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KEY ASPECTS FOR DESIGN AND FITNESS FOR SERVICE OF MECHANICAL COMPONENTS IN SMALL MODULAR REACTORS

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ABSTRACT – A recent surge of nuclear industry interest in the development of small, factory built, and inherently safe nuclear reactors is underway for the last few years. Most of the proposed new designs use non-conventional cooling mediums and operate at high temperatures. Such combination will likely create many new challenges to the regulators and the designers. In particular, the focus of this paper is to initiate the discussions regarding regulatory requirements for the design of mechanical components and how to bridge the gap in knowledge of material behaviour for these reactors.

Introduction

Several different types of Small Modular Reactors (SMRs) are under development for different purposes. Some of these SMRs are proposed to operate under high neutron fluxes and at elevated temperatures to achieve high thermal efficiency. However, their operating conditions could accelerate degradation of materials. In particular, development and application of design rules for metallic and non-metallic mechanical components operated at elevated temperatures is challenging. Structures Systems and Components (SSCs) of SMR operated in very high temperatures are not fully covered by the current provisions of American Society of Mechanical Engineers (ASME) Code Section III, Subsection NH on class 1 metallic components in elevated temperature service. Thus, systematic approach and a well-designed research and development program to address the knowledge gap in material behavior in the early design stage for SMR, so that potential/plausible degradation mechanisms are accounted for and structural integrity of mechanical components is maintained over their design life. The purpose of this paper is to discuss key aspects that need to be considered in design and Fitness-For-Service (FFS) of mechanical components in SMRs in view of the requirements of CNSC REGDOC-2.5.2 for design and CNSC REGDOC-2.6.3 for FFS.

1. Design Aspects

In the author's opinion, the following issues represent potential challenges for the design vendors, applicants, licensees and the regulators that should be addressed at early stages of the process:

1.1 Safety Concept

Sections 4.3 and 6.1 of REGDOC-2.5.2 states that two safety concepts are required to be applied to SSCs: One is defense-in-depth, the other is operational limits and conditions. The purpose of defense-in-depth is to ensure SSCs are subject to overlapping provisions and demonstrate the provision of a series of physical barriers to confine radioactive material at specific location. In order to do that, REGDOC-2.5.2 states that the design shall provide five levels of defense. For instance, implementation of leak detection system is required to satisfy Level 2 defense-in-depth

on control of abnormal operation and detection of failures. The purpose of operational limits and conditions is to ensure that plants operate in accordance with design assumptions and intent (parameters and components), and include the limits within which the facility has been shown to be safe. Therefore, operation history of SSCs must be recorded and tracked by monitoring systems (e.g., thermal/pressure transient monitoring system or vibration monitoring system, etc.) over entire life of SSCs.

1.2 Safety Classification

The major elements of the safety classification methodology in Section 7.1 in REGDOC-2.5.2 include the plant design envelope, plant states, postulated initiating events, safety functions and their categorization, classification of SSCs, and selection of design requirements. The most critical step is the categorization of the safety functions. The safety categories must be defined based on the likelihood and consequence of the failure of safety functions. The definition for each category must be clear enough so that it cannot be applied discretionarily. The next step is then classification of SSCs based on the safety function they are to perform.

1.3 Design Rules and Limits

As per Section 7.5 in REGDOC-2.5.2, *the design authority shall specify the engineering design rules for all SSCs.* These rules shall comply with appropriate accepted engineering practices. Development and application of design rules of metallic and non- metallic mechanical components operated at elevated temperature under high radiation is challenging. Current codes and standards cover some high temperature materials, however Structures Systems and Components (SSCs) of SMR operated under very high temperature are not fully accommodated by the current provisions of American Society of Mechanical Engineers (ASME) Code. Several types of metallic and non-metallic materials (e.g., low alloy steel, nickel basis alloy, graphite, or ceramic, etc.) are proposed for use in SMR. In particular, design of pressure retaining components is challenging as there is lack of operating experience of a SMR operated under severe operating conditions over its design life. Thus, determination of safety factors and acceptance criteria in design code for metallic and non-metallic components is important to appropriately accommodate uncertainties (e.g., material imperfection, unknown degradation mechanisms, and deterioration rate of SSCs due to degradation mechanisms, etc.). In addition, the design should take into consideration the fatigue life of each component subject to cyclic load, therefore development of S-N curve in high temperature water or other types of high temperature coolant (e.g., molten salt, etc.) would be a challenging task, particularly, when considering the impact of the operation environment on fatigue damage. Moreover, understand and characterization of governing parameters on Environmentally Assisted Fatigue (EAF) is important because the composition, the dissolved components and the operating conditions of the primary coolant would affect crack initiation/growth of metallic component carrying it. As a result, factors that will be applied to test data for the design S-N curve must be determined by consideration of the effects of several parameters (e.g., effects of chemical contents in coolant, size and surface roughness of tests specimen, temperature, strain rate, strain (or stress) amplitude, type of steel, and S content of the steel, etc.).

