Letter Report
TLR-RES/DE/REB/2022-08

STATUS OF ADVANCED NON-LIGHT WATER REACTOR RESEARCH ACTIVITIES: MATERIALS, CHEMISTRY, AND COMPONENT INTEGRITY

September 2022

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Executive Summary

The U.S. Nuclear Regulatory Commission (NRC) developed a vision and strategy to assure regulatory readiness for efficiently and effectively licensing and regulating a new generation of advanced non-light water reactors (ANLWRs) (Agencywide Documents Access and Management System (ADAMS) Accession No. ML16356A670). The vision and strategy utilize three objectives: 1) enhancing technical readiness, 2) optimizing regulatory readiness, and 3) optimizing communication. To meet these objectives, the NRC developed an implementation action plan with six strategies and associated near- and mid-term goals (ADAMS Accession Nos. ML17165A069 and ML17164A173). This report documents activities being conducted for the Strategy 2 goals which includes identifying, developing, and acquiring sufficient computer codes and tools to address materials, chemistry, and component integrity (MCCI) issues. A multi-pronged approach to proactively prepare the agency to review license submittals was implemented. The overarching objectives were to assess the performance needs and issues, identify gaps in knowledge, data, and assessment tools, and develop resources and computational tools. Significant progress has been achieved and near-term goals were completed in 2021 and supported pre-application ANLWR submittals.

Accomplishments of near-term goals was accomplished through staff efforts and through coordination with national laboratories, industry, and international regulatory partners. The staff identified technical gaps for high-temperature behavior of metals, salt compatibility, molten salt chemistry, high-temperature corrosion/erosion/oxidation of structural materials, and graphite degradation. Contracts with national laboratories were implemented to gather materials information, provide training, and perform testing and analysis. Achievements include:

- Issuance of high-temperature materials guidance documents and development of a computer tool.
- Assessment of the methodologies for design and fitness-for-service evaluation practices for components subject to creep-fatigue damage, in several different construction/design codes and standards.
- Analysis of international regulatory frameworks through survey on materials qualification and lifetime performance.
- Computational tool to assess aging and degradation of graphite components, based on probability-of-failure approaches.
- A draft regulatory guide documenting the staff’s endorsement (with limitations) of the ASME Section III, Division 5 code “High Temperature Reactors,” was issued for public comment, along with associated technical basis documents.
- A draft regulatory guide endorsing ASME Section XI. Division 2 “Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Power Plants” for ANLWR applications.

Mid-term goals commenced this year, which include the continued development of tools and addressing emerging challenges as licensee applications are reviewed. Pre-applications and licensing reviews for fifteen advanced reactor designs are in the review process. Mid-term goals focus on identifying emerging needs, maintaining a knowledge base, leveraging international partnerships, and ongoing development of new codes and tools. The outcome from these activities is to have sufficient analytical capabilities within the needed timeframes to support regulatory interactions and reviews of applications for licenses, certifications, and approvals.

The NRC continues to address MCCI gaps in research focus areas to better understand the unique computational tools, experimental data, features, phenomena, and knowledge gaps related to ANLWR technologies. The NRC has ongoing contracts with national laboratories, including

Argonne National Laboratory, Idaho National Laboratory, Pacific Northwest National Laboratories (PNNL) and Oak Ridge National Laboratory (ORNL), to further develop technical assessments and tools. The NRC continues to expand engagement with international groups and regulatory counterparts that include the Office for Nuclear Regulation (United Kingdom), Japan Atomic Energy Agency, and Řež Nuclear Research Institute (Czech Republic) to promote the exchange of technical and regulatory experience while establishing pathways for collaboration and research.

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1. Introduction

To prepare for potential license applications for ANLWR types, the U.S. Nuclear Regulatory Commission (NRC) developed a vision and strategy to ensure effective and efficient preparation. In December 2016, the NRC issued “Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness” [1], which describes the overarching objectives, strategies, and contributing activities necessary to achieve ANLWR mission readiness.

The NRC developed and summarized the near-term actions identified in the vision and strategy document in “NRC Non-Light Water Reactor Near-Term Implementation Action Plans,” issued July 2017 [2]. In “NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy—Staff Report: Near-Term Implementation Action Plans,” Volume 2, “Detailed Information,” issued November 2016 [3], the NRC listed several contributing activities, which provide the details of how the NRC will achieve the goals and objectives stated in the vision and strategy document. Near-term is defined as five years and the period of near-term is now complete. The NRC has made significant progress in achieving the near-term goals to understand and develop tools that support ANLWR licensing activities. Mid-term actions are underway with the goals of continued research and tool development, ongoing assessment of structural materials issues and performance needs, and support for regulatory framework development.

This report documents work conducted in support of several contributing activities related to the area of MCCI in Strategy 2, “Acquire/develop sufficient computer codes and tools to perform non-LWR regulatory reviews.” These contributing activities include the following:

> Contributing Activity No. 2.29: Assess the performance needs and issues for structural materials to be used in non-light-water reactors (non-LWRs), such as high-temperature gas-cooled reactors (HTGRs), sodium-cooled fast reactors (SFRs), and molten salt reactors (MSRs). The assessment will include the state-of-the-knowledge, ongoing domestic and international research, applicable international Operational Experience (OpE), codes and standards activities, gaps in knowledge, data, and assessment tools.
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> Contributing Activity No. 2.30: Conduct research activities to develop technical bases to resolve major materials-related issues. Collaborate with domestic (Department of Energy (DOE)), Electric Power Research Institute (EPRI)) vendors and international regulatory partners [based on the recommendations from the assessment report from Contributing Activity No. 2.29].
>
> Contributing Activity No. 2.31: Support the development of a draft regulatory framework for materials-related issues (relevant Standard Review Plan chapters, guidance, etc.) for non-light water reactors.

