

ADVANCED REACTOR MATERIALS CHALLENGE

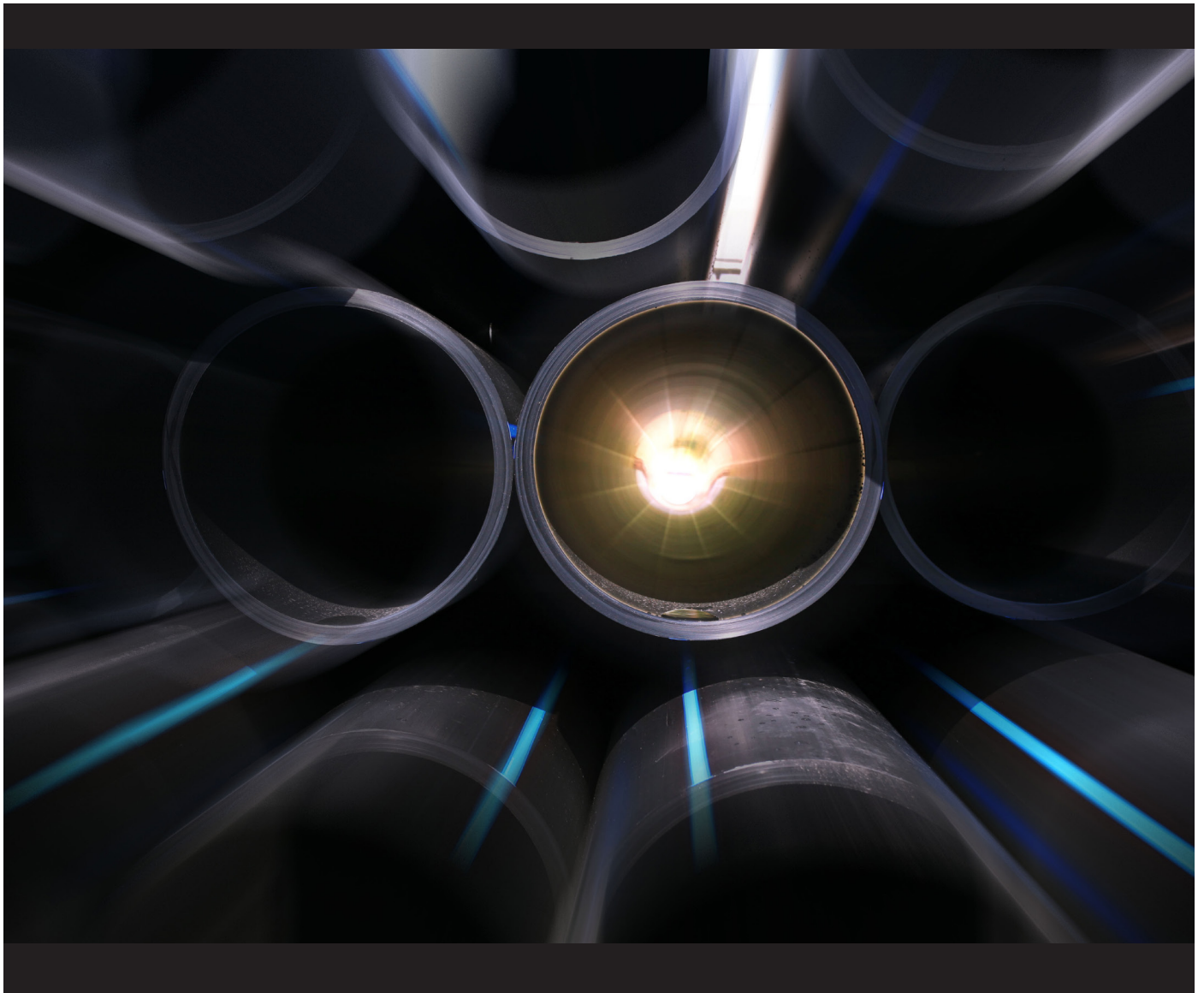


Table of Contents

Abstract.....	2
Background.....	2
Advanced Reactors Overview.....	2
Material Qualification.....	3
Overview on Advanced Reactors Technologies.....	4
Sodium Fast Reactors.....	4
Lead Fast Reactors.....	4
High-Temperature Gas-Cooled Reactors.....	4
Molten Salt Reactors.....	5
AR Materials and Challenges.....	5
Austenitic Alloys.....	5
Nickel-Based Alloys.....	5
Ferritic/Martensitic Alloys.....	5
Molybdenum and other Refractory Alloys.....	5
Graphite.....	6
Conclusions.....	6
References.....	7

KEY TERMS

Advanced Reactor (AR) – designs that employ fuels, coolants, technologies, deployment models, and other attributes and capabilities that extend beyond the current operating fleet (of large Light-Water Reactor (LWRs).

