Ontario Power Generation

Darlington Fuel Channel

Fitness for Service

June 2015

ONTARIO POWER GENERATION

1.0 Introduction

The purpose of any power station, regardless of type is to produce electricity safely, reliably and economically. CANDU nuclear power stations are no exception. The objective of reactor safety program is to protect the public, employees and environment from radiological hazards resulting from regular station operations or in the unlikely event of an accident. The three primary principles that provide this protection are control the power, cool the fuel, and contain the radioactivity. These three principles are paramount requirements, which must be met in the operation of CANDU stations.

The Canadian approach to reactor safety is about "defense in depth." This means providing multiple technological and operational safety measures that act first to lessen the chance of an accident and then, if an accident does take place, reduce the possibility of harmful effects on people or the environment. It includes multiple, overlapping barriers, each of which is treated as the primary defence and can be physical or procedural in nature.

The five physical barriers are:

- Fuel in the form of a solid stable pellet.
- Fuel pellets are contained within a fuel sheath, which are assembled into fuel bundles.
- Fuel bundles are contained within the cooling system pressure tubes, with water pumped through the pressure tubes to cool the hot fuel bundles.
- These barriers are enclosed within the airtight reactor building, with concrete walls at least four feet thick.
- The reactor building is connected to a large vacuum building, which will remove any radioactive material released into the reactor building in the event of an accident.

In addition, the station is surrounded by a one-kilometre exclusion zone where there are no permanent residences.

This report focuses on one of the five physical barriers: the system designed to cool the fuel, called the heat transport system. Fuel channels, which are a critical component of the heat transport system, are specifically addressed in this report.

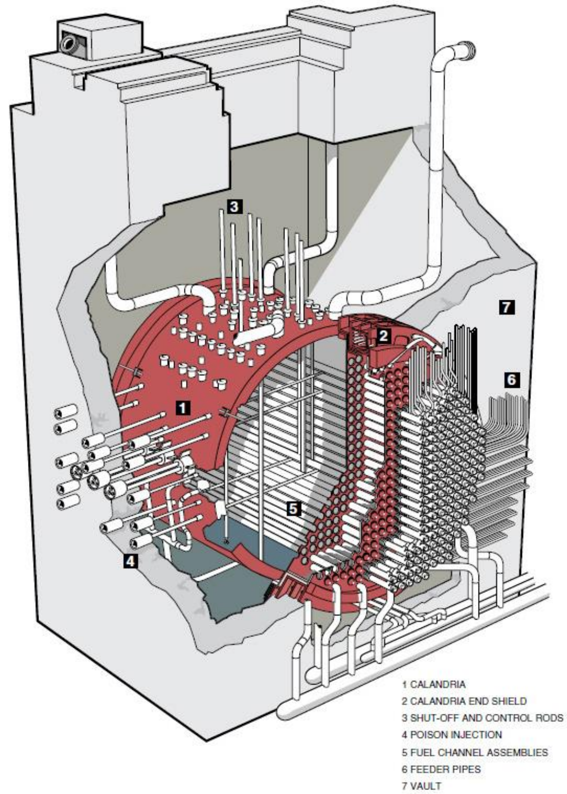

Figure 1 – Section View of CANDU Calandria Assembly

Fuel channels support the fuel bundles inside the reactor. The fuel channels are located inside the calandria-endshield assembly, as shown in Figure 1. At Darlington NGS, all units contain 480 fuel channels which are made of a zirconium alloy. Figure 2 shows a reactor face of a typical CANDU reactor core.

