 indicates that more than half of the companies represented in the survey are owned by a parent company with the highest number of responses indicating employment of at least 500 workers.

Does your company have a parent company?



How many employees does your company have?

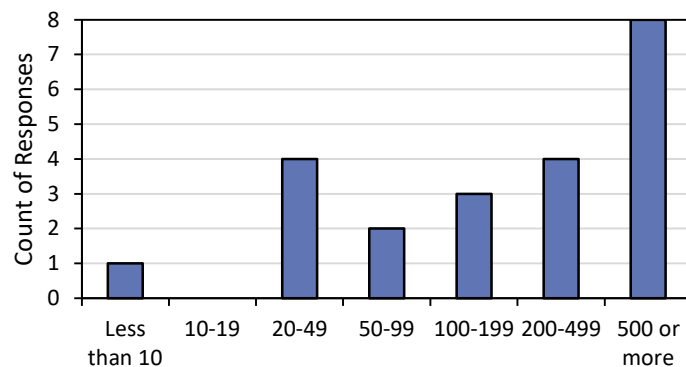


Figure 9. Breakdown of surveyed company size and structure.

Overall Assessment

The survey provided an opportunity to assess the various components at an individual company production level and at an industry level. This section of the report provides an overall assessment of these results. Figures highlighting individual component results are available in the appendix. Note that responses were not received for all components surveyed. This is likely due to the inability of the team to connect with the appropriate companies that can produce those

items. The other potential reason is that the capability does not exist to produce those components in the United States.

The goal of this report was to determine the suppliers in the United States that could produce these components. While the study focused on United States-based companies, several of them are multinational, with operations in the United States as well as other parts of the world. Part of this occurs in the supply of graphite. Some companies may produce the graphite overseas, but the American company performs the machining on the graphite for its final delivery. Similarly, certain sensor wires may not be produced in the United States, but the final sensor is produced there. This is similar to sourcing of raw materials where the United States does not produce everything consumed and relies on imports for various raw materials. While this is an assessment of the domestic supply chain, the report did not trace back all sub-component or raw material sources that went into each component to determine whether it was in fact 100% based in the United States. The report does however look at American companies and their ability to meet certain capacities.

Industry Readiness Rating by Component

Survey participants were asked about their industry's ability to meet demand targets over the next year, in 5 years, and in 10 years. Respondents could indicate the industry was unable to meet demand targets by providing a "1" rating. A maximum rating of "5" could be given to a component if the respondent felt the industry was fully able to meet the demand target.

The average rating for a "next year" production target was 2.5. As time extended to 5 and 10 years, the average industry readiness rating increased to 3.5 and 3.8 respectively. This highlights the benefit of long-term planning when sourcing components. The quantitative responses for these questions do not give a complete answer as to why industry readiness improves with time. Some of the causes may be discovered by looking at subsequent responses. Suppliers do suggest that lead time can stretch out beyond a year. Some suppliers indicated that production facilities have limitations, and they are facing heavy workloads that compete for available production resources. With more time to plan, these obstacles may become less problematic which could lead to increased industry readiness ratings.

The highest level of industry readiness was observed for thermocouples, as well as with salt and sodium pumps categories. Respondents were most pessimistic about short term production targets for HTGR reactor vessel assemblies, MSR heat exchangers, and MSR reactor vessel assemblies.

In general, most answers were pessimistic about their industry's near-term ability to meet demand but were more optimistic for long-term demand projections. Interestingly, however, this did not agree with the aggregate analysis once individual company production was assessed, which will be discussed later in this report.

The lowest rated components for near term and longer-term demand here tend to be more large, complex fabricated components (large vessels and heat exchangers). This follows common perceptions in the industry as most large vessels for current LWRs are made overseas in countries with large fabrication infrastructure (namely Japan, Korea, France). The increasing trend in industry's ability to meet demand, as forecasts are further in the future, points to optimism in its ability to expand if a known market exists. As noted later in the report, an inability to quantify the known market with certainty is one issue that will hold back investment in the supply chain due to previous issues around nuclear growth that never came to fruition.

Table 6. Overview of surveyed companies' perspective on their industry's ability to meet various market demand targets.

Industry Rating* on Ability to Meet Market Demand			
Component	Next Year	5 Years	10 Years
Flux Monitors	2.0	3.0	3.0
HTGR Helical Coil Steam Generators	1.7	2.7	3.3
HTGR Helium Circulators	2.7	4.0	3.8
HTGR Reactor Vessel Heads	2.0	3.0	3.3
HTGR Reactor Vessel Rings	2.3	3.2	3.3
HTRG - Reactor Vessel Assemblies	1.5	2.8	3.2
MSR Fuel Salt Pumps	3.5	4.5	4.5
MSR Heat Exchangers	1.5	3.5	4.0
MSR Reactor Vessel Assemblies	1.5	4.0	4.3
MSR Reactor Vessel Heads	2.4	3.7	4.0
MSR Reactor Vessel Rings	2.8	3.5	4.0
SFR Primary Heat Exchangers	1.7	3.0	3.5
SFR Reactor Vessel Assemblies	2.0	4.0	4.3
SFR Reactor Vessel Heads	2.8	3.7	3.7
SFR Reactor Vessel Rings	3.0	3.7	3.5
SFR Sodium Pumps	3.8	4.5	4.5
Shaped Graphite	2.7	2.6	3.3
Thermocouples	5.0	4.5	4.5
Average	2.5	3.5	3.8
*1=Unable to meet demand targets, 5=Fully able to meet demand targets			

Aggregated Production by Component

Surveyed supplier assessment of their respective industry readiness was then compared against aggregated production assessment by each participant. Figure 10 shows the sum of production estimates provided by individual survey respondents. Each survey respondent provided an estimated market share, by component, they felt their company would control. These market shares were combined by component to help analyze component supply and demand gaps that may exist. In most cases the combined production forecasts provided by survey respondents were more than adequate to meet the goals presented in the survey. Based on the survey results, the combined production provided by the survey respondents and the remaining companies in the total market, would be more than adequate to achieve targets. While some aggregated supply values were unable to reach demand, these did not account for the estimated market share of the respective survey participant. Accounting for this and combining with the market share provided by competitors, it is possible to forecast production for the market. The only instances where market share adjusted production levels appear to fall short of targets included flux monitors, which averaged 93% of the production target, and MSR heat exchangers, which could produce 80% of the production target. Some of the components that may struggle to meet the overall target again appear to be some components that would be larger and more complex.

Based on the industry readiness assessment, it was initially expected that the production of advanced reactor components would be severely limited due to the lack of domestic manufacturing capacity. There does appear to be a limited but still significant initial ability to produce components given some of the early targets. However, given enough time to scale up, and with firm orders, suppliers noted that production can be increased to meet larger demand goals. The big takeaway here is that a scale up of production would be required to meet these larger market demands. If that scale up in production does not occur due to lack of market clarity, funding, or other issues, then the more aggressive nuclear deployment targets cannot be met using a United States-based supply chain alone.

