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Best Practices in the Refurbishment of Pressurized Heavy Water Reactors

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International Atomic Energy Agency

BEST PRACTICES IN THE REFURBISHMENT OF PRESSURIZED HEAVY WATER REACTORS

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IAEA-TECDOC-2015

BEST PRACTICES IN THE REFURBISHMENT OF PRESSURIZED HEAVY WATER REACTORS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2022

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Printed by the IAEA in Austria
November 2022

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Best practices in the refurbishment of pressurized heavy water reactors / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2022. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 2015 | Includes bibliographical references.
Identifiers: IAEAL 22-01553 | ISBN 978–92–0–146422–4 (paperback : alk. paper) | ISBN 978–92–0–146322–7 (pdf)
Subjects: LCSH: Pressurized water reactors. | Pressurized water reactors — Maintenance and repair. | Nuclear reactors.

FOREWORD

Continued and increasing demand for safe, clean, reliable and cost effective electricity generation is a strong factor in nuclear power countries efforts to extend the operating lives of their nuclear power plants. The life of a nuclear power plant can be extended by several decades through refurbishment, which involves modernizing and enhancing major equipment and systems to support long term operation. Refurbishing a facility through component upgrades and modifications provides opportunities to enhance plant safety and reliability by modernizing and updating technology and knowledge.

In addition to the number of Canada deuterium-uranium (CANDU) and other pressurized heavy water reactors (PHWRs) that have been refurbished in recent decades, several PHWR refurbishment projects are currently being implemented or planned over the next ten years. In order to provide a venue for knowledge sharing among stakeholders in PHWR refurbishment projects around the world, the IAEA in collaboration with CANDU Owners Group organized a Technical Meeting on Best Practices in the Refurbishment of PHWRs. The meeting accomplished its objectives of sharing experience and transferring knowledge from the planning, scope setting and execution of PHWR refurbishment programmes in various Member States. The Technical Meeting received strong support from all members of the 2018 meeting of the Technical Working Group on Heavy Water Reactors.

This publication summarizes the outcome of this Technical Meeting on Best Practices in the Refurbishment of PHWRs held in Toronto, Canada, in December 2019. The publication presents some highlights of past and ongoing refurbishment projects from lessons identified by the participants of the Technical Meeting.

The IAEA is grateful for the contributions from the Technical Meeting participants and the contributors listed at the end of this publication. The IAEA also acknowledges the efforts and assistance provided by the CANDU Owners Group, particularly the Refurbishment Forum Program Manager, M.M. Cobanoglu. The IAEA officer responsible for this publication was E.-L. Pelletier of the Division of Nuclear Power.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The IAEA organizes Technical Meetings to facilitate the information exchange and co-operation on advanced reactor technology related activities. In line with those activities, a Technical Meeting on Best Practices in the Refurbishment of Pressurized Heavy Water Reactors (PHWRs) was held in Toronto, Canada on 2–6 December 2019 to share experience and transfer knowledge regarding the planning, scope-setting and execution of PHWR refurbishment programmes in various Member States.

PHWRs need the replacement of their fuel channels after approximately 30 years of operation, because of the dimensional and metallurgical changes in their fuel channel pressure tubes, to allow the reactor units to operate for a longer time [1]. The term refurbishment, as used in this publication, envelopes major projects undertaken by various PHWR operators with scope ranging from fuel channel replacements only to wider scopes that include replacement or refurbishment of feeder pipes, steam generators, turbines, and other nuclear steam supply system and Balance of Plant (BOP) components, as well as the incorporation of safety enhancements. These refurbishment projects are referred to as En-Masse Coolant Channel Replacements (EMCCRs) in India, major component replacements by Bruce Power, and large-scale fuel channel replacements for Ontario Hydro's Pickering A Units 1, 2, 3, and 4.

Large-scale fuel channel replacements in CANDU reactors began in the mid-1980s with all four units of Pickering A Nuclear Generating Station (NGS) in Ontario, Canada. Subsequently, several similar pressure tube replacements, or EMCCRs, were undertaken in Indian PHWRs starting with the Rajasthan Atomic Power Station 2 (RAPS-2) in 1995–1998. Both major PHWR operating Member States' approaches were described in an IAEA publication [2].

Multiple CANDU reactor refurbishment projects have been completed in Canada and worldwide since the mid 2000's, beginning with Bruce A Units 1 and 2 (2006–2012), and Point Lepreau NGS (2008–2012), followed by Wolsong Unit 1 (2009–2011), and Embalse (2016–2019). More recently, refurbishment projects of multiple units have continued with Bruce Power's major component replacement programme to refurbish the remaining six units (Units 3–8) at Bruce and Ontario Power Generation (OPG) refurbishment project for the four units at Darlington. The refurbishment of these units aims to extend the unit operation by another 30 years, and results in enormous benefits to the operating utilities and their customers.

1.2. OBJECTIVE

The objective of this publication is to summarize the lessons learnt and knowledge gained from the past and current PHWR refurbishment projects as presented at the Technical Meeting. The information is detailed in terms of project definition and planning of past, present and future projects, regulatory considerations, supporting research and development, and lessons learnt and best practices.

1.3. SCOPE

This publication summarizes various aspects of the refurbishment projects based on the materials and discussions presented at the Technical Meeting on Best Practices in the Refurbishment of PHWRs focused on sharing lessons learnt and best practices from the completed and ongoing PHWR refurbishment projects.

The following topics, relevant for refurbishment projects, were discussed:

- Description and key aspects of completed and current refurbishment projects;
- Major tasks in refurbishment projects including project definition and planning, and critical path in execution;
- Description and key aspects of regulatory issues associated with refurbishments;
- Key lessons learnt and best practices;
- Research and development in support of PHWR life extensions and refurbishments.

1.4.STRUCTURE

Section 2 of this publication provides background on fuel channel aging mechanisms and refurbishments general scope. Section 3 reviews completed, and ongoing refurbishment projects based on the information presented at the Technical Meeting. Section 4 offers an overview of the project definition and planning activities for the next planned refurbishments. In Section 5, selected regulatory aspects of refurbishment projects are discussed. Section 6 deals with supporting Research and Development (R&D) that has been critical to life extensions by enabling the utilities to spread out their refurbishments without having to prematurely shutdown units. R&D also facilitated the development of innovative tools and processes important to the success of refurbishment projects. Section 7 provides some of the key lessons learnt and best practices in a variety of areas. Finally, Section 8 summarizes the key conclusions. The Technical Meeting presentation abstracts are provided in Appendix I.

2. BACKGROUND ON FUEL CHANNEL AGEING AND REFURBISHMENTS

CANDU reactor design life has historically been tied to fuel channel operating life. This section therefore first presents an overview of the PHWR fuel channel ageing mechanisms, followed by a description of the physical scope of work common to most of the refurbishment projects to provide background to the remaining sections of the publication.

2.1.OVERVIEW OF FUEL CHANNEL AGEING MECHANISMS

Figure 1 shows the CANDU 6 fuel channel components. Pressure tubes are supported on end shields by the end fittings. Four annulus spacers (or garter springs) over each pressure tube maintain a gap between the pressure tubes and the calandria tubes.

During operation, primary heat transport system coolant flows from the inlet end of the fuel channel to the outlet end. This fluid flow causes a temperature gradient in the fuel channel components with an approximate temperature of 250–265°C at the inlet end to 290–315°C at the outlet end. The neutron flux profile of a channel resembles a bell with its peak at mid-span. Figure 2 shows the temperature and flux profile of a CANDU fuel channel.

Extended operation under fast neutron fluence results in corrosion and deuterium level increase in zircalloy pressure tubes and makes them more susceptible to delayed hydride cracking (DHC). Risks of DHC also increase with tensile stress. Pressure tubes are rolled expanded into the end fittings, and these junctions are referred to as rolled joints. The rolled joints are where the tensile stresses are typically highest making them more at risk to DHC. The high residual stresses found in rolled joints of early PHWR designs, caused by improper positioning of the rollers, required pre-services stress relief or early replacements.

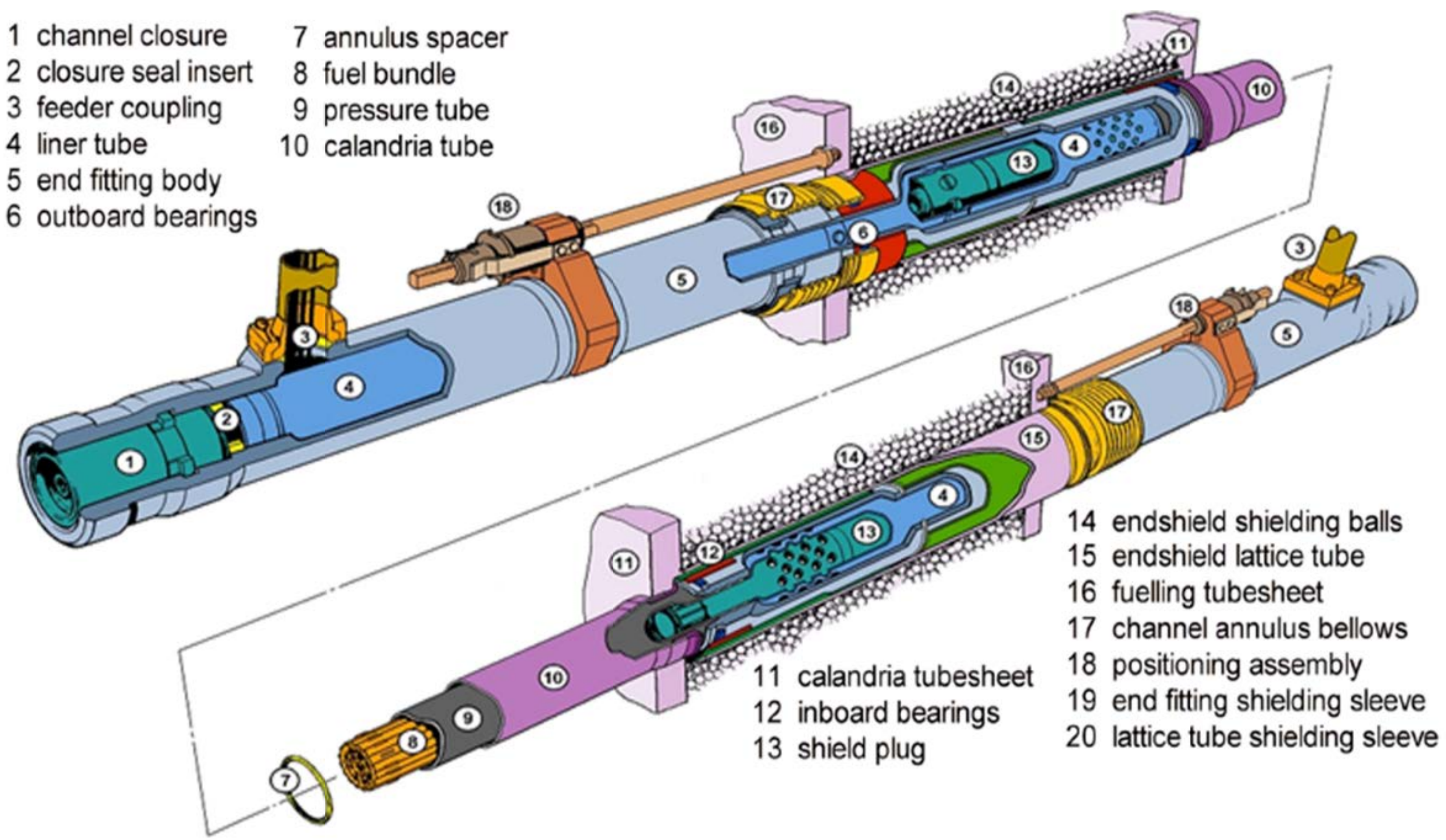

FIG. 1. CANDU 6 fuel channel showing key components (courtesy of SNC Lavalin Nuclear [31]).

Pressure tubes also undergo dimensional changes (sag, elongation, diametral expansion and wall thinning). Those changes could eventually lead to contact between the pressure tube and the calandria tube and result in hydride blisters, which may lead to cracking. These life limiting phenomena have been extensively covered in Ref [3].

CANDU reactor design life has therefore historically been tied to fuel channel operating life. Early design reports selected 210 000 effective full power hours (EFPH) as a basis for estimating operating life (30 years at ~80% capacity factor, assuming 7000 EFPH/year). However, the full scope of fuel channel degradation mechanisms was not well understood, and early reactors did not reach that target.

The feedback from early CANDUs and Indian reactors has however led to improvement in fuel channel fabrication (e.g., zircaloy-2, used in first CANDUs pressure tubes, was replaced by Zr-2.5%Nb starting with Pickering A retubes in the mid-1980's) and installation techniques. These improvements are described in their respective projects in Section 3.

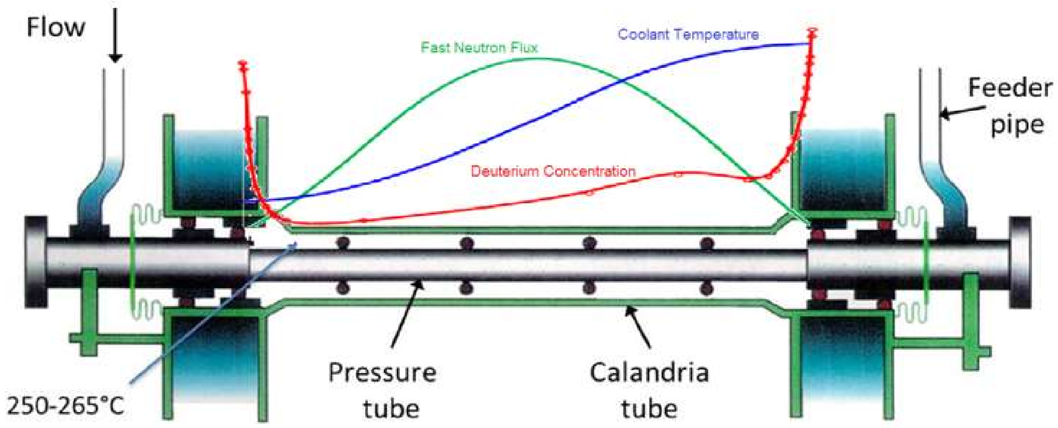

FIG. 2. Typical temperature, flux and deuterium concentration profiles in CANDU fuel channels [16].

2.2.GENERAL REFURBISHMENT SCOPE

The refurbishments scope invariably includes the replacement of the aged pressure tubes. In most cases, the entire fuel channel is replaced, and a more generous allowance is made for elongation. Additional utility-specific modifications are also often performed as part of the refurbishment outage. The scope is established based on the utility's assessment of the ageing of the key systems and components, and to incorporate conformance to newer requirements, address generic safety issues, commitments or license conditions, or to incorporate operating experience.

Although the exact physical work and execution steps vary between utilities, this section aims to provide an overview of those, starting from shutdown to defueling, replacement of fuel channels, refuelling and start-up. It is understood that detailed planning and extensive preparatory works are necessary prior to shutdown and defueling. Those are beyond the scope of this section and are treated in the project-specific sections as they were reported at the Technical Meeting.

2.2.1. Shutdown, defueling and draining

After shutdown, defueling and heavy water removal is accomplished through:

Decontamination and conditioning: before the defueling activity, decontamination of the coolant circuit can be carried out to reduce the radiation fields in the fuelling machine vaults where the major tasks associated with the removal of highly radioactive reactor components are performed. Hot conditioning (passivation) can also be performed to preserve the rest of the coolant circuit for future use by creating an impervious magnetite protective layer on them.

Defueling: defueling of the reactor core is carried out using fuelling machines to transfer the fuel bundles to the spent fuel storage bay. The spent fuel storage bay has sufficient margins for the anticipated space and head load considerations.

Primary heat transport system (PHTS) and moderator drain: after decontamination and defueling, the heavy water is drained from the PHTS and the moderator system to facilitate the beginning of the channel cutting and subsequent removal. Subsequently, PHTS is flushed with demineralized water and drained completely. After this, the PHTS is dried with instrument air and temporary seal plugs are installed. The drying of the PHTS is ensured based on the dew point reading of the instrument air passed through the system and by inventory checks.

2.2.2. Removal of plant interferences and islanding

The islanding is a unique requirement for multi-unit plants like Darlington and Bruce A and B where a common fuel handling system is shared by the four units. After the reactor is defueled, it is separated (islanded) from the operating units with physical barriers. Islanding helps employees perform work safely while reducing impact on the operating units in a multi-unit station.