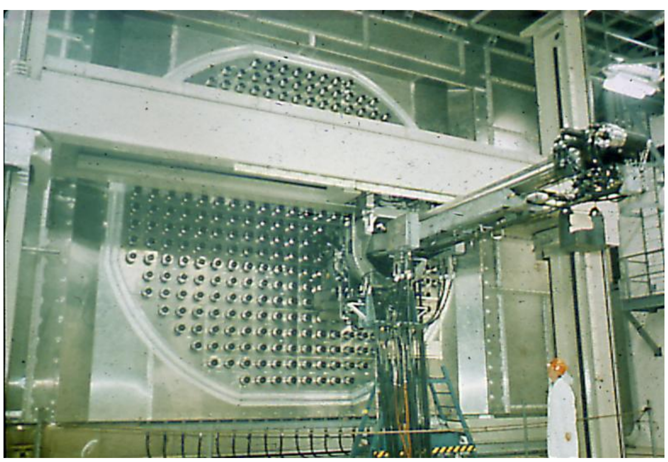

Figure 2 - Reactor Face of a typical CANDU Reactor, showing a Fuelling Machine

Pressurized heavy water coolant is pumped through the pressure tubes, transporting the heat produced by the nuclear fission process in the fuel to the boiler system, in order to produce high-pressure steam. The pressure tube forms the primary pressure boundary containing the fuel bundles and heat transport system coolant. Fuel channels consist of two end fittings, four annulus spacers, a calandria tube, and a pressure tube as shown in Figure 3. The fuel channels are surrounded by heavy water used to moderate the fission process within the calandria vessel. The annulus spacers provide a support to the pressure tube, maintaining a gap between the hot pressure tube and cooler calandria tube. Dry gas flows in the annulus space between the pressure tube and the calandria tube, insulating the hot pressure tubes from the cooler calandria tube to maximize efficiency of nuclear heat removal through the heat transport system and providing a moisture detection capability in the unlikelihood of a pressure tube leak. A detailed view of the Darlington fuel channel is illustrated in Figure 4.

As with other station components, fuel channels are subject to in-service aging mechanisms and require regular proactive inspections to monitor their condition and demonstrate fitness-for-service for the operating life of the reactor. As part of the Fuel Channels Life Cycle Management Plan (FCLCMP), ongoing in-service inspections and material surveillance of fuel channels are performed in accordance with Canadian Standards Association Standard CSA N285.4 [1]. Fuel channel fitness-for-service (FFS) assessments are performed as specified in CSA Standards N285.4 [1] and N285.8 [2]. The CSA Standards, as well as the FCLCMP, are discussed in detail in Section 2 (Periodic Inspection and Aging Management Program) of this report.

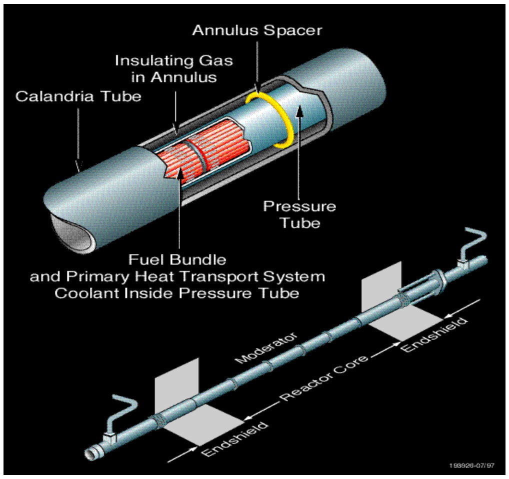

Figure 3 - Section View of Fuel Channel Assembly

Exposure to high temperature, pressure and neutron irradiation during operation results in changes to pressure tube dimensions and material properties. The fuel channel annulus spacers also experience changes in material properties in the high temperature and neutron irradiation environment. The changes are managed by the strategies provided in the FCLCMP. The plan includes in-service inspections, material surveillance, maintenance, engineering assessments, and research and development work. Based on the known aging mechanisms, strategic plans and mitigating actions have been developed to ensure the fuel channels meet the intended functions to end of the pre-refurbishment period for each unit at Darlington.

OPG is confident that Darlington’s pressure tubes are fit for service and that annulus spacers are integral and continue to perform their design function.

Safe operation is the top priority at OPG, and our confidence in fitness-for-service of the Darlington fuel channels is based on our operating experience, extensive research and development evidence, in-service inspection, as well as the use of predictive models and component condition assessments. OPG recognizes that fitness for service (FFS) requirements must continue to be met at all times, and regular monitoring and inspection are required to confirm fuel channel components are bounded by predicted conditions.