2. Completed Near-Term Research Activities

Strategy 2 supports the ANLWR vision and strategy objective of enhancing ANLWR technical readiness and optimizing regulatory readiness. To address Strategy 2, the NRC staff identified MCCI activities that focused on (1) assessing performance needs and issues for materials and component integrity in ANLWRs, (2) supporting the development of a regulatory framework for ANLWRs, (3) enhancing staff knowledge and review readiness, and (4) closing gaps in knowledge, data, and assessment tools. The staff developed and implemented transformational approaches to identify, prioritize, and conduct research activities to meet the objectives of Strategy 2 and facilitate a more effective and efficient review of ANLWR applications as a more modern and risk-informed regulator.

2.1. Research Focus Areas

To support Strategy 2, the staff identified major MCCI gaps associated with various ANLWR technologies. Applying risk insights and available knowledge, these technical areas were identified to focus NRC efforts and resources on addressing MCCI areas that could most impact performance needs and issues for ANLWRs. The NRC conducted activities to address the MCCI gaps in these research focus areas. These activities, as described below, allow the staff to better understand the unique codes, experimental data, features, phenomena, and knowledge gaps related to ANLWR technologies.

Periodic status meetings are held quarterly between NRC-DOE-EPRI to share information, data, and knowledge of ANLWR MCCI research activities. The aim of these meetings is to enhance common understanding of technical issues impacting safety and to address areas of potential gaps in knowledge useful for engineering assessments, as well as looking for areas for collaboration.

2.1.1. High Temperature Materials

2.1.1.1. Creep-Fatigue

The design of structural components for high-temperature ANLWRs requires considering an expanded set of potential structural failure modes when compared to LWR designs. For example, under high-temperature cyclic service, the combination of creep and fatigue deformation reduces the service life of components when compared to low-temperature, pure fatigue conditions. Component designs must then account for creep-fatigue failure.

The NRC contracted with Argonne National Laboratory (ANL) to review the best practices for elevated-temperature creep-fatigue in creep-induced cracking design. This included surveying available design methods and creep-fatigue engineering practices from various design/construction codes including ASME Section III, Division 5, and several other international standards. In a similar manner, ANL assessed creep-induced cracking in the heat-affected zone of weldments.

The report on this work, ANL-19/13, "Environmental Creep-Fatigue and Weld Creep Cracking: A Summary of Design and Fitness-for-Service Practices," issued January 2020 [6], listed in Table 1, found that the American Society of Mechanical Engineers (ASME) Section III, Division 5, creep-fatigue design procedures are generally conservative, not accounting for environmental effects. The report identified the interaction of environmental effects with creep-fatigue as the biggest concern because the current ASME procedures do not account for these effects. The report recommended additional research in several areas. For general creep-fatigue design procedures, the report recommended:

(1) investigation of the adequacy of the current time-fraction approach used in the code for long design lives and multiaxial stress states, (2) investigation of the conservatism of the current procedures to address complex stress states (notch effects), and (3) assessment of the true margins in the ASME Code creep-fatigue design procedures accounting for uncertainties. For environmental effects on creep-fatigue design, the report recommended development of: (1) an assessment method for creep-fatigue in harsh environments, (2) a technical basis for in situ surveillance programs for creep and creep-fatigue damage, (3) an assessment method for clad components for high-temperature service, and (4) a method for establishing corrosion allowances. For creep-fatigue of weldments and evaluation of flaws, the report recommended: (1) development of a high-temperature flaw assessment method, and (2) development of methods for assessing an assumed flaw in a high-temperature component (flaw-tolerant design).

Additionally, ANL developed post-processing tools, listed in Table 1 below, to aid in executing the ASME Code, Section III, Division 5, rules and made these tools available to the NRC. The tools are agnostic to the choice of analysis method or to the finite element analysis package. The tools include a digitization of the Division 5 design data, methods for handling and combining design load cases, tools to ease stress classification and linearization, and methods for executing particular design provisions. These tools, developed under an ASME Nuclear Quality Assurance (NQA-1) program, are now available on the NRC public Web site.

In accordance with the recommendation from ANL-19/13 to investigate the conservatism of the current creep-fatigue design procedures to address complex stress states (notch effects), ANL investigated whether the current creep-fatigue design rules are conservative for components with complex, multiaxial stresses (notch effects). In this effort, numerical analyses were used to compare the life predictions made by different creep-fatigue design processes for structures with increasingly triaxial, three-dimensional stress states.

2.1.1.2. High-Temperature Corrosion/Erosion/Oxidation of Structural Materials

Impurities in the primary helium of HTGR can result in corrosion, oxidation, and other degradation of mechanical properties that may degrade important advanced reactor system structures and components. More mechanistically based predictive methods are needed to handle the various material-specific damage mechanisms in different environments. The potential for environmental degradation can be significant for high-temperature materials.

OpE with SFR has demonstrated that austenitic stainless steels are highly corrosion resistant to molten sodium; however, this corrosion resistance depends on sodium purity. Impurities, oxygen, and moisture in the primary sodium of an SFR are among the factors that can significantly accelerate corrosion rates. Historically, oxygen and moisture ingress has led to prolonged shutdowns and repairs in SFRs (e.g., Super Phoénix). A technical basis for impurity limits in the primary sodium will be necessary to help inform regulatory guidance.

Similar to molten salt compatibility issues, there is a significant need to develop guidance for surveillance programs, irradiation testing criteria, and corrosion tests in HTGR and SFR environments.