2.2.3. Removal of fuel channels

Feeders can be removed to gain enhanced access to the channels. It has been established that feeder replacement has net overall benefits in terms of productivity (reduced cost and schedule) and ability to use improved feeder materials and better post-refurbishment geometry. Removal and disposal of fuel channels involve various sub activities, including feeder hanger and shock absorber assembly removal, pressure tube cutting, anulus gas monitoring system (AGMS) bellows weld cutting, and removal and storage of end fittings, pressure tubes, and channel annulus spacers. These activities need ongoing monitoring of air borne particulate activity and contamination levels.

2.2.4. Inspection of calandria vessel internals, removal of any debris and cleaning of retained components

The internals of calandria vessel are inspected after heavy water and tubes are removed. Retained components (such as bearing sleeves, lattice tubes of the end shields, and the AGMS bellows, etc.) are cleaned in various stages including vacuum cleaning through high efficiency particulate air filters to avoid contamination spread and trapping of debris in the components. The cleaning is followed by inspections to confirm components are free from loose material or foreign particles.

The retained components are finally inspected to assess their fitness for further service. Materials and components that are not retained are safely stored in licensed waste facilities.

2.2.5. Installation of replacement fuel channel components and feeders

This critical step includes the installation of new calandria tubes, pressure tubes, feeder pipes, and feeder support hardware. Prior to these steps, pre-assembly activities such as degreasing of components, shrink fitting of bellows attachment ring on the end fitting, pressure tube trimming, and end fitting body assembly are performed.

Installation of fuel channel assemblies involves connecting each pressure tube to the end fittings at both ends by cold rolled joints. The installation phase involves making the fuel channel sub assembly (pressure tube end fitting assembly) rolled joint outside the reactor (in a components assembly building) under clean room conditions. The pressure tube to end fitting assembly is inserted in the calandria and locked from one end. The four annulus spacers are either installed one by one from the opposite vault or pre-installed on a sleeve on the pressure tube that is part of an annulus spacer installation tool and released at the designated axial locations as part of the subassembly installation process. After installation of annulus spacers, the second end-fitting assembly is installed. An on-reactor (in-situ) rolled joint is then made while maintaining clean room conditions in the fuelling machine vault. The installation continues with welding of AGMS bellows, air hold test of fuel channels through AGMS, and shock absorber assembly (fuel channel positioning assembly) installation.

Qualified procedures, tools, equipment, and personnel as well as constant monitoring are important during this crucial phase of the project, specially to ensure that the rolled joints meet the leak tightness specifications. Helium leak rate tests, visual inspections, ultrasonic testing, examinations of the pressure tube bore for flaws, and examinations of the pull-out strength and fracture toughness of the pressure tube material are done on-site or at the manufacturing stage.

Installation of fuel channel assemblies is followed by feeder installation, when applicable. Prerequisites to feeder installation include inspection of the feeder header nozzles, fabrication of feeders in the shop, and erecting and welding of feeders in the vault.

2.2.6. Restoration of the reactor vault, completion of component replacement, fuel load, heavy water fill, commissioning and startup

Fuel loading and subsequent unit startup activities are the final steps in refurbishments. Fuel loading is preceded by completion of various surveillance activities, as specified in applicable technical specification, and dictated by operational needs prior to unit synchronization. Typical sequence of activities for reactor startup include:

- Loading the reactor with new fuel bundles;
- Filling the PHTS system with clean heavy and the calandria vessel with de-tritiated moderator heavy water;
- Conduct of hydro test and hot conditioning of PHTS;
- Approach to critical and low power testing;
- High power testing and power escalation to full power.

More details on this phase are provided in section 5 along with the regulatory interface typically required at that stage.

3. COMPLETED AND ONGOING REFURBISHMENT PROJECTS

This section summarizes the completed and ongoing refurbishment projects' specific scopes and highlights. The summaries are presented in chronological order of project initiation date, starting with CANDU refurbishments, and followed by Indian PHWR EMCCRs. The depth and content presented in each section varies and depends on the inputs provided during the Technical Meeting on Best Practices in the Refurbishment of PHWRs held in Toronto, Canada on 2–6 December 2019.

3.1.FIRST REFURBISHMENTS IN ONTARIO, CANADA

3.1.1. Pickering A Units 1,2,3 and 4 retubing

In August 1983, the pressure tube of channel G16 ruptured at Pickering A Unit 2. The rupture was a consequence of the high deuterium ingress rates in the zircaloy-2 pressure tubes and having only 2 loose fitting annulus spacers, which were relatively free to move, leading to pressure tube to contact the calandria tube and to the formation of brittle hydride blisters that initiated the failure [4, 5].

The event led Ontario Hydro (the publicly owned electricity utility in the Province of Ontario until 1999) to the decision to retube all four Pickering A units over the period 1985–1992. These were the first large scale fuel channel replacements undertaken in Canada.

Pickering Units 1 and 2 were retubed after only approximately 90 000 EFPH. Pickering Units 3 and 4 were retubed after approximately 120 000 EFPH, again primarily due to blister formation concerns stemming from having only two loose fitting annulus spacers and the choice of non-oxidizing N_2 for the annulus gas, which again led to high deuterium ingress rates, even though the Zr-2.5%Nb pressure tubes in Units 3 and 4 were subsequently shown to have acceptably low water-side deuterium ingress.

Pickering A retube mainly involved the replacement of pressure tubes. Feeder pipes and calandria tubes were not replaced as they were determined to be fit for post retube service life of the units through a series of analyses and testing of samples. The calandria tubes and feeder pipes in Pickering A units had thicker walls than those installed in subsequent CANDU units.

3.1.2. Bruce A Units 1 and 2 refurbishments

Bruce A Units 1 and 2 were the first two units at the Bruce site to undergo a major refurbishment after years of dormancy following the decision by Ontario Hydro to shut down the units. The decision was based on a fleetwide study that concluded with a recommendation to focus on newer units to improve overall efficiencies in the operation of their nuclear fleet.

Bruce Power operates the nuclear reactors at the Bruce site under a long-term lease agreement with the Government of the Province of Ontario (owner of the units). On 17 October 2005, Bruce Power announced its intention to refurbish and restart Bruce A Units 1 and 2. These units were laid-up after ~90 000–100 000 EFPH (and subsequently refurbished). They had only 2 loose-fitting annulus spacers although the switch to a CO_2 annulus gas had given tolerable deuterium ingress rates. In the case of Unit 2, a lead blanket, foreign material exclusion event had seriously degraded the steam generators. All fuel channel components (including the calandria tubes) and feeder pipes were replaced during the Bruce A Units 1 and 2 refurbishments.

At the time, Bruce Units 1 and 2 refurbishment was one of the largest infrastructure projects in Canada. It was also widely considered one of the most complex engineering challenges and introduced improvement in radiation protection programs for better accounting of alpha contamination [26, 27]. The project's focus was the replacement of reactor core components including pressure tubes, calandria tubes, and feeder pipes along with the eight steam generators. In addition, several plant equipment required significant repair, refurbishment, or replacement since the units had remained dormant for many years prior to refurbishment. The focus having been essentially on refurbishment of reactor components, less attention was paid to the conduct of a thorough and robust condition assessment of the remaining plant equipment. Cost overruns and schedule delays therefore resulted from the degraded condition of much of the plant equipment and by the fact that parts for equipment requiring repairs, refurbishments, or replacements were not readily available.

In October 2012, Bruce A Units 1 and 2 were returned to commercial operation, a few weeks after synchronizing to Ontario's electricity grid for the first time since 1997 and 1995, respectively [32, 33]. Successful completion of Bruce A Units 1 and 2, although significantly late and over budget led to the decision to refurbish the remaining six units at the Bruce site starting with Unit 6 major component replacement in 2020 [34]. Bruce Power decided to use the term major component replacement instead of retubing or refurbishment to emphasize the fact that only the major components would be replaced during these refurbishment outages and many of the other components would be repaired or replaced during the regular unit outages. This strategy was meant to help Bruce Power avoid many of the problems experienced during Bruce A Units 1 and 2 refurbishments.

3.2. COMPLETED CANDU-6 REFURBISHMENTS

Completed CANDU 6 refurbishments include Point Lepreau NGS (2008–2012), Wolsong NGS Unit 1 (2009–2011), and Embalse (2016–2019). De-rating due to pressure tube diametral creep, insufficient bearing travel to accommodate axial elongation, and loose-fitting annulus spacer design and commensurate blister concerns are some of the factors that challenged reaching the original design life. Point Lepreau had an additional issue with feeder cracking.

3.2.1. Point Lepreau nuclear generating station refurbishment

The Point Lepreau NGS was the first CANDU 6 unit to be refurbished. The modifications that were included in the retube contract scope covered the replacement of the 380 calandria tubes, the 380 pressure tubes and the 760 feeders (380 inlet and 380 outlet) and auxiliary supports. Point Lepreau's refurbishment scope of work also included several significant replacements and modifications to the station including:

- Replacement of Shutdown System #1 (SDS #1) and Shutdown System #2 (SDS #2) programmable digital comparators, and installation of additional trips as well as changes to reactor regulating system setpoints;
- Staking of moderator heat exchanger tubes for increased sub-cooling margin;
- Replacement of various moderator, end shield cooling and shutdown cooling valves;
- Replacement of emergency power supply underground diesel storage tank;
- Relining of the dousing tank;
- Replacement of the uninterrupted power supply inverters and rectifiers;
- Replacement of the electro-hydraulic governor on the turbine system;
- Rewind of the rotor and stator of the generator;
- Replacement of the low-pressure turbine rotors;
- Installation of a containment filtered venting system;

— Fire systems upgrade to current National Fire Protection Association standards.

Those replacements allowed an increase in the turbine gross output from 680 MW to 705 MW after refurbishment due to the installation of three new low pressure turbine modules.

Point Lepreau experienced several first of a kind challenges and setbacks as it was the lead unit for refurbishment activities of CANDU 6 NPPs. NB Power's (Point Lepreau's owner and operator) relied heavy on its turnkey contract with Atomic Energy of Canada Limited (AECL). The challenges encountered during the early stages of execution phase of the project translated into tool performance issues, insufficient preparation and training of workers, and timely resolution of issues. The largest schedule and cost impact resulted from the initial replacement of Point Lepreau calandria tubes requiring removal due to failed calandria tube rolled joint leak tightness tests. The problem was related to the use of a calandria-side tube-sheet bore brushing tool that produced axial scratches deemed to impact the integrity and leak tightness of calandria tube rolled joints.

3.2.2. Wolsong Unit 1 refurbishment

Korea Hydro Nuclear Power (KHNP) Co.'s Wolsong Unit 1 refurbishment project had a scope very similar to that of Point Lepreau. All pressure tubes, end fittings, calandria tubes, and feeder pipes were replaced. Although Point Lepreau outage started before Wolsong Unit 1, it was completed over a year after Wolsong Unit 1 due to the first of a kind challenge faced during Point Lepreau refurbishment execution phase, as mentioned in Section 3.2.1. KHNP could benefit from the experience gained at Point Lepreau and stop the calandria tube installation as soon as the calandria-side tube-sheet bore condition issue was identified. Calandria tube installations did not resume at Wolsong Unit 1 until a tested and proven technique was developed to refurbish the calandria-side tube-sheet bores.

Wolsong Unit 1 was reconnected to the electrical grid on 18 July 2011. The entire retubing outage took 839 days to complete, during which time KHNP undertook other refurbishment activities. KHNP did not participate in the Technical Meeting, and hence there were no Wolsong Unit 1 refurbishment related presentations made.

KHNP approved the shutdown of Wolsong Unit 1 in December 2018 earlier than planned (7 years after the completion of its refurbishment), as part of the long-term nuclear phase out scheme adopted by the government of the Republic of Korea at the time.

3.2.3. Embalse life extension

A margin assessment was completed to increase the first life cycle of Embalse Nuclear Power Plant (NPP) from 210 000 to 225 000 EFPH. The assessment results enabled Nucleoeléctrica Argentina S.A. (NA-SA, the owner and operator of Embalse NPP) to delay the start of refurbishment to 31 December 2015 with the approval of the Argentinian Nuclear Regulatory Authority. Embalse NPP reached its design life after 224 286 EFPH and started the refurbishment outage after providing the grid with 143 710 993 MWh energy.

The Embalse life extension project (LEP) involved a high degree of local supply, particularly in procurement of reactor components and the use of technical labour in comparison with previous CANDU 6 refurbishments. The total radiation dose was well below estimates and lower than previous refurbishment campaigns thanks to the lessons learnt from the previous projects.

The Embalse LEP [6, 7] scope was greater than the previous CANDU 6 refurbishments, including significant seismic upgrades to the site and a 6% (35 MWe) power uprate. Prior to refurbishment, Embalse operated at a lower power level compared to the other CANDU 6 units due to lack of installation of a full set of reactors regulating system components at initial construction. The power uprate was achieved through a combination of enhancements to the reactor protection systems, the turbines, and the BOP components.

Steam generator replacement: Replacement was decided to correct deficiencies in the original design of internal components (the internal carbon steel tube support plates experienced significant erosion during the 30 years of plant operation and were deemed not suitable for the post refurbishment operating cycle) and to accommodate the power uprate.

The steam generator replacements at Embalse were first of a kind work for a CANDU 6 plant as the layout design did not consider the replacement of large components. Therefore, the lower part of the steam generators (or cartridge) including the tube bundles was replaced and the upper part, including the steam drums, were refurbished in-situ. The resulting scope involved the movement of approximately 3000 ton of devices, systems, structures and components inside the reactor building, and the installation of a 117-ton capacity temporary crane and of 900 m^2 temporary platforms. Planning of the welding activities was needed well in advance to avoid interferences with new feeders welding. The construction effort was completed in 34 months and resulted in a 15% cost overrun. More details are given in Reference [24].

Replacement of moderator system components: The refurbishments of the moderator system included the replacement of both heat exchangers with better thermohydraulic performance, including the tube bundle and the main shell because of flow induced vibration related degradation. The new component had design improvements to avoid the occurrence of this degradation mechanism.

The main moderator system valves (8 isolation valves and 2 check valves) were replaced with more reliable designs that prevent risks of internal leakage and use improved materials. The main pumps were also refurbished; they were disassembled, inspected, and their internal components were replaced.

Improvements to safety systems: The modifications included improved reactor shutdown system coverage, enhanced emergency core cooling system reliability and bolstered plant robustness to cover seismic events through increased emergency power supply and emergency water supply capacities. Those were implemented to increase the level of safety in response to emergency scenarios, addressed the safety lessons learnt from the Fukushima accident, the new Fukushima driven regulations for CANDU 6 stations, and the updated site seismic requirements.

Upgrades to mechanical, electrical, and instrumentation and control systems: Embalse also identified that replacement of power and instrumentation and control cables utilizing advanced materials with superior performance characteristics was needed by regulation and to adopt changes identified by international experience.

Turbine and BOP: The modifications and upgrades in this area involved the replacement of turbine blades and rotors with a better design. Turbine steam extractors were added, and new high pressure and temperature preheaters installed. Turbine and BOP modifications accommodated the changes to the thermal cycle to achieve the 6% power uprate.

3.3.ONGOING REFURBISHMENTS IN CANADA

Refurbishment of all four units at Darlington began with Unit 2 in October 2016. Unit 2 was refurbished and returned to service in June 2020. The refurbishment of Unit 3 began in September 2020 and scheduled for completion by January 2024 following a 40-month outage. Darlington Unit 1 was shutdown for refurbishment on February 15, 2022. The Bruce major components replacement at Unit 6 was initiated in January 2020. It is to be followed by Units 3, 4, 5, 7 and 8.

3.3.1. Darlington refurbishments

OPG (owner and operator of Darlington NPPs) is using a phased management approach on Darlington refurbishment. The initiation phase and planning phase comprised the entire site. Each unit refurbishment then had a separate execution phase, with Unit 2 being the first.

The ***initiation phase*** started well in advance and consisted in establishing the scope of the of the refurbishment through technical assessments of all major components and condition assessments of BOP components. The project initiation phase also included the development of reference plans for cost and schedule, an economic feasibility assessment, the overall contracting strategy, and the project management approach and governance. OPG board and shareholder agreement was secured at this point with recommendation to proceed with preliminary planning within the project definition phase. The regulatory process was also initiated in this phase. The initiation phase was completed in 2009.

The ***definition phase*** began in 2010 with detailed planning. Definition phase scope of work included finalizing project scope through the completion of comprehensive inspections and component condition assessments, implementing project management and oversight, and developing release quality cost and schedule estimates. At this point, OPG awarded major contracts, procured long lead materials, and initiated mobilization and training of trades staff.

