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

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Executive Summary

The U.S. Nuclear Regulatory Commission (NRC) developed a vision and strategy to assure NRC readiness to efficiently and effectively license and regulate a new generation of advanced non-light water reactors (ANLWRs). Operating experience and advances in the technical, business, and regulatory aspects of ANLWRs are increasing rapidly both domestically and internationally. The NRC is prepared to review and license an ANLWR design today, if needed. However, in its mission to become a more modern and risk-informed regulator, the NRC is focused on maintaining efficiency and effectiveness to succeed in the overall mission.

The NRC vision and strategy utilizes three objectives: enhancing technical readiness, optimizing regulatory readiness, and optimizing communication. To meet these objectives, the NRC developed an implementation action plan with six near-term strategies. Strategy 2 is to acquire/develop sufficient computer codes and tools to perform ANLWR regulatory reviews. This report documents the activities being conducted to address materials, chemistry, and component integrity (MCCI) issues related to Strategy 2.

Because materials selection and qualification for advanced reactor designs are long lead and design-limiting. the NRC staff developed a multi-pronged approach to proactively prepare the agency to review license submittals on high-temperature materials and components for ANLWRs. The overarching objectives of this approach are to:

- Assess the performance needs and issues for materials and component integrity in ANLWRs.
- Identify gaps in knowledge, data, and assessment tools.
- Develop:
    - compendium of domestic and international operational experience ,
    - technical bases for materials applications,
    - confirmatory predictive tools for assessing component integrity, and
    - evaluation methods for assessing corrosion and chemistry effects on structures and components.

Applying risk insights and available knowledge, the staff identified major MCCI gaps associated with various ANLWR technologies so that the NRC can focus its efforts and resources on addressing the MCCI areas that could most impact performance needs and issues for ANLWRs. The technical gaps that the staff identified are high temperature behavior of metals, salt compatibility, molten salt chemistry, high-temperature corrosion/erosion/oxidation of structural materials, and graphite degradation.

The NRC is addressing the MCCI gaps in these research focus areas to better understand the unique codes, experimental data, features, phenomena, and knowledge gaps related to ANLWR technologies. The NRC has contracted with national laboratories, including Argonne National Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory, to develop technical assessments of these technical gaps. Such assessments have included surveys of current design and fitness-for-service evaluation practices for structures subject to creep-fatigue damage and assessments of the molten salt compatibility that address guidance for surveillance programs, irradiation testing criteria, and corrosion tests. Computational tools and models, such as probability-of-failure models for graphite degradation, are also being developed to support staff reviews. This report also discusses other activities that augment technical knowledge and expertise, such as developing training, conducting technical seminars, and completing literature reviews.

The NRC is also actively engaged through collaborations and partnerships with international groups, including international regulatory counterparts. These partnerships, such as those with the Office for Nuclear Regulation (United Kingdom), Japan Atomic Energy Agency, and Řež Nuclear Research Institute (Czech Republic), 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.

Though these ongoing research activities target near-term goals and strategies, the report also discusses potential future activities that would build on current efforts and results and support longer term implementation action plans to address aspects specific to the technology and materials used. The planned activities focus on technology-specific and materials-specific aspects. Proactive planning and engagement for future activities will help the NRC achieve the overall objectives of NRC's ANLWR vision and strategy.

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1. Introduction

To prepare for potential license applications for advanced non-light water reactor (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 further 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.

This report documents work conducted in support of several contributing activities related to the area of materials, chemistry, and component integrity (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.

- 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. Current 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.

<u>Creep-Fatigue</u>

The design of structural components for high-temperature ANLWRs requires considering an expanded set of potential structural failure modes when compared to light-water reactor (LWR) design. 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.

<u>Salt Compatibility</u>

Potential MSR applicants may restrict their designs to use materials currently approved in American Society of Mechanical Engineers (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 shows a significant 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.

A significant amount of data on molten salt corrosion for austenitic stainless steels was generated by the DOE in the 1970s and 1980s and by universities in the 2010s through the DOE’s Nuclear Energy University Program. These data may be available to fill data gaps correlating molten salt purity and the corrosion resistance of structural alloys being considered for MSR designs.