2.1.1.3. ASME Section III, Division 5, Review and Endorsement Activities

- The NRC reviewed the 2017 Edition of the ASME Code, Section III, Division 5, for endorsement. The Division 5 code provides rules for design of high-temperature metallic and graphite reactor components (operating temperature ≥ 425°C (800°F)), along with rules for components operating at lower temperatures in high-temperature reactor systems.

Endorsement of Division 5 will enable applicants for ANLWR designs to design components to a set of rules endorsed by the NRC. The NRC has documented the technical basis of its review in a Nuclear Regulatory Report (NUREG), “Technical Review of the 2017 Edition of ASME Section III, Division 5, ‘High Temperature Reactors,’” NUREG-2245, and guidance will be provided in a revision to Regulatory Guide 1.87, “Guidance for Construction of Class 1 Components in Elevated-Temperature Reactors” [9]. The endorsement of Division 5 is covered under Strategy 4, “Facilitate industry codes and standards needed to support the non-LWR life cycles (including fuels and materials),” but there is considerable synergy with most of the Strategy 2 research areas.

- The NRC issued the draft regulatory guide DG-1380 (proposed Revision 2 to RG 1.87) for public comment on August 20, 2021, and the public comment period closed on October 20, along with NUREG-2245 which contains the technical basis for DG-1380’s endorsement of ASME Section III Division 5. Additionally, the staff reviewed two code cases (N-872 and N-898) permitting the use of Alloy 617 in conjunction with Section III, Division 5, for endorsement in DG-1380. The NRC issued a Federal Register Notice (87 FR 11490) describing the additions to DG-1380 related to the endorsement of the Alloy 617 code case for a 30-day public comment period, which ended on March 31, 2022. The technical basis for the staff’s review of code cases N-872 and N-898 is documented in technical letter report, TLR/RES/DE/REB-2022-01. The staff has prepared responses to the public comments and revised DG-1380 and NUREG-2245, accordingly. The final regulatory guide (i.e., RG 1.87 Revision 2) and NUREG-2245 are going through internal review and approval and the staff anticipates that they will be issued before the end of this calendar year 2022.

2.1.2. Molten Salt

MSRs, particularly the fluid-fueled types, pose unique challenges with regards to materials, fuel performance, and radionuclide management. Compatibility of materials with molten salt coolants is one of the more unique aspects of MSR design.

2.1.2.1. Molten Salt Compatibility

Potential MSR applicants may restrict their designs to use materials currently approved in ASME Boiler and Pressure Vessel Code, Section III, “Rules for Construction of Nuclear Facility Components,” Division 5, “High Temperature Reactors” [4] (e.g., 316H), or choose cladding materials that provide adequate corrosion resistance to molten salts. Therefore, the molten salt compatibility of materials currently approved in Division 5, with and without protective cladding, need evaluation. Preliminary NRC-funded research identified a need to develop guidance for surveillance programs, irradiation testing criteria, and corrosion tests. Factors such as salt purity and material chemistry have a significant impact on the corrosion resistance of structural alloys. In the area of molten salt compatibility, NRC contracted with ORNL to develop a report on molten salt compatibility that addresses guidance for surveillance programs, irradiation testing criteria, and corrosion tests, along with factors such as salt purity, material chemistry, and others that have a significant impact on the corrosion resistance of structural alloys. The report, Technical Assessment of Materials Compatibility in MSRs (ADAMS Accession No. ML21084A039) was issued in March 2021. The second phase of work that will look at standardization for molten salt corrosion testing with a view to aiding the NRC in evaluating corrosion data submitted as part of a license application. Currently there is no systematic comparison of static corrosion methodologies, in which different tests are compared with all other variables controlled, such as the quality of the salt. This effort looks to provide guidance to the NRC staff with regard to evaluation of static corrosion test data submitted by vendors during any potential pre-application or licensing actions.

This work is scheduled to be completed later this calendar year.

2.1.2.2. Technical Expertise

The NRC continues to expand its technical expertise in this molten salt chemistry and materials through various activities. These activities support the NRC's efforts to identify data needs for analytical tools and codes in the context of Strategy 2. Since the previous report, the NRC staff has continued to review reports and peer-reviewed journal articles to identify knowledge gaps and potential regulatory gaps with a particular focus on corrosion and materials-related issues. The NRC staff participated on an ORNL-led working group, along with National Laboratory subject matter experts and industry representatives to evaluate the current capability to assess the ability of liquid-salt–fueled MSRs to achieve their fundamental safety functions (FSFs), using a phenomenon identification and ranking table (PIRT) process. The final report was issued in September 2021 [Holcomb, D.E., et al, Molten Salt Reactor Fundamental Safety Function PIRT, ORNL/TM-2021/2176]. RES staff took the role of agency representative on the American Nuclear Society (ANS) working group to develop to ANS 20.2, "Nuclear Safety Design Criteria and Functional Performance Requirements for Liquid-Fuel Molten Salt Reactor Nuclear Power Plants." The standard is currently under ANS review. Additionally, the staff conducts periodic meetings with the DOE MSR National Technical Director to discuss research priorities and identify areas for collaboration.

2.1.3. Graphite Degradation

Graphite undergoes significant stress and distortion due to oxidation and irradiation in an operating nuclear environment, with accompanying dramatic changes in material properties from irradiation damage and oxidative degradation. Nonmetallic graphite and ceramic composite components for nuclear applications have recently been added to the ASME Code, Section III, Division 5, with the replacement of the traditional deterministic approach with a statistical, probability-of-failure (POF) methodology. The POF is calculated by comparing the distribution of expected operational stresses of a component during operation to the inherent material strength for the graphite grade. This is currently done independently for each component.