American Society of Mechanical Engineers (ASME) – an organization that enables collaboration, knowledge sharing and skills development across all engineering disciplines, including through the development of Code Cases.

Code Cases – revisions or editions to code to clarify existing requirements, provide new rules for materials or construction not covered by the existing rules. They are reviewed and approved by ASME committees on a continual basis.

Refractory Materials – materials including elements with very high melting points (like molybdenum or tungsten).

MAX-Phases – are ternary materials where M is an early transition metal, A is an A-group element (like aluminum or silicon), and X is carbon or nitrogen.

Abstract

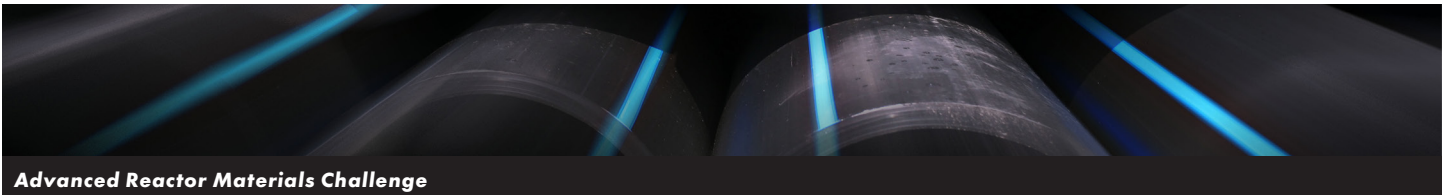
Advanced reactors (AR) are expected to be deployed in the next decade and anticipate needing new material qualifications for operating conditions that differ from traditional Light Water Reactors (LWRs), namely higher temperatures and different operating fluid environments. Two of the main challenges related to the deployment of ARs are the qualification and fabrication of the materials to be used under these new operating conditions. For these materials, some data on material properties and environmental compatibility are available to support conceptual design, but there are many gaps in the data to evaluate and qualify long-term service suitability.

This paper highlights features of selected materials for potential AR applications and describes a planned approach for their development and qualification. Using stakeholders' input, EPRI is developing AR material roadmaps by identifying key gaps in the qualification and fabrication processes, prioritizing the main actions to take, and coordinating the industry to produce the data needed. The roadmaps [14] include materials development and validation, ASME Code Cases, and accelerated qualification strategies to support fleetwide deployment of ARs in the 2030–2035 timeframe.

Background

Advanced Reactors Overview

Advanced Reactor designs typically offer attributes that depart from those of existing LWRs in terms of fuel forms, coolants, or deployment model. This includes water-cooled small modular reactors (SMRs), non-water-cooled reactors (such as high-temperature gas-cooled reactors or molten salt reactors), and various microreactor concepts. These technologies potentially offer substantial improvements over current generation technology in terms of safety, economics, performance, and long-term energy security. As efforts for global deep decarbonization continue to gain momentum, there is increased interest in ARs as a carbon-free, reliable, economical, and inherently safe source for generation of electricity and heat. These features derive from differences in temperature and environment, which necessitate the qualification of alternative materials for higher and sometimes harsher operating conditions.



Material Qualification

Currently, the ASME Boiler and Pressure Vessel Code Section III Division 5 for High Temperature Reactors (which will be referred to as *ASME Code*) includes only six materials with maximum allowed temperatures greater than 427°C, where many ARs are intended to operate. These include Type 304SS and Type 316SS up to 815°C, Alloy 800H up to 750°C, 2¼ Cr-1Mo and 9Cr-1MoV up to 650°C, and Alloy 617 up to 954°C. While these may provide a starting point, additional materials beyond these six will likely need to be qualified for the variety of decarbonization missions ARs are designed to fulfill.

