DESIGNING AND OPERATING NEW NUCLEAR POWER PLANTS FOR FUTURE REFURBISHMENT – REGULATORY PERSPECTIVE

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Abstract

Designers and operators of future Heavy Water (HW) nuclear power plants (NPPs) should take into consideration the likelihood that when the NPP reaches the end of its "assumed design life" it may be subject to refurbishment or extended operation rather than decommissioning. This consideration may impact the design requirements and operation provisions by placing emphasis on, for example, designing and maintaining specific structures, systems and components (SSCs) such that expected plant-life-limiting SSCs remain functional, or can be replaced or repaired to ensure the continued validity of the licensing basis for extended plant operation. As such, designers and operators should consider lessons learned from the refurbishment projects undertaken around the world, as well as insights from the use of the Periodic (or Integrated) Safety Review, to conceptualize HW NPPs that could effectively be refurbished to extend their operation beyond the originally assumed design life.

This paper presents a regulatory perspective regarding the potential for designing and operating new NPPs with refurbishment taken into account at the outset of the design process. Examples of regulatory experience gained from current Canadian refurbishment projects are also given.

1 Introduction

For nuclear power reactors that are approaching their assumed design life, the recent trend for the operator is to opt for refurbishment or extended operation prior to decommissioning. Even for the new heavy water reactor designs that have an assumed design life of 60 years, planned mid-life refurbishment is required due to aging effects of critical components such as fuel-channels and feeders. As such, designers of new reactors must think, proactively, to address how activities required for refurbishment or extended operation will be undertaken to minimize the risk to workers, public or the environment. Designers also will have to expect that design, operation, and safety requirements continually evolve with time and experience, and may become more stringent at the time of refurbishment, 30 or 40 years from the time of the original design. The challenge then is how to cater to potential future improvements in a current state-of-the-art design.

Recognizing the eventual need for a regulatory document dealing with the issue of refurbishment or life extension, the Canadian Nuclear Safety Commission (CNSC) issued in 2008 a Regulatory Document RD-360 "*Life Extension of Nuclear Power Plants*" [1] which requires a licensee to conduct an Integrated Safety Review (ISR) for a single-unit or multiple-unit nuclear power plant (NPP) approaching the end of its assumed design life. Omar and Carrier [2] described the ISR process as a systematic and comprehensive approach to determine the:

- Actual state of plant's structures, systems and components (SSCs);
- Adequacy and quality of plant design, licensing and operational documentation;
- Presence of established and effectively implemented management and operation programs; and
- Reasonable and practical modifications to improve or maintain plant safety in line with modern national and international codes, standards and practices.

In addition to RD-360, the conduct of the ISR by the licensee and the corresponding regulatory oversight utilize the guiding process of the International Atomic Energy Agency (IAEA) Standard Guide NS-G-2.10 *"Periodic Safety Review of Nuclear Power Plants"* [3].

In the last few years, the CNSC and the Canadian industry have been involved in a number of refurbishment and extension-of-operation projects not only for NPPs but also for a research reactor. The cumulative CNSC experience is documented in a Staff Review Guide [4] which is consistently and routinely used by the CNSC staff as guidance on how to assess licensee's documents resulting from an ISR.

Based on Canadian and international refurbishment or extended operation experiences, it became evident that at the outset specific areas related to the design, aging, operation, and management of a nuclear reactor have to be considered for potential refurbishment and upgrade, or for extended and continued operation after the assumed design life of the reactor is reached.

For a nuclear reactor to continue to function safely after 30 or 40 years of operation, assurance of the following is expected based on the codes and standards of the day:

a) Structures, systems and components (SSCs) important to safety [5] are fit-for-service and supported by a systematic and integrated aging management program [6] with documented records;
b) The licensing basis [7] remains valid;
c) The safety case is updated [8, 9] considering the state of condition of the SSCs at that time;
d) Dose to workers are kept as low as reasonably achievable (ALARA), with social and economic factors being taken into account [10], during operation and refurbishment; and
e) Operating provisions and programs exist and are effectively implemented within a well structured organization committed to effective safety culture.

The remainder of this paper will focus on refurbishment since extended operation beyond the assumed design life of an NPP is considered a special case of limited refurbishment/upgrade.