2.1.3.1. Training on Graphite Degradation, Aging, and Failure Mechanisms

The NRC has contracted with Idaho National Laboratory (INL) to provide training to NRC staff on graphite degradation, aging, and failure mechanisms for graphite in ANLWRs, consistent with ASME Code, Section III, Division 5. This training will develop the technical expertise of the NRC staff to promote effective and efficient reviews related to nuclear graphite in high-temperature applications.

2.1.3.2. Tools for Graphite Behavior Modeling for ANLWRs

The NRC has contracted with INL to develop simple, empirically derived POF models for graphite degradation that are based on both the intrinsic material properties of graphite and the approximate behavior of graphite inferred from operating temperature, received dose, and oxidation. These models will not be mechanistic but will combine graphite properties (from the open literature or from the Advanced Graphite Capsule irradiation program); user input operating conditions; and irradiation-induced stresses calculated by finite element analysis to yield a POF for simple component geometries, based on the rules in the ASME Boiler and Pressure Vessel Code. The completed models will be made publicly available.

2.2. Supporting Activities

2.2.1. International Engagement

As part of its goal to be a modern risk-informed regulator and build strong partnerships, the NRC shares information and engages with various international groups, including international regulatory counterparts. International collaborations and communication with industry expands as tools and regulatory applications progress. These partnerships promote the exchange of ANLWR technical and regulatory experience, establish pathways for collaboration and research activities, and enhance the NRC's preparations for licensing ANLWRs.

The NRC and the United Kingdom's (U.K.'s) Office for Nuclear Regulation (ONR) are collaborating to better use their knowledge and experience to achieve more effective and efficient regulation of advanced reactor materials and advanced manufacturing. The NRC and ONR held a bilateral meeting with ONR on November 10, 2020, to provide updates on information-sharing activities, to continue discussion of future collaboration, and to establish appropriate technical and managerial contacts for research activities. The NRC staff presented its efforts on advanced reactor materials and component integrity and its efforts on advanced manufacturing technologies. The ONR staff presented on the U.K.'s Advanced Reactors Program, graphite and probabilistic modeling tools, and the U.K.'s Advanced Manufacturing Program.

The NRC and the Czech Republic's Research Centre Řež have ongoing collaborative efforts to better leverage knowledge and experience in the effective and efficient regulation of MSRs and electrochemistry. A bilateral meeting was held on April 5, 2022, where the two organizations discussed research and other preparatory activities being performed related to MSRs. The aim of this bilateral meeting was for the NRC to gain further insights into the Czech program for research and development of MSR technology, specifically in the areas of MSR electrochemistry, neutronics, fuel cycle and structural materials development, and for Řež to gain insights into the NRC's research and regulatory readiness activities for potential licensing of MSRs.

The NRC and the Japan Atomic Energy Agency have ongoing information exchanges on OpE with SFR, high-temperature materials, materials surveillance programs, and system-based codes for high-temperature materials. The system-based code is a precursor to ASME Section XI, "Rules for In-Service Inspection of Nuclear Power Plant Components," Division 2, "Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Power Plants" [10].

2.2.2. Training and Knowledge Management

Several ongoing training and knowledge management activities have been completed. Most notably:

- Graphite Training - The Office of Nuclear Regulatory Research (RES) hosted a seminar entitled "Graphite Degradation, Aging, and Failure Mechanisms" that covered graphite behavior and ASME rules associated with nuclear application. Topics included graphite fabrication and properties; property changes in a nuclear environment and life-limiting mechanisms; degradation issues (e.g., oxidation, irradiation, molten salt); and ASME design and construction. Two sessions were held on August 30, 2021, and a follow-up session was held on September 20, 2021. The seminar had over 70 attendees.

- Digital Twins Workshop – As a follow-on to the workshop hosted in December 2020 ((ADAMS Accession No. ML21083A132), RES sponsored a virtual workshop in September 2021 (ADAMS Accession No. ML21348A020) that covered the application of digital twins and digital twin enabling technologies (e.g., advanced sensors and instrumentation, data analytics, machine learning and artificial intelligence) in the current light water reactor (LWR) fleet and advanced reactor designs.

2.3. Additional Research Activities

The NRC is engaged in other research activities that have implications for the review of ANLWRs. The NRC is leveraging these other research activities to increase the efficiency of staff efforts and use of resources. The agency is applying the regulatory and technical bases being developed in the other research activities to inform and augment its efforts in enhancing ANLWR technical readiness and optimizing regulatory readiness.

2.3.1. Advanced Manufacturing Technologies (AMTs)

The NRC has engaged proactively to prepare for the adoption of AMTs in nuclear applications including the development of an agency action plan for these technologies, in anticipation of industry applications and licensee submittals. While the research activities are focused on the near-term applications of AMT components for operating reactors, the impact of this technology is expected to be more profound for advanced reactor applications. NRC efforts in developing technical bases for use of these technologies and guidelines for AMT submittals as well as enhancing knowledge in this emerging area will prepare the agency well for advanced reactor applications. Revision 1 of the AMT Action Plan [11] outlined the initial technical, regulatory, communications, and knowledge management activities conducted by the NRC. The NRC has completed the objectives of AMT Action Plans. The issued deliverables are available publicly on the NRC public site [12]. The NRC has initiated the next phase of its AMT activities which focuses on assessing additional AMTs, non-destructive examination and materials performance of AMT components, and data and modeling for qualification of AMT materials.