Some detailed engineering design as well as prerequisite and preliminary works were also completed at this stage. Significant infrastructure upgrades were completed, including new road works, parking lots, project offices, work annexes, and waste management facilities. Upgrades to the Darlington Energy Centre were implemented and a full-scale mock-up of the reactor vault was constructed at the Darlington Energy Centre. Fabricating and testing of tooling was also performed. All necessary licenses and permits were obtained at this stage including the regulatory approval of OPG’s Environmental Assessment and Integrated Implementation Plan (see Section 5).

In 2015, OPG finished the work required in the definition phase and obtained approvals to proceed to the ***execution phase***, beginning with testing and training. On 15 October 2016, OPG took the Unit 2 nuclear reactor offline to execute Darlington refurbishment. OPG called this step “breaker open”, because the unit is officially disconnected from Ontario’s power grid to start the work. The 44-month project was the first of four such outages as OPG refurbishes the plant’s four units over a 10-year period as shown in Figure 3.

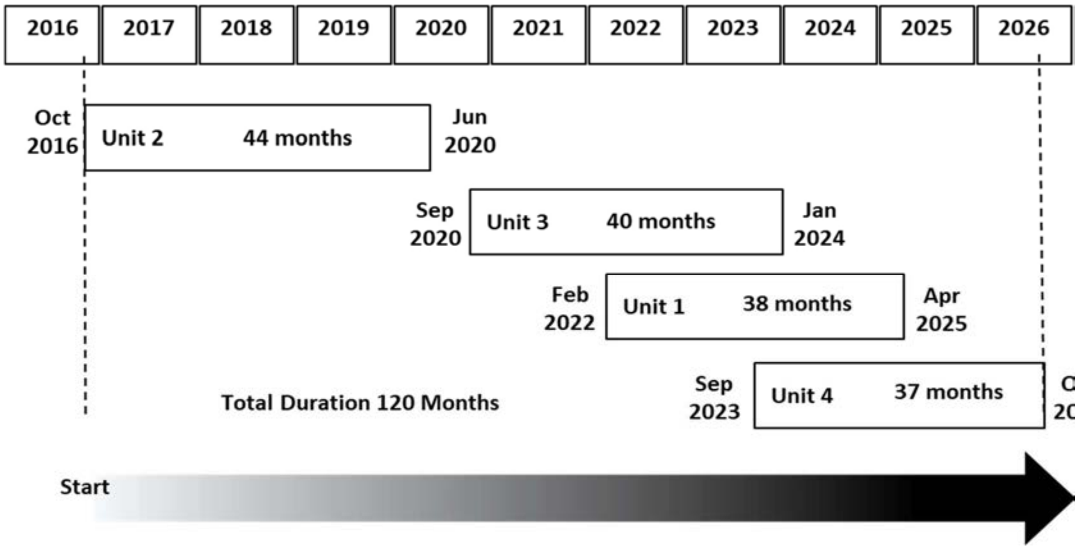

FIG. 3. Timelines for Darlington refurbishments (from the data presented by OPG at the Technical Meeting).

The lead-in activities to start the project execution included finalizing workforce mobilization and completing final readiness reviews. Facilities and infrastructure projects have to be completed and ready for preparation of clearance orders, work packages and training.

Darlington being a multi-unit station, islanding of the refurbished unit is needed. The Unit shutdown and defueling is a critical path activity and was scheduled to take approximately 80 days. In parallel to those tasks, work is done to ensure all other components including turbine generators, steam generators, fuel handling machines are ready for another 30 years of operation. This work is expected to take 300 days with larger scope in Units 3, 1 and 4 that includes turbine control upgrades. The following refurbishment scope is executed at Darlington:

Turbine and generator: The activities performed on the turbine and auxiliaries include:

- Completion of the disassembly, inspection, and reassembly of low-pressure and high-pressure turbines and auxiliaries;
- Provision of long lead and maintenance spares for the assembly and disassembly of the steam turbines and auxiliaries;
- Installation of erosion protection rings on blade carriers of low-pressure turbines to address erosion-corrosion;
- Inspection and repair of condenser struts, as required.

The activities performed on the generator and auxiliaries include:

- Provision of a new generator midsection (stator frame, stator core, winding and terminal box) and reuse of components such as end shields and covers;
- Rewinding of the stator and making it ready for installation in the next unit;
- Rewinding of last unit's stator to make it available as a station spare;
- Replacement of the stator cooling water, hydrogen cooling, and seal oil skids and their integration with turbine controls.

The activities performed on the moisture separator reheater include inspections and repair/refurbishment/replacement of moisture pre-separators, all internal components of the moisture separator reheater vessel and inspection of selected moisture separator reheater motor operated valves, as required.

The activities performed on the steam turbine-generator electronic controls include the installation of new control panels in the main output control and protection equipment room, and new control panel cubicles in the excitation room. Modifications are also made to the main control room including changes to the digital computer control software, push buttons, annunciation windows and alarms.

Steam generators: The steam generator main activity involving primary side cleaning and miscellaneous inspections is expected to take 120 days. The project has been broken down into the following separate elements of work to be performed throughout refurbishment:

- Primary side cleaning involving mechanical cleaning of magnetite build-up from the inner diameter of the steam generator tubes;
- Secondary side cleaning – water lancing;
- Access port installation;
- Inspections and repairs;
- Divider plate inspections;
- Bleed cooler inspection and bundle replacement.

Other structures and components: Preventive maintenance and rehabilitation work is performed on the PHTS, adjusters, auxiliary shutdown cooling system heat sink, containment, electrical components, emergency heat sink, emergency service water lines and stopple plug, fire protection system, fission chambers and regulating flux detectors, and other SSCs.

***Waste processing and storage*:** This portion of the scope includes the design, construction, and commissioning of a retube waste processing building. Removed reactor components (pressure tubes, end fittings, calandria tubes, feeders, and other reactor hardware) are transferred via an enclosed corridor to the building where machines put some of the removed components through a volume reduction process by cutting and crushing in preparation for interim storage. The volume reduced waste is then transferred using shielded retube waste containers from the building to the retube waste storage building for interim storage.

3.3.2. Bruce major components replacements

Bruce and Darlington reactors have very similar core designs as both were constructed by Ontario Hydro in the 1970s and 1980s. Hence, much of the information provided for the Darlington refurbishment applies to Bruce major component replacements. Main differences between Darlington and Bruce refurbishments [8, 9, 10] are summarized below:

— Bruce major component replacement projects include the replacement of all eight steam generators in each refurbished unit. In contrast, pre-refurbishment condition assessments by OPG determined that the four larger steam generators at each Darlington unit would only require primary and secondary side cleaning and several modifications without the need for replacement;

— Bruce major component replacements volume reduce the removed pressure tubes and calandria tubes using equipment installed inside the reactor vault and transfer the volume reduced waste to shielded storage containers. Darlington refurbishments utilize large, shielded and remotely operated flasks to move the pressure tubes and calandria tubes to the retube waste processing building for volume reduction. Subsequently, the volume reduced waste is transferred to shielded containers for interim storage at site.

Figure 4 provides comparative information on Darlington refurbishment and Bruce major component replacement schedules. Figure 5 is a photograph taken during Bruce Unit 6 steam generator replacements.

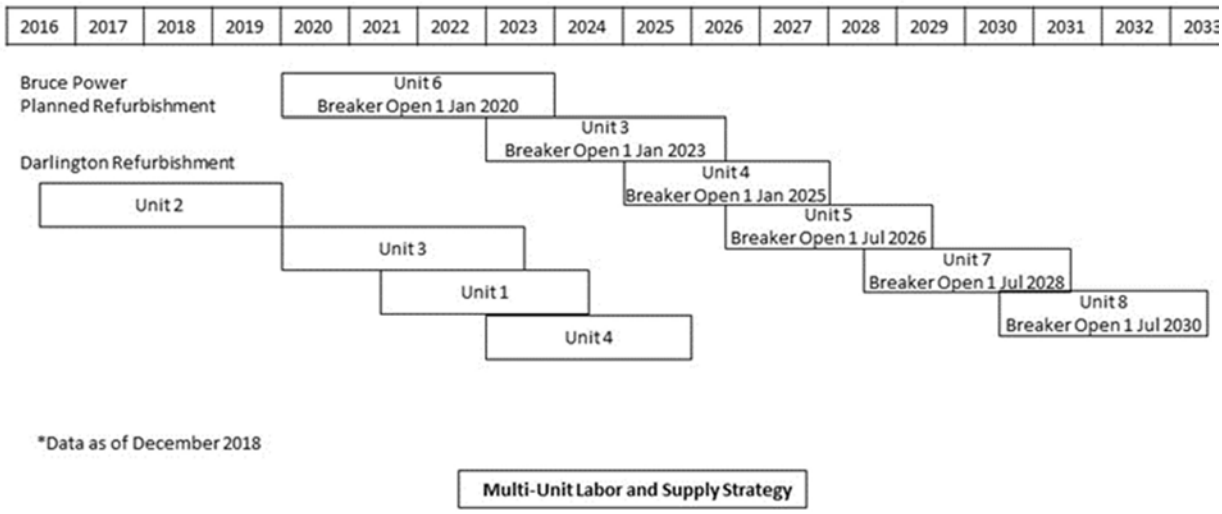

FIG. 4. Bruce major components replacement and Darlington refurbishment schedules (from the data presented by OPG at the Technical Meeting and [10]).

FIG. 5. Bruce major component replacement includes replacement of all 8 steam generators in each unit [28].

3.4.EN-MASSE COOLANT CHANNEL REPLACEMENTS IN INDIA

The first EMCCR was implemented in India at RAPS-2 during the period 1995–1998 by indigenously developed tools and expertise. The EMCCR activity was necessitated owing to degradation mechanisms observed in Zircaloy pressure tube which limited the life of the pressure tubes due to hydrogen pick up and formation of brittle hydrides at locations where the hot pressure tube contacted relatively colder calandria tube. The pressure tubes were replaced with improved fuel channel material; Zr-2.5%Nb that had superior material properties such as low hydrogen pick up, low creep rate and high strength at operating conditions. In addition to the improved material, the hardware and rolled joint geometry were also upgraded to enhance the post EMCCR life of fuel channels.

The key upgrades included the introduction of:

- Four tight fitting annulus spacers that support the pressure tube inside the calandria tube, instead of two loose fitting annulus spacers that were part of the original design;
- A zero-clearance shop rolled joint, and a low clearance field rolled joint between the pressure tube and the end fitting with lower residual stresses that reduced the risk of formation of cracks in the rolled joint areas;
- Modified journal rings on the end fittings to accommodate higher pressure tube axial elongation.

Subsequently, EMCCRs were completed at other units as shown in TABLE 1. In recent years, EMCCR of two units of Kakrapara Atomic Power Station, Units 1 and 2 (KAPS-1 and KAPS-2) has been completed. These more recent EMCCRs were prompted by pressure tube degradations resulting from impurities in the annulus gas monitoring system gas mixture. Under reactor conditions, reactive chemical species were formed in the annular space between the calandria tube and the pressure tube that caused localized corrosion on the outer surface of pressure tubes.

TABLE 1. LIST OF COMPLETED EMCCRS

EMCCR Campaign	NPP	Reason for EMCCR	Timing of EMCCR	Effective Full Power Years at time of EMCCR
1	RAPS-2	Life limiting pressure tube degradation	1995–1998	8
2	MAPS-2	Life limiting pressure tube degradation	2002–2003	8.5
3	MAPS-1	Life limiting pressure tube degradation	2004–2006	10.1
4	NAPS-1	Life limiting pressure tube degradation	2005–2007	10
5	NAPS-2	Life limiting pressure tube degradation	2008–2010	11
6	KAPS-1	Life limiting pressure tube degradation	2008–2010	11
7	KAPS-2	Pressure tube degradation resulting from AGMS impurities	2016–2018	15.3
8	KAPS-1	Pressure tube degradation resulting from AGMS impurities	2017–2019	4.8

EMCCRs are typically initiated with a ***planning phase*** that consists of satisfying certain prerequisites for assessing the preparedness of the utility planning to undertake the activity. The utility also prepares different submissions for review by regulatory body (see Section 5).

Experience gained from past EMCCR campaigns are used for preparation of plans, procedures, and technical specifications towards ensuring adoption of best practices and lessons learnt.

A ***preparatory phase*** is needed prior to the defueling. The preparatory work in the fuelling machine vault includes the erecting of self-elevating platforms and cranes; installation of additional radiation and contamination monitors, a decontamination facility, a monitoring system, and a material handling system; establishment of communication and ventilation provisions; setting up of a mock-up facility for trials, and provision of shielding flasks ready to receive the removed reactor components. The self-elevating platforms are erected in the fuelling machine vaults for carrying out the work on each channel. These platforms are shielded and provide accessibility to each channel. The top shielding plates can be opened and closed for material movement. The preparatory phase also includes development, functional testing, and demonstration of special remote tools required for EMCCR activities. The review of this stage is the responsibility of the operator.

The EMCCRs then proceed to the entire ***fuel channel removal and replacement*** (see Section 0). The feeders are also entirely removed to gain enhanced access to the channels and replaced due to the limited remaining life of feeders. In the past, feeder replacement activity also gave opportunity to upgrade the feeder material, feeder design thickness and nominal diameter due to concerns related to flow assisted corrosion or high channel outlet temperature issues.

Limiting conditions for operations related to fuel, reactivity control, reactor protection system, PHTS, emergency core cooling system, fuel handling and various other systems become inapplicable during EMCCR. Only the clauses related to radioactive effluents, monitoring and control of activity in the process water system, common systems like firewater and compressed air systems, and power supply remain applicable. Surveillance tests related to ventilation system filter bank efficiency, stack and liquid effluent monitors, firefighting system, compressed air system, and seismic switches are carried out.

A detailed written plan is prepared early enough to provide time to identify all potential radiation hazards during an EMCCR campaign, and a detailed record of radiological aspects such as collective dose consumption, radiation fields, and contamination monitoring are maintained during the EMCCR campaign for future reference. Availability of radiation monitoring is stressed to be of utmost importance and health physics coverage along with departmental supervision is provided for all the radioactive operations throughout the EMCCR campaign. Radiation dose of all the personnel involved is monitored closely through radiation work permits and management review meetings. In some cases, chemical decontamination of the system may be needed to reduce the radioactive contamination to bring down the radiation levels at certain work locations.

A radioactive waste management plan is prepared well in advance. The removed fuel channel components are stored in stainless-steel lined and seismically qualified reactor core component vaults constructed at the near surface (partially underground) disposal facility at site. The storage facility is designed with the provision to facilitate the eventual retrieval of the radioactive waste for long term storage and arrangements to maintain a radiation field that is less than 0.01mGy/hr on the side wall. The top hatch and the vault concrete temperatures are kept well below the acceptable limit and the top elevation of the storage vaults is kept above the design basis flood level.

4. PLANNED REFURBISHMENT PROJECTS

Completed refurbishments have demonstrated that NPP lifetime extension is a valuable economical option. In addition, figure 6 shows the Levelized Cost of Energy and value adjusted Levelized Cost of Energy for various generation technologies in the United States and Europe projected to 2040, which demonstrates the superior value offered by the life extended (refurbished) NPPs.