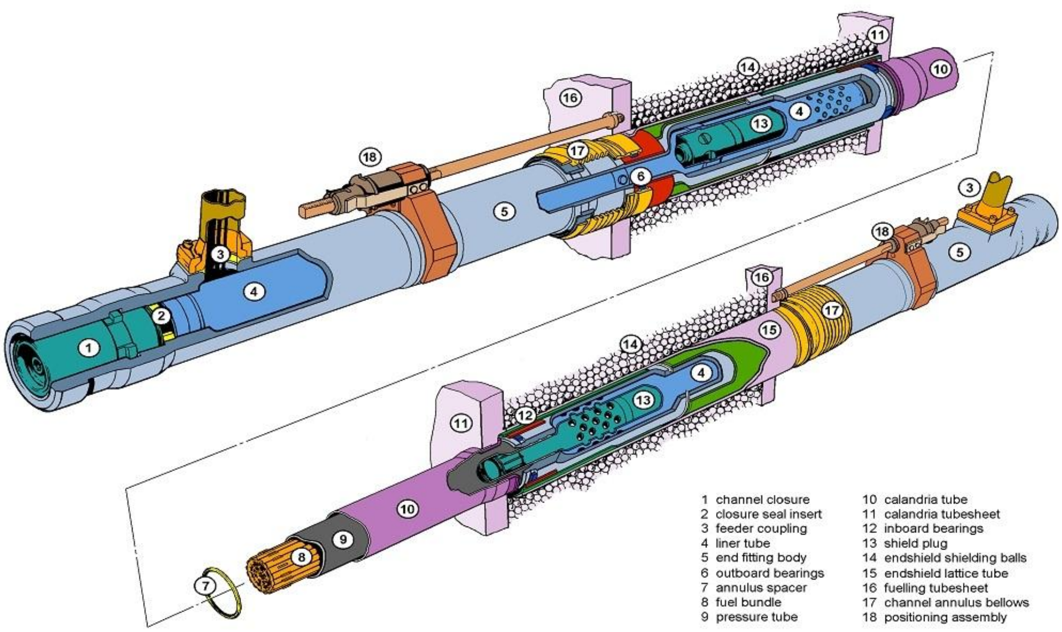

Figure 4 - Detailed view of a Fuel Channel

2.0 Periodic Inspection and Aging Management Program

The purpose of the Aging Management Program is to ensure the condition of critical nuclear power plant (NPP) equipment is fully understood and that required activities are in place to ensure the health of these components and systems as the plant ages. The Aging Management Program is consistent with International Atomic Energy Agency (IAEA) Safety Guide NS-G-2.12 [3], which is an internationally accepted systematic approach and integrated within Canadian Nuclear Safety Commission (CNSC) Regulatory Document RD-334 [4], a requirement of the station's Power Reactor Operating Licence.

While the Aging Management Program covers all critical NPP systems, structures and components, the focus of this report is fuel channels. The fuel channels are a major component in CANDU reactors and OPG utilizes the Aging Management Program to ensure fuel channel integrity is well managed throughout the operational life of the plant. This is accomplished by establishing an integrated set of programs and activities that ensure fuel channel performance requirements are met on an ongoing basis. This program also requires preparation of life cycle plans and condition assessments, which are discussed in Sections 2.1 and 4.0 respectively.

The Aging Management Program and activities it drives are key to ensuring critical equipment aging is managed such that operation of the NPP remains within the licensing basis of the facility and allows for station safety and operational goals to be met.

Aging Management considerations are applicable throughout the plant life cycle, including design, construction, commissioning and operation. Actions to ensure critical aging management considerations are addressed and included in each of these phases.

Figure 5 illustrates the Integrated Aging Management Process. The basic framework for the process is "Plan-Do-Check-Act". This framework ensures that planning is in place; the plant is operated in accordance with this plan; the plant condition is monitored; and that action is taken to manage the effects of aging.