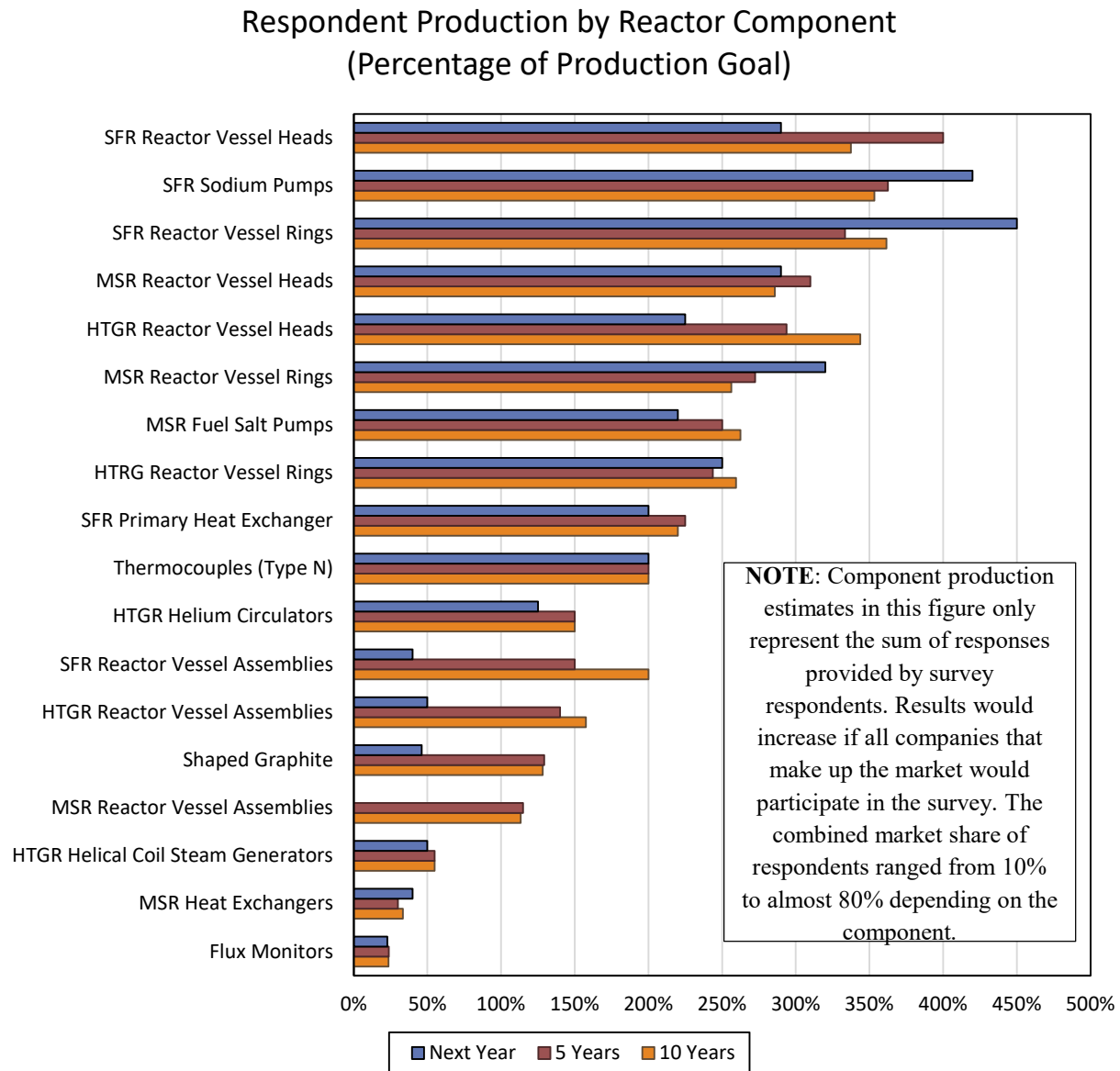


Figure 10. Total Production vs. Goal for all Components. Note that even items that are not achieving goals (e.g., HTGR Steam Generators) do so (or are close to) when adjusting for the market share of survey participants.

Supplier Concerns

Surveyed participants were asked about challenges they would face when attempting to reach production targets in previous questions. Their answers are summarized in Figure 11. As shown, the greatest challenges are workforce availability/experience, workload from other projects, uncertainty of demand, and facility limitations. The results presented in Figure 11 are sorted with the highest count of “very challenging” plus “extremely challenging” concerns listed in

descending order. Workforce availability was identified as moderate or greater challenge by 90% of respondents. Workforce availability was selected by 20% of respondents as extremely challenging. No respondents categorized workforce availability as a something that was “not challenging at all.” The least concerning categories included access to subcontractors although respondents did indicate this category was moderately challenging roughly 50% of the time. Shipping/logistical considerations, environmental regulators, quality control, and access to financing, were not frequently selected as very or extremely challenging. More than 40% of respondents indicated obtaining nuclear certifications was “not challenging at all.” This was the least challenging concern, followed by shipping and logistics at 35%.

Workforce issues are present in many industries in the current state of the global economy. It is therefore no surprise that workforce concerns are top of mind for many of the companies surveyed. For this work, the workforce being discussed is directly related to the supply of these components and does not even consider the workforce required to construct and operate advanced reactors. It should be noted that excessive workload from other projects does point to a larger challenge. The net-zero transition will require building many types of power/energy generation even outside of nuclear energy. Many technologies may be competing for the same resources and thus it may strain multiple supply chains. While many companies did not directly select obtaining nuclear certifications as an issue, it should be noted that over half of respondents were already supporting the nuclear industry. Therefore, this is not representative of newcomer suppliers who will likely be needed to meet some of the more ambitious demand targets.

Additional Supplier Concerns

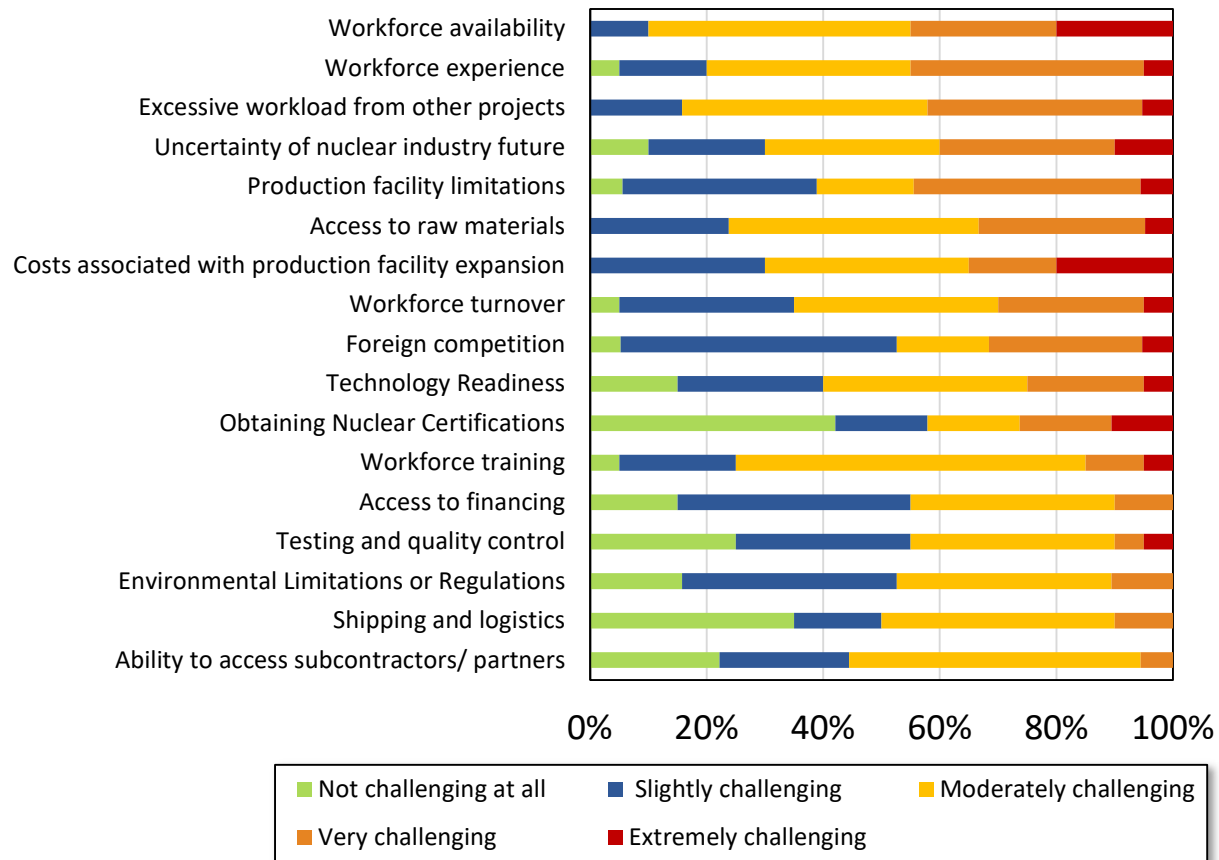


Figure 11. Additional Supplier Concerns.