ASME Code qualification for a new material, or an existing material under new operating conditions or environments, requires characterization of many phenomena that occur in the material, such as creep-fatigue, relaxation strength, tensile reduction factors for aging, cyclic stresses at high temperatures, and weldments. These

data allow estimation of the expected life of the material, which can determine the expected service life of the AR design and therefore its economic viability. Conducting testing to evaluate, analyze, and qualify materials under these new conditions is time-consuming and requires a significant amount of resources. The last metal added to the ASME Code was Alloy 617, which required 12 years and a \$15 million investment from the U.S. Department of Energy [1].

In addition to code qualification, environmental effects such as irradiation and corrosion on structural failure modes are analyzed. For this step, the owner/operator or the AR developer has the responsibility to demonstrate that the environmental effects are accounted for in their specific reactor design.

Lastly, the supply chain must be sufficiently developed to understand the fabrication methods and how the fabrication affects the material and the component performance. These three fundamental steps to deploy new materials are summarized in Figure 1.

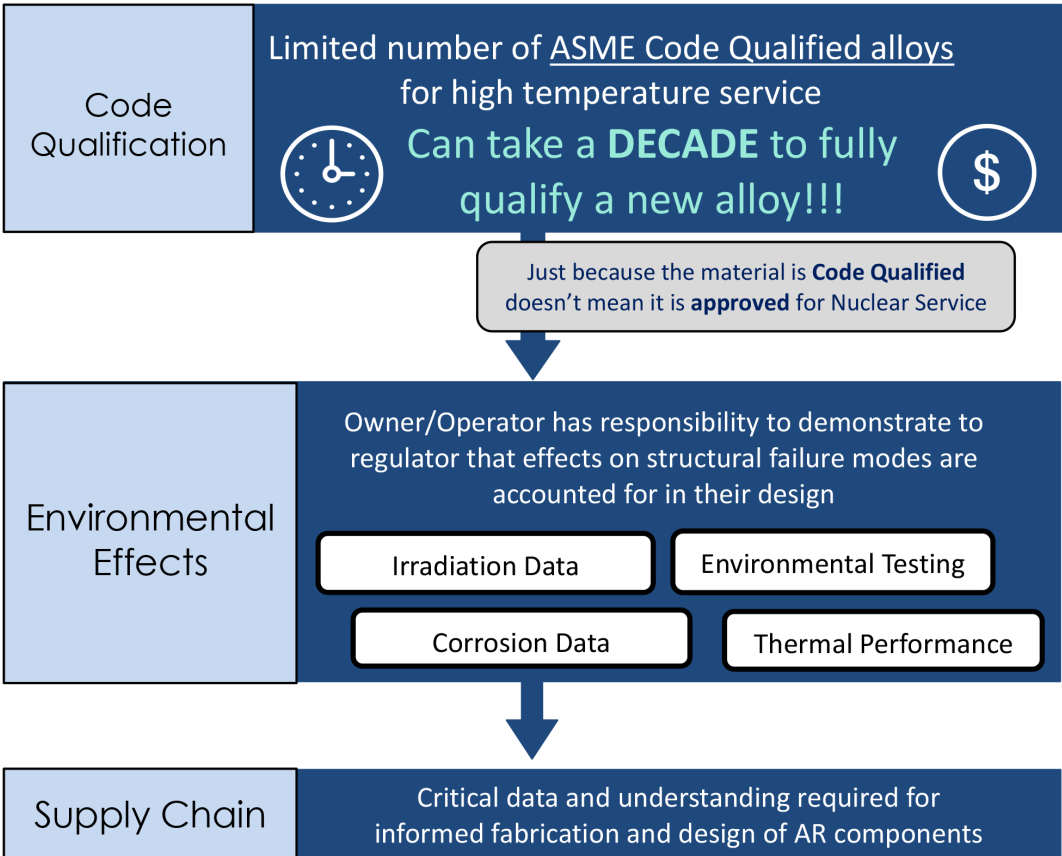
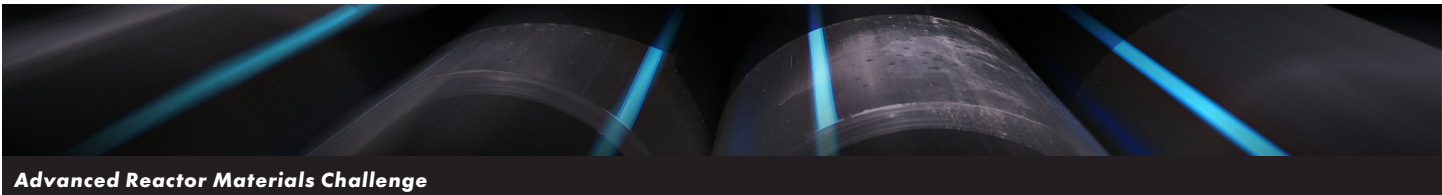


Figure 1 – Materials challenges for advanced reactors.