2 Designing Specific SSCs for Refurbishment

Specific nuclear power plant (NPP) structures, systems, and components (SSCs) are designed and operated with an expected life of 30 or more years. Due to known aging-related degradation mechanisms (ARDMs) some of these SSCs will have to be replaced or refurbished to restore their functional performance; and upgraded to the requirements of the codes and standards of the time. Even if the SSCs are well maintained during their operating life, some may have to be replaced due to advances in technology or unavailability of parts caused by obsolescence. Thinking about these eventualities, and that licensees may wish to operate a refurbished plant for additional 30 years rather than build a new one, designers must conceptualize the factors that would facilitate the refurbishment process and make it most effective and efficient.

2.1 Importance of Establishing and Implementing an Integrated Aging Management program (AMP)

Aging management is the engineering, operational, inspection, and maintenance actions that control, within acceptable limits, the effects of physical aging and obsolescence of SSCs occurring over time or with use. An aging management program (AMP) is a set of policies, processes, procedures, arrangements, and activities for managing the aging of the SSCs for an NPP. The CNSC regulatory document RD-334 [6] sets out the requirements of the CNSC for managing the aging of SSCs of an NPP.

CNSC RD-334 [6] requires that appropriate measures and features are introduced in the design stage to facilitate effective aging management throughout the lifetime of the NPP. The designer of a new NPP should therefore take into consideration the requirement for implementing an effective integrated aging management program for addressing both physical aging of SSCs, resulting in degradation of their performance characteristics, and obsolescence of SSCs. Aging management applies to SSCs that can, directly or indirectly, have an adverse effect on the safe operation [5] of the NPP.

The designer is expected to apply a systematic approach to ascertain the understanding of aging of SSCs; evaluate effective means and design features for aging prevention, monitoring, and mitigation; and establish AMPs for SSCs important to safety. Design documentation should demonstrate how past relevant generic aging issues, relevant aging management experience, and research results are addressed.

The safe service life or qualified life for SSCs must be defined in the design documentation, with an assessment of design margins that takes into account all known aging and wear mechanisms as well as potential degradation, including the effects of testing and maintenance processes. SSCs that have shorter service life than the NPP life are to be identified, along with management strategies, in the design documentation.

The plant layout and design of SSCs should include features to facilitate inspection, testing, surveillance, maintenance, and other activities, including major refurbishment activities, in order to keep potential radiation exposures from these activities as low as reasonably achievable (ALARA) [10]. This should include not only small components, but also large components such as steam generators, main pumps, heat exchangers, filters, valves, pressure/calandria tubes, feeders, etc. Details should be meticulously studied to the extent required to check or replace parts, even down to the level of flange bolts, carry out required non-destructive evaluation (NDE) inspections, or collect material samples for assessment. Of course, advances in tooling and robotics would minimize dosage to workers who are involved in routine day-to-day activities or activities related to refurbishment.

Potential obsolescence issues for SSCs should also be identified as practicable as possible, to evaluate their effect on safety and reliability performance, and establish management strategies. Provisions for spare parts for the planned service life timely replacement of parts, long-term arrangements for manufacturers and spare parts suppliers, and required technical support are to be identified.

Maintaining records on ARDMs of SSCs and on mitigating activities regarding their functional capabilities and fitness for service is essential not only during operation but also as input to the ISR and later for establishing the refurbishment plan.

A key element to the concept of an "integrated" AMP is the fact that systems are not maintained in isolation. Engineering, operation, inspection and maintenance activities considered for one system are analyzed to ensure there will be no adverse effects on interrelated or neighbouring systems to the extent possible. One example of this would be the implementation of chemistry controls for the feedwater system. Chemistry controls utilized to protect against ARDMs for materials used in the construction of a component, such as a condenser, dearator, etc., should not result in degradation of steam generator internals or steam generator tubes. Of course this also leads back to the concept of considering aging management requirements in the design stage to ensure the compatibility of materials. Where material compatibility is not possible, provisions should be incorporated into a design to permit the plant operator to carry out replacement or refurbishment activities for SSCs which may be impacted.

2.2 Regulatory Requirements and Expectations

The operating licence for Canadian NPPs recognizes, through the inclusion of specific licence conditions, the necessity for plant operators to maintain an adequate knowledge of key SSCs which impact safe plant operation. Licensees are required to implement maintenance programs which comply with CNSC Regulatory Standard S-210 "*Maintenance Program for Nuclear Power Plants*" [11], as well as implement periodic and in-service inspection programs which comply with Canadian Standards Association (CSA) Standards N285.4 [12], N285.5 [13] and N287.7 [14]. Licensees are also required to develop in-service inspection programs focusing on balance-of-plant pressure boundary systems and structures which may impact safe operation.