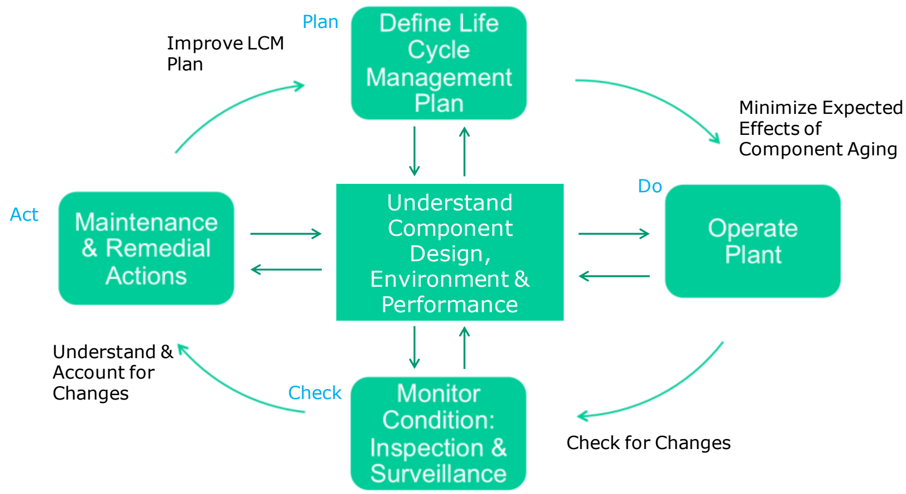

Figure 5 - Integrated Aging Management Process

The key to effective aging management is understanding the component design, environment and performance. It is seen as central to the Aging Management process as it defines inputs and outputs to all other steps in the process. To understand the design, it is necessary not only to understand the configuration and design rationale, but also the materials and material properties. The environment within which the component operates must be understood in order to predict the type and rate of aging which the component will experience. This involves understanding the operating conditions and stressors present at all stages of reactor operation. To understand component performance, the aging mechanisms, condition indicators, and the consequences of aging must be known.

Planning means defining the Aging Management Program by means of the FCLCMP. The plan ensures deliverables are well defined and activities are planned and coordinated. The plan is optimized based on current understanding and routine assessment. Execution of the plan allows projections to be made regarding remaining life of the components. This process ensures the effect of component aging can be minimized, allowing for safe operation of the reactor to the end of the pre-refurbishment service life of the Darlington NGS.

Managing and minimizing the impact of aging effects allows for adherence to safe operating envelopes. Understanding of the component design, environment and performance is a vital input in this process. In order to operate the plant in a manner that minimizes the effects of aging mechanisms, these aging mechanisms must be understood.

Another key element of Aging Management is inspection, monitoring, and assessment of component condition on an ongoing and planned basis to confirm plant condition is as per design intent. In order to monitor component condition, proactive in-service inspections, surveillance activities, and fitness for service (FFS) assessments are performed and their findings are reported to the regulator (CNSC). In the event that FFS acceptance criteria are not initially satisfied, the condition is dispositioned and appropriate corrective actions are taken.

Maintenance activities and mitigating actions can be the result of planned activities or corrective actions. These measures are used to manage the effects of aging and rely on all previous steps in the process to be effective. Preventative maintenance is based on understanding the rate of aging and must be properly planned to be effective. Condition-based maintenance depends on the results of inspection and monitoring activities. Understanding of the design, environment and performance is vital in deciding the type of maintenance required. Successful maintenance and remedial actions improve the Aging Management Program and support a better overall understanding of aging.

2.1 Fuel Channel Life Cycle Management Plan

The OPG FCLCMP is based on:

- Component performance and design requirements.
- An understanding of aging mechanisms and their consequences.
- An assessment of the current condition of the components.
- The available strategies for managing these aging mechanisms.
- An inspection plan and maintenance activities projected years into the future.
- An assessment of issues and risks associated with the plan.

The FCLCMP is updated on a regular basis to include results of recent inspections, industry operating experience, and research and development (R&D) findings. Work requirements are established and incorporated into outage and maintenance plans.