<u>Molten Salt Chemistry</u>

MSRs, both fluid fueled and solid fueled, pose unique chemistry-related challenges for safe and successful operation. Understanding molten salt chemistry is key to the successful deployment of the technology. Of major importance in this understanding are (1) the behavior of the salt species, fission and activation products, and the effect of impurities, (2) speciation and therefore phase diagram behavior for mixtures, (3) the use of acid-base effects, and (4) the control of the redox potential of the salt medium, as it affects corrosion and other chemical processes. This understanding will be essential to develop accurate codes and models for the reactor.

For example, the ability to predict important physicochemical properties, which could impact the materials behavior of the MSR fuel, is crucial to development of a phase diagram, which shows the stable phase fields as a function of any variable (e.g., temperature (T), pressure, composition, electric potential). The most common type shows stable phase fields as a function of T and composition (T-x). This allows deduction of the temperature at which a certain fuel or coolant composition melts, boils, or decomposes. Knowledge of the equilibrium state is usually the starting point for understanding the system. Many of the fluoride binary salt mixtures for potential use in MSRs have been established; for example, LiF-BeF_2 was examined in detail for the Molten Salt Reactor Experiment [5].

High-Temperature Corrosion/Erosion/Oxidation of Structural Materials

Impurities in the primary helium of HTGRs 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 SFRs 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.

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.

2.2 Ongoing Activities

2.2.1 Research Activities

The NRC is conducting 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. Table 1, which is found in Section 2.3 of this report, lists the documents resulting from these ongoing activities.

- Creep-Fatigue

  The NRC contracted with Argonne National Laboratory (ANL) to develop and provide a collection of best practices for elevated temperature creep-fatigue in creep-induced cracking design. This included surveying available design methods and creep-fatigue engineering practices. It included more basic research aimed at determining the design margin of creep-fatigue design procedures. This included research into fundamental methods for predicting creep-fatigue damage, assessing the effect of prior load history on subsequent creep-fatigue damage, and assessing design methods through comparisons to large-scale simulations using physically realistic models of inelastic deformation coupled to creep-fatigue damage. In a similar manner, ANL assessed creep-induced cracking in the heat-affected zone.

  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 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.

ANL is also investigating whether the current creep-fatigue design rules are conservative for components with complex, multiaxial stresses (notch effects). In this effort, numerical analyses will be used to compare the life predictions made by different creep-fatigue design processes for structures with increasingly triaxial, three-dimensional stress states. The results will be used to assess the adequacy of the current stress-triaxiality correction approaches in the design codes and to identify gaps requiring additional work or justification if the codes are found to be inadequate.

- 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.

- 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.

- Molten Salt Chemistry

  The NRC is developing technical expertise in this area 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. The NRC staff has reviewed 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 has engaged in meetings and document reviews related to MSRs, such as pre-application submittals (e.g., Kairos Power coolant topical report). The staff has also formed working groups and reviewed multiple contractor reports, including an Oak Ridge National Laboratory (ORNL) report on fuel qualification challenges fluid-fueled MSRs, "MSR Fuel Salt Qualification Methodology," issued July 2020 [7] and "Proposed Guidance for Preparing and Reviewing a Molten Salt Non-Power Reactor Application," dated November 18, 2020 [8].

  In addition, the NRC staff is conducting other activities to build skills and help develop staff competencies in MSR chemistry. These activities include the development of a technical seminar, which summarized the state of knowledge and technical gaps in the area of molten salt chemistry and the back end of the MSR fuel cycle, and observation of a recent Canada Nuclear Safety Commission meeting with Terrestrial Energy.

The NRC staff has also identified capabilities related to chemistry that should ideally be incorporated into computational codes. Such tools would contribute to the understanding of salt chemistry in these reactors and could also inform the NRC's review of the validity and accuracy of an applicant's calculations. This was part of a broader effort to identify code parameter needs in a variety of disciplines to help inform the DOE's efforts in this area. The NRC identified the following capabilities relating to chemistry that would ideally be incorporated into codes:

- salt composition and its impacts on phase changes
- redox potential
- reaction kinetics
- mass transfer of species and compounds
- phases of different species and compounds in the salt
- properties of frozen salts
- effect of additives
- transportation of fission products
- graphite erosion

- Salt Compatibility

  The NRC has 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 NRC has also initiated a second phase of work that will look at standardization for molten salt corrosion testing and the effect of fission products and impurities on salt properties.