Component Lead Time

The following tables and figures provide a summary of lead times for each component. As shown, the longest lead items are HTGR steam generators, followed by sodium pumps, MSR vessels and heat exchangers. For these cases, the larger and more complex components have the longer lead times. These are current lead times and if construction and deployment of advanced reactors ramped up, it is uncertain if these times would get longer or shorter.

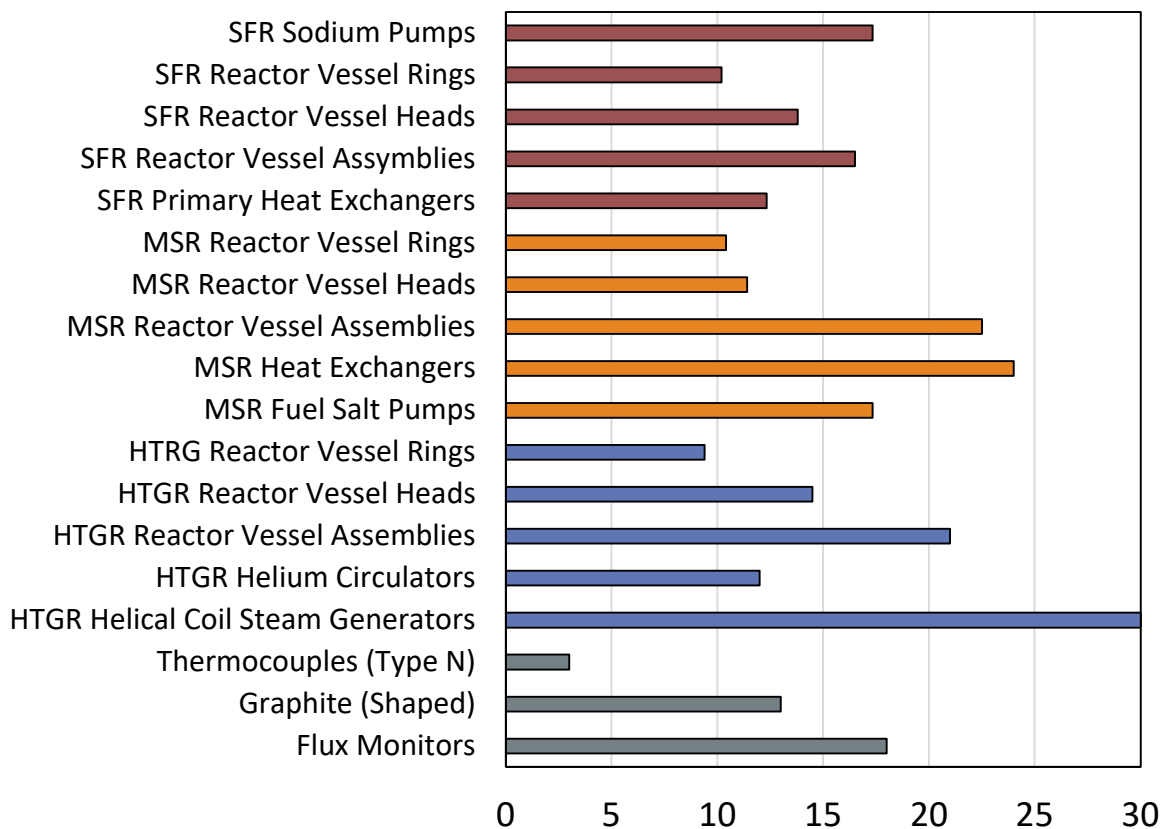
Table 7. Average Lead Time by Reactor Type.

Average Lead Time by Reactor Type (Months)	
HTGR	17
MSR	17
SFR	14

Table 8. Average Lead Time by Component.

Average Lead Time by Component Type (Months)	
Rings	10
Pumps	12
Heads	13
Vessel Assemblies	20
Heat Exchangers	22

Average Lead Time (Months)

**Figure 12. Component Lead Times.**

Comments on Future Investment Requirements

Survey participants were given an opportunity to provide additional comments regarding investments needed to meet demand targets. Some of these comments discussed significant financial investments for capital improvements ranging from \$100 million to \$1 billion. In some cases, the manufacturer would require their customer to share 50% of the financial burden.

Most of the investment-related comments were focused on three consistent themes: facilities, equipment, and workforce. The word cloud in Figure 13 illustrates the frequency key words were used in respondents' comments on future investment requirements. As a specific word is used more frequently, the word appears in larger font. As shown, the words 'Large', 'Production', and 'Facility' seemed to be a recurring theme. The words 'Parts' and 'Order' also appeared frequently, attributing to the need for concrete orders being placed prior to component production. The need for new machinery was also discussed.



Figure 13. Investment Word Cloud.

Comments on Other Concerns

Respondents were provided an opportunity to discuss other concerns or constraints they felt were important but were not a part of the survey. Many of the comments in this section of the survey provided additional insight on supply chain and production related issues and sometimes identified specific components that could create production bottlenecks. These specific items included the need for domestic thermocouple wire producers and unspecified materials needed for MSRs. As shown in Figure 14, respondents (a) expressed a need for more coordination and involvement across the whole advanced reactor supply chain; and (b) highlighted the exponential growth rate of other markets that will compete for goods and services needed for advanced reactors.



There are certain key takeaway points that need to be noted about the United States supply chain for advanced reactors. In general, it does appear that there is an initial capacity to produce some of the critical components for these advanced reactors. Note that this survey does not delve into the full fabrication criteria for specific components, but only provides general material/size components to obtain a general understanding of capacity. These results cannot be treated as applicable to any particular advanced reactor design as there may be specific fabrication requirements that were not considered in this work.

- Capacity appears to exist for the beginning of deployment; however, lead times can be significant in some instances.
- Significant investment, which was not quantified in this work, will be required to ramp up capacity. Investment is most likely needed to meet the 5-year demand targets and beyond.
- Components that are larger and more complex appear to be the earlier limiting components for scaling production.
- The suppliers are looking to de-risk the investments needed to expand capacity. One way to help de-risk that investment is firm orders to signal clearly to the supply chain that expanded support for the market is needed.

General caveats from the findings:

- None of this analysis considers whether the United States supply chain is cost competitive with international competitors. As noted in the Boston Consulting Group report, developing a robust pipeline for demand can de-risk investment in manufacturing and enable cost reductions (BCG 2022). If the domestic supply chain is not cost competitive, it is quite likely that many of these components could end up being manufactured in overseas markets. However, theoretically, this should not impact the roll-out of advanced reactors.
- While the study did ask respondents to consider their other work in other markets when forecasting future capacity, another market could boom that causes capacity to be shifted elsewhere. One potential competing market is the United States military which builds both ships and reactors for the Navy. Many United States suppliers supply components for the Navy. The international demand for nuclear may also lead to a larger demand on suppliers. Any larger demand on supplies will add to the need to expand the supply chains and may lead to a more limited supply chain for U.S. civil nuclear expansion.
- The study does not consider the technology readiness level of individual components. This may impact some of the surveyed answers regarding lead times for some components and ability to meet projected targets. One example of this is that while graphite suppliers can meet targets, there are only a limited number of graphite grades that may already be qualified through irradiation testing. Any additional time required for this testing is not included in this study. Similarly, any advanced materials and supporting qualifications are not included in this study.
- Advanced reactor design-specific considerations are not considered in this assessment. There will likely be developmental challenges to supply certain specific components.
- By asking about components in silos, the study does not account for potential challenges toward ramping up capacity across various areas. For instance, a manufacturer may need to rely on the same capacity to produce both pumps and heat exchangers. A ramp in both orders could strain overall ability to meet rapid demand spikes.