The first objective of the FCLCMP is to maintain adequate margins on fitness-for-service for the station operational life. The end of component operational life is generally defined as the point at which FFS cannot be assured for the upcoming operating cycle, or when it is no longer economically viable to carry out the activities required to demonstrate its fitness for service. At this point, the component must either be repaired or replaced for continued operation. FFS assessments are conservative and include margins to ensure unexpected adverse conditions can be accommodated. These assessments are based on the condition of the components throughout the life of the plant, usually as determined from the periodic inspections. The inspection results are assessed according to industry standard guideline documents, which set out the mandatory requirements that need to be met and the permissible assessment methodologies. The results are submitted for regulatory approval in accordance with the requirements of CSA Standards N285.4 and N285.8 [1 and 2]. The inspection techniques and assessment methodologies continue to improve through the extensive R&D program carried out by OPG and its industry partners.

The second objective of the FCLCMP is the preservation of the assets. These activities, which are not necessarily required for fitness-for-service, can be employed to support the extended operating life of the components.

The fuel channel (FC) aging management strategy identifies and manages degradation mechanisms, generic issues and interfaces with other systems, structures and components.

The life cycle strategy inspection and maintenance requirements are defined in terms of three time frames: short-term, mid-term and long-term as follows:

- The main objective of the short-term window is to demonstrate component FFS for safe operation, and to meet regulatory requirements.
- The main objective of the mid-term window is to prescribe the work that is integrated into business planning processes.
- The long-term strategy is mainly used to define inspection and maintenance scope for asset management and economic forecasting.

The strategic goals of the FCLCMP are as follows:

- Monitor FC configuration.
- Know the current state of degradation and be able to project future condition of the component.
- Manage pressure tube (PT)/calandria tube (CT) contact before unit specific refurbishment outages to avoid hydride blister formation.
- Upgrade PT flaw assessment methodologies.
- Maintain PT integrity, fracture protection and leak-before-break (LBB) assurance including operation within a defined operating envelope.
- Manage dimensional changes including PT elongation to assure FCs remain on bearing, and PT sag to prevent contact between CT and reactivity mechanisms.
- Maintain end fitting (EF) seal integrity.
- Maintain integrity of associated FC hardware.

These strategic goals are achieved by:

- Prioritization and identification of the windows for inspections, monitoring and assessments to determine the extent and rate of degradation.
- Development of plans for maintenance activities to counteract degradation mechanisms.
- Implementation of R&D programs to develop a better understanding of the degradation mechanisms.
- Identification and development of the appropriate tooling required to inspect, maintain, and rehabilitate.
- Analyses to support inspections and monitor trends.
- Performing leak-before-break (LBB), fracture protection, and probabilistic core assessment studies, and updating as necessary to incorporate operating experience and inspection results.

The FCLCMP provides projections of the service life using the most up-to-date knowledge of the component condition, and updates these projections as new information becomes available from ongoing PT inspection and maintenance campaigns. The impact of other components and systems on the performance of fuel channels, and the impacts of fuel channel aging on other systems are also considered.

Figure 6 provides a graphical representation of the three major aging mechanisms, which are monitored for fuel channel components, and the defense in depth strategy in place to mitigate the risk of radiological releases. The FCLCMP identifies the major in-service aging mechanisms with respect to PT deformation, changes in material properties and flaws. These mechanisms can result in crack initiation in the PT material. By achieving the operating envelope strategic goals, the potential for crack initiation is eliminated.

The FCLCMP prescribes the inspection and maintenance requirements for each of the operating OPG nuclear units for a minimum ten-year projection or to end of operating life. The inspection and maintenance focuses on these areas of aging in order to ensure that fuel channel condition is known and understood at all times. As a defense in depth measure, crack propagation is postulated and evaluated to prepare for the unlikely event that a crack is initiated in the PT, ensuring that multiple barriers remain to prevent release to the public (illustrated in Figures 6 and 9).