2.3.2. Digital Twins

As part of becoming a modern, risk-informed regulator, the NRC, through its Future Focused Research program, is investigating the potential applications of digital twin (DT) technology by the nuclear power industry. This is especially important for projected use in advanced reactor designs, as well as the types of regulatory infrastructure needed to respond to the use of DT technology in supporting the NRC mission. The research will assess the following with respect to DT technology: technical preparedness as related to nuclear power applications, regulatory readiness, state-of-practice and gaps in standards, and needs for communication and knowledge management. Developing an understanding of DT applications now will prepare the NRC for future activities needed to establish a technical basis for the use of DT technologies within future advanced reactors. The NRC has partnered with INL and ORNL to support this project.

3. Ongoing and Planned Research Activities

The NRC is conducting the ongoing research activities discussed in Section 2 of this report to facilitate a more effective and efficient review of ANLWR applications in keeping with the agency's drive to become a more modern and risk-informed regulator. These efforts also support ANLWR developers in near-term pre-application activities through the issuance of technical assessment reports on MCCI gaps and through active engagements and information exchange. "NRC Non-Light Water Reactor Mid-Term and Long-Term Implementation Action Plans," issued July 2017 [22], describes the planned activities that are expected to be further developed and implemented in the mid-term and long-term. Listed below are potential future research activities to address technology-specific and materials-specific aspects that support these mid-term and long-term implementation action plans. These potential future activities build on the ongoing research activities and can help achieve the overall objectives of the NRC's ANLWR vision and strategy to enhance technical readiness, optimize regulatory readiness, and optimize communications.

3.1. Research Focus Areas

3.1.1. High Temperature Materials

3.1.1.1. High-Temperature Corrosion/Erosion/Oxidation of Structural Materials

Stress relaxation cracking (SRC, also referred to as reheat cracking) is a mechanism that can cause enhanced creep crack growth by relaxation of weld residual stresses in components in high-temperature service. Therefore, SRC is a concern for the metallic materials allowed by ASME Section III-5 for high-temperature components. However, Section III-5 contains no explicit provisions that address SRC. Therefore, the NRC included a limitation in DG-1380 (DG-1380 will become RG 1.87, Rev. 2, when final), "Acceptability of ASME Code, Section III, Division 5, "High Temperature Reactors," (ML21091A276) that applicants should address the potential for SRC in their designs. Some of the allowed materials for Division 5, Class A high-temperature components may be more susceptible to SRC, so ongoing work will identify and focus on the higher-susceptibility materials. It is possible that the existing Section III, Division 5 rules, in particular the stress rupture factors, and strain limits applied to welds, provide sufficient margin to account for SRC, without the need for additional actions. Practices to minimize the likelihood of SRC could include controls on fabrication and welding, heat treatment, and design practices (including available industry models for evaluation of stress relaxation cracking). Results of this task will assist the NRC review of expected future applications for ANLWRs that will use the Section III, Division 5 Code for design of the reactor vessel and will need to meet the limitation in RG 1.87, Rev. 2 related to prevention of SRC.

3.1.1.2. Creep Fatigue

ANLWR components may be exposed to higher temperatures and are susceptible to additional failure modes compared to the current LWR fleet. These include failure modes such as creep rupture and creep-fatigue. Creep-fatigue in particular has been identified as a potential life-limiting failure mode for ANLWR components. Ongoing work to determine the actual margins in the ASME Code creep-fatigue design rules. A model could be developed to predict the actual failure time of simulated components designed to the ASME Code Section III, Division 5, rules.

The NRC has also contracted with ANL to develop a software tool, known as the "ASME Section III, Division 5 Design Tool" (HBB Tool) in May 2020. The tool is based on the Python computer language and provides the capability to check component compliance with the Section III-5 primary design rules for Class A components (Subsection HB, Subpart B) and also the design checks of Nonmandatory Appendix HBB-T, which include criteria for creep-fatigue. The current tool is not very user friendly, requiring input of commands through a Python prompt, and does not allow saving files with analysis results. The proposed Task 3 will develop a graphic user interface (GUI) for inputs plus enhanced output capability for the Section III, Division 5 Design Tool Software.

3.1.2. Molten Salt

In the last report, staff identified aspects of MSRs that warranted further research by the staff. Since that time, the NRC has developed plans to look at these areas, which are outlined below.

3.1.2.1. Electrochemical Monitoring

Electroanalytical techniques can be used to study redox reactions, determine product stability, characterize electron transfer kinetics, detect the presence of intermediate species, and measure reaction thermodynamics. These techniques may well be used to control redox potential and to monitor salt performance in a molten salt reactor. Valuate the potential application of electrochemical methods to monitor and/or control redox of the molten salt in MSRs. The NRC is looking to conduct work that will provide the staff insight into the reliability of electrochemical potential (ECP) methods to monitor corrosion behavior and measure redox potential; long-term electrode stability and the ability to use ECP methods to accurately predict material lifetimes and diagnose salt chemical issues.

3.1.2.2. Fission Product Behavior

In the case of fluid-fueled MSRs, the full array of fission products is generated in the circulating fuel. The fission products can be loosely grouped into three categories: (1) soluble species, which include Groups I-IV of the periodic table, and the rare earths (lanthanides plus scandium and yttrium), or "Salt-seeking elements"; (2) noble gases; and (3) noble metals. The noble metals, including molybdenum, technetium, ruthenium, rhodium, palladium, silver, tin and tellurium, are less soluble in molten salts and could plate out on surfaces. A general understanding of how these elements will behave in an MSR and their impact on the salt performance is necessary for predictable operation of these reactors. These fission products can also affect both the corrosivity of the salt (i.e., fission leads to a more oxidizing environment, which can facilitate corrosion) and, most notably, tellurium was found to cause intergranular cracking of the reactor vessel during the Molten Salt Reactor Experiment at Oak Ridge National Laboratory. The NRC is looking to gain a fuller understanding of the behavior of fission products in the reactor and their safety implication.