CONCLUSION

Based on the findings of the survey conducted in this study, assuming the various caveats and issues can be met, it does appear that the United States has the domestic ability to expand a supply chain to meet the advanced nuclear demand of the components considered. Capabilities exist to produce many if not all these more complex components. This assessment showed that there is an initial capacity to support advanced reactors. However, substantial investments will be needed in the future to meet net-zero goals in order to substantially ramp up production. The survey indicates that production can indeed be ramped up to meet targets, provided that firm orders are obtained early on to justify appropriate investment. However, workforce availability for these specific supply chains appears to be a key challenge in expanding capacity. While

typical lead times are less than 2 years with existing capacity, expanding the capacity will likely require a timeframe of up to 5 years to secure adequate investments and produce new components. However, until clear market signals come from the demand side, total capacity of the supply chain for advanced reactor deployment will remain limited.

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APPENDIX

Background on SFR Component Specs

Sodium Pump

The two main SFR pumps are centrifugal pumps and electromagnetic pumps (EM pumps). Within a centrifugal pump, fluid enters the impeller where rotational energy is converted into hydrodynamic energy. Centrifugal pumps can suffer from cavitation, malfunctioning impeller, surge, and clogging (Sulzer 2010). Because liquid sodium is an electrically conductive fluid, SFRs can also use EM pumps. An EM pump creates a current and magnetic field that are both perpendicular to the axis of the pump, thus inducing a force for the liquid to follow (Dannen 1997). However, EM pumps can be less efficient at converting electromagnetic energy into hydrodynamic energy. The PRISM design uses four electromagnetic pumps with a sodium flow rate of 86,000 gal/min ($5.4 \text{ m}^3/\text{s}$) made of SS316 steel (Triplett 2012).

Sodium Heat Exchanger

Because the pool-type SFR is the design that is considered within this report, a sodium-to-sodium intermediate heat exchanger (IHX) will be required (Ohshima 2016). The primary loop (through the reactor core) is separated from the secondary loop (through the steam generator). For the PRISM SFR design there are two sodium-to-sodium IHXs made of SS316 steel contained within the reactor vessel (Triplett 2012). The dimensions for the two IHXs are approximately 1 m wide, by 12 m long, by 14.65 m deep in the mock-up PRISM design (Triplett 2012).

Reactor Guard, Vessel, and Ring Head

SFR concepts tend to use two vessels to mitigate the risk of sodium fires in the case of a leak. The first is referred to as a primary vessel which is the reactor vessel, while the second is referred to as the guard vessel to help capture any sodium leaks. The PRISM SFR reactor vessel has a 10 m diameter, a 17.5 m height, (Triplett 2012) and a 20 mm thickness (Paredes 2020) made of SS316 (Triplett 2012). For this assessment, it was assumed that the reactor vessel is assembled from rings, a standard PWR RPV was used to calculate the number of rings (Tanaka 2015). The height of GE's PRISM design is close to a standard PWR. A 2.5 m–3 m ring was therefore assumed, creating six rings per PRISM design. Each SFR vessel is assumed to have a top and a bottom head (Tanaka 2015).

Background on HTGR Component Specs

Nuclear Grade Graphite

A potential supply chain constraint for HTGR is procuring nuclear grade graphite. Nuclear graphite must be very pure to minimize excess neutron absorption. For instance, trace amounts of boron have been a known impurity concern since the Manhattan Project (Burchell 2001). The specifications for nuclear grade graphite depend on the use of manufacturing techniques, choice of coke, and application of binder to change the graphite's microstructural properties and porosity. Nuclear grade graphite should be 15–20% porous providing a density between 1.8 g/cm³ and 1.92 g/cm³ to ensure thermal and irradiation stability (Wright 2019). It has a thermal conductivity of above 145 W/m/K, measured at room temperature. And the chemical impurities should be below 300 ppm, ensuring an absorption cross section is less than five mbarns, and moisture reactivity of less than 0.2 mg/g-h. (Marsden 2001). ASME Code for graphite core components under Section III, Division 5, Subsection HA & HH, Subpart B & A (High-Temperature Reactors) applies to graphite reflectors, shielding, and any interconnecting dowels or keys (Wright 2019). A deterministic or probabilistic design approach can be used to assess the structural integrity of HTGR graphite components, which can include qualification by testing or a full analysis method (ASME 2017).

The quantity of graphite required per reactor output power was estimated using both shaped graphite and powdered graphite. For an HTGR, an example of shaped graphite would be graphite reflectors and the powdered graphite would be the TRISO embedded, compacted graphite pebble balls. The amount of shaped graphite was taken from the X-energy design (X-energy 2022). This study did not look at the powder graphite since that is most likely going to be addressed as part of fuel fabrication and the overall fuel cycle.

Reactor Pressure Vessels

Many HTGR vendors will consider using low alloy steels to forge and fabricate their RPVs, an example specifically being Xe-100 using SA-508, Grade 3, Class 2 forgings (Burton 2022). The size of the HTGR reactor vessel is small enough to avoid the ultra large forging requirements, which opens up the capability of additional forging company and manufacturers. Most current light water reactor vessels require ultra large forging capabilities, which is not available in the United States and would require international vendors (MPR 2018). From an MPR 2010 report, an estimation of \$2 billion would be needed to build ultra large forging capacities in the United States (MPR 2010).

The ASME Code for metallic pressure boundary components is published under Section III, Division 5, Class A & B, Subsection HA & HB, Subpart B (ASME 2021). The NRC is in the

process of endorsing this code with conditions. Currently, a draft regulatory guide has been published for comment (NRC 2021).

Helium Circulators

HTGRs use circulators to transfer heat from the gaseous working fluid to the steam generator. Helium circulators have historically been the cause of many operational challenges for HTGRs. For the Fort St. Vrain (FSV) commercial HTGR in Colorado, water invading the reactor's helium circulators led to the premature closure of the plant. The bearing for FSV's helium circulators was water lubricated, and the varying reactor gas pressure led to excess water infiltration. Other designs have active magnetic bearings to address this issue (Zhou 2002). Most helium circulator designs are made of stainless steel, like X-energy using 17-4PH and 15-5PH (Burton 2022). For the component calculations, two helium circulators were used per 80 MWe reactor module.

Helical Coil Steam Generator (HCSG)

A Helical Coil Steam Generator (HCSG) consists of two compact, helically wound upper and lower bundles designed for high-temperature steam. The most popular HCSG design is a vertically oriented, once-through, up-boiling, cross-counter-flow, shell and tube heat exchanger (Hoffer 2011). The upper bundle is made of a high-temperature alloy like Inconel 617 and Incoloy 800H, and the lower bundle is made of a low temperature alloy like 2-1/4Cr-1Mo (Hoffer 2011). Compared to traditional steam generators, HCSGs are designed to be more modular and to better exploit the efficiency gains of HTGR's high temperatures. For the component calculations, 1 HCSG was used per 80MWe reactor module.

Background on MSR Component Specs

While most of the critical components and materials for MSRs will be similar to those for SFR and HTGR designs, the main exception is needing enriched compounds for salt solutions. This refers to both enriched lithium-7 and enriched chlorine-37. 400 kg/yr of pure Lithium-7 are used for chemistry control for the existing fleet. The largest supply of Li-7 is provided by Russia. Because of the larger mass differential between Li-6 and Li-7, lithium is easier to enrich than uranium, but building up facilities for lithium or boron enrichment is still a very capital-intensive endeavor.