3 Maintaining the Licensing Basis and Safety Case

The licensing basis [7] includes regulatory requirements described in the applicable laws and regulations; licence and documents referenced in the licence; and the licence application and documents needed to support the licence application.

At the time of performing an ISR to support a refurbishment, a comparison is conducted between the state of design and safety of the NPP and the requirements of CNSC regulatory documents, industry codes and standards, and licensee's documents supporting the licence such as Operating Limits of Conditions, Management System Manual, etc.). As such, it is expected that:

a) Design-basis documents are updated based on current plant configuration;

b) The safety case is updated through the periodic review of safety analyses [8] to account for, among other factors, plant configuration, plant condition including effect of aging, research findings, effective implementation of licensee's processes for the conduct of safety engineering, validated safety analysis tools that reflect the plant conditions, initiating events that are re-evaluated and adequately classified, operating limits and conditions that are updated and reflected in operating processes and procedures, and a defence-in-depth analysis that is validated by current SSCs condition and an established management system; and

c) Safety analyses include both deterministic and probabilistic safety analyses, as well as hazard analysis.

The designer of a new NPP must then ensure that the documentation in support of the design basis is clear, consistent and comprehensive. Also, in support of the safety case, the Safety Analysis Report (SAR) must include all the necessary information [8] in support of the safe operation of the plant, and in support of evaluating the continued operating of the plant beyond its assumed design life.

3.1 Regulatory Expectations

The regulatory requirements and expectations for updating the licensing case including safety analyses are stated clearly in RD-310 [8] and S-99 [9]. At the time of refurbishment, safety analyses are updated to meet the current standards. Also, emerging issues or circumstances may place emphasis on specific aspects of safety or hazards analysis. For instance, the March 11, 2011 Fukushima Daiichi accident in Japan highlighted the need to consider including in the severe accident analysis combinations of internal/ external hazards and consequential initiating events. In fact, the CNSC issued on March 17, 2011, a request for action pursuant to Subsection 12(2) of the Canadian General Nuclear Safety and Control Regulations [15] requiring all major nuclear facilities in Canada to review lessons learned from the Fukushima Daiichi accident and to re-examine the safety case and report on plans to address any significant findings.

Even before the Fukushima Daiichi accident, operators of existing NPPs began to develop a severe accident management guideline (SAMG), and considered measures to reduce the impact of a severe accident. For example, to meet the safety goals of RD-337 [5], the probabilistic safety assessment (PSA) of an NPP in Canada identified a number of SAMG-related recommendations with respect to plant design and operation, such as:

- Installation of containment emergency filtered vent system;
- Installation of calandria vault water make-up;
- Installation of Passive Autocatalytic Recombiners (PARs);

- Upgrading fire detection and protection systems; and
- Seismic re-assessment and upgrades.

4 The Economics of ALARA during Refurbishment

Subsection 4(a) of the Canadian Radiation Protection Regulations [10] sets the requirements on the licensee to keep exposure to and doses received from radiation as low as reasonably achievable (ALARA), social and economic factors being taken into account, through management control over work practices, personnel qualification and training; control of occupational and public exposure to radiation; and planning for unusual situations.

During operation of an NPP, the licensee develops and effectively implements a radiation protection program that aims at achieving this objective. The designer of a new NPP also contributes to achieving the ALARA targets by the effective design [5] of, for example, radiation zones with controlled access; biological shielding to protect workers from direct or scattered radiation during daily activities such as operation, surveillance, inspection and maintenance; ventilation and filtering systems to control airborne radioactive materials; and effective decontamination provisions..

Refurbishment activities necessitate the additional requirement to consider that contaminated SSCs may require repair or replacement. The designer of a new reactor must have the foresight to provide for the appropriate space, biological shielding, and decontamination provisions for workers undertaking such activities, to ensure that effective and equivalent doses received and committed by a worker are kept ALARA in such work environments.