Based on the AR designs currently being developed, new material qualification work is needed for alloys, refractory materials, and non-metallic materials under high temperature and novel coolant conditions. In addition, data are still needed to ensure that the supply chain can produce material that is appropriately fabricated.

Overview on Advanced Reactors Technologies

Advanced Reactor designs can be grouped in many ways. In a series of material gap analysis reports produced by the Advanced Nuclear Technology program at EPRI, reactors were divided into high temperature gas-cooled reactors, sodium fast reactors, molten salt reactors, and lead fast reactors. These reports identify candidate materials for each of these reactor types, review the available data to support material implementations into designs, and plan for coordinated materials development and validation programs. The main design features of these types of ARs that dictate materials needs are described below.

Sodium Fast Reactors

Sodium fast reactors (SFRs) use liquid sodium as their coolant. The planned operating temperatures of SFRs are on the order of 450-550 °C which is considerably lower than the coolant’s boiling point, creating a favorable envelope of safety for these designs [3]. The extensive historical experience operating SFRs has allowed significant progress in the technology of handling liquid sodium, and degradation of materials in contact with sodium.

According to the EPRI Material Gap Analysis for SFRs [3], austenitic Type 316SS is currently considered as a material for internal piping for short-term systems exposed to liquid sodium, while ferritic-martensitic (FM) steels are preferred candidate materials for long-term applications. While Type 316SS is approved by the ASME Code, FM steels besides T91 are not approved for these applications.

Lead Fast Reactors

Molten lead allows reactors to operate at higher temperatures and thermal efficiencies than LWRs, while operating at near atmospheric pressure due to a boiling point even higher than liquid sodium. Lead fast reactors (LFR) can use pure lead, but also may be cooled by a lead-bismuth eutectic fluid (LBE), due to the lower melting point of LBE. The maximum temperature reached is expected to be 550°C for the lower temperature LBE-cooled LFR and 800°C for higher temperature pure lead-cooled LFRs [4].

According to the EPRI Gap Analysis for LFRs [4], materials of interest are austenitic, ferritic, and FM steels; refractory materials such as molybdenum; and non-metallic materials, such as silicon carbide and MAX Phases. While some austenitic and ferritic steels are currently approved by the ASME Code, most of the FM steels being considered for ARs, as well as refractory, and non-metallic materials, are not approved by the ASME Code for these structural applications.

High-Temperature Gas-Cooled Reactors

Contemporary high-temperature gas-cooled reactor (HTGR) designs use helium as the working fluid and feature an outlet temperature between 750°C and 1000°C. The very high-temperature reactor design (VHTR) and gas fast reactor design (GFR) are two subsets of HTGRs, though the industry has begun to refer to all of these helium-cooled designs collectively as HTGRs.

HTGR designers have selected nuclear grade graphite as one of the materials for reactor cores (commonly as the structure in which fuel particles are embedded), moderator, reflector, and structural components. It has favorable properties relating to neutron moderation, low neutron absorption, and stability at high temperature to name a few [2]. Graphite quality can be highly process dependent, so the way to qualify graphite for nuclear may be less straightforward than for the metallics mentioned already.

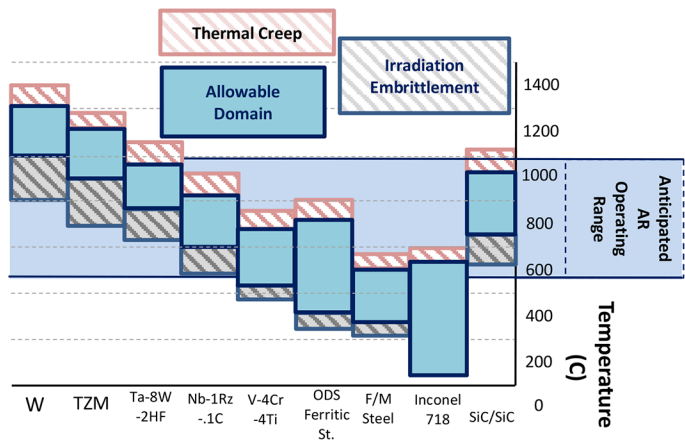


Figure 2 – Potential HTGR structural material estimated temperatures in a 10-50 dpa operating window (Adapted from [12]).