Fuel Salt Pump

For the pumps within the primary circuit, the MSRE was referenced using the document "MSRE Systems and Components Performance" (ORNL 1973) to obtain reference specifications. The pump specifications were selected as they are widely available in the open literature. The pump speed in the MSRE was 1250 gpm (ORNL 1973). While the MSRE did not produce electricity,

the nominal electrical production capacity from Terrestrial Energy of 160 MWe was assumed (Ion 2018) to normalize the number (assuming two pumps per reactor).

Heat Exchanger

The MSR heat exchanger will be a unique design per each reactor. Since each reactor type will be different, the exact heat exchanger size will be unique. In discussion with some of the reactor vendors it was noted that one heat exchanger would be utilized for the primary circuit and that heat exchanger would be made of austenitic stainless steel².

Reactor Guard, Vessel, and Ring Head

Similarly, as for an SFR, two vessels are typically used for MSRs as well. The first will also be referred to as a primary vessel which is the reactor vessel while the second is referred to as the guard vessel to help capture any salt leaks. The dimensions for a representative vessel provided by a MSR vendor² were utilized. The vessel height is 12–18 m, the outer diameter is 3.6–4.2 m, and the thickness is 4–6 cm made of Austenitic Steel.

For this assessment, the same assumption as the SFR was assumed to estimate the number of rings and heads. Since the height is similar, the MSR assumed six rings and two vessel heads.

Graphite

Here the Mark-I was also used as the upper limit for graphite needed per thermal MSR (UCB 2014). This is because a fluoride salt-cooled high-temperature reactor (FHR) uses graphite both within the core design and within fuel design. Each pebble was assumed to be mostly graphite, resulting in ~150 MT of Graphite per GW.

Background on Other Advanced Reactors

Other advanced reactors are under development and some LWR designs are close to commercialization and deployment. A reactor that is not considered in this study is a lead fast reactor. Lead fast reactors will be similar to SFRs, but they utilize lead as the coolant instead of sodium. There would be specific considerations to handle based on using lead as a coolant, but the overall components would be similar.

There are also many different microreactors under consideration by many vendors. Many microreactors will have sizes in the MWe range up to ~20 MWe. There are many different coolants and designs under consideration for these microreactors and the end goal of a microreactor is to build it in a specific factory on an assembly line to reduce the cost.

² Private communication with MSR vendor.

The other reactor type that can support net-zero goals are advanced LWRs. These reactors are new light water reactor designs (NuScale) or scaled down version of existing LWRs (GE-Hitachi BWRX-300). Since they are LWRs, many of the materials and components needed are similar to those produced for current LWRs. The main concern will be understanding if the reactor vessels can be fabricated in the United States. An example reactor vessel is contained in Table 9. Note that this vessel size is similar to some of the HTGR vessels, such that HTGR vessel production will be comparable to advanced LWR.

Table 9. Overview of the reference Advanced LWR Vessel (GEH 2022).

Component	Specs
Reactor Vessel built with Rings and Heads as shown below	22 m (72 ft) high x 4.5 m (15 ft) diameter thickness 4.5 in. SA-508 Low Alloy Steel
Reactor Vessel Ring	2.5–3 m (8.5–10 ft), thickness 4.5 in., SA-508
Reactor Vessel Head	0.75 m (2.5 ft) high, thickness 4.5 in., SA-508

Background on Other Cross-Cutting Components

High-Temperature Sensors

Because many of these advanced nuclear designs will operate at temperature greater than 500°C, thermocouples with wide temperature ranges will be needed. Type-N was the representative example used within the supplier survey. Based on INL expert judgement³, each reactor is likely to require hundreds of thermocouples. A value of 400 sensors/reactor was chosen to calculate supply chain capacity. There are novel thermocouples in research and development that may be adopted by industry, such as Gold-Platinum Thermocouples (ORNL 2016).

Flux Monitors

It is expected that standard flux monitoring equipment and systems will be used for advanced reactors. There are various types of flux monitors, namely flux foils, fission chambers, self-powered neutron detectors (SPNDs), etc. For simplicity, a single type is assumed in this study. An order of magnitude fewer sensors is expected to be needed compared to thermocouples. Again, based on INL expert judgement³, a value of 40 sensors/reactor was selected to estimate supply chain capacity.

³ Private communications with INL Instrumentation & Controls experts.

Component Specific Assessments

The following figures (Figure 15 through Figure 28) provide a detailed view of survey respondent production capabilities and reported levels of industry readiness. The results for respondent production are shown as a percentage of the production target based on the combined production capabilities from each survey respondent. As a result, combined industry production could exceed more than 100% of the production target. Market share estimates were also reported by survey participants to help understand potential production by the whole market if the sum of individual respondents did not satisfy demand targets. The figures listed in this appendix are not adjusted using market shares unless specifically noted.

Industry readiness ratings were created by taking the average value reported for each component. Individual respondents provided a rating of “1” if they felt their industry would be unable to meet the demand targets. A rating of “5” indicated the respondent felt their industry would be fully able to meet demand targets.

In all cases the respondent production capabilities and industry readiness ratings were assessed for “next year”, in 5 years, and 10 years away.

Pumps & Circulators

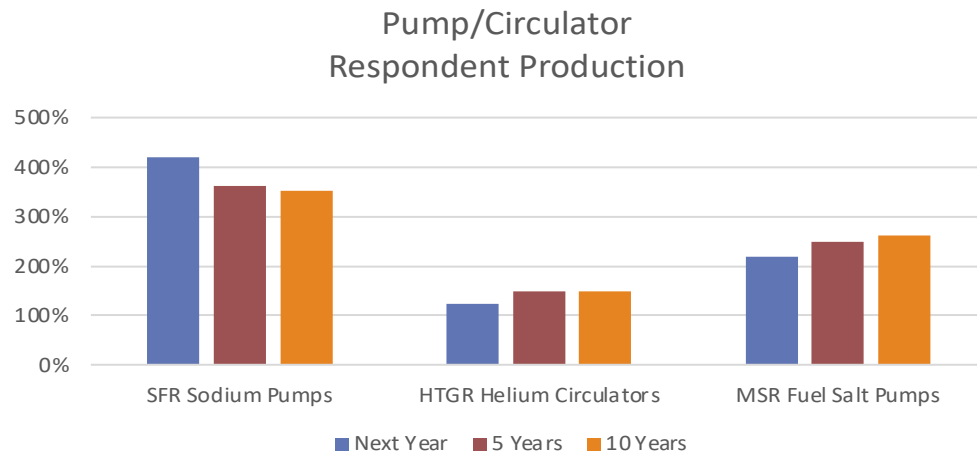


Figure 15. Aggregate pump/circulator production capacity relative to 1, 5, and 10-year targets based on all company responses (not adjusted for market share).

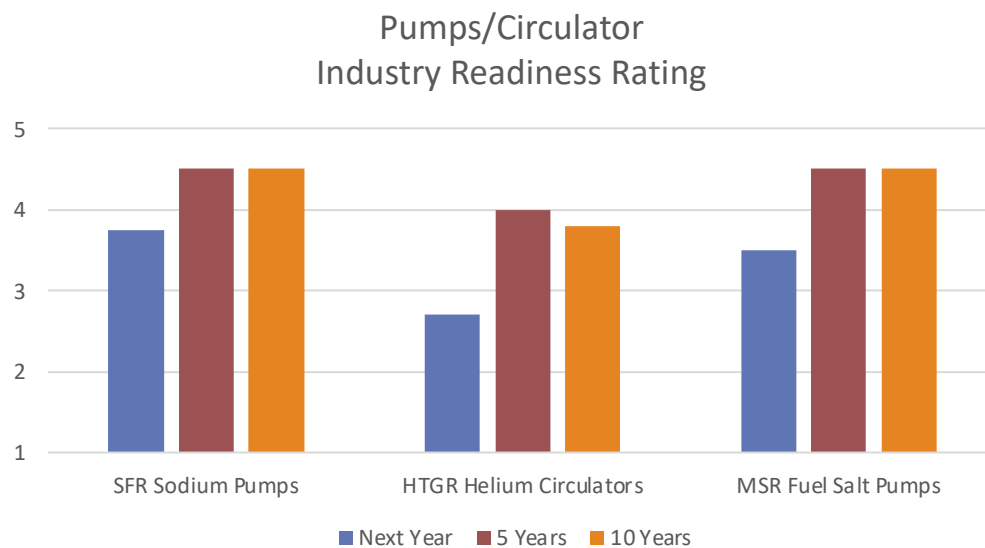


Figure 16. Assessment of industry readiness to meet pump/circulator production targets in 1, 5, and 10-year targets based on averaged company responses.