3.1.2.3. Off-Gas System

During MSR operations, there will be a likely need to assess off-gas performance. Gamma spectroscopy is used for current reactor designs, but the background in an MSR off-gas may reduce the effectiveness of gamma analysis. Online sampling methods for FP compounds such as the use of optical spectroscopy are being considered. Laser-induced breakdown spectroscopy and laser-induced fluorescence analyses have been shown to be effective in determining metals loading in industrial environments such as flue gas emissions.

Configuration of the off-gas system to confine fission gases and trap particulates means that it will be operating continuously and also that online maintenance will be required. Maintenance will have to be performed with remote handling because of the quantity of radioactive elements. In some cases, such as if a hydroxide scrubber is used, there will be a chemical hazard, but this is being used in other industries, and similar safety protocols can be used. Replaceable components of the off-gas system such as filter beds or hydroxide salt will need to be contained on site in the same manner as for used fuel before preparation for permanent disposal.

Additionally, since there is no cladding on the fuel to act as a barrier to radionuclide release in fluid-fueled MSRs, a robust off-gas system will be needed to manage the noble and non-noble gases, aerosols, volatile species, tritium, and radionuclides leaving the core. There is a need to address these and other novel issues for fluid-fueled MSRs so that the NRC will be better prepared to review a license application for one of these reactors.

3.1.3. Graphite

Nonmetallic graphite and ceramic composite components for nuclear applications have recently been added to the ASME Code, Section III, Division 5, with the replacement of the traditional deterministic approach with a statistical, POF methodology. The POF is calculated by comparing the distribution of expected operational stresses of a component during operation to the inherent material strength for the graphite grade. The NRC has contracted with INL to develop simple, empirically derived POF models for graphite degradation that are based on both the intrinsic material properties of graphite and the approximate behavior of graphite inferred from operating temperature, received dose, and oxidation. Mid-term work will complete the development of the assessment tool for integrity of graphite components undergoing aging and degradation.

A longer-term plan is to look at graphite waste. Graphite poses many challenges in terms of its use in MSRs, either as structural material or as moderator. NRC recognizes that a better understanding of on-site storage of used graphite in terms of potential amount, form (e.g., large or small sized graphite components) and activity is needed. It has been recognized that graphite could be a limiting step in terms of reactor operation and that there could be a need to replace graphite during the reactor lifetime.

3.1.4. Reliability Integrity Management

The NRC recently issued a draft regulatory guide DG-1383 to endorse ASME Section XI, Division 2 “Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Power Plants”. Section XI, Division 2 provides a methodology for developing a RIM program as an alternate to the traditional pre-service inspection (PSI) and in-service inspection (ISI) program under ASME Section XI, Division 1. The RIM program contains provisions to develop reliability targets for the components within the scope of the program and implement RIM strategies to ensure the reliability targets are met. It is necessary to evaluate approaches for determining reliability targets for passive components, assess how PSI and ISI requirements support the targets, and develop guidance to support staff review of applications using Section XI, Division 2. The NRC is looking to conduct an assessment of the current state of knowledge on the use of RIM for integrity management of passive comments and to evaluate potential methodologies for determining appropriate reliability targets for structures, systems, and components (SSCs) and assess how various RIM strategies could be used to achieve the established reliability targets.

3.2. Supporting Activities

3.2.1. International & Industry Engagement

Ongoing engagement with international regulators and industry has shown to be significantly beneficial. A survey was distributed to gage how different organizations are addressing materials and components issues for advanced reactor licensing. The survey responses are currently being compiled in a report for distribution to the participants. Collaboration with several key groups includes:

3.2.2. Training and Knowledge Management

Trainings that have been conducted include:

- Nuclear Graphite Modeling – The Office of Nuclear Regulatory Research (RES) held a training course on graphite behavior, graphite degradation mechanisms, graphite modeling in MOOSE, and ASME qualification methodology on August 1-2, 2022. The training presented a graphite model which was developed in the MOOSE framework and provided instruction on how to use the model. Example problems were run and the application of the modeling results within the ASME Code was discussed. The training was attended by 65 NRC staff.

3.3. Emerging Research Areas

3.3.1. Advanced Manufacturing

Ongoing assessment of the use of AMTs for ANLWRs (accelerated qualification) (e.g., high-temperature alloys) is taking place.

Staff has engaged proactively to prepare for the adoption of advanced manufacturing technologies (known as AMTs) in nuclear applications, in anticipation of industry applications and licensee submittals. While the current research activities are focused on applications of these components for operating reactors, impact of this technology is expected to be more profound for advanced reactors. Focused areas of directed research on AMT topics are also underway. These efforts can be expanded to provide an integrated and interactive database with machine learning capabilities for data validation and licensing efforts, therefore accelerating the qualification process needed by new reactor technologies.

3.3.2. Advanced Sensors

Evaluation of the application of advanced sensors, such as their use in tritium control, chemistry control, off-gas control, and structural health monitoring. The NRC's understanding of the capabilities and limitations of novel sensors will help the agency determine the adequacy of an applicant's chosen method of monitoring parameters related to safety. Current activities include assessment of efforts to reduce uncertainties and risk (e.g., surveillance, online monitoring) and assessment of data analytics applications for online monitoring and remote operations.