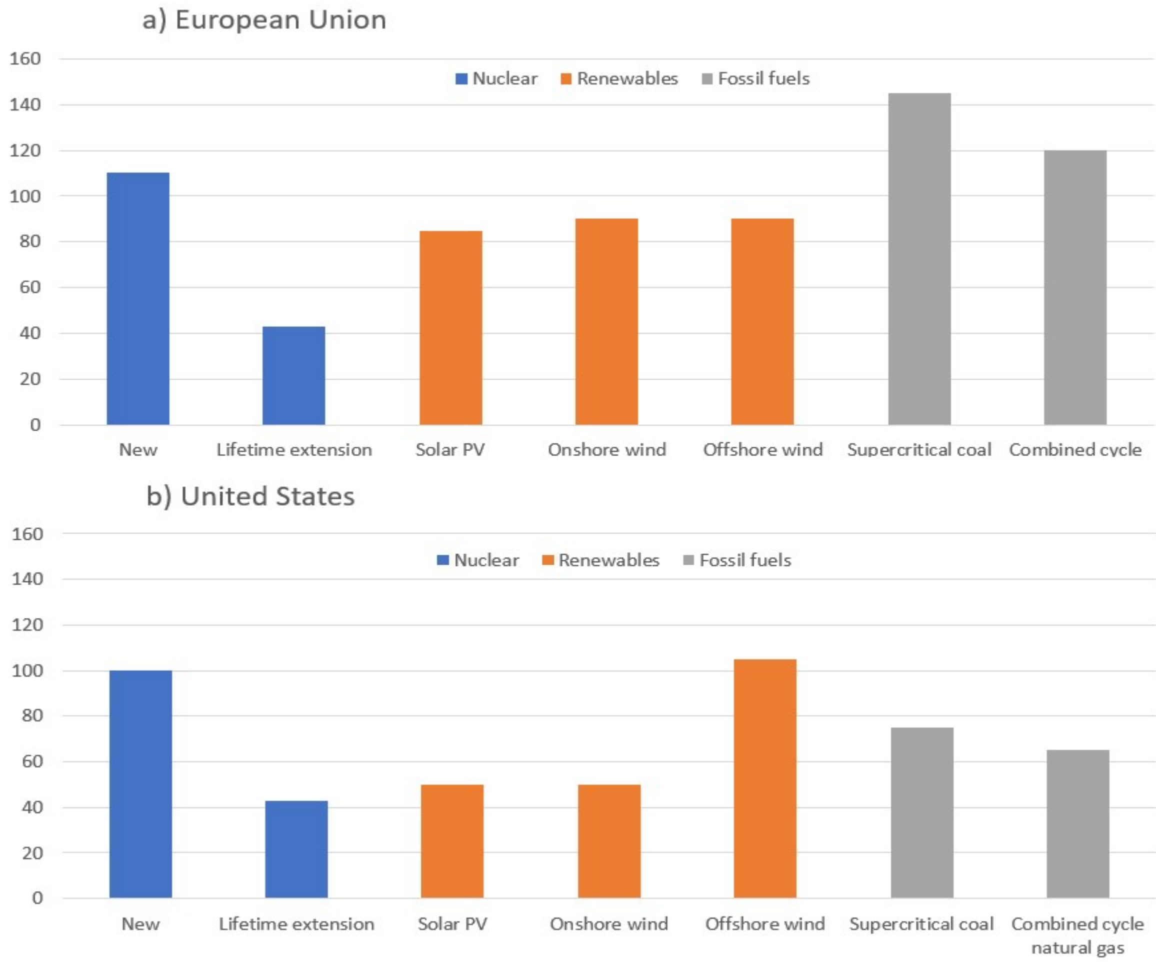

FIG. 6. Levelized Cost of Energy by technology, 2040 (from IEA data [30]).

Therefore, most of the CANDU fleet has (or is currently being) refurbished for an approximate 30-year lifetime extension. Refurbished utilities have demonstrated good project management capabilities, and schedule and cost reductions are being realized in successive units through improvements in refurbishment processes and adoption of lessons learnt and best practices.

In line with CANDU fleet, two refurbishments are currently planned: Qinshan in China and Cernavoda in Romania. This section presents an overview of the planning of these two projects at the time of the Technical Meeting (2019).

4.1. QINSHAN REFURBISHMENT PROJECT

There are two CANDU 6 PHWRs at the Third Qinshan Nuclear Power Plant (TQNPP) with an installed capacity of 728 MWe per unit. Qinshan Units 1 and 2 were put into commercial operation on 31 December 2002 and 24 July 2003, respectively.

The design life of the CANDU 6 units at TQNPP is 40 years, while that of the pressure tube is 186 000 EFPH (about 23.6 years based on 90% capacity factor of actual operation). Therefore, it had been assumed that a pressure tube replacement would be necessary at the midpoint of plant design life, even though the Qinshan CANDU 6 units had pressure tube material with superior properties incorporating the latest advances in pressure tube R&D (see Section 6). Other CANDU 6 plants with less advanced pressure tube materials were able to run beyond the original 210 000 EFPH design life of the pressure tube. Hence, TQNPP has decided to initiate two separate projects:

1) A fuel channel life extension project: The objective of the project is to study the possibility of running the plant until 236 000 EFPH (similar to Embalse, see Section 3.2.3). The fuel channel life extension project is divided into two stages. The first stage focused on extending pressure tube life from 186 000 to 210 000 EFPH has been completed and was approved by the China National Nuclear Safety Administration in January 2020. The second stage is in progress and has the objective of extending pressure tube life from 210 000 to 236 000 EFPH;

2) A refurbishment project: The objective of the project is to replace all 380 fuel channels and 760 feeders in each of the two Qinshan units, similar to Point Lepreau, Wolsong Unit 1, and Embalse. The project scope includes the replacement of all fuel channel assemblies, calandria tubes, and feeder pipes. A variety of other systems and components that are assessed not to last to the end of the extended plant life will also be replaced or refurbished.

Currently, China National Nuclear Operations (CNNO) Co. (the owner operator of TQNPP) is in the process of performing condition assessments and evaluations of key TQNPP systems and components to identify those that will need to be replaced or refurbished.

It is estimated that the pressure tubes in Qinshan Unit 2 will achieve their operating life in February 2030. Working back 22 months from this date, the pressure tube replacement outage for Unit 1 is planned to start in April 2028 [11].

CNNO plans to adopt a staged management mode for the pressure tube replacement project. The project will be divided into three stages: pre-project, preparation, and execution. The main work scope of each stage will be as follows:

— Pre-project stage (2017–2023): Prepare project proposal, feasibility study report, and preliminary design report, and obtain approvals;
— Preparation stage (2024–2028): Detailed design, preparation of retubing components and tools, nuclear safety application and approval, mock-up training, and human resources preparation;
— Execution stage (2028–2032): Full core fuel discharge, PHT and main moderator systems drainage, fuel channel and feeder pipe replacement, and returning of systems to service.

The planned duration of pressure tube replacement is 24 months for a single unit, and 46 months for the two units. CNNO plans to perform the refurbishment scope of work for the two units in series. After Unit1 hydraulic test and fuel loading, Unit 2 will commence shutdown. The execution of the two units will overlap for only two months. This arrangement has the following advantages for CNNO:

- Low risk of core staff shortage: There will be less core staff requirement and the personnel radiation dose will be relatively easy to manage, leading to improved stability in core human resources;
- Abundant experience feedback time: In case of execution delay, technical problem handling, or on-site accidents on Unit 1, there will be sufficient buffer time to correct for Unit 2 and reduce the impact on the overall quality and progress of the project;
- Better economy: The two-month overlap of pressure tube replacement in the two units will allow Unit 1 to postpone outage and to generate additional power for two months. The reduction of the core work interval by two months will also reduce the labour costs.

4.2.CERNAVODA REFURBISHMENT PROJECT

The Strategy for long term operation of Cernavoda NPP Unit 1 includes two stages:

- Extension of fuel channel life to 245 000 EFPH;
- Refurbishment of the unit.

Life extension of the existing nuclear assets will allow the accumulation of more investment funds and better preparation for the refurbishment. The life extension of the existing assets will also contribute a socio-economic benefit to Romania's economy and the local community.

Life assessment analyses for calandria vessel, fuel channels, feeders and other reactor components demonstrated their ability to operate beyond the original design life of 210 000 EFPH. A preliminary evaluation done by the original designer, based on results of the periodic inspection of reactor components, indicates a possible life extension up to 245 000 EFPH.

Based on existing facts from nuclear industry, refurbishment is expected to allow Societatea Nationala Nuclearelectrica (SNN) to operate Unit 1 for another 30 years with a capacity factor between 80% to 90%. Refurbishment of Cernavoda Unit 1 is planned in three phases:

- Refurbishment assessments and scope definition;
- Refurbishment preparation;
- Unit shutdown and implementation of refurbishment.

The first phase of the project was finalized in February 2022. The project activities are optimized by contracting companies with refurbishment experience and expertise to provide technical assistance and support to SNN specialists in managing the project [12].

5. REGULATORY CONSIDERATIONS

Almost every PHWR station differs in terms of design due to the various jurisdictions' regulatory requirements, environmental conditions, and non-uniform adoption of design improvements. As part of refurbishment projects, upgrades and modifications are implemented to bring the plant closer to the latest safety standards and to fulfil regulatory commitments. A risk informed approach is typically used to determine which safety improvements are warranted. Furthermore, the long refurbishment shutdowns provide the opportunity to update the various plant systems to enhance safety and efficiency and, in some cases, increase plant output.

Prior to refurbishment, utilities are typically required to conduct safety reviews (a periodic safety review for instance) and prepare a series of submittals that can take the form of an environmental assessment, updates to the Safety Analysis Report, descriptions and assessment of the changes, and other submittals that vary depending on the regulatory environment. The detailed scope and schedule of the modifications are usually part of those submittals along with the roles and responsibilities of the nuclear refurbishment organization, its governance, and interfaces with the authorities of the operating plant. Commissioning tests with agreed criteria and regulatory hold points are also typically submitted to the regulator. Post-refurbishment operating policies and principles, and changes in conduct of operation (including maintenance and engineering) and in technical specifications to reflect the updated boundaries of the safe operating envelope, are also usually required to be submitted for approval.

This section illustrates examples of the required submittals and interactions with the regulatory body during refurbishments projects. It first presents the example of the Kakrapara Atomic Power Station in India and the corresponding submittals and approvals needed prior to the initiation of the project and until fuel load. An example of a Return to Service (RTS) Programme, as implemented in Canada with the example of Darlington and Point Lepreau NPPs, is then presented to illustrate regulatory activities and hold points during reload and startup stages.

Refurbished components, and more specifically fuel channels, benefit from the experience gained in the first PHWRs and from improvements in fuel channel fabrication and installation techniques as presented in the section on Completed and ongoing refurbishment projects. Those allow the extension of the design life of existing and refurbished plants. This is however contingent to stringent monitoring and the implementation of robust fuel channel lifecycle management programmes. An overview of the corresponding regulations and norms, focussed on the Canadian experience, is also covered in this section.

5.1. REGULATORY APPROVAL IN INDIAN EN-MASSE COOLANT CHANNEL REPLACEMENTS – KAKRAPARA ATOMIC POWER STATION EXPERIENCE

India's Atomic Energy Regulatory Board (AERB) regulates the safe conduct of the EMCCR activities and subsequent reactor startup in India. The utilities have to submit applications covering various phases of EMCCR activity and unit startup. For instance, in the planning phase, submissions would include:

- A radiation protection plan that identifies all potential radiation hazards and exposure control, along with a proposal for a total dose budget based on comparison with past EMCCR campaigns;
- Technical specifications required during the execution of EMCCR and post-EMCCR plant operation;

- Procedures to be used for various EMCCR removal phase activities;
- Results of mock-up trials;
- Proposal for storage and disposal of radioactive waste. This would include details on quantity of core components, inventory of radiological waste for disposal, storage scheme, details of near surface disposal facility, safety features and equipment specifications, operating procedures, surveillance, and radiation protection consideration and associated quality assurance program;
- Emergency plans;
- Proposal for preservation of various systems during the EMCCR outage;
- Proposal outlining the planned modifications and upgrades aimed at maintaining or enhancing the safety and integrity of retained components including safety systems adopted in newer NPPs.

The applications are reviewed by AERB, and clearances are given for various EMCCR activities in stages leading up to the eventual startup of the reactor. The entire EMCCR activity is reviewed by AERB through a multi-level process. The reviews involve various in-house AERB safety committees and expert groups with combined expertise from various fields and expert staff from the Department of Atomic Energy, India.

The regulatory body requires that acceptance criteria are developed for each of the retained components and used for qualification of the components for post EMCCR service. AERB reviews and approves the developed acceptance criteria and scope of inspections proposed by the utility. The retained components are assessed in terms of fitness for service during the remaining life of the plant. Acceptance for new fuel channel components and rolled joint integrity are also required. The selection, acceptance criteria, and scope of the corresponding inspections are proposed by the utility and reviewed and deliberated by expert groups before clearance obtained from the AERB.

Following the completion of agreed upgrades, AERB reviews the commissioning reports, the revised documents for the modified systems, and operator training on upgraded and modified systems prior to start-up. The compliance with equipment qualification requirements also needs to be reviewed and accepted by the regulatory body.

5.1.1. Regulatory approvals and hold points prior to fuel load

The stages of review and clearance by AERB is identified before the commencement of the EMCCR, and appropriate authority is decided for granting the clearance. A report of the previous activity is reviewed before approval of the next activity. Various hold points during the EMCCR correspond to each major activity. Any deviation from the practices followed from the previous campaigns of EMCCR are justified by the utility and are deliberated by the review committees of the regulatory body. The following outlines the major regulatory approvals and hold points during EMCCR execution phase.

Defueling and draining: A series of preparatory work is needed prior to defueling and draining of the reactor, including the development, functional testing, and demonstration of special remote tools required for EMCCR activities. The review of this stage is the responsibility of the operator that is required to submit to the authority a report on those activities as a pre-requisite for the next phase.

Removal of Feeders: Next major activity, which requires AERB review and approval, involves the removal and disposal of feeders. An integrated EMCCR quality assurance plan and job hazard analysis associated with EMCCR activities are required before commencement of each activity. Authorization for near surface disposal facility also needs to be obtained prior to commencement of removal of reactor components.

Removal and disposal of fuel channels: Prior to commencement of the cutting and removal of channels, qualification of tools (including remotely operated tooling and equipment), procedures and operators, along with the plan for disposal of fuel channel components are reviewed and approved by the AERB.

Cleaning of retained components: For this stage, a series of inspections are carried out to assess the fitness for service of the retained components. The AERB reviews the methodology, acceptance criteria and the results of those inspections.

Installation of fuel channels: At this stage, AERB reviews in detail each aspect of fuel channel installation, design qualification of newly installed components and rolled joint qualification. The regulatory body also reviews the procedures for the installation phase and demonstration of these activities at the mock-up facility before granting permission to carry out the activities. Preparedness of the operators for installation of fuel channels is assessed based on the availability of tooling and equipment, workplans, procedures, and operator qualifications for end fitting pre-assembly and pressure tube-to-end fitting joint rolling. The utility ensures that enough qualified manpower is available at site for executing the EMCCR activities. An integrated quality assurance plan needs to be prepared and approved for the installation phase.

Feeder installation: Approval for collective dose budget for feeder installation activity needs to be granted by the regulator. Feeder installation and the following normalization of work in fuelling machine vault is reviewed by the operator and a report submitted to AERB as a prerequisite for the next set of activities.

Fuel load: Fuel loading and subsequent AERB mandated unit startup activities are the final steps in the EMCCR process. Before granting permission for fuel loading, the regulatory body reviews the status of EMCCR and the various implemented upgrades and modifications, results of the in-service inspections, system availability, status of equipment, and pending regulatory recommendations. The regulatory body requires revision of the operational documents such as operating manuals, emergency operating procedures, technical specification, flow sheets, and data sheets to reflect implemented upgrades and modifications. Furthermore, AERB requires the completion of training and certification for all operating personnel prior to start of fuel loading.

5.2.RETURN TO SERVICE PROGRAMMES AND HOLD POINTS – DARLINGTON AND POINT LEPREAU EXPERIENCES

Canadian Nuclear Safety Commission (CNSC) regulates the safe conduct of NPPs and related activities in Canada. The utilities are required to submit a Periodic Safety Review (formerly an Integrated Safety Review), a Global Assessment, and an Integrated Implementation Plan. A Return to Service (RTS) plan was also required to be submitted [13, 14]. The RTS, as implemented at Point-Lepreau and Darlington refurbishments projects, would cover the range of activities from completion of installation work by the contractors to full reactor power operation, including modification, commissioning, and restart activities.

The plan documents the processes, procedures and organization that will be used during the refurbishment project to manage the activities. The plan and process documents are compliant with the Canadian Standards Association (CSA) N286-12 Management System Requirements for Nuclear Facilities [15] and other applicable codes, standards, and laws.

The programme includes normal start-up testing and non-standard tests that are unique to a refurbishment outage and used to provide assurance that the design basis and license requirements are met. Any outstanding modification commissioning tests also has to be integrated with the restart testing and scheduled for execution when the appropriate unit conditions are established. The programme would also include processes such as handling of non-conformances, contingency planning, emergency responses, control of workplan changes, design changes resulting from restart testing, training, re-testing, and impact to operating units.

5.2.1. Programme phases and regulatory hold points

Per RD-360 (Reference [13]), a return to service programme is subdivided into the following four phases:

— ***Phase A:*** Restart activities prior to fuel load;
— ***Phase B:*** Fuel load and activities leading up to, but not including, Guaranteed Shutdown State removal;
— ***Phase C:*** Over-poisoned Guaranteed Shutdown State removal, approach to critical and low power testing (<1%);
— ***Phase D:*** High power testing and power escalation to full power.

Each phase includes Restart Control Hold Points (RCHPs), ensuring prerequisites are complete and approvals are obtained prior to transitioning from one state to another. Some of those hold points are contingent on CNSC approval. As an example, TABLE 2 lists the RCHPs as applied in the Darlington RTS, their associated phase, and if they are regulatory or not.