Molten Salt Reactors

Molten salt reactors (MSR) use molten salts as the primary working fluid. These salts can be exclusively used as coolant, but also can dissolve fissile material and function as a homogeneous fuel fluid. The very high boiling points of the molten salts permit higher temperatures and thermal efficiency at near-atmospheric pressures when compared to water. MSR designs differ in the chemical composition of fuel, salt, temperature of operation, identity of the fissile isotope, and the sophistication of online reprocessing. Additional information on MSR designs can be found in the EPRI Quick Insight on Molten Salt Reactors [11].

For components in contact with fluoride or chloride salts, Type 316H SS and Hastelloy N (and its variants) are being considered [5], while graphite is being considered as a moderator. Note that Hastelloy N is not currently approved by the ASME Code for these applications.

AR Materials and Challenges

Advanced reactor technology developers seek new applications for materials that are not currently approved in code for the conditions considered. The development and qualification of these materials is important for the development of ARs, but would also benefit multiple advanced power generation technologies besides ARs, such as supercritical steam or CO₂ power cycles, molten salt heat transfer, and thermal energy storage.

Austenitic Alloys

Due to the existing ASME Code-qualified austenitic stainless steels (e.g., Types 304SS and 316SS) for 60-year lifetime components, these materials are considered as structural materials for the demonstration phase of some of the reactor concepts previously discussed. However, they present some challenges for long-term applications. For example, the oxide layer that protects the material in liquid lead dissolves at temperatures higher than 400 °C unless the amount of oxygen is tightly controlled. In liquid sodium, loss of nickel can occur. In both environments, creep and creep-fatigue at very high temperatures are not fully assessed and need additional investigation to allow inclusion for very high temperatures applications in the ASME Code [8].

Nickel-Based Alloys

Nickel-based alloys such as Hastelloy N are currently considered for MSRs due to their corrosion resistance in the salt mixtures most developers intend to use. Modifications of Hastelloy N have been developed worldwide (EM-721 in France, HN80MTY in Russia, GH3535 in China) to enhance corrosion resistance. Hastelloy N was used in the Molten Salt Reactor Experiment at Oak Ridge National Lab and is currently qualified for use in Section VIII, “Design Rules for Unfired Vessels,” Division 1, up to 704°C and, Division 2, up to 427°C [10]. This alloy is not currently qualified for construction of nuclear components in ASME Section III, Division 5. The qualification of this material for Division 5 would require considerably more testing, including long-time aging and creep rupture of base metal in the requested product forms and weldments, as well as creep-fatigue characterization.

Ferritic/Martensitic Alloys

For many AR designs, FM alloys, such as T91, EM10, EM12, and HT-9, are being considered for in-core and out-of-core applications due to their higher thermal conductivity [9], reduced swelling, and smaller radiation-induced ductile-brittle transition shifts compared to austenitic stainless steels. While these FM materials look promising, demonstration is needed for their swelling behavior, welding techniques, and other properties such as their coefficients of friction in sodium. Additionally, FM alloys are not available in large sections and sufficient volume to support fabrication of large plant components. Large-scale production capability would be needed to allow wide-spread usage of FM alloys for this scope. Currently, T91 is included in the ASME Code, while the other FM alloys mentioned are not [3].

Molybdenum and other Refractory Alloys

Molybdenum is a refractory metal that is commercially available, although it is not typically used for fabrication of large components because it is brittle and difficult to weld. Other refractory alloys with niobium and tantalum as the base metal are also being considered for AR applications, though molybdenum is still the most common choice. Molybdenum is alloyed with other elements such as rhenium for ease of welding, and titanium, zirconium, and carbon for manufacturing. Its high corrosion resistance has led AR designers to consider it as a cladding to protect materials in harsh environments.

Some basic material properties are available for molybdenum, and some of its alloys. Corrosion data at the temperatures of interest are largely limited to short times and static conditions [4]; irradiation performance data are also limited. Additionally, molybdenum and its alloys typically lack specifications or codification (no refractory metals or alloys are currently included in the ASME Code), requiring the demonstration of high-temperature mechanical properties. Therefore, substantial basic materials research and demonstration of acceptable properties are required before moving towards the necessary component-level and combined-effects testing.