Heat Exchanger

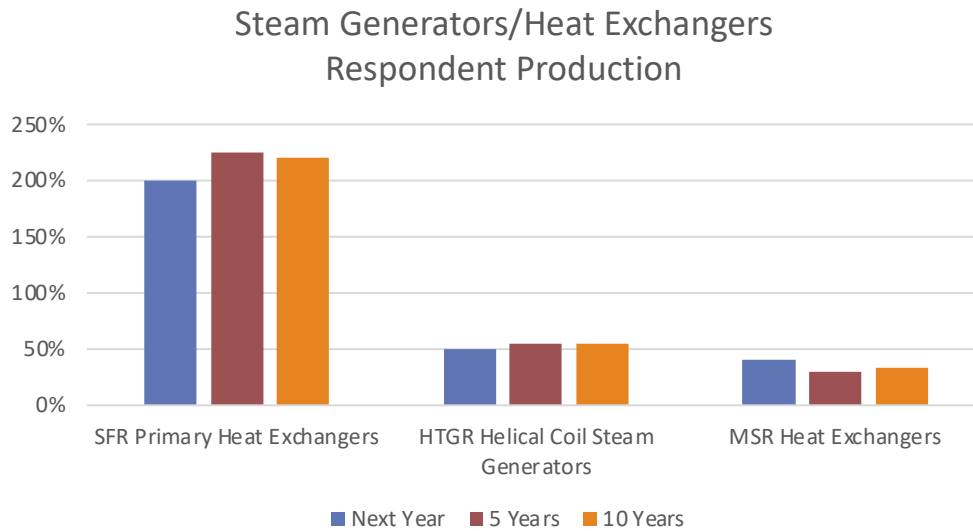


Figure 17. Aggregate heat exchanger production capacity relative to 1, 5, and 10-year targets based on all company responses (not adjusted for market share).

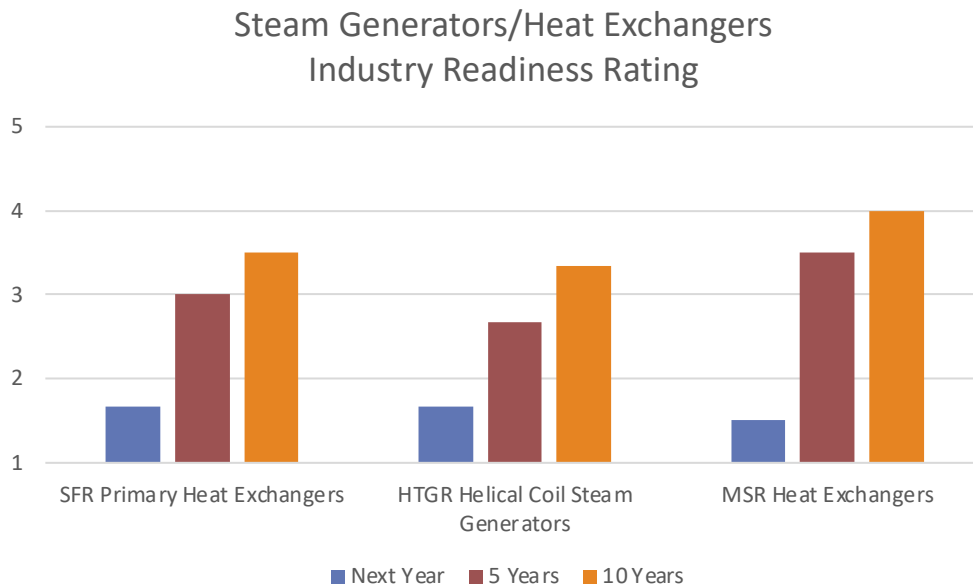


Figure 18. Assessment of industry readiness to meet heat exchanger production targets in 1, 5, and 10-year targets based on averaged company responses.

Vessel Assemblies

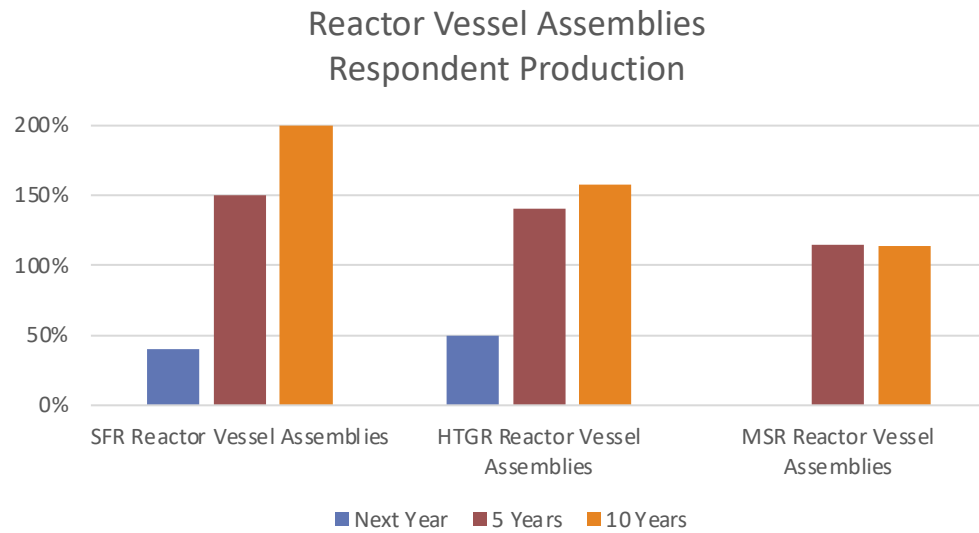


Figure 19. Aggregate reactor vessel production capacity relative to 1, 5, and 10-year targets based on all company responses (not adjusted for market share).

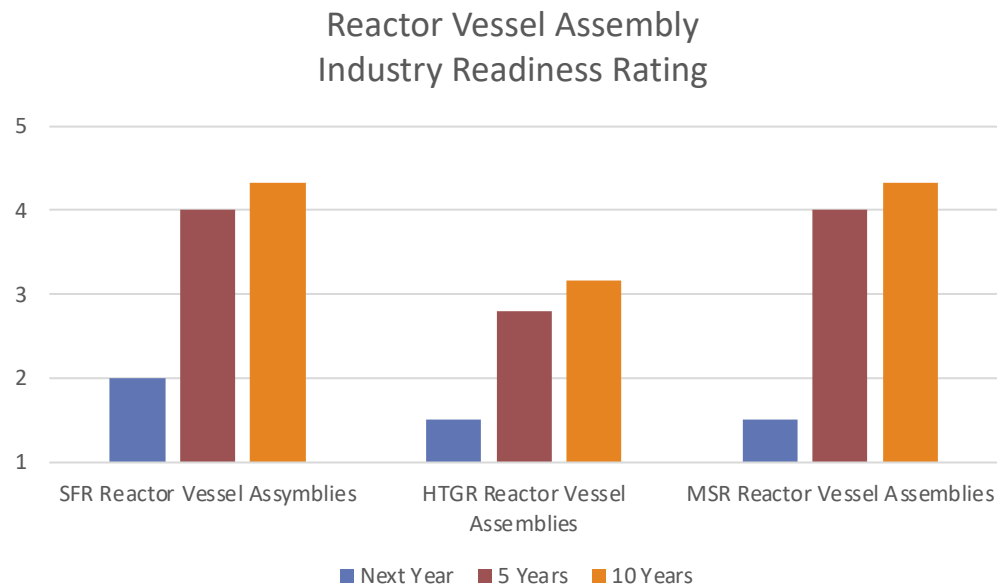


Figure 20. Assessment of industry readiness to meet vessel assembly production targets in 1, 5, and 10-year targets based on averaged company responses.