TABLE 2. HOLD POINTS IN THE DARLINGTON RETURN TO SERVICE PROGRAMME

Phase	RCHP	RCHP Description	Regulatory Hold Point
Phase A	RCHP 1	Prior to moderator fill	No
	RCHP 2	Prior to fuel load	Yes
Phase B	RCHP 3	Prior to bulkhead removal	No
	RCHP 4	Prior to PHTS fill	No
	RCHP 5	Prior to guaranteed shutdown state removal	Yes
Phase C	RCHP 6	Prior to exceeding 1% full power	Yes
Phase D	RCHP 7	Prior to exceeding 35% full power	Yes
	RCHP 8	Prior to unit available for commercial operation	No

The administrative process to manage the regulatory interaction with the CNSC is formalized in a protocol document. The protocol identifies deliverables that provide the assurance CNSC seeks to allow the utility to clear hold points in accordance with license conditions. Those would include written confirmation of the following:

— All related project commitments tied to the hold point are completed;
— All required system functions for safe operation beyond the hold point are available;

- All specified operating procedures have been formally validated;
- Specified training completed and staff is qualified;
- All non-conformances and unexpected results identified leading up to the end of the phase are addressed;
- All systems structures and components being returned to service meet the quality and completion requirements of N286.12 clause 7.11 through completion of construction completion declaration, modifications available for service, and System Available for Service;
- Other information as appropriate or agreed with the regulator.

5.2.2. Completion assurance documents

Per RD-360 [13], completion assurance documents have to be prepared and submitted in support of a request for each RCHP removal. For the RTS as implemented at Darlington, those include:

- ***Construction completion declaration***: This is the process used to document the completion of work associated with installation of modifications or non-modification work (such as inspections, maintenance, and repairs) to a system during a unit refurbishment outage;
- ***Commissioning and modification available for service***: Following the commissioning of new or modified equipment, the project team prepares a turnover declaration to document the acceptance of the modification by the refurbishment operations manager. The turnover declaration may be a modification available for service or an operations acceptance;
- ***System Available for Service***: A System Available for Service declaration means that individual systems, or groups of systems, can be credited to perform their design functions safely and reliably for continued operations;
- ***Unit Readiness for Service***: A Unit Readiness for Service documents and controls how the unit is restarted. It provides assurance, at identified restart milestones, that integrated system testing is completed, and that systems, conditions and pre-requisites are acceptable to progress to the next milestone.

5.3.REGULATIONS AND STANDARDS RELATED TO FUEL CHANNEL LIFE CYCLE MANAGEMENT

The 1991 pressure tube fitness for service guidelines was the first attempt by the industry to codify requirements for evaluating fitness for service for CANDU fuel channels. A major revision with a companion technical basis document was issued in 1996. Just prior to this, the first edition of CSA N285.4 [17], Periodic Inspection of CANDU Nuclear Power Plant Components was issued in 1994. Together, the CSA N285.4 and the fitness for service guidelines provided the technical basis for inspection to monitor known degradation mechanisms in pressure tubes and disposition of the results.

A second major revision was issued in 2005. CSA N285.4 became more station-specific, and the CANDU lead unit concept was deleted. The fitness for service guidelines became CSA N285.8 Technical Requirements for In-service Evaluation of Zirconium Alloy Pressure Tubes in CANDU reactors [18]. New requirements for core assessments, leak-before-break and fracture protection were included in Clause 7 to address degradation of the balance of the core, along with a table of acceptance criteria. Compliance with CSA N285.4 & N285.8 has since become a licensing requirement in Canada.

While the regulator may accept that a utility wishes to extend the target operating life of one or more units to a specified target, e.g., 300 000 EFPH, achieving this is contingent upon continuing to demonstrate fitness-for-service in accordance with the CSA standards on an incremental basis for a prescribed evaluation interval or disposition period. Canadian nuclear utilities therefore maintain major component life cycle management plans. In March 2014, the CNSC issued REGDOC 2.6.3, Ageing Management [19], which outlines a systematic and integrated approach, drawing on the IAEA Safety Guide NS-G-Ageing Management for Nuclear Power Plants, Vienna, 2009 [20]. Canadian utilities' fuel channel life cycle management plans are compliant with this framework as illustrated in Figure 7.

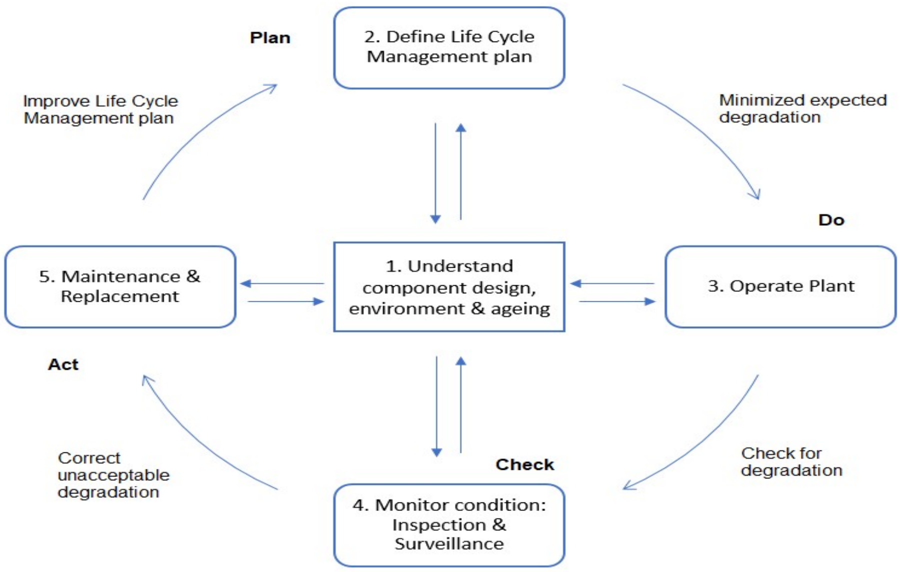

FIG. 7. Overview of the Framework followed by Canadian utilities for major component life cycle management plans (adapted from on [19])

Such plans require determining the life limits through R&D and demonstrating by inspection, surveillance testing and evaluation that the acceptance criteria based on those limits continue to be satisfied for the evaluation period. As units age, it may be needed to place limits on temperature, pressure and time spent in certain regimes to reduce the risk of fast fracture and crack initiation by DHC.

The CANDU fuel channel life cycle management plans have evolved with operational experience. The current approach is consistent with internationally accepted ageing management approaches [3, 20]. It provides a robust, incremental approach for ensuring that degradation is appropriately monitored and understood, and that corrective actions are initiated well in advance of reaching limits. This provides regulators and utilities with greater certainty that long term operation can be safely achieved.

Although the information in this section was presented with the perspective of the Canadian regulatory regime, the AERB regulates lifecycle management and in-service inspection in India in a similar manner [23]. Similar regulations and regulatory guidance are in place in other countries.

6. FUEL CHANNEL SUPPORTING RESEARCH AND DEVELOPMENT

Despite several improvements in fuel channel fabrication and installation techniques, DHC at large tensile stress, specially at the rolled joints, and/or large temperature gradients through the tube wall will always remain a concern. Strict fuel channel lifecycle management programmes are in place and supported by ongoing research and development conducted within the industry, as presented in [1] and [16].

This section presents a selection of updates on ongoing research conducted within the industry in support of PHWR fuel channel life management programmes based on the information presented at the Technical Meeting on Best Practices in the Refurbishment of PHWRs held in Toronto, Canada on 2–6 December 2019. Some of the tooling and process improvements made during the different refurbishment projects is also presented.

6.1.FUEL CHANNEL AGEING SUPPORTING RESEARCH

CANDU Owners Group (COG) and the Canadian Nuclear Laboratories (CNL) have established Fuel Channel Life Management (FCLM) research programmes. They provide greater clarity of the operational limits and enable more rigorous processes for fitness for continued operation and life extension. The fuel channel operational limits are now considered to be close to 300 000 EFPH at Bruce and Pickering.

The key focus areas of the supporting research include:

- Deuterium ingress modelling;
- Irradiated and hydride fracture toughness;
- Crack initiation;
- Annulus spacer integrity;
- Probabilistic assessment methodologies for the balance of core.

Deuterium ingress:

Figure 2 shows a typical axial deuterium uptake profile for a CANDU pressure tube. The three lines show the scatter in measured values from the same tube. As can be seen, there is more scatter in the body of the tube data. The lines on the left-hand side of the graph are the inlet end measurements in the rolled joint region. The right-hand side values at the outlet end of the tube show the highest deuterium uptake. The highest rates of deuterium ingress are outboard of the rolled joint burnish mark. Inboard diffusion means regions inboard of the burnish mark are likely to be limiting for fracture toughness. This is a region of elevated residual stress in some units. Related research is generally directed towards understanding the reasons for distributions of deuterium in the body of tube and rolled joint regions and developing higher confidence projections.

Fracture toughness:

Ex-service irradiated pressure tube sections with known quantities of hydrogen additions are used to measure fracture toughness. The results of those tests, conducted through COG, have been used to develop models of fracture toughness as a function of temperature and hydrogen concentration, and include secondary variables such as hydride morphology and pressure tube impurity chemistry. The models are used to ensure that reactors are operated appropriately in various regimes to minimize the risk of unstable fracture from undetected pre-existing flaws.

Zr-2.5%Nb pressure tube material fracture toughness tests are also conducted at CNL through burst testing (the burst pressure directly correlates to fracture toughness). A wealth of data exists from the surveillance program as part of the testing mandated by the regulatory body, testing of as-received pressure tubes from CANDU stations and testing in the FCLM program where pressure tube material is artificially aged for elevated hydrogen concentrations. Artificial ageing is done through either the electrolytic method or low pressure gaseous hydriding to obtain the correct hydride morphology.

Burst testing is conducted in a hot cell since pressure tubes extracted from CANDU reactors emit strong radiation fields. A flaw is produced at the mid-span of the tube and a crack is grown through load cycling (pressurization with water as the hydraulic fluid). The specimen is then pressurized until failure. In the case of the FCLM program burst tests, additional thermal cycling is performed prior to flaw generation. The key outputs from fracture toughness testing are data at hydrogen concentrations between 60 and 150 ppm that provides assurance that pressure tube material exhibits adequate toughness behaviour above 250 °C (normal operating conditions in a CANDU reactor). The tests also provide better understanding and modelling of the brittle-to-ductile transition.

Crack initiation:

In-service flaws provide potential sites for crack initiation by DHC, fatigue and hydride region overload. Initiation criteria have to be be clearly understood, and flaws detected during in-service inspection to prevent crack initiation and continue safe operation. Figure 8 shows a replica of a debris fret mark taken during an inspection outage, courtesy of Kinectrics. It provides the detailed geometry required to support evaluation for crack initiation.

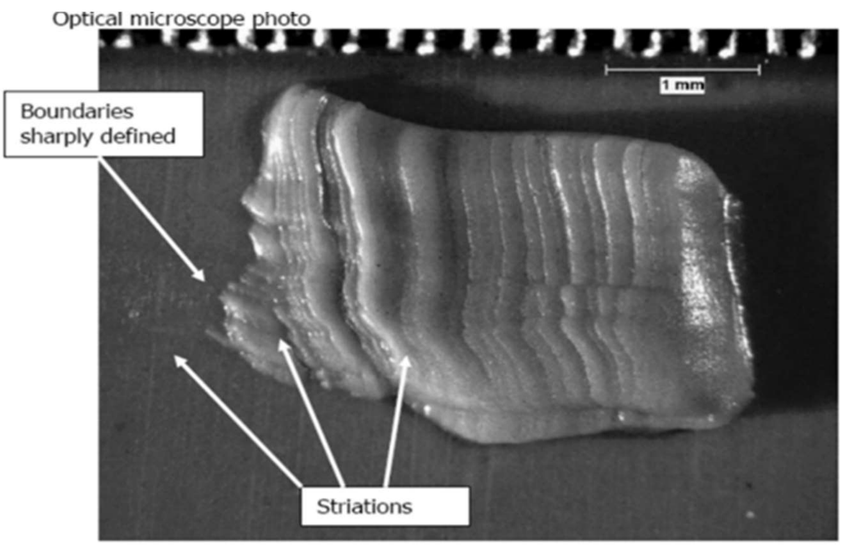

FIG. 8. Replica of a pressure tube debris fret (courtesy of Kinectrics).

Inconel X-750 spacer degradation:

Annulus spacers between the pressure tube (250–315°C) and calandria tube (60–70°C) maintain the annular gap. The spacer resembles a tightly wound extension spring with its ends hooked together with a girdle wire running through the centre. When the pressure tube sags due to its weight, it rests on the spacer at the 6 o'clock position where the spacer is pinched. The largest gap nominally exists at the 12 o'clock position. The spacer is subjected to a temperature gradient due to contact with the hot pressure tube and the cool calandria tube. The temperature range experienced by the spacer where the spacer is pinched is larger compared to the un-pinched zone. Annulus spacer geometry and operating conditions are depicted in Figure 9, courtesy of CNL.

Extensive tests and examinations have been performed through COG on ex-service Inconel X-750 spacer annulus material. Figure 10 compares the fracture surfaces for unirradiated and irradiated spacers after fracture at room temperature. The unirradiated sample exhibits ductile failure while the irradiated sample exhibits brittle intergranular failure, attributed to a build-up of helium near grain boundaries. Ex-service spacer test data and microstructural examination results have been analysed to develop predictive models of spacer load-bearing capacity as a function of irradiation.

After their receipt at CNL, post-service annulus spacers are visually inspected, dimensioned, and sectioned. Each segment of the spacer is routed to a downstream test, each conducted within a hot cell:

— ***Crush tests*** are performed in a machine that resembles a die set. The spacer segment is placed on the machine and then compressed with a punch until failure. The fracture surface is then examined. For both pinched and un-pinched cases, the segment typically experiences brittle fracture, both inter-granular and trans-granular. The cracks appear at the locations of maximum bending stress;

— ***Endurance tests*** are performed in a machine that features a set of platens, between which the spacer segment is placed. A static weight is applied to the upper platen and then the segment is rolled back and forth via cyclic translation of the two platens relative to each other. The machine continues to cycle until a spacer failure is experienced (typically >20k cycles). Again, the failure is typically brittle;

— ***Microstructural examinations***: those include fractography, transmission electron microscopy, focused ion beam scanning electron microscopy, microhardness testing, and micro-tensile testing. Microstructure changes such as helium bubbles on grain boundaries can be discerned through these examinations.

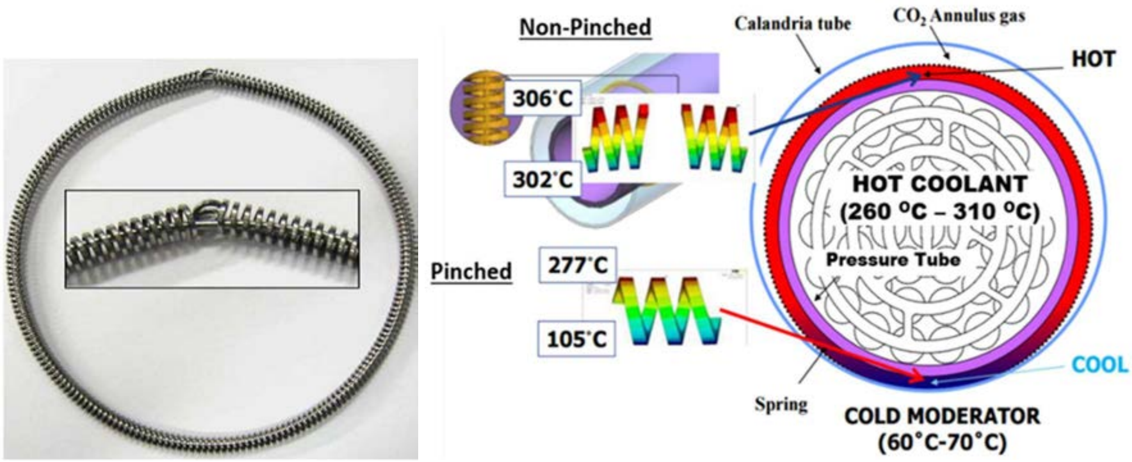

FIG. 9. Annulus spacer geometry and operating conditions (courtesy of CNL).

Additionally, spacer material, both unirradiated and ex-service, have been irradiated in a high-flux reactor until the desired dose is reached, at which point the material is similarly examined and tested. The key outputs of annulus spacer testing at CNL show a reduction in load carrying capacity with neutron dose and the trends are complex but confirm that their load carrying capacity exceeds the acceptance criteria at all tested doses and temperatures.