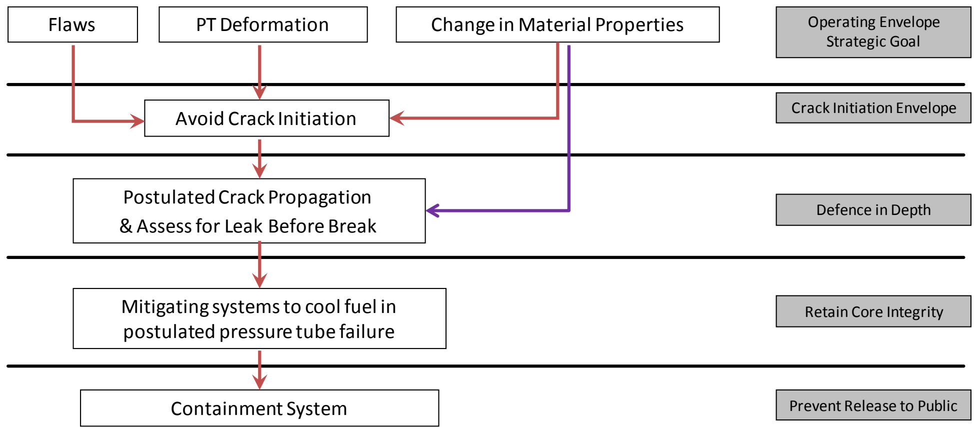

Figure 6 - Management of Fuel Channel Aging and Defense in Depth

All known and postulated flaws (minor imperfections) in core assessments are evaluated to demonstrate compliance with acceptance criteria established to provide a very low likelihood of crack initiation.

As a result of exposure to an environment of fast neutron flux, high temperature and high pressure during operation, pressure tubes experience dimensional changes, which must be managed over the operating life of the plant. Axial elongation, diametral expansion, and wall thinning deformations are inspected on an ongoing basis to confirm projections and ensure fitness-for-service for current and future planned operation.

Some pressure tube material properties change due to neutron irradiation, long-term exposure to elevated temperatures and increasing hydrogen isotope concentrations (as a result of deuterium ingress). The key material properties used in FFS assessments are tensile properties, fracture toughness, fatigue crack initiation resistance, crack growth rate, and threshold stresses related to delayed hydride cracking (DHC)[1] initiation.

To monitor the changes to pressure tube material properties, a pressure tube is removed on a periodic basis for detailed material surveillance and monitoring of key material properties. In addition, as hydrogen content is a key input to FFS assessments, hydrogen isotope concentrations are measured for the body-of-tube and rolled joint regions of the pressure tubes.

Some annulus spacer material properties change due to neutron irradiation and long-term exposure to elevated temperatures.   To monitor the changes to spacer

[1] Delayed hydride cracking is a mechanism, which can occur in zirconium alloy components.

material properties, spacer examination and property testing is performed when a pressure tube is removed on a periodic basis for detailed pressure tube material surveillance.

2.2 Periodic Fuel Channel Inspections

CSA Standard N285.4, Periodic Inspection of CANDU Nuclear Power Plant Components, [1] defines the fuel channel inspection requirements in CANDU reactors, and compliance is required by the CNSC in order to maintain the station's Power Reactor Operating Licence (PROL). The purpose of periodic inspection is to ensure that an unacceptable degradation in component quality is not occurring and the probability of failure remains acceptably low for the life of the plant.

The CSA N285.4 specifies inspection requirements, which align with identified aging mechanisms:

- Full-length volumetric inspection of pressure tubes can identify and size both surface breaking flaws, and sub-surface flaws.
- Pressure tube to calandria tube gap is determined through measurement or the determination of garter spring location and tube sag.
- Internal diameter and tube wall thickness measurements are taken to validate projected deformation.
- Measurements are taken to determine fuel channel position on its bearings in order to ensure axial elongation is well managed.

The results from each inspection are evaluated to determine compliance with defined acceptance criteria that is extracted from the component design basis and represent an unconditionally acceptable condition. If the result of an inspection does not satisfy the acceptance criteria, evaluation and further action must be taken. The Regulator, CNSC, must be notified of the result (as required by the operating licence), possible inspection program modifications must be considered, and where needed, corrective actions (such as repair or replacement) must take place.