Heads

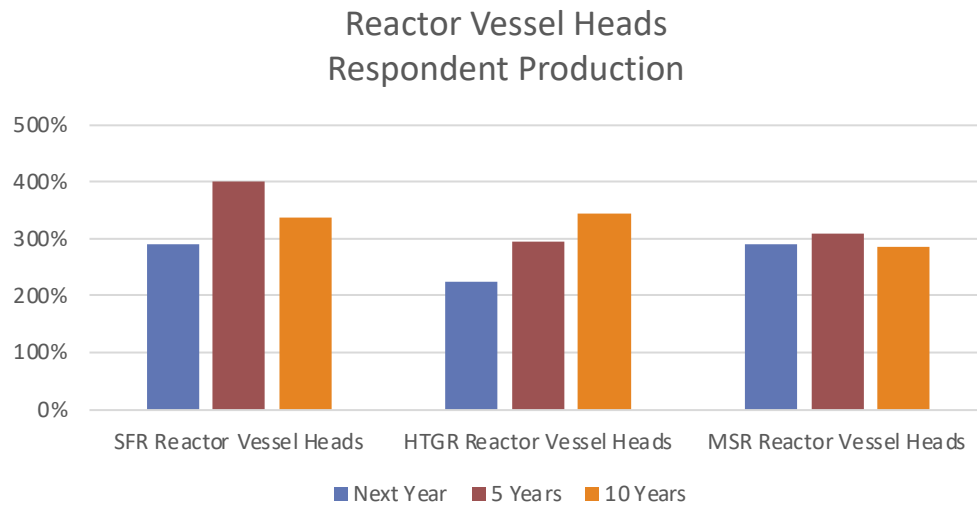


Figure 21. Aggregate vessel head production capacity relative to 1, 5, and 10-year targets based on all company responses (not adjusted for market share).

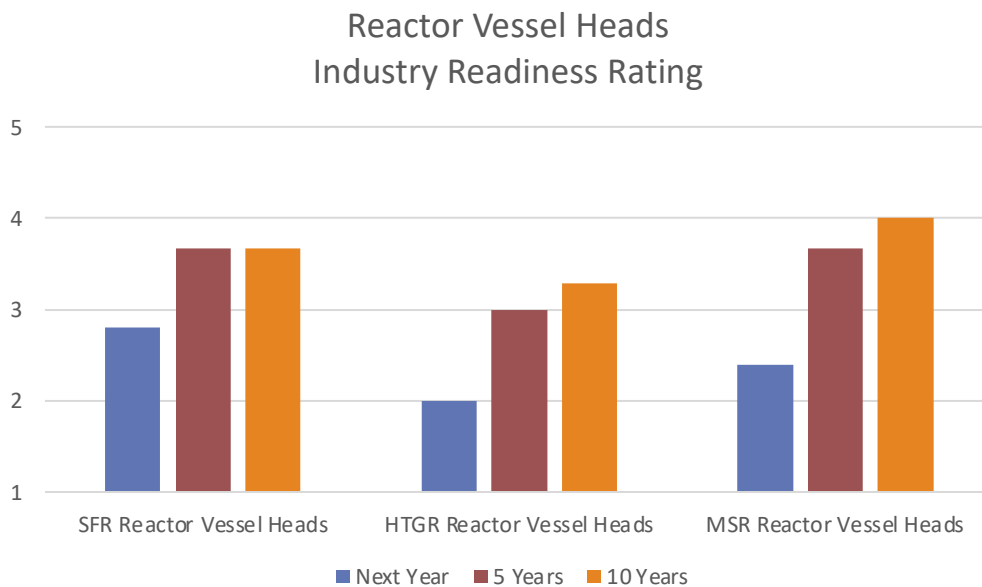


Figure 22. Assessment of industry readiness to meet vessel head production targets in 1, 5, and 10-year targets based on averaged company responses.

Rings

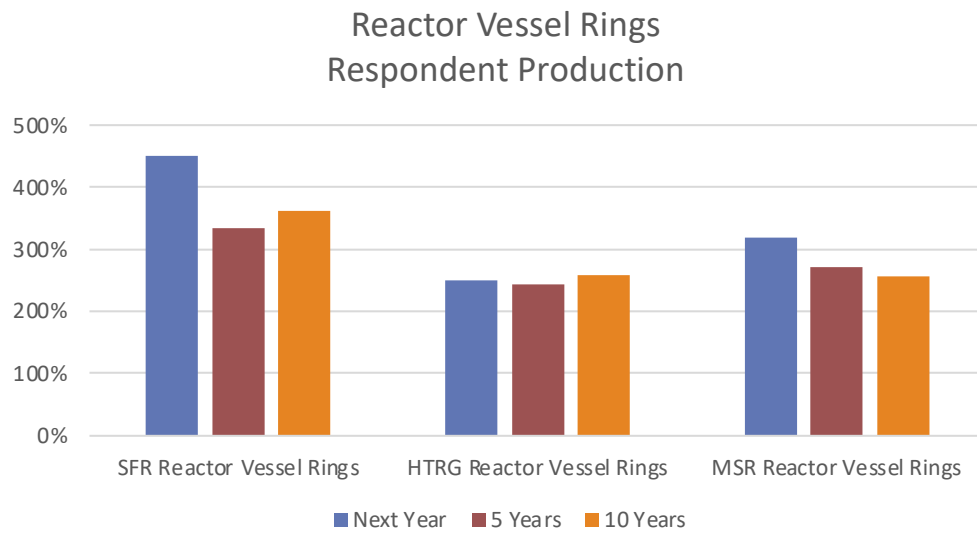


Figure 23. Aggregate vessel ring production capacity relative to 1, 5, and 10-year targets based on all company responses (not adjusted for market share).

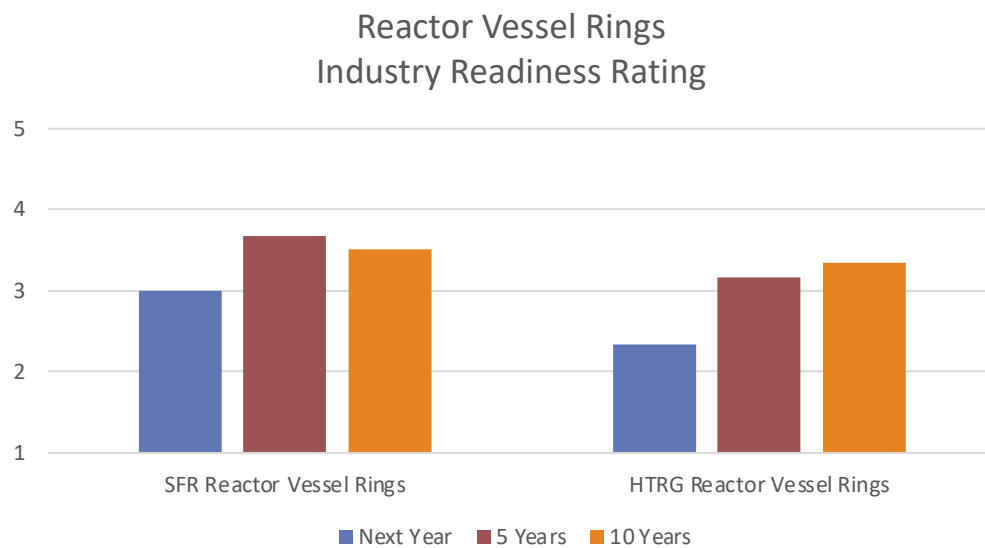


Figure 24. Assessment of industry readiness to meet vessel rings production targets in 1, 5, and 10-year targets based on averaged company responses.