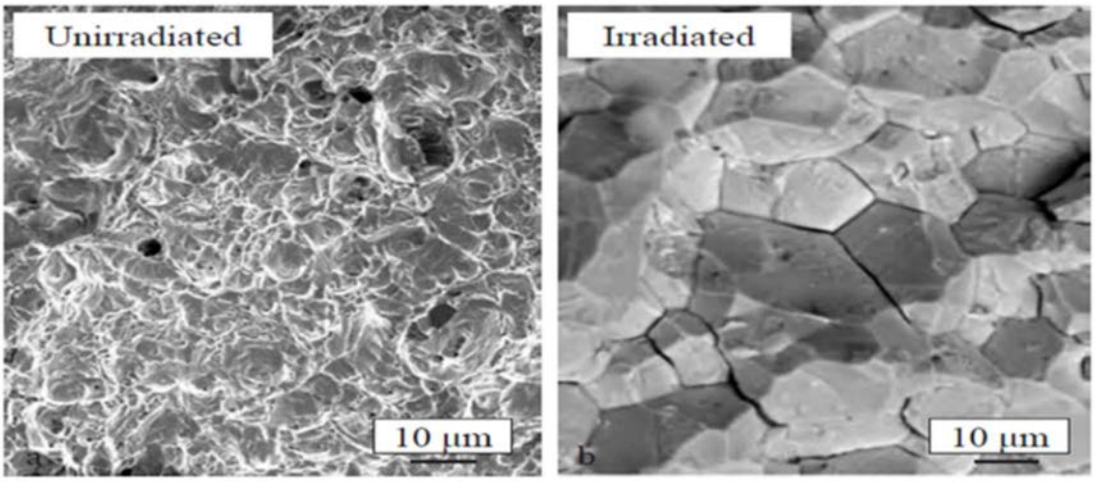

FIG. 10. Comparison of the fracture surfaces for unirradiated and irradiated Inconel X-750 tight-fitting annulus spacers after fracture at room temperature [29]

Addressing the balance of the reactor core:

Periodic inspections only examine a small percentage of the total number of pressure tubes in any reactor core over a plant's lifespan. CSA N285.8 Clause 7 requires the balance of core to be addressed. Numerical tools (software) and input databases have been developed under the COG FCLM program to evaluate the increased probability of pressure tube rupture with time as units age. Leak-before-break and fracture protection are also addressed. Figure 11 shows an example of the output of a probabilistic core assessment to predict the probability of pressure tube rupture from degradation due to flaws over the plant's lifespan.

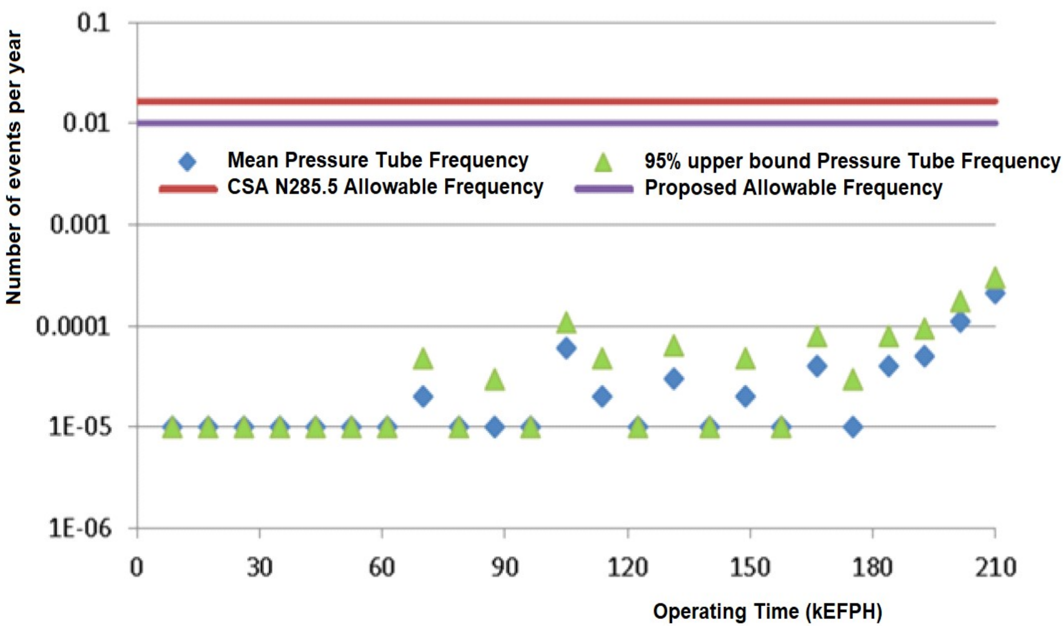

FIG. 11. An example of probabilistic core assessment output to predict the probability of tube rupture due to flaws (courtesy of Kinectrics Inc).

6.2.FUEL CHANNEL INSPECTION TECHNOLOGIES AND MARGINS RECOVERY

The need to manage the various fuel channel degradation mechanisms drove the development of various fuel channel inspection and maintenance technologies. This was initiated by utilities (such as Ontario Hydro), and subsequently with the support of COG. A comprehensive review of the inspection and monitoring methods and tools for PHWR pressure tubes has been presented in Reference [3].

Development and improvements to the inspection tools and delivery systems have continued and now include the advanced delivery machine and the advanced fuel channel inspection system for CANDU 6 units, the universal delivery machine [21] and the advanced non-destructive examination for OPG reactors, and the Bruce Power reactors inspection and maintenance system. Besides the spacer location and repositioning tool, the modal detection and repositioning tool has been developed for repositioning tight-fitting annulus spacers (TFS).

Newer and refurbished reactors have also incorporated design improvements in various areas:

- AGMS design improvements for improved leak detection;
- Enhanced bearing travel and positioning assemblies to manage greater axial elongation;
- Quadruple-melted pressure tubes for higher fracture toughness;
- TFS that are more resistant to movement, but not detectable until pinched. The first generation of Inconel X-750 TFS was found to be subject to degradation (around the year 2005) due to helium evolution leading to embrittlement, reduced load-carrying capacity, swelling and potential movement. Consequently, the second generation of TFS returned to the Zr-Cu-Nb alloy used for the original loose-fitting spacers. These are now being used in refurbished units at OPG and Bruce Power. These new TFSs also utilise a triple-melted coil wire with closer dimensional control. Zr-Nb-Cu TFS may de-tension more rapidly, increasing the risk of movement before pinching. Refurbished Bruce Units 1 and 2, Point Lepreau, Wolsong Unit 1, and Embalse still have the Inconel X-750 spacers;
- 37M fuel and neutron overpower/reactor overpower margin recovery methodologies to manage higher diametral creep.

6.3.REFURBISHMENT TOOLING AND PROCESS INNOVATIONS

The process to retube a CANDU reactor is relatively unchanged since 2005. There are only slight differences between the Bruce A Units 1 and 2, CANDU 6, and Darlington processes.

Figure 12 presents the days needed to complete the component removal series for Bruce Units 1 and 2 along with the two consecutive CANDU 6 projects (Point Lepreau and Wolsong Unit 1). These projects could be considered the first-generation projects and were carried out around the same timeframe and utilized similar retube systems. The figure shows that there is a marked schedule improvement with the gain in expertise and experience.

In Figure 12, “Future” days (light blue line) represents the durations that would be achievable with incorporation of the tooling system innovations that are under development. “Theoretical” days (green bars) show the durations that would be achieved under ideal conditions, by taking the time required to complete one cycle of work on one lattice site and multiplying it by the number of lattice sites. It does not include stoppages in work due to the shift turnover delays, worker inefficiencies, time to recover from events, etc.

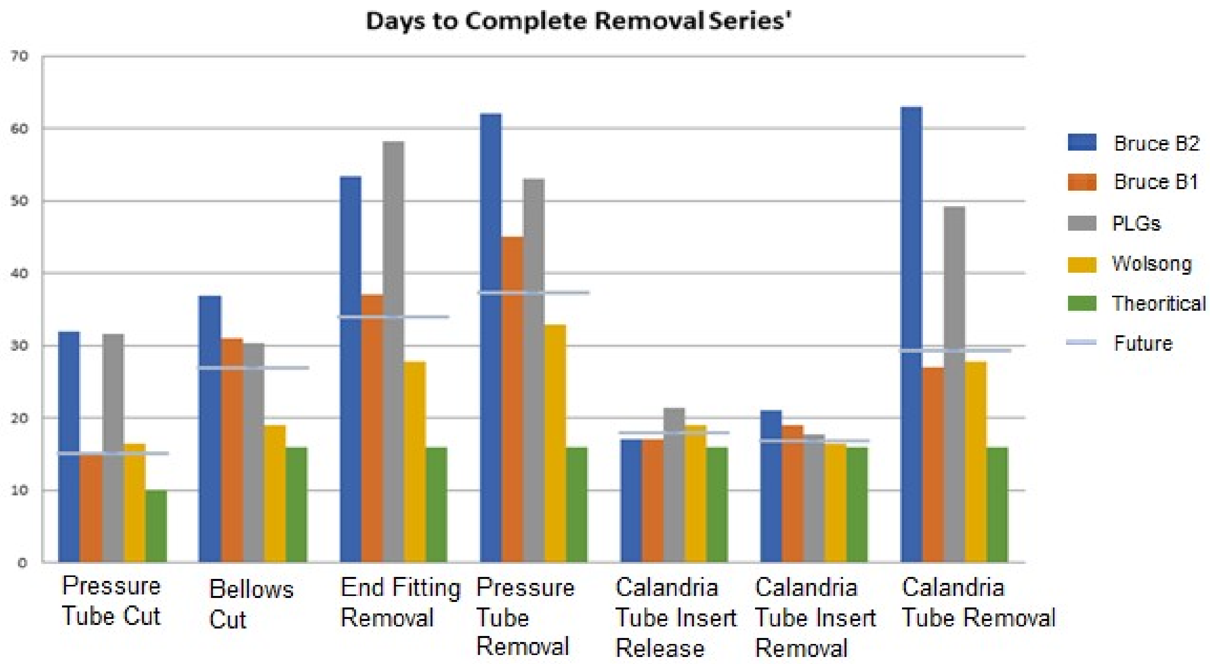

FIG. 12. Progress in removal series durations attributable to innovations (courtesy of SNC Lavalin Nuclear – Candu Energy).

More than 20 patents outline the critical baseline retube activities. In addition to these baseline patents, innovative processes and systems have been developed and patented to seek further significant improvements in retube durations.

Efforts focused on optimizing tooling systems yield gains through removal of delays in sequencing and eliminating manual intervention. Major reductions in the retube process duration are however only possible if the new tooling systems, concepts, and designs are adopted in combination with the re-evaluation and re-design of the entire processes.

Implementing new process and tools however presents many first of a kind issues, and the development teams need to be able to manage the issues by ensuring there is sufficient experience on the team, effective usage of operating experience, thorough planning of failure modes and contingencies, and creating a collaborative environment across disciplines.

The Retube and Feeder Replacement (RFR) portion of the Darlington refurbishment project provides a good basis for studying the development of processes and systems. Several initiatives were pursued. The seven listed below, if all implemented, were identified as feasible to reduce the retube outage duration by approximately 80 days per reactor unit.

- Combining removal of pressure tube and calandria tube;
- Elimination of the need to measure pressure tube to end fitting alignment;
- Combining calandria tube insert release and removal;
- Calandria tube installation improvements;
- Automating calandria tube sheet bore inspections;
- Pre-installing and inserting end fitting liners;
- Automating bellows inspections.

For instance, the combined removal of pressure tube and calandria tube can be expected to lead to a total removal work time of the order of 30 days for these combined actities, close to “Future” days in Figure 12.

Reduction in overall outage schedule yields cost benefits to projects and the reduced timeline has cascading benefits in the areas of nuclear safety, conventional safety, and quality. Examples include:

— **Nuclear safety**: Nuclear safety is improved by reducing workers’ time in a hazardous environment, which reduces dose to the workers. In addition, the combined pressure tube, calandria tube and annulus spacers removal as a single package during Darlington Unit 3 RFR has not only saved 30 days from the project schedule but has also significantly reduced the risk of the brittle annulus spacers from breaking apart and exiting the package, thus reducing another potential source of contamination;
— **Conventional safety**: The reduction in flask movements through the combined pressure tube and calandria tube removal initiative reduced the amount of hoisting and rigging events and platform movements by approximately 25%, thus reducing the risk of incidents and improving conventional safety;
— **Quality**: Automation and innovation in fuel channel inspection processes improve consistency, traceability and hence the overall quality of inspection. The results can be digitally archived and technically defended, which reduces risks of human performance errors.

7. LESSONS LEARNT AND BEST PRACTICES

Future refurbishment projects can benefit from the lessons learnt from Bruce A Units 1 and 2, Point Lepreau, Wolsong Unit 1, Embalse and ongoing refurbishments. This section presents some of the key lessons learnt and best practices from these projects as discussed during the Technical Meeting.

7.1.PLANNING AND SCHEDULING

It is important to ensure there is only one schedule that includes all activities and provides an integrated view of the refurbishment outage, covering the work to be done by the contractors as well as the maintenance work that the utility wants to complete. This was one of the key lessons learnt during the Point Lepreau refurbishment project, where there were examples of schedule conflicts that resulted in delaying the owner’s work and led to a bow wave of non-critical path work that needed to be completed before the unit could be restarted.

The schedule needs to include realistic (but challenging) execution targets based on actual experience (not on commercial objectives) and include sufficient allowances for contingencies. Task durations can be verified through mock-up trials in an environment representative of actual workforce conditions, but to use slightly longer durations than the target established during mock-up trials is important to account for the fact that the training environment cannot fully represent all field conditions. It is also important to ensure that the labour groups have input into the schedule; often labour groups will identify opportunities to improve the schedule.

Finally, refurbishment projects have traditionally been executed around the clock (on a 24/7 basis) to minimize the outage duration. This has however led to inefficient use of trades labour and resulted in added costs due to overtime premiums associated with work done on nights and weekends. A 24/7 schedule also needs a much larger workforce.

7.2. PROJECT MANAGEMENT AND CONTROL

Embalse LEP had more than 10 000 schedule activities. The manager responsible for each activity was involved in every step, beginning with contract negotiations throughout procurement, fabrication, and installation of systems. Active participation of activity responsible managers in the manufacturing facilities during the fabrication process and during the acceptance testing of main components was a key to identifying and solving issues that could have negatively impacted installation and commissioning. Overall progress was measured on a daily and weekly basis with regular interdisciplinary meetings to ensure corrective or mitigating actions were taken in a timely manner. All teams worked together, sharing space almost constantly during the LEP [6, 7], and were involved in an integrated decision-making process. Good teamwork with the rest of the organization, and constant communication between activity responsible workers and the supervising managers was also highly beneficial to the project.

A robust “T-minus” (time remaining until the launch of an activity) process with detailed checklists is important for field work. In advance of the field work, developing detailed production metrics that provide insights into all parameters that can impact overall productivity (e.g., weld failure rate, tool downtime, wrench time) was also demonstrated to be important. Good metrics will provide immediate and clear indication of any issues. Granular productivity targets can be measured on the scale of 2–4 hours, such that it can become apparent quickly if there are production issues. Time should be built into the day to ensure these metrics are reviewed frequently.

Establishment of clear interfaces between work groups, and having those interfaces documented in advance can avoid delays attributed to unclear hand-offs between work groups. As early as possible, establishment and clear definition of roles and responsibilities as to whom (which trade work group, station staff, contractor staff) will perform the actual work has been determined to be another key success factor. Establishing a War Room (a physical space that allows centralized decision making and communication) has proven to be very effective for these types of projects.

The effectiveness of transitioning from operations to refurbishment environment, and subsequently from refurbishment to station, is critical to the overall success of refurbishment projects. For example, transition planning for Darlington refurbishment is described in an interface agreement that clarifies the essential roles and responsibilities to achieve the project objectives. A site-integrated transition plan is established to ensure that all station and refurbishment staff are aligned and have a clear understanding of the specific deliverables required to support the transition to refurbishment and back to station operations. Department ownership transfer plans ensure that personnel in a department have a clear understanding of specific activities and responsibilities associated with the transition to refurbishment and back to station operations.

7.3. COST AND CONTRACT MANAGEMENT

To limit contractual issues and ensure appropriate control and oversight on the project, OPG had to put in place the following commercial strategy for awarding contracts:

- As there were several prime contractors, OPG had a separate contract with each prime contractor with responsibility for the completion of contracted work;
- OPG acted as the integrator between the prime contractors and retained overall responsibility for the entire project;

— OPG and the contractors were aligned on common goals;
— OPG used pricing models that avoid significant risk premiums and allocated risk to the entity best able to manage it;
— OPG retained project management responsibility and remained the design authority for the Darlington refurbishment project.