1.4 Pressure-Retaining Structures, Systems, and Components

Section 7.7 in REGDOC-2.5.2 stipulates that *all pressure retaining SSCs shall be protected against overpressure conditions, and shall be classified, designed, fabricated, erected, inspected, and tested in accordance with established standards.* Further, section 7.7 provides key elements to be considered in the design stage of pressure retaining SSCs to maintain/check their structural integrity and to minimize consequence of their failure under static and dynamic loads anticipated in operational states, and Design Basis Accident (DBA). Moreover, REGDOC-2.5.2 states that Leak Before Break (LBB) assessment is permitted to optimize protective hardware (e.g., pipe whip restraints or jet impingement barriers, etc.) and to redesign pipe-connected components, their supports and their internals. In particular, determination of a critical crack size of a given pressure retaining component is one of essential elements to apply the LBB under its operating conditions. However, it must be noted that LBB is only applicable in a condition that there is no active degradation mechanism in a given SSC. In addition, leak detection methods for the reactor coolant should be examined at the design stage. Sensitivity and response time of a leak detection system are key elements to demonstrate adequate margins from leak through a through wall crack/flaw to Unit shutdown.

1.5 Aging and Wear

As per Section 7.17 in REGDOC-2.5.2 and Attribute #1 in REGDOC-2.6.3, *the design shall take due account of the effects of aging and wear on SSCs.* Time Limited Aging Analyses (TLAA) is essential to evaluate the effect of aging during an extended operating life. The TLAA analyses should be conducted based on an explicitly assumed time of plant operation (type of TLAAs: radiation-induced deformation and neutron embrittlement, fatigue, thermal ageing, loss of material and equipment qualification, etc.). In particular, material degradation and corrosion/erosion are typical aging mechanisms for SSCs subjected to high operating temperature and radiation. In addition, application of Failure Modes and Effects Analysis (FMEA) would be effective way to identify and address the following aspects: typical/plausible degradation mechanisms, failure location, failure mode, failure effect, detection method, mitigation task, and governing parameters leading to a given degradation. The FMEA can be used to support ongoing confidence in the condition of a given system/component in SMR. In addition, effects on structural integrity due to non-design basis cyclic loads (e.g., thermal stratification, thermal mixing, or vibration, etc.) must be assessed through the FMEA as well.

1.6 Research Activities

As per Section 5.1 in REGDOC-2.5.2 and Attribute #1 in REGDOC-2.6.3, *Research activities are important to establish 1) a knowledge base of relevant aspects of the plant design and 2) establish solutions to Aging Management problems in order to mitigate or prevent degradation.* For instance, researches shall be conducted to identify 1) any changes in material properties under operating conditions (e.g., changes in material strength, strain hardening rate or fracture toughness with operation time), 2) a crack initiation/growth under a given operating conditions, and 3) to further support long term operation of SMR. In particular, stress-strain curves in non-mandatory Appendix T in ASME NH have been primarily developed by consideration of the effects of thermal creep. However, material embrittlement due to the increment of helium bubbles resulting from high radiation is a well-known degradation mechanism for nickel alloys. Therefore, a degradation rate of materials in SMR must be assessed by consideration of the effects of several parameters such as

temperature (e.g., thermal creep or thermal embrittlement, etc.), radiation (e.g., radiation embrittlement, etc.), hydrogen (e.g., hydrogen embrittlement, etc.) and chemical contents in coolant and steel (e.g., Environmentally-Assisted-Cracking (EAC), etc.). In addition, literature review should be conducted at early stage of the design to identify current knowledge, practices and pending issues associated with design rules of metallic and non- metallic mechanical components, types of plausible/potential degradation mechanism, and material degradation in elevated temperature with high radiation.