CSA N285.4 requires the measurement of hydrogen isotope concentration. These measurements are obtained through a pressure tube scrape sampling program covering both body of tube and rolled joint regions. Acceptable hydrogen concentrations are those consistent with the original design basis as defined in the CSA N285.4 Standard.

CSA N285.4 also requires a material property surveillance program for each reactor unit as a condition of the PROL. The extent of material property testing includes fracture toughness, hydrogen isotope concentration, delayed hydride cracking growth rate, and isothermal threshold stress intensity for onset of DHC initiation. In order to establish the variation in material properties along the length of the pressure tube, a sufficient number of measurements must be taken. The acceptance criteria relating to these material properties are defined in Clause 8 of CSA N285.8 [2] and must be satisfied.

The fuel channel service life for the Darlington NGS is planned for 235,000 equivalent full power hours. Through the implementation of fuel channel aging management processes and strategies, including an extensive Fuel Channel Life Management Project, OPG has obtained the information required to assess fuel channel fitness-for-service and predict component properties later in life.

OPG's predictions of pressure tube properties at planned refurbishment dates support the conclusion that pressure tubes will remain fit for their full pre-refurbishment service life. The fitness-for-service of fuel channel annulus spacers for the remainder of their pre-refurbishment service life is managed through the Long Term Darlington Life Management Plan for Inconel X-750 Annulus Spacers. The spacer plan, like the FCLCMP, is a living document, which is updated as needed to address inspection results, R&D findings, operating experience, or other inputs potentially affecting fitness-for-service.

OPG will ensure the fuel channel condition is predictable and remains within the licensing basis and fitness for service criteria of the CSA N285.4 and N285.8 [1 and 2] standards for the proposed period of operation up to the refurbishment outages. The condition of the fuel channel components is regularly monitored via inspection programs, consistent with the life cycle management approach used for all major components. Inspection and surveillance reports, used to establish component condition, are routinely submitted to CNSC, as required by the CSA Standards. In cases where inspection or surveillance results do not initially satisfy the prescribed acceptance criteria, a request for disposition is submitted for CNSC acceptance and appropriate corrective actions are taken. The provision of these reports, and dispositions (as required), provide information allowing independent oversight by CNSC.

3.0 Demonstrating Fitness for Service

In-service inspection requirements are governed by CSA Standard N285.4 [1], which includes volumetric and dimensional inspection of pressure tubes (PT). Monitoring PT hydrogen isotope concentration (including ingress of deuterium – an isotope of hydrogen) is a requirement of CSA-N285.4 [1], as is periodic removal of PT for material property surveillance.

In-service inspections are needed to effectively monitor and assess degradation. Sufficient inspection data is required to characterize flaw populations and monitor for change. Data from these inspections is required as inputs into core assessments of degradation related to flaws and to determine if the flaw population is changing.

The FCLCMP includes inspection scope that exceeds CSA N285.4 minimum requirements. If a flaw, dimensional condition or material surveillance result that is detected by in-service inspections does not initially satisfy the acceptance criteria, it is necessary to engage the component disposition process and implement appropriate corrective actions. This process requires an evaluation of the component to demonstrate fitness for service (FFS) throughout the next operating interval.

Predictive models are required to demonstrate pressure tube fitness for service. These models are employed for deformation (axial elongation, diametral expansion, pressure tube/calandria tube sag for contact) and PT hydrogen isotope concentration. Routine measurements, trending, and research and development support aimed at modeling and understanding degradation are a continuous activity.

Tools that have been developed to support PT fitness for service assessments include: models to determine PT core rupture frequency for a reactor unit via core assessments, deuterium ingress models, and diametral strain models to address flow bypass impact on safety analysis.

The FFS assessment approach is used to ensure PTs have adequate integrity for continued service and that OPG continues to operate its reactors safely and within the licensing basis. Figure 7 graphically depicts this FFS framework.