In addition, Darlington refurbishment project cost estimate was developed in accordance with OPG’s practices and the Association for the Advancement of Cost Engineering estimate classification model.

Refurbishments projects showed the need to have representatives of key vendors on site early during the project. For instance, non-conformances were found in pieces of equipment during the early days of Point Lepreau refurbishment. The utility management quickly realized the need for site resident vendor service representatives since vendors can be in different countries and time zones, which challenges timely support for emerging equipment issues.

Multiple vendors on the project tend to work in silos. This risk can be mitigated by engaging the vendors early and establishing strong interface control mechanisms from the very beginning of the project. Such engagement amongst all stakeholders with clearly defined division of responsibilities promote the one team mentality and significantly contributes to project success. The integrated system design approach further enhances the one team approach.

7.4.TRAINING

Some of the training related lessons learnt and best practices highlighted during the Technical Meeting include:

— Extensive training of all workers on high-fidelity mock-ups representative of reactor vault conditions is critical. The mock-up and tooling conditions in training have to accurately reflect the field environment;
— It is important not to underestimate the amount of training required for all work including the modification work scheduled for completion during the outage. A key success factor at Embalse, influenced in part by external factors, was to start the training early. Delays to breaker open allowed for more than a year of additional training and created more efficient know-how transfer between existing and new personnel;
— New Brunswick Power paid close attention to have their certified staff trained and tested on the plant simulator prior to taking duty in the station. Even though Maintenance and Engineering Staff were assigned as trainers, a more focused effort to have additional maintenance and engineering staff trained could have been more effective;
— The training environment is where worker expectations are set. The right expectations need to be clearly and consistently communicated during training. The learning curve happens at the training facility, not at the reactor face;
— Training plans need to include resources (time, consumables, tooling and equipment, people, and a realistic mock-up) and allow for high-fidelity dress rehearsals in advance of the work. The dress rehearsals need to include participation of all work groups who will be involved in execution (e.g., trades, quality, radiation protection, engineering);
— Sending lead trainers to the field to support the start of execution has proven to be beneficial. As the first few days of each series are typically the most challenging, the lead trainers can help addressing issues and ensuring workers clearly understand the work and feel confident;

7.5. FIELD WORK AND WORK PACKAGES

Projects identified that it is beneficial to use the mock-up as a testing environment for the construction work package preparation to ensure they reflect the real field conditions. Careful reviews can be conducted to determine if simple work orders can be used for the removal phase work that does not impact the permanent plant in lieu of an extensive work package. This has the potential to save time and cost and simplify the close out. However, invariably this needs to be complemented by robust temporary plant modification and configuration management processes. Close out paperwork should be treated with the same urgency as the field work; leaving close-out after the field work can result in additional project delays and costs.

It is also important to ensure the design requirements are based on real field experiences and conditions and are frozen well in advance of work packages and training deliverables; a technical change made a few years before execution is far less expensive than just before or during execution.

7.6. QUALITY AND CHALLENGING ACTIVITIES

Quality lapses can lead to serious cost, schedule, and safety implications. For instance, a major delay during the Point Lepreau refurbishment outage was caused by cleaning of the calandria-side tube sheet bores by the vendor using a brushing tool and procedure that was not fully proven and qualified. This resulted in the removal and reinstallation of new calandria tubes due to leakage concerns, thus delaying the overall project schedule by more than 10 months. KHNP benefited from Point Lepreau experience by halting the calandria tube sheet bore brushing activity and undertaking an extensive testing and verification process to resolve the calandria tube sheet bore issue. As a result, the schedule impact at Wolsong Unit 1 was insignificant. When quality issues are detected, the work should stop immediately and root causes investigated, and a solution developed, tested, and validated before the work can resume.

The feeder installation has been identified as one of the most critical and challenging activities at Embalse, needing stringent quality controls. For instance, the installation of the upper feeders necessitated the expansion of number of control points used to determine the position of the templates due to the bending caused by their own weight. In addition, the welding of the feeders needed the implementation of following quality measures:

- Instructing all personnel carrying out activities on the platform to avoid air and equipment hose movements, accidental power cuts and congestion of spaces;
- Use of uniform criteria among the welding operators to achieve a standardized and systematic work method and to evaluate defects more accurately. It was necessary to reinforce the weld crew supervision to maintain uniform performance while respecting the established work methodology;
- Tight control of welding equipment connection cables and argon supply hoses;
- Guaranteeing the supply of argon and avoiding changes and reconfigurations during the process;
- Welding wire used turned out to be critical when analysing welding defects. Hence, it was essential to maintain its adequate traceability and control by quality control personnel;
- Having backup tools available to speed up replacement in case of damage or defects; the demands of the field work led to a large rotation of tools and equipment.

7.7.LABOUR AND SUPPLY CHAIN

In Canada and Argentina, utilities had extensive discussions and collaboration with trade labour unions involved in the refurbishment projects. Existing agreements were modified to accommodate working hours, shift arrangements, work assignments, use of apprentices, meal and rest periods, and dose management, etc, needed to enhance safety and productivity for the refurbishment projects. Utilities and the labour union representatives also worked with local colleges engaged in training of tradespersons to ensure an adequate supply of trades.

Domestic supply chains and qualified labour forces in Korea and Argentina were recognized as key to successful completion of their refurbishment projects. For instance, more than 3700 workers were involved in the Embalse LEP. For the fuel channel and feeder pipe replacements, the external support was limited to the rental of equipment and the technical advice from approximately 30 foreign specialists. Some other work scopes such as steam generator replacement, moderator heat exchanger replacement and balance of plant modifications were implemented with even more limited foreign support. Fortunately, the recent completion of Atucha-II NPP construction offered the opportunity to move many skilled workers with nuclear construction experience to Embalse for the LEP. The new environment for the local trades was to work in a radiologically controlled area. They were therefore educated on radioprotection and safety culture, trained on full scale representative mock-ups, qualified at site to special processes such as welding and constantly audited by the owner's quality control and quality assurance during the process. In many cases, the contractors' local workers were directly supervised by NA-SA project staff.

Although the CANDU refurbishment projects had made a concerted effort to ensure lessons learnt are fully incorporated into planning of future projects, there were concerns about the ability of the CANDU supply chain and the trades workforce to cope with planned simultaneous multiple unit refurbishments. OPG and Bruce therefore, at the encouragement of the government of Ontario, had established collaboration agreements that include, amongst others, procurement and supply chain, tooling, lessons learnt, labour arrangements, and logistics [25].

7.8.IMPLEMENTATION OF A REFURBISHMENT LESSONS-LEARNT PROCESS

Based on the many lessons learnt, the Bruce Power and OPG refurbishment project teams continue to drive for efficiencies in schedule, cost, and dose uptake. The Darlington refurbishment program management team brought together a wealth of experience and knowledge to the project and gathered a significant amount of industry information on the planning and execution of major construction projects. To capture and utilise their own refurbishment lessons learnt, OPG has established a three-phase process for the Darlington through the refurbishment sequence that includes:

- ***Phase 1 - Identification and documentation****:* Refurbishment employees and vendors have a responsibility to identify and document lessons learnt. Those are identified on an ongoing basis during the planning and execution of work or as soon as possible after completion of key work;
- ***Phase 2 - Evaluation****:* Project or functional managers evaluate each lesson into a four-tier priority to ensure appropriate focus and to determine the priority for implementation of actions;
- ***Phase 3 - Verification****:* The approval to use the learned lessons for subsequent units includes project confirmation that lessons learnt have been incorporated and managed through the established process.

8. CONCLUSIONS

The IAEA organizes Technical Meetings and Workshops to facilitate the information exchange and cooperation on advanced reactor technology related activities. In line with those activities, a Technical Meeting on Best Practices in the Refurbishment of PHWRs was organized in collaboration with COG on 2–6 December 2019 in Toronto, Canada. The purpose of the meeting was to share experience and transfer knowledge regarding the PHWR refurbishment programmes in various Member States.

This publication summarizes the presentations and discussions held during this Technical Meeting. It is not intended to be a state-of-the-art documentation on the subject, but a summary of the information presented at the Technical Meeting.

The publication first reviewed the general scope of PHWR refurbishment projects and presented the highlights of completed, ongoing and future PHWR projects. Selected general regulatory considerations of Member States were then reviewed. The PHWR operating life being closely linked to fuel channel and pressure tube ageing mechanisms, supporting ongoing research and development in this field, along with fuel channel life management approaches and innovations in support of refurbishment activities were also documented.

Finally, this publication captures the lessons learnt shared during the Technical Meeting. Those were summarized from the various participants' presentations in terms of project planning and scheduling, project management and control, cost and contract management, training, field work and work packages, quality and challenging activities, labour and supply chain and the implementation of a lessons learnt process. These lessons learnt are documented with the aim of helping future projects to follow best practices in their planning and execution.

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APPENDIX I.

ANNEX I SUBMITTED TECHNICAL MEETING ABSTRACTS

I.1. TECHNICAL MEETING SESSION 1 – COMPLETED PROJECTS

Retube capabilities, experience, and best practices
Tim Freeman and Kamal Verma
(SNC Lavalin – Candu Energy)

The presentation will focus on SNC Lavalin – Candu Energy's capabilities and experience on retubing and refurbishment of CANDU stations covering activities from the definition phase, detailed engineering/procurement phase, and the execution phase. In addition to the retubing experience for the previously retubed units, the presentation will also include SNC Lavalin – Candu Energy's involvement in the Darlington RFR projects as part of the CanAtom joint venture and the future Bruce Unit 6 major component replacement as part of the Shoreline joint venture. The presentation will cover company's capabilities in systems and components engineering, design of retubing tools, support facilities and structures, and waste management tools and facilities. From the execution perspective, it will cover different execution and contracting strategies, and its actual execution experience. It will cover company's capabilities in developing commissioning and start-up strategies. Finally, the presentation will describe how lessons learnt from one refurbishment project have been incorporated into successive life extension projects to enhance efficient completion of all phases including optimization of the execution phase duration.

Point Lepreau NGS determining scope and execution activities
Michael Hare
(New Brunswick Power)

The purpose of the presentation is to provide lessons learnt from the scoping and execution activities of the Point Lepreau NGS refurbishment outage that occurred from March 2008–November 2012.

The Point Lepreau NGS entered a refurbishment outage in March of 2008 to replace the reactor components including pressure tubes, calandria tubes and feeder pipes. While this work determined the critical path outage duration, other important and necessary work was completed as outlined below:

A. Plant related

- Layup of the station and monitoring to preserve the asset for the length of refurbishment for equipment not worked on;
- Installation of modifications and subsequent integration of testing;
- Removal of layup and return to service activities to return systems to service;
- Core surveillance and testing to confirm operation of all reactivity monitoring and control systems.

B. Process related

- CNSC regulatory hold points and approvals;
- WANO readiness for restart review;
- Internal and external oversight.

C. People related

— Re-establishing an operating mindset (removal of construction mindset);
— Training of operations, engineering, and maintenance staff on all modifications.

The conclusion of the discussion will be that the plant, process, and people all need to have equal focus for the safe restart and subsequent operation of the station.

Bruce Units 1 and 2 fuel channel removal and volume reduction
Nicholas Simpson
(Canadian Nuclear Laboratories – CNL)

The foundational research and development that enabled fuel channel removal and volume reduction was conducted by Atomic Energy of Canada Ltd. (AECL) – separate entities as Candu Energy Inc. and CNL since the mid-1990's. While single fuel channel replacement tooling existed, the need for removal of all fuel channels from a reactor core as part of a large-scale retube campaign was expected. At the time, it was a race between Point Lepreau and Bruce Units 1 and 2 for deployment. At CNL, the initial focus of research was on volume reduction, and this is where the patented checker-pattern die set design originates. Later, but in parallel, the means to release a calandria tube insert from the calandria tube joint was developed along with the ability to remove a calandria tube from the reactor through the calandria tube-sheet bores. Once research into these key capabilities was completed, the remotely operated and semi-automated reactor face tools and volume reduction system located on the vault floor were designed, fabricated, tested, and delivered for the Bruce Unit 1 and 2 campaign. The equipment set was used in separate work series to remove flow restricting outlet bundles, remove pressure tubes, release and remove calandria tube inserts, remove calandria tubes, and inspect and dress the calandria tube-sheet bores.

Bruce Power lessons learnt
Chris Elliot
(Bruce Power)

The purpose of this presentation is to provide a summary of lessons learnt on Bruce Power refurbishment projects, starting with Units 1 and 2, and then progressing to major component replacements for Units 6 and 3.

It will be an examination of the lessons collected from the Bruce units as well as lessons collected from the other CANDUs that have completed or undergoing refurbishments such as Darlington, Point Lepreau, and Embalse, and the extent to which these lessons have been effectively applied at Bruce.

Major component replacement continues to benefit from close collaboration with OPG. Bruce Power will incorporate best practices from Darlington RFR lessons learnt process to enhance Unit 6 major component replacement execution phase and Unit 3 planning using OPG's three-phase approach:

— Phase 1: Collection and documentation (already incorporated for major component replacement);
— Phase 2: Evaluation to incorporate the lessons learnt (adapt Darlington RFR execution lessons learnt approach);
— Phase 3: Validation to ensure that lessons are incorporated (applied to subsequent units).

Bruce Power will model Darlington RFR by assigning construction resources with bench strength to the lessons learnt team. Their specific responsibility will be to identify potential cost savings opportunities to be used for planning and execution of subsequent major component replacements.

Point Lepreau NGS return to service
Michael Hare
(NB Power)

The purpose of this presentation is to provide lessons learnt from the return to service of the Point Lepreau NGS in late 2012. The Point Lepreau NGS entered a refurbishment outage in March of 2008 to replace the pressure tubes, calandria tubes and feeder pipes. While this work determined the critical path outage duration, other work listed below was approved and completed:

— System condition assessments;
— Age and obsolescence of existing equipment;
— Industry related improvements required due to deterministic or probabilistic assessments;
— Maintenance of station equipment that plant state would allow (core defuel for instance).

The main topics to be covered in this presentation are:

— Fission chamber electrical interference on restart;
— Unexpected release of moderator water during refill activities;
— PHT hydrostatic test during restart;
— Turbine run up and testing program during restart;
— Maintenance activities that were not considered in the original schedule as emergent issues occurred during restart.

The discussion will focus on:

— What issues occurred during each topic;
— What methods were used to recover and plan a path forward;
— Schedule implication that occurred;
— Resultant corrective actions that were taken to allow return to service for safe continued operation.

The conclusion of the discussion will then propose lessons learnt that would deal with generic issues (maintenance, modification, testing) and the communication strategy to the staff to keep morale high as RTS issues were discovered after the plant had been shut down for over 48 months.

Embalse life extension project safety design changes related lessons learnt
Anibal Barrera
(NA-SA)

Following several years of detailed planning and preparation, the Embalse NPP (Córdoba Province, Argentina), was shut down on 31 December 2015 to embark on the execution phase of the LEP. The ambitious scope of the Embalse LEP included the following main activities that were led by NA-SA with the technical support from the original designers and the main component manufacturers:

— Reactor fuel channels replacement;
— Steam generator replacement;
— Digital control computer replacement;
— Turbine and BOP refurbishment and uprating;

— Diesel generator replacement;
— Moderator heat exchanger and valves replacement;
— Safety system improvements and modernization;
— Main generator rewinding;
— Electrical pumps nuclear and conventional area: Overhaul, inspection, and internals replacement.

Safety system improvements and modernization included several modifications to achieve improvements in:

— Reactor shutdown systems coverage;
— Emergency core cooling system reliability;
— Plant robustness to cover seismic events through increased emergency power supply and emergency water supply capacities.

The necessity of implementing these changes stemmed from new regulations for CANDU 6 stations, probabilistic safety analysis results, and updated seismic requirements. All these modifications were implemented to comply with current codes and regulations and alleviate several restrictions imposed by the original plant design.

In addition to the modernization of existing Embalse NPP safety systems, new systems were installed to deal with beyond design basis events, thus updating Embalse NPP to meet the new international standards for CANDU 6. To deal with new accident scenarios that were not considered in the original Embalse NPP design, a rupture disk was installed in the inspection port of the calandria vault, and a light water make-up line was installed from outside the reactor building up to the calandria vault. Likewise, 33 passive autocatalytic hydrogen recombiners (PARs), a filtered containment venting system and a new PHTS main pump trip were installed during the LEP.

The plant was restarted on 4 January 2019. All on-site required modifications have been executed successfully according to plan, along with the post-design changes needed for the correct operation of updated safety systems and other new systems within the LEP scope.