4.1 Regulatory Perspective

The regulatory mandate includes ensuring that the use of nuclear energy does not pose undue risk to workers, public and the environment. During operation, CNSC assesses licensee's operational programs and performs routine inspection to gain confidence that such operational programs are effectively implemented. For refurbishment, radiation protection consideration is of paramount importance since not only nuclear operator will be involved but also will be outsourced contractors. CNSC sends inspectors regularly during refurbishment to ascertain that measures are in place by the licensee so that contamination is controlled and confined, personal dosimeters are worn, and the radiation protection provisions are effectively planned and implemented at every stage of the refurbishment work.

5 Lessons Learned from Refurbishment Projects

5.1 Existing Heavy Water Reactor Design

Several key lessons have been learned from current and planned refurbishment projects which make it apparent that the current fleet of HW NPPs were not originally designed with large scale refurbishment projects in mind. NPP operators have had to overcome significant challenges which have resulted in cost overruns and delays in the completion of refurbishment projects. Examples of such challenges include:

- Containment and reactor building designs that do not allow for easy removal of large or awkward components such as steam generators or feeders.
- Poor choices in material selection for the operating environment which resulted in having to replace large components. For instance, the use of carbon steel for steam generator tube supports instead of stainless steel which is resistant to flow accelerated corrosion.
- The design of the Calandria vessel is such that it is impossible to carry out in-service inspection and the vessel can only be internally inspected through the development of a limited suite of specialized tools and after the removal of fuel channels. Further to this concept, the calandria is not equipped with material samples which can be extracted periodically to monitor possible effects of irradiation on material properties over time.
- Access limitations which can limit the ability to carry out post-replacement/refurbishment inspections while maintaining low dose rates to inspection personnel.

To address many of these examples, a great deal of time and financial effort was required on the part of the NPP owner to develop special tooling. Further efforts were required to satisfy the regulator that methodologies chosen to overcome these challenges were consistent with the safety requirements of modern codes and standards. Designers of new CNADU reactors should therefore consider modifications to the design of containment and reactor building structures to facilitate activities related to monitoring, testing, inspection or replacement of SSCs, in particular the large or awkward components.

5.2 SAMG

During a routine exercise through SAMG at a Canadian NPP, it was revealed that under some accident conditions, the addition of water to the building is restricted by the location of the Personnel Airlocks (PAL) and/or vent system air intake. In reviewing the sequence of event and preventive measures, it was recognized that operators will have to stop adding water at a level lower than that of the Calandria to prevent a containment breach. It was therefore recognized that modification should be considered to the location and design of the PAL to allow level of water to be added at a higher level in relation to the Calandria.

5.3 Radiation Protection

<u>Personnel Dose</u>

The following are examples of lessons learned from recent ISR and refurbishment projects in Canada regarding personal doses:

a) During refurbishment projects, a large number of workers were hired from local unions with:
   - Little to no work experience in nuclear facilities,
   - Apprehension regarding hazards associated with radiation, and
   - “Trade rules” leading to more people in work areas absorbing unnecessary dose.

b) Importance of presence of qualified and experienced Protection Assistants (PAs) as related to knowledge of radiation hazards, and ensuring the effectiveness of compliance with, and adherence to procedures.

c) High levels loose contamination in Reactor Building during Pressure Tube (P/T) removal causing high radiation fields around equipment.

d) Contamination on flasks returned from waste site.

e) Persistent problems with fuel channel volume reduction tooling had to be overcome to prevent the spread of contamination; for example, maintaining low system pressures, eliminating hydraulic fluid leaks, and addressing issues related to waste flasks door closure. In addition, it was also necessary to ensure that the vault vapour recovery dampers were open and that the primary filter was in place.

Alpha Contamination

Recent components that were worked-on at an NPP in Canada have caused in one incident air-born alpha contamination in the work area. Preliminary monitoring of affected workers indicated no exposure above regulatory limits. However, the licensee continued increased monitoring of the affected workers and started a root-cause investigation. Since contamination was confined to the affected reactor unit, there was no risk to the public or the environment. However, pursuant to Subsection 12(2) of the *General Nuclear Safety and Control Regulations* [15], CNSC issued a request to all NPP licensees to assess and implement immediate compensatory measures to protect workers from alpha hazards. Subsequently, all NPP licensees took immediate measures to protect workers. These measures were submitted for CNSC staff reviews and were deemed acceptable [16].

The above-mentioned practical experiences demonstrated field challenges to the site-staffs of the operator and regulator. Lessons learned should be used to introduce changes to the design of new HW NPPs to minimize the impact of exposure to radiation on workers involved in the refurbishment activities.