1.7 In-Service Testing, Maintenance, Repair, Inspection and Monitoring

Section 7.14 in REGDOC-2.5.2, *the design should incorporate provisions recognizing the need for in-service testing, maintenance, repair, inspection, and monitoring for the purpose of maintaining the SSCs within the boundaries of the design.* Thus, the development of strategies and programs to address in-service testing, maintenance, repair, inspection, and monitoring is a necessary aspect of the plant design stage. In particular, SSCs important to safety should be designed and located to make surveillance and maintenance simple, to permit timely access, and in case of failure, to allow diagnosis and repair, and minimize risks to maintenance personnel. In addition, REGDOC-2.5.2 states the Risk-Informed In-Service Inspection could be used when the methodology is clearly documented.

1.8 Fitness For Service (FFS)

As per Section 7.17 in REGDOC-2.5.2, *the design shall take due account of the effects of aging and wear on SSCs to maintain structural integrity over their design life.* In addition, CNSC REGDOC-2.6.3 on Aging Management for FFS provides key aspects that shall be included in an Aging Management Program (AMP). The AMP summarizes the activities for the understanding of aging and methods to minimize aging, detect and monitor aging, and mitigate aging. Implementation of the AMP is a mandatory regulatory requirement for a new license or a licensing renewal of each Canadian utility. The CNSC REGDOC-2.6.3 requests that the AMP should be evaluated against nine attributes for effective AMPs.

1.9 Plant States

As per Sections 4 and 7 in REGDOC-2.5.2, *SSCs are designed / operated in a manner that will protect individuals, society and the environment during operation and or during an accident.* In order to do that, the safety analysis shall examine the plant performance during different plant conditions, namely 1) normal operation, 2) Anticipated Operational Occurrence (AOO); Design-Basis Accident (DBA); and Beyond-Design-Basis Accident (BDBA). Assumptions and engineering judgment concerning the operating information (e.g., transient history of pressure and temperature, and type of load, etc.) in each state is essential to design SSCs.

1.10 Quantitative Application of the Safety Goals and PSA

As per Section 4.2.2 in REGDOC-2.5.2, *quantitative safety goals have been established.* The three quantitative safety goals are 1) core damage frequency, 2) small release frequency, and 3) large release frequency. However, certain types of SMR use liquid fuel. In this case, definition of core

melting, which has been used to define Core Damage in Probabilistic Safety Analysis (PSA), should be revisited. In addition, failure probability of passive components is generally provided as input for PSA as a form of initiating event. Certain types of SMRs use non-conventional form of fuel (e.g. molten salt fuel, thorium) along with the elevated operating temperatures. The determination of failure rates of novel materials, SSCs exposed to high temperatures and neutron fluxes and passive components in some SMRs is challenging. These failure rates are inputs into PSAs. Events are to be classified, based on the results of probabilistic studies and engineering judgment, into one of the following three classes of events: 1) ***AOOs*** *include all events with frequencies of occurrence equal to or greater than* 10^{-2} *per reactor year, 2)* ***DBAs*** *include all events with frequencies of occurrence equal to or greater than* 10^{-5} *per reactor year but less than* 10^{-2} *per reactor year. This class of events also includes any events that are used as a design basis for a safety system, regardless of whether the estimated frequencies are less than* 10^{-5} *per reactor year, and 3)* ***BDBAs*** *include events with frequencies of occurrence less than* 10^{-5} *per reactor year*. Uncertainty in material behavior also poses a challenge for classification of initiating events.

1.11 Equipment Environmental qualification

As per Section 7.8 in REGDOC-2.5.2, the design shall include an equipment environmental qualification (EQ) program. Development and implementation of this program shall ensure that required safety functions can be carried out. Design classification, codes and standard should be provided.

1.12 Seismic Qualification and Design

As per Section 7.13 in REGDOC-2.5.2, *SSCs important to safety should be seismically classified and qualified accordingly.* The seismic qualification of all SSCs shall meet the requirements of Canadian national or equivalent standards. The design shall include instrumentation for monitoring seismic activity at the site for the life of the plant.

References

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