The development of LEP allowed NA–SA to gain new capabilities regarding management, supervision, coordination, and execution of large-scale projects. NA–SA personnel gained knowledge and expertise from lessons learnt applicable to future projects by performing as activity responsible engineers and managers for individual systems. NA–SA `s knowledge base expanded significantly due to participation of NA–SA staff throughout the entire project, from the design stage through to assembly, commissioning, and operation of each system.

I.2. TECHNICAL MEETING SESSION 2 – CURRENT PROJECTS

Regulatory assessment of coolant channel replacement and associated activity

Ritu Singh
(AERB – India)

Coolant channel replacement activities are undertaken in a PHWR because of service induced degradation like hydride blister formation due to pressure tube cold spots - hydride embrittlement and DHC - which becomes life limiting in nature. In India, EMCCR was first undertaken in Rajasthan Atomic Power Station Unit 2 in 1995 and later in 5 other reactors. Important design improvements were implemented including replacement of Zircaloy-2 pressure tubes with Zr-2.5% Nb material, use of four tight fit annulus spacers (garter springs), modified journal rings design and concept of zero clearance rolled joints. In recent years, two more PHWR units have undergone coolant channel replacement activity. EMCCR involves development of technology and tools, mechanization of activities, manpower training, job execution, quality assurance, generation of database, and several other challenges. However, most challenging aspect of the activity is the management of personnel dose and control of contamination spread. Therefore, it becomes important that safety is given utmost importance during the EMCCR execution phase.

EMCCR involves dose intensive activities with several aspects important to safety. It involves control of occupational radiation exposure, cutting, removal and safe disposal of radioactive pressure tubes and other hardware removed from reactor core. It also involves cleaning and inspection of the retained components to ascertain fitness for service assessments, installation of new pressure tubes and other hardware, review of system improvements or changes, assessment of the use of newer technologies, post irradiation examination of selected removed components like pressure tube specimens, retrieval of removed components, rolled joint qualification, dose budgeting, requirements for start-up after refurbishment, and a variety of other activities.

AERB regulates the safe conduct of EMCCR activities and subsequent start-up of the reactor. The regulatory aspects of each replacement activity include identification of hold points for the activity; review and qualification of various tools, procedures, and personnel; assessment of health and qualification of the retained components; issues related to handling and disposal of the radioactive components removed from the reactor; control of occupational radiation exposure; and design safety review of the components being replaced. This presentation intends to discuss the above-mentioned regulatory aspects of safety during EMCCR.

Darlington refurbishment lessons learnt

Paul Ross
(OPG)

Darlington nuclear refurbishment mega project will refurbish four CANDU reactors over approximately ten years. The first unit, Darlington Unit 2, was completed as a standalone project ahead of refurbishment of the remaining three units. As Darlington Units 3, 1 and 4 will have overlaps during execution, there is a need for a robust lesson learned program from Darlington Unit 2 to ensure repeat events and recurrent successes are captured for subsequent unit execution. This will help ensure that both the cost and schedule improvements unit over unit are well managed and benefits realized.

Lessons learnt is defined in OPG governance as the knowledge gained during a project, which shows how project events were addressed or are to be addressed in the future with the purpose of improving future performance. The presentation will discuss the purpose and structure of the OPG nuclear refurbishment lessons learnt program as well as examples of key learnings in the areas of human performance, tooling initiatives, training initiatives, and overarching strategic changes required to manage a nuclear mega project.

Darlington refurbishment training – key to success

Kathy Brining
(OPG)

Darlington nuclear refurbishment mega project will refurbish Units 2, 3, 1 and 4 over a ten-year period, which requires a robust training program and RTS strategy. The major focus from the project onset was to create a fully systematic approach to training compliant program that would ensure that Darlington’s OPG employees and supplemental personnel are properly prepared and qualified to perform their job functions throughout the refurbishment period and following the safe RTS of each unit.

The presentation will discuss the vendor training requirements focused on the critical path work for the trades' hands-on skills, and the use of the full-scale Unit 2 mock-up housed within the Darlington Energy Centre, and all relevant lessons learnt.

The complete spectrum of Unit 2 refurbishment activities was examined to ensure that every modification was included in the assessment of the RTS training requirements. The presentation will explain the unique refurbishment training model that was implemented strategically to reduce the impact on the fleet training groups, thus allowing them to focus on the training and qualification activities for the operating nuclear units.

Darlington Unit 2 defueling lessons learnt
Kevin Garbutt
(BWXT)

This presentation will provide a brief description of the Darlington refurbishment defueling components design and supply project and highlight the following:

— Defueling components used to defuel all 480 reactor channels on RFR critical path;
— Defueling campaign was completed 26 days ahead of schedule;
— Designed universal carrier under the defueling contract to replace all fuelling and defueling carriers. This allowed for a single carrier to be used for fuelling and defueling operations and resulted in significant time savings and eliminated significant radiological dose;
— Mechanical tooling modifications, including flow restricting outlet bundle, dummy fuel bundle, fuel push tool, grapple, and other tooling;
— Fuel handling software changes and fuel handling operation data changes were successfully made to allow operation of the defueling components.

Darlington Unit 2 return to service – bringing the unit back
Terri Lilley and Val Bevacqua
(OPG)

Past refurbishment mega projects have shown that the large amount of scope, resource challenges and knowledge gaps in nuclear documentation requirements led to lack of focus and prioritization on documentation completion and final closure. This resulted in a reduced level of quality and schedule adherence for documentation expectations for RTS of refurbished units.

In support of Darlington Unit 2 RTS a documentation program is in place to ensure management of documentation quality and standards with controls in place for every element of readiness to return each plant system to operation.

OPG will share the development of the RTS program, including the tools utilized, processes used, reporting and controls, with a focus on lessons learnt for future unit refurbishments.

Setting priorities is key in determining the success of a nuclear unit refurbishment project, as conflicts may arise in supporting project work in parallel with the preventive and corrective (cyclical) maintenance required by the unit during the refurbishment period. These conflicts can lead to priority challenges for operator and maintenance resources, availability of physical space within the unit and the maintenance of material condition.

For the refurbishment of Darlington Unit 2, a program titled System Available for Service was used to strategically place systems in service as early as possible. This strategy was resource loaded and balanced such that the critical resource of operators was available to support both project and cyclical maintenance. The presentation will describe how the project team developed and executed the System Available for Service program and how it mitigated resource and commissioning risks on Unit 2.

I.3. TECHNICAL MEETING SESSION 3 – PLANNED PROJECTS

Bruce major component replacement Units 6 and 3 planning issues

Simon Ellison
(Bruce Power)

The purpose of this presentation is to provide an update on the progress Bruce Power is making in preparation for execution of Unit 6 and planning for Unit 3 major component replacements.

Bruce Power is currently less than 50 days away from breaker open and commencement of the lead-in activities on Unit 6. The major component replacement team members are finalizing the mobilization activities and completing the final readiness reviews. Facilities and infrastructure projects are nearing completion and the major component replacement project team members are currently preparing clearance orders, work packages and planning for work series training.

Meanwhile on Unit 3 major component replacement, planning is gathering pace with the team closing in on critical decision 2 milestone, which concludes preliminary design engineering, class 3 estimate, level 3 schedule, and identification of long lead materials. With breaker open scheduled for January 2023, the team members are driving for efficiencies in schedule, cost and dose uptake through a series of innovation projects and productivity improvement initiatives.

The Bruce Power team will provide a summary of progress to date and the plan going forward for the major component replacement portfolio.

Cernavoda life extension and refurbishment plans

Ionel Bucur and Romeo Urjan
(SNN)

SNN successfully operates two CANDU 6 units at Cernavoda site in Romania. Cernavoda NPP has been awarded the coveted INPO 1 rating twice, following WANO peer review missions at the plant.

As most utilities operating nuclear reactors, SNN has already started to develop a long-term operation program for Cernavoda NPP Unit 1, which began commercial operation in 1996. The long-term operation program will extend the life of Unit 1 reactor existing components up to the end of 2026. This will be followed by refurbishment of the systems, structures, and components to enable SNN to operate Unit 1 for another 30 years.

Life-time operation program: At the present time, refurbishment project is in the initiation phase, main activities being carried out to identify the scope of work and preliminary information and dates as input for the feasibility study. The current plan is to have the feasibility study ready and approved by middle of 2022; followed by the start of the definition phase. The unit is planned to be shut down for refurbishment work at the end of 2026.

Integrated construction planning - key to refurbishment success
Jamie Higgs
(AECON)

Less than two decades ago, the CANDU industry was embarking on an exciting and challenging endeavour to plan and safely execute refurbishment of CANDU units economically to significantly extend their useful life. In many ways, this was deemed a substantial challenge as both the technical and construction means to undertake this work successfully were conceptual and not yet proven.

Now with six CANDU units successfully refurbished both in Canada and abroad, the practices and approaches to the work are reaching new levels of maturity. Through experience and innovation over the past 15 years, robust and efficient techniques have been developed to reduce cost and schedule.

This presentation will retrospectively review the evolution of some key practices employed on the various refurbishment projects, particularly around the execution of the field work. Across the projects, certain execution practices have been shown to be particularly effective. Some of these key practices will be discussed with the objective of demonstrating that execution of CANDU refurbishments has evolved, and in many ways, is converging on common best practices that contribute to predictable and efficient project execution.

Tooling approach for refurbishment success
Matt Wong
(ATS Automation)

Specialized tooling is required to perform the reactor refurbishments, typically involving various tooling vendors and suppliers. It is crucial for the utilities that the tooling be reliable to facilitate on time and on budget project delivery and meet the design requirements set by either the utility or the contractor. ATS is a major supplier of fuel channel removal tooling, systems, and common equipment. Based on experience to date, this presentation will provide a vendor's perspective on how reliability and cost can be improved through integrated system design, early vendor involvement, robust testing programs, and well-defined requirements and specifications.

I.4. TECHNICAL MEETING SESSION 4 – FUEL CHANNEL LIFE EXTENSION, INNOVATION AND R&D IN SUPPORT OF REFURBISHMENTS

Tooling systems, patents, and innovations including combined pressure tube and calandria tube removal
Robert Mallozzi and Nicholas Simpson
(SNC Lavalin – Candu Energy, CNL)

Even though SNC Lavalin – Candu Energy already owns hundreds of patents covering retubing of CANDU reactors, it has continued investing on initiatives that further develop and enhance the processes and systems deployed on CANDU refurbishment projects. Many additional patented systems and processes are in various stages of development with an aim to reduce refurbishment outage duration.

Depending on when and how the initiatives are incorporated into the CANDU retube process, the refurbishment outage duration has the potential to be reduced by months, not days. The reduction in overall outage schedule will yield cost benefits to the utility associated with reduced labour and replacement generation costs. In addition to these obvious elements, reducing timelines has cascading benefits in the areas of nuclear safety, conventional safety, quality, equipment downtime, and overall enhanced value for the CANDU product. In that context, Candu Energy partnered with CNL in 2018, to redesign the reactor face tooling to enable removal of both the pressure tube and calandria tube together from the reactor core in one work series. Proof-of-principle testing and substantial finite element analysis were conducted at CNL to substantiate the design robustness considering the constraints intrinsic in combined removal of these two key reactor core components.

Bruce major component replacement use of building information systems (3D modelling/scanning)
Simon Ellison and Kshitij Ahuja
(Bruce Power, NPX Innovations)

The purpose of this presentation is to provide an overview of the initiative Bruce Power is undertaking to implement building information modelling (BIM) at Bruce Power.

Bruce Power is currently assessing the business value of implementing BIM. As part of the assessment, the major component replacement team is undertaking a proof of concept trial on a flow control valve in the boiler feeder system at Bruce B. The proof of concept will validate the benefits of BIM and help inform a decision upon a phased implementation of the tool.

The presentation will discuss the Why, What and How behind building information modelling:

— Why:
  - Introduction to BIM;
  - Business benefits for Bruce Power – why do we need BIM?

— What:
  - What does BIM mean for Bruce Power?

— How;
  - Proof of concept – Details and objectives;
  - Next steps – Roadmap;
  - Key stakeholders.

— Q&A.

Next generation refurbishment tools
David Morikawa
(ATS Automation)

Utilities undertaking refurbishment projects have made commitments to their stakeholders to meet project budget and schedule targets. In addition, utilities are under increasing pressure to achieve significantly shorter durations and significant cost savings for subsequent units. To meet these challenges, design innovations to existing tooling and processes are being developed. However, to achieve large step changes, the industry may also need to consider more radical approaches that, if not implemented wholesale or in the short-term, could lead to new innovations not currently being considered. Additionally, such approaches tend to lend themselves to decommissioning strategies where significant gains are mandatory in the first-off tool sets. This presentation describes some of these changes that are aimed at minimizing outage duration, and providing a high degree of modularity, interchangeability, and cost reduction.

Fuel channel life extension
Nicholas Simpson
(CNL)

An extensive program exists at CNL to examine and test ex-service CANDU fuel channel components. Surveillance testing is performed to meet fitness-for-service guidelines. CNL also actively conducts research and development activities directed towards extending the life of fuel channel components such as the pressure tube and annulus spacers. Entire fuel channel assemblies are tested and analysed in CNL's hot cell facilities

Ex-service pressure tubes are burst tested in the as-found condition as well as after being charged with additional hydrogen to represent a projected end-of-life condition. Historically, hydriding has been achieved through an electrolytic process. However, a relatively new process known as low-pressure gaseous hydriding, patented by CNL, has been developed to artificially age the pressure tube. As part of burst testing, several small specimens are obtained to perform multi-scale tensile testing of the pressure tube material. CNL is investing in new equipment to conduct burst testing well into the next decade as well as developing a technique to remove hydrogen isotopes from in-service pressure tubes, specifically near the rolled-joint region. The technique relies on the temporary application of a hydrogen getter to rapidly decrease the hydrogen content of the tube and has shown great promise in preliminary testing to extend the safe operational lifetime of the pressure tube.

Upon receipt, annulus spacers are sectioned and routed to downstream testing activities such as: crush testing, endurance testing, density determination, helium content, hydrogen deuterium analysis (for Zr-Nb-Cu spacers), metallography, micro hardness, micro mechanical testing, and microstructure characterization. A detailed plan is formed for each spacer as each reside in different axial locations on the fuel channel. Test specimens are taken from various circumferential positions to characterize the degradation at pinched and un-pinched positions between the pressure tube and the calandria tube.

Approach for maximizing the operating lives of fuel channels
Andy Wallace
(Kinectrics)

The timing of CANDU reactor refurbishments is generally dictated by the operating lives of fuel channels that are subject to several different degradation modes that can be life-limiting. To optimize the scheduling of major refurbishment projects, particularly for multi-unit stations, it is necessary to be able to predict the safe operating lives of fuel channels with high confidence.

To assist with the planning of the refurbishments at Darlington and the Bruce nuclear site, OPG and Bruce Power have initiated a series of FCLM joint projects under COG with the goal of developing the information and evaluation tools needed to safely and confidently manage fuel channel degradation to target end-of-life within the life cycle management framework laid out by CSA standards N285.4 and N285.8. The main activities and outcomes of these supplementary R&D projects are reviewed and discussed from the perspective of minimizing the business risks associated with long term refurbishment plans.

ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
AERB	Atomic Energy Regulatory Board
AGMS	Annulus Gas Monitoring System
ATS	Automation Tooling Systems
BIM	Building Information Modelling
BOP	Balance of Plant
CANDU	CANada Deuterium Uranium
CNL	Canadian Nuclear Laboratories
CNNO	China National Nuclear Operations Co.
CNSC	Canadian Nuclear Safety Commission
COG	CANDU Owners Group
CSA	Canadian Standards Association
DHC	Delayed Hydride Cracking
EFPH	Equivalent Full Power Hours
EMCCR	En-Masse Coolant Channel Replacement
FCLM	Fuel Channel Life Management
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INPO	Institute of Nuclear Power Operations
KAPS	Kakrapar Atomic Power Station
KHNP	Korea Hydro Nuclear Power Co.
LEP	Life Extension Project
NA–SA	Nucleoeléctrica Argentina S.A.
NGS	Nuclear Generating Station

NPP	Nuclear Power Plant
OPG	Ontario Power Generation
PHT	Primary Heat Transport
PHWR	Pressurised Heavy Water Reactor
R&D	Research and Development
RAPS	Rajasthan Atomic Power Station
RCHP	Restart Control Hold Points
RD	Regulatory Document
RFR	Retube and Feeder Replacement
RTS	Return to Service
SDS	Shutdown System
SNN	Societatea Nationala Nuclearelectrica
TFS	Tight Fitting (annulus) Spacer
TQNPP	Third Qinshan Nuclear Power Plant
WANO	World Association of Nuclear Operators

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TECHNICAL MEETING

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