3.3.3. Alternative Framework for Postulating Pipe Break

The NRC is developing and documenting an alternative framework and, as appropriate, acceptance criteria for postulating pipe ruptures in fluid system piping at nuclear power plants for evaluating the dynamic and environmental effects of such ruptures in accordance with General Design Criterion 4, "Environmental and Dynamic Effects Design Bases," in Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic licensing of production and utilization facilities" [13]. As part of this effort, the NRC contracted with Engineering Mechanics Corporation of Columbus to conduct piping analyses to support the development of the technical basis for the alternative framework. The final TLR documenting the alternative approach and the methodology is expected to be published in September 2022. The NRC staff has developed an initial draft of the alternative framework and the associated acceptance criteria for demonstrating break preclusion in piping systems. This risk-informed alternative framework provides a general approach that can be used for operating reactor, new reactor and advanced reactor applications and would allow applicants/licenses to comply with GDC

4 requirements without unnecessary conservatisms. The NRC staff will use the alternative, risk-informed acceptance criteria primarily for evaluating applications for new LWR nuclear power plant design certification (and license applications, to the extent that issues are not addressed by a design certification). This work will support NRC readiness to review LWR and new reactor applications by enhancing the efficiency and effectiveness of NRC staff reviews and will also be valuable for communicating clearly with stakeholders.

4. External Cooperation

The NRC holds ongoing coordination meetings with national labs, external stakeholders and international agencies to discuss ongoing research activities, facilitate potential collaborative efforts, and disseminate information to remain up to date with various technical issues, regulatory updates, general knowledge gaps, and associated safety impacts. The NRC's current ongoing coordination activities are detailed below:

- MSR: Periodic meetings with DOE MSR National Technical Director (RES/DE-NRR/DANU)
  - The NRC staff conducts periodic meetings with the DOE MSR National Technical Director to discuss research priorities and identify areas for collaboration.
- ANLWR Materials/Component Performance: Periodic meetings with DOE-NE and EPRI (RES/DE, NRR/DANU)
  - Periodic status meetings are held quarterly between NRC-DOE-EPRI to share information, data, and knowledge of ANLWR MCCI research activities. The aim of these meetings is to enhance common understanding of technical issues impacting safety and to address areas of potential gaps in knowledge useful for engineering assessments, as well as looking for areas for collaboration.
- MSR & Electrochemistry: Periodic meetings with Research Centre Řež, Czech Republic (RES/DE and NRR/DANU)
  - The aim of this bilateral meeting is for the NRC to gain further insights into the Czech program for research and development of MSR technology, specifically in the areas of MSR electrochemistry, neutronics, fuel cycle and structural materials development, and for Řež to gain insights into the NRC's research and regulatory readiness activities for potential licensing of MSRs
- Advanced Reactor Materials and Advanced Manufacturing: Periodic meetings with Office of Nuclear Regulation, U.K. (RES/DE and NRR/DANU, NRR/DNRL)
  - The NRC staff holds a bilateral meeting with ONR to provide updates on information-sharing activities, to continue discussion of future collaboration, and to establish appropriate technical and managerial contacts for research activities.

5. Summary of Issued Documents

Table 1 lists the documents issued as a result of the ongoing research activities.

Table 1. List of Issued Documents

Report	**Summary**	**Date**	**ADAMS Accession No.**
"Technical Gap Assessment for Materials and Component Integrity Issues for Molten Salt Reactors" [14]	Material selection and qualification are important considerations for the deployment of MSRs. This report summarizes the most important materials issues that must be considered for licensing MSRs.	March 2019	ML19077A137

"Advanced Non-Light-Water Reactors Materials and Operational Experience" [15]	This report summarizes the available domestic and international OpE for both power and research ANLWRs with regard to materials and component integrity. It focuses on both SFRs and HTGRs.	March 2019	ML18353B121
ANL-19/13, "Environmental Creep-Fatigue and Weld Creep Cracking: A Summary of Design and Fitness-for-Service Practices"	This report surveys current design and fitness-for-service evaluation practices for structures subject to creep-fatigue damage. The purpose of this survey is to identify potential challenges to a regulatory assessment of an advanced reactor design, with a particular focus on the interaction of creep-fatigue damage with the reactor environment and on creep-fatigue cracking near weldments. The report identifies gaps in current practices and recommends future development work required to address these deficiencies.	April 2020	ML20099A140
ASME Section III, Division 5, Design Tool [16]	This tool executes the ASME Code, Section III, Division 5, design rules for high-temperature metallic components.	June 2020	ML20153A360
Research Information Letter 2020-09, "International Workshop on Advanced Non-Light Water Reactor – Materials and Component Integrity," Dec. 9–11, 2019 [17]	The NRC met with representatives from the international nuclear community to discuss the state of knowledge, operating experience, and research activities related to high-temperature metallic and nonmetallic materials, coolant chemistry, reactor component integrity, and applicable codes and standards. This report provides a summary of this workshop.	September 2020	ML20245E186
TLR/RES/DE/CIB-2020-04, "Advanced Nonlight-Water Reactors: Summary of Gap Identification and Recommendations on Consensus Codes and Computational Codes" [18]	This technical letter report (TLR) is a high-level summary of the RIM program included in ASME Section XI, Division 2. This report also identifies potential gaps in ASME Section XI, Division 2, based on OpE.	October 2020	ML20254A155