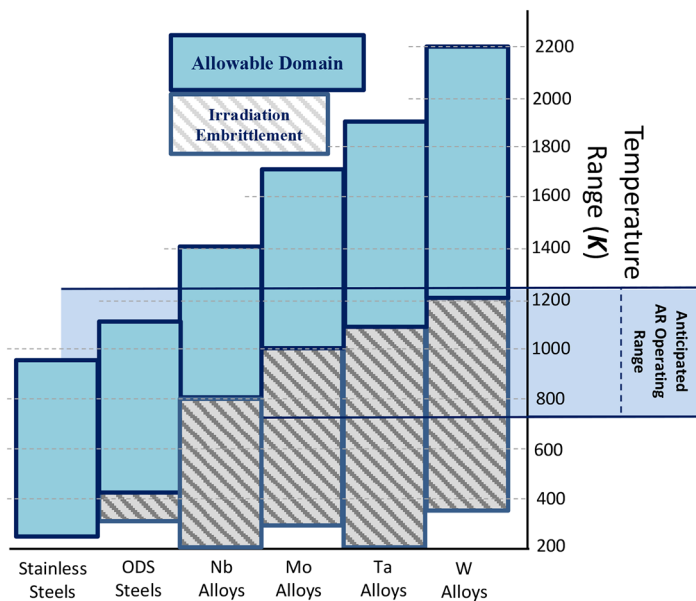


Figure 3 – Effective temperature range of various high-temperature alloys (Adapted from [13]).

Graphite

Graphite material properties are very different from steels and present many unique challenges, such as variability of properties depending on the precursors and manufacturing process (e.g., graphite strength can vary within a single billet of graphite).

While data on graphite properties are available from past operating reactors, previously characterized graphite grades are no longer produced. Therefore, new campaigns to acquire data and tools to predict the behavior of currently available graphite grades are required to commercialize selected graphite grades for component applications.

Although graphite is not Code-qualified, the ASME Code includes rules for design, construction, examination, and testing of graphite core components and graphite core assemblies. These rules specify that the designer is responsible for obtaining the necessary graphite design data [6]. Additionally, because graphite properties change with operating time, the designer must predict stresses over the lifetime of the graphite component.

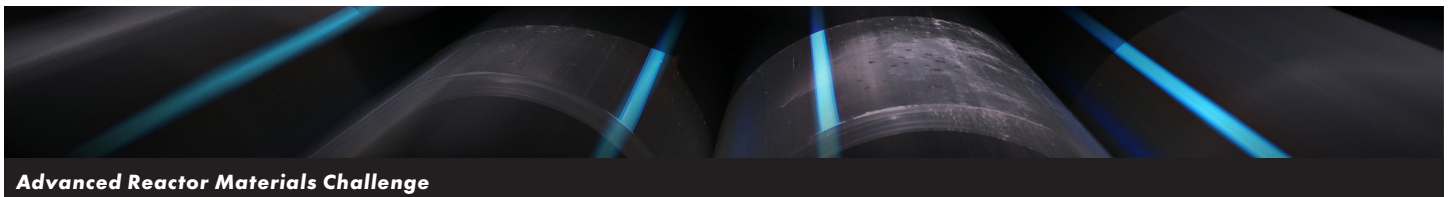
EPRI’s gap analysis for the prospective materials for HTGRs [7] provides a list of technology gaps for graphite identified for long term operation, which includes: irradiation effects on material properties, availability of graphite supply for long lifetime design, consensus design codes, materials testing standards, development of improved understanding and models for neutron irradiation-induced displacement damage, and development of non-destructive examination/inspection methods for use in and out of the core.

Conclusions

AR designs are substantially different than conventional LWRs. Accordingly, new development work is needed to qualify materials to be added to the ASME Section III Division 5 and for applications to specific conditions of ARs.

For new materials to be qualified and proposed for AR applications, some properties may already be available to support conceptual design, but there are likely many gaps in the data for evaluating long-term service. Often, the main need is to develop ‘long-term’ data, for which the exact testing duration depends on component design life and the extent of extrapolation that can be justified. While test campaigns are currently underway worldwide for some of the materials selected, a collective and organized effort is needed to produce the data required to qualify and manufacture components for ARs.

In this framework, EPRI has assessed the main gaps for several probable materials, prioritized them, and identified a path forward [3, 4, 7, 10]. The gap analysis information is summarized in the roadmap that discusses each material considered for AR applications. The interactive roadmap [14] is available online to guide the effort for the successful construction of ARs in the 2030–2035 timeframe.