6 Lessons Learned from ISR reviews

6.1 Outsourcing

Due to the scale of the ISR and the workload faced by licensee staff dealing with day to day operations, the conduct of the ISR and preparation of corresponding documents are often contracted out by the licensee. In order for outsourcing to become efficient, the licensee must ensure that the contractor has direct access to staff members who are most familiar with the SSCs and programs relevant to the ISR. The Canadian regulatory assessment of ISR documents has revealed that, at times, contractors who prepare the documents do not accurately reflect the most up to date knowledge of SSC conditions and programs.

6.2 Documenting Current Actual Condition of SSCs

A key element of the ISR process is the completion of a comprehensive report documenting the current actual condition of SSCs that impact the safe operation of an NPP. While licensees have mature maintenance and inspection programs, the methods used to gather and store key information related to condition of SSCs does not always lend itself well to permit the licensees to report the information in a clear and concise manner. Consequently, the regulatory assessment of the report on actual condition of the SSCs has required, in one ISR project, multiple iterations of correspondence and technical meetings between the staff of the regulatory body and licensee which were drawn out for more than one year. It is anticipated that as licensee's AMPs are kept fully developed and effectively implemented, this process would be less onerous on both the licensee and the regulator.

7 Lessons Learned from Regulatory Assessment of Refurbishment Projects

7.1 Sufficiency of RD-360

While the CNSC has applied RD-360 [1], which outlines the main elements of an ISR, experience has shown that the document alone does not have sufficient and detailed information to respond to numerous challenging application and implementation questions faced by regulatory and licensee staffs in undertaking an ISR project to successful completion.

Three additional documents have proven to be useful;

1) The establishment of a "protocol' document between senior management of the CNSC and the licensee detailing the administrative process and management of high-level milestones of the ISR. The protocol facilitates adherence to schedules and ensures timely completion of the ISR related submissions and corresponding CNSC staff assessments. The protocol also entice staff involved to be proactively innovative in resolving challenges and prioritizing work to successfully meet the intended target dates set in the protocol. It also represents senior management commitment and acknowledgement of the priority assigned to the project which facilitates resolving issues related to availability of resources.

2) The development by the licensee and acceptance by the CNSC of a solidly founded and technically supported ISR Basis Document [2], the first deliverable of an ISR project.

3) The CNSC Staff review Guide [4] that distils experience gained by the CNSC staff through their own ISR-related assessments and via discussions and information exchange with foreign regulatory bodies and in international fora. It contains valuable guidance, acceptance criteria and templates that systematically assist the CNSC staff in making determination based on documented rationales.

Currently, RD-360 [1] is subject to revision that will reflect experience acquired and best practices. A companion regulatory guidance document (to be labelled as GD-360) is also being developed to support the application of the revised RD-360.

7.2 Regulatory Acceptance of ISR Documents

As per RD-360 [1], regulatory acceptance is required for the ISR Basis Document and the Integrated Implementation Plan (IIP), the last deliverable in the ISR process. Other licensee's documents are reviewed and assessed. It proved essential that regulatory expectations and acceptance criteria be written clearly by the CNSC and shared with the licensee before and during the conduct of the ISR. This ensures that regulatory assessment and acceptance are transparent and are performed without surprises at any stage of the assessment. For this reason, the CNSC Staff Review Guide [4] was shared with the industry at a workshop, and distributed to licensees contemplating undertaking an ISR.

8 Conclusions

Even though existing NPPs have an assumed design life of 30 or 40 years, refurbishing or extending the operation of a nuclear reactor is becoming and will continue to be a reality for the foreseeable future. Designers and operators of a new NPP should then plan to design, maintain and operate for, say, 60 years specific structures, systems or components (SSCs), such as civil concrete structures and steam generators with the aim of maintaining valid the licensing basis. Specifically, designers and operators must plan to maintain SSCs important to safety fit for service by developing and effectively implementing an integrated aging management program with documented data recording the current condition of the SSCs and prognosis for continued operation. Also, for SSCs that are known to degrade and must be replaced to maintain safe operation of the NPP, the designers of new nuclear plants must consider this eventuality when conceptualizing the layout of the plant to allow for such activities while adhering to the ALARA concept.

From the regulatory view point, safe operation of the NPP, including safety of workers, public and environment, is one key issue whether the NPP can operate for 30 or 60 years, and whether or not it can be refurbished to support extended operation.

9 References

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