TLR/RES/DE/CIB-2020-10, "Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, 'High Temperature Reactors,' Subsection HH, 'Class A Nonmetallic Core Support Structures,' Subpart A, 'Graphite Materials'" [19]	This report assesses and provides recommendations in Subsection HH, Subpart A, used to inform the technical bases in the upcoming staff generated NUREG for the potential endorsement of ASME Section III, Division 5.	December 2020	ML20344A001
TLR/RES/DE/CIB-2020-13, "Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, High-Temperature Reactors": HBB-T, HBB-II, HCB-I, HCB-II, and HCB-III for Metallic Components" [20]	This report assesses and provides recommendations on portions of Division 5 (HBB-T, HBB-II, HCB-I, HCB-II, and HCB-III) used to inform the technical bases in the upcoming staff generated NUREG for the potential endorsement of ASME Section III, Division 5.	December 2020	ML20349A003
TLR/RES/DE/CIB-2020-14, "Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, 'High-Temperature Reactors.' Review of Code Case N- 861 and N-862: Elastic- Perfect Plastic Methods for Satisfaction of Strain Limits and Creep-Fatigue Damage Evaluation in BPV-III-5 Rules" [21]	This report assesses and provides recommendations on Code Cases N-861 and N-862, which are used to inform the technical bases in the upcoming staff generated NUREG for the potential endorsement of ASME Section III, Division 5.	December 2020	ML20349A002

U.S. Nuclear Regulatory Commission “NRC Non-Light Water Reactor Mid-Term and Long-Term Implementation Action Plans, [22]	This report provides the mid- and long-term implementation action plans (IAPs) that support the U.S. NRC’s readiness to license and regulate ANLWR designs in an effective, efficient, and predictable manner.	July 2017	ML17164A173
TLR-RES/DE/CIB-CMB-2021-03, Technical Assessment of Materials Compatibility in Molten Salt Reactors	The report outlines relevant knowledge on measurement, management, and mitigation of corrosion in MSRs. It discusses fundamentals of salt chemistry and salt purification, as well as corrosion and mechanical properties of alloys, and graphite compatibility.	March 2021	ML21084A039
TLR-RES/DE/CIB-CMB-2021-04; Corrosion in Gas-Cooled Reactors,	This report focuses on degradation issues related to gas-cooled reactors, with an emphasis on He cooled types, and identifies knowledge needs, including in the areas of corrosion and radiation embrittlement.	March 2021	ML21084A041

TLR-RES/DE/CIB-CMB-2021-07, Corrosion in Sodium Fast Reactors	This report reviews relevant and publicly available knowledge on the interaction between sodium chemistry and thermodynamics with structural materials in static and flowing Na conditions. The report also included discussion of corrosion mechanisms in SFRs.	May 2021	ML21116A231
TLR-RES/DE/REB-2021-08; Assessment of Graphite Properties and Degradation, Including Source Dependence & Appendices to Assessment of Graphite Properties and Degradation, Including Source Dependence	This report contains data from publicly available sources in the MDS format for IG-110, NBG-17, NBG-18, and PCEA graphites.	August 2021	ML21215A345 & ML21215A346
TLR-RES/DE/CIB-2021-07; Additional Technical Information in Support of the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Code, Section III, Division 5, "High Temperature Reactors," Subsection HH, "Class A Nonmetallic Core Support Structures," Subpart A, "Graphite Materials"	This report is a companion report to TLR/RES/DE/CIB-2020-10, "Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, 'High Temperature Reactors': Subsection HH, 'Class A Nonmetallic Core Support Structures,' Subpart A, 'Graphite Materials,'" issued December 2020 (ADAMS Accession No. ML20344A001).	May 2021	ML21109A123

TLR-RES/DE/CIB-CMB/2021-05; Status of Advanced Non-Light Water Reactor Research Activities - Materials Chemistry and Component Integrity	This report discusses The U.S. NRC vision and strategy to assure NRC readiness to efficiently and effectively license and regulate a new generation of ANLWRs.	March 2021	ML21088A013
Technical Gap Assessment for Materials and Component Integrity Issues for Molten Salt Reactors	Material selection and qualification is an important consideration for the deployment of MSRs. This report summarizes the most important materials issues that must be considered for licensing MSRs.	March 2019	ML19077A137
TLR-RES/DE/REB-2022-01; Review of Code Cases Permitting Use of Nickel-Based Alloy 617 in Conjunction with ASME Section III, Division 5	This report recommends endorsement of Code Case N-872 without limitations or exceptions. Technical basis for this recommendation is provided.	January 2022	ML22031A137

TLR-RES/DE/REB-2021-17; Assessing the ASME Section III, Division 5, Class A Primary Load Design Rules Against Creep Notch Effects	This report assesses the ASME Section III, Division 5, Subsection HB, Subpart B rules covering the design and construction of high-temperature Class A nuclear reactor components for their robustness against creep notch effects.	November 2021	ML21319A160

6. Summary

The purpose of this report is to document the MCCI activities being conducted to support the review and regulation of ANLWRs. These activities align with the NRC vision and strategy developed to assure NRC readiness to efficiently and effectively conduct its mission for these technologies. Specifically, these activities support Strategy 2 of the NRC vision and strategy by enhancing ANLWR technical readiness and optimizing regulatory readiness.

The NRC staff focused its research efforts on identified MCCI gaps associated with various ANLWR technologies: high temperature behavior of metals, salt compatibility, molten salt chemistry, high-temperature corrosion/erosion/oxidation of structural materials, and graphite degradation. This report described the various activities being conducted to address these technical gaps. The NRC staff has developed technical assessments and computational tools and models, conducted technical seminars and training, completed literature reviews, and actively engaged with domestic and international stakeholders. The agency is also leveraging other research activities to inform and augment its review and regulation of ANLWRs. Finally, the report also describes potential activities that could build on these current activities and support the mid- and long-term strategies.

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