In accordance with the roadmap priorities, EPRI is working with stakeholders to generate data needed for code qualification, environmental tests, and supply chain preparation. EPRI is also working to focus industry on defining accelerated qualification approaches with faster approval time to enable material options for AR designs, such as a staggered qualification approach with initial approval for shorter design/operating lifetimes & component monitoring. Sharing the data generated in non-proprietary databases would support the industry as a whole to meet their AR timelines.

References

1. World Nuclear News, “Alloy clear for use in high-temperature reactors,” May 2020, <https://world-nuclear-news.org/Articles/Alloy-qualified-for-use-in-high-temperature-reactor>, accessed on June 16, 2021.
2. W.E. Windes, T.D. Burchell, M. Davenport, “The Advanced Reactor Technologies (ART) Graphite R&D Program,” *Nuclear Engineering and Design*, Volume 362, 2020, <https://doi.org/10.1016/j.nucengdes.2020.110586>.
3. *Program on Technology Innovation: Material Property Assessment and Data Gap Analysis for Sodium-Cooled Fast Reactors*. EPRI, Palo Alto, CA: 2020. 3002016949.
4. *Program on Technology Innovation: Materials Properties Assessment and Gap Analysis for Lead-Cooled Fast Reactors – A Survey of Available Materials Data*. EPRI, Palo Alto, CA: 2019. 3002016950.
5. “Status of Metallic Structural Materials for Molten Salt Reactors,” Rev. 0 Idaho National Laboratory, (INL/EXT-18-45171), U.S. Department of Energy, May 2018.
6. D. Morton, R. Jetter, J. Nestell, T. Burchell, S. Sham, “Section III, Division 5: Development and Future Directions,” PVP2012-78062, 2012.
7. *Program on Technology Innovation: Material Property Assessment and Data Gap Analysis for the Prospective Materials for Very High Temperature Reactors (VHTRs) and Gas-Cooled Fast Reactors (GFRs)*. EPRI, Palo Alto, CA: 2020. 3002015815.
8. “Development of Advanced 9Cr Ferritic Martensitic Steels and Austenitic Stainless Steels for Sodium Cooled Fast Reactors,” Oak Ridge National Laboratory, March 2016.
9. R. Klueh, A. Nelson, “Ferritic steels for next-generation reactors,” *Journal of Nuclear Materials*, (2007). 371. 37-52. 10.1016/j.jnucmat.2007.05.005.
10. *Program on Technology Innovation: Material Property Assessment and Data Gap Analysis for the Prospective Materials for Molten Salt Reactors*. EPRI Palo Alto, CA: 2019. 3002010726.
11. *Molten Salt Reactors*. EPRI, Palo Alto, CA: 2020. 3002020066.
12. Zinkle, S. J. and J. T. Busby, “Structural Materials for Fission and Fusion Energy,” *Materials Today*, Volume 12, No. 11, November 2009.
13. M. S. El-Genk, J. M. Tournier, “A Review of Refractory Metal Alloys and Mechanically Alloyed-oxide Dispersion Strengthened Steels for Space Nuclear Power Systems,” *Journal of Nuclear Materials* 340 (2005) 93–112, doi:10.1016/j.jnucmat.2004.10.118.
14. *Advanced Reactor Materials Development Roadmap*. EPRI, Palo Alto, CA: 2021. 3002022979.

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.:

EPRI prepared this report.

THE TECHNICAL CONTENTS OF THIS PRODUCT WERE NOT PREPARED IN ACCORDANCE WITH THE EPRI QUALITY PROGRAM MANUAL THAT FULFILLS THE REQUIREMENTS OF 10 CFR 50, APPENDIX B. THIS PRODUCT IS NOT SUBJECT TO THE REQUIREMENTS OF 10CFR PART 21.

Note

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

EPRI RESOURCES

Daniel Moneghan, *Technical Leader*
704.595.2458, dmoneghan@epri.com

Advanced Nuclear Technology

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.



Export Control Restrictions

Access to and use of this EPRI product is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or U.S. permanent resident is permitted access under applicable U.S. and foreign export laws and regulations.

In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI product, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI products, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes.

Your obligations regarding U.S. export control requirements apply during and after you and your company's engagement with EPRI. To be clear, the obligations continue after your retirement or other departure from your company, and include any knowledge retained after gaining access to EPRI products.

You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of this EPRI product hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.