Graphite

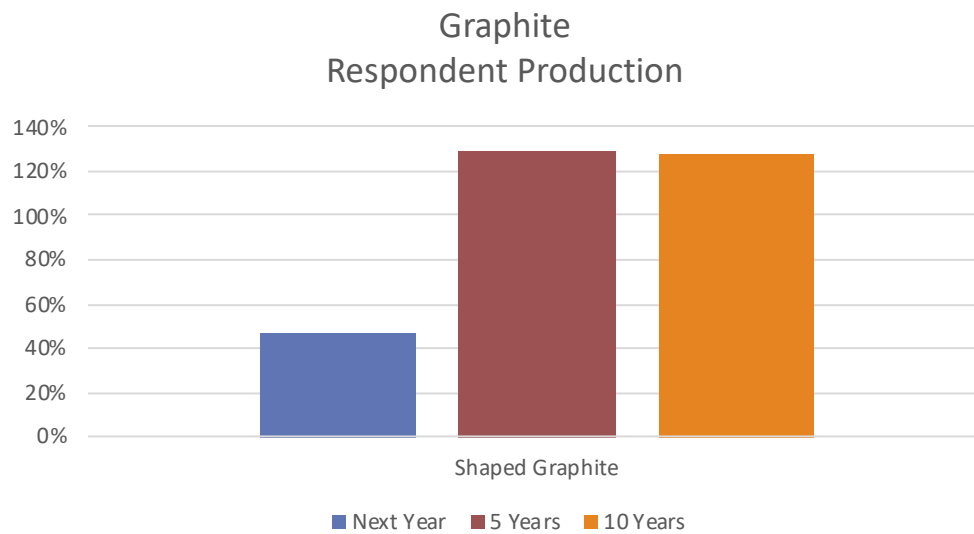


Figure 25. Aggregate graphite production capacity relative to 1, 5, and 10-year targets based on all company responses (not adjusted for market share).

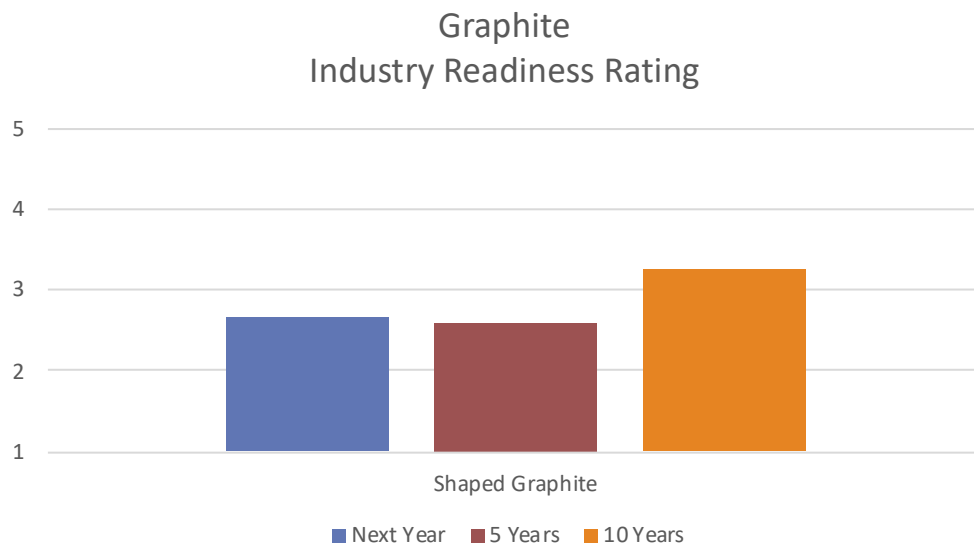


Figure 26. Assessment of industry readiness to meet graphite production targets in 1, 5, and 10-year targets based on averaged company responses.

Sensors

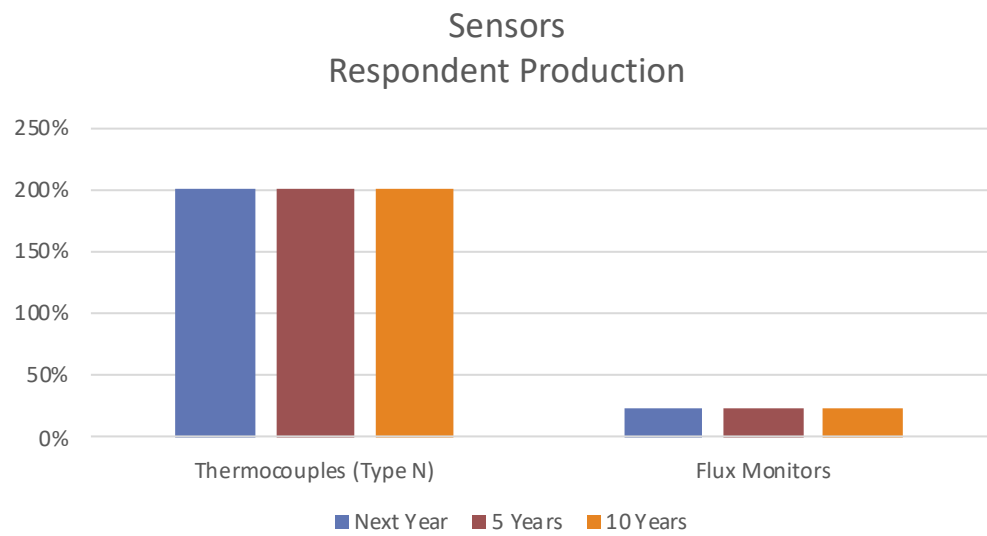


Figure 27. Aggregate sensor production capacity relative to 1, 5, and 10-year targets based on all company responses (not adjusted for market share).

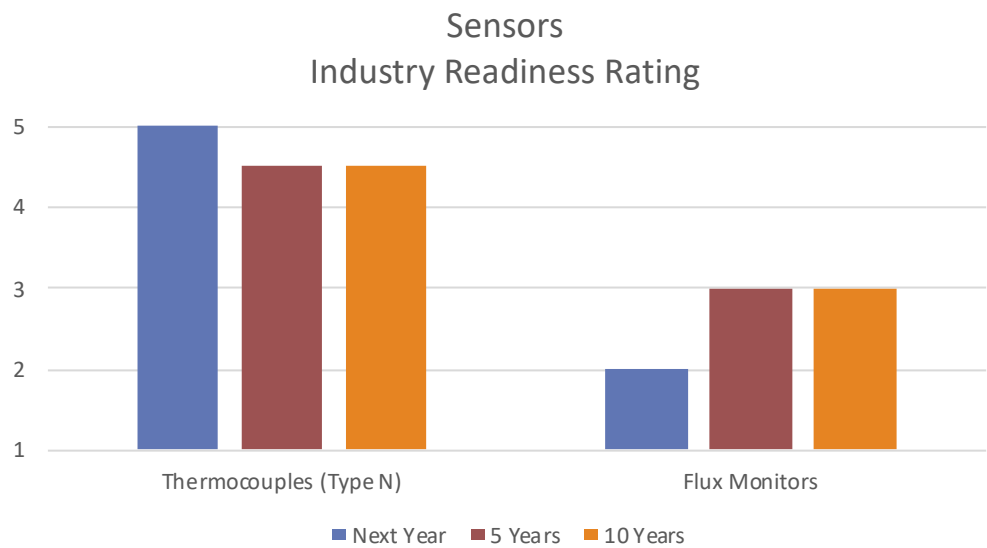


Figure 28. Assessment of industry readiness to meet sensor production targets in 1, 5, and 10-year targets based on averaged company responses.

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