  The NRC is also continuing to monitor outside activities being conducted in this area (for example, the DOE's corrosion testing of advanced nickel-based alloys being considered in the ASME Code, Section III, Division 5).

- NRC-DOE-EPRI ANLWR Materials, Chemistry, and Component Integrity Status Meetings

  The NRC conducts meetings every quarter to share information, data, and knowledge of 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.

- ASME Section III, Division 5, Review and Endorsement Activities

  The NRC is currently reviewing 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 will document the technical basis of its review in a NUREG, "Technical Review of the 2017 Edition of ASME Section III, Division 5, 'High Temperature Reactors,'" 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.

2.2.2 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. 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. 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 Center Řež have ongoing collaborative efforts to better leverage knowledge and experience in the effective and efficient regulation of MSRs. In a bilateral meeting held on March 16, 2021, 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 insights into the Czech program for research and development of MSR technology 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 operational experience with sodium fast reactors, 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].

2.2.3 Leveraging Other 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.

- 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 submittal and enhancing knowledge in this emerging area will prepare the agency well for advanced reactor applications. Recognizing the need to build staff capabilities through hands-on activities, an NRC staff member is detailed to ORNL on a part-time basis to work with the Transformational Challenge Reactor Program team.

- 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.

- Alternative Framework for Postulating Pipe Break Locations

  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" [11]. The NRC staff will use these 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 applications by enhancing the efficiency and effectiveness of NRC staff reviews and will also be valuable for communicating clearly with stakeholders. Ongoing ANLWR efforts will continue to provide information and data (e.g., international operating experience of ANLWRs) that may be used to assess the applicability of this framework to ANLWRs.

2.3 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" [12]	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" [13]	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 [14]	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 [15]	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" [16]	This report 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

Table 1 List of Issued Documents Continued

Report	Summary	Date	ADAMS Accession No.
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’” [17]	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” [18]	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” [19]	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

3. Potential Future 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 [20], 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.

- 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.

- Evaluation of materials and component integrity issues related to a molten chloride salt environment. MSRs, both fluid-fueled and solid-fueled, pose unique challenges for safe and successful operation. Continued evaluation of these issues will enhance staff knowledge and review readiness for MSRs.

- Assessment of the use of AMTs for ANLWRs (accelerated qualification) (e.g., high-temperature alloys).

  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 the near-term 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. Continued assessment of technical and regulatory areas related to ASME Section XI, Division 2, and ASME Section III, Division 5, to support the licensing and regulation of ANLWRs.

  - Assess the adequacy of RIM programs proposed by licensees and confirm proposed reliability targets for various components of various designs.

  - Based on conditions from the ASME Section III, Division 5, endorsement, develop recommendations to address stress relaxation cracking of advanced reactor materials that are used at temperatures where creep is significant.

    - 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.

- Gap assessment for 10 CFR Part 71 "Packaging and transportation of radioactive material," [21] and 10 CFR Part 72, "Licensing requirements for the independent storage of spent nuclear fuel, high-level radioactive waste and reactor-related greater than Class C waste" [22] based on safety significance and technology-specific concepts (e.g., performance/degradation issues, fuel release mechanisms and fractions, system material limitations). The assessment would include specific focus on MSRs to address the novel challenges in terms of waste forms and the water-solubility of salts.

- Identification of and implementation activities to address remaining technical and regulatory gaps. Building upon the current research activities and identifying and addressing remaining and emerging MCCI gaps will help the agency as operating experience and advances in the ANLWRs continue. These efforts will help the NRC maintain its ability to conduct effective and efficient reviews.

- Assessment of efforts to reduce uncertainties and risk (e.g., surveillance, online monitoring).

- Assessment of data analytics applications for online monitoring and remote operations.

- Expanded engagement with DOE and international partners. This could benefit the agency by providing enhanced information exchanges, avenues for collaborative and leveraged efforts, and communications and awareness with external stakeholders.

4. 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.

5. References

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