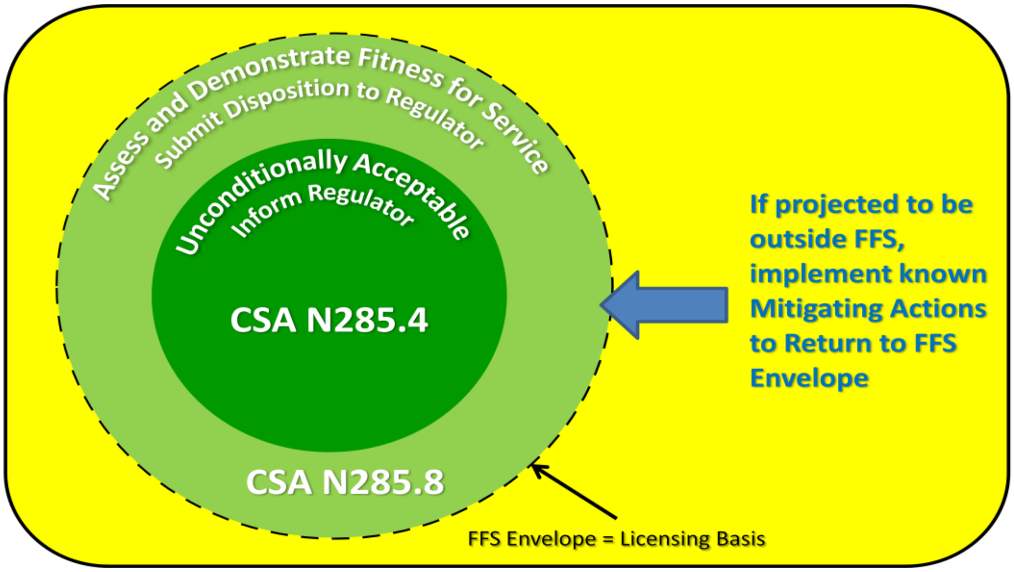

Figure 7 - Fuel Channel Fitness for Service (FFS) Assessment Approach

CSA N285.4 [1] forms the basis for the FFS envelope and defines acceptance criteria for fuel channel condition that must be met. If fuel channel condition satisfies these acceptance criteria then it is considered unconditionally acceptable, as it remains within the design basis for the component. When in-service inspection detects a degradation condition that does not fully satisfy the acceptance criteria of CSA N285.4 [1], OPG must demonstrate compliance with the technical requirements of CSA N285.8 [2]. Where neither N285.4 nor N285.8 have yet established acceptance criteria for a component, OPG has developed acceptance criteria for demonstration of fitness-for-service, and submitted the criteria and assessments to the regulatory authority.

By using refined knowledge of core condition and actual operating conditions, it is possible to demonstrate that design margins for the component are maintained. This process of further evaluation requires a disposition be submitted to the Regulator for acceptance.

If projections of fuel channel conditions suggest future departure from the FFS envelope, mitigating actions are available and will be implemented in order to remain within the envelope. The ability to project fuel channel conditions and respond as needed relates back to the Aging Management Program and the FCLCMP.

The FFS envelope forms the licensing basis, without which OPG cannot legally operate its reactors. Through periodic inspection, the FFS framework ensures that OPG continually understands the condition of the fuel channels, is able to predict future fuel channel condition and ensure operation always remains within the acceptable fit for service envelope.

4.0 Condition Assessment

The condition assessment process is used to evaluate the health of critical components and establish actions necessary to maintain component health and assure continued fitness-for-service for planned future operation. For fuel channels, the method of condition assessment used is FFS assessment. The condition assessment process seeks to identify and understand aging mechanisms, collect data, conduct analyses, evaluate component condition by comparison with defined acceptance criteria, and establishes actions required to maintain acceptable component condition.

Condition assessments for pressure tubes involve monitoring all of the aging mechanisms affecting fuel channels. As shown in Figure 6 of Section 2.1, fuel channel aging mechanisms are broken into three main categories; pressure tube deformation, changes to pressure tube material properties, and pressure tube flaws.

Pressure tube (PT) deformation includes axial growth, sag, PT-Calandria tube (CT) gap changes, diametral expansion and wall thinning. As part of the FCLCMP, elongation, sag, gap, wall thickness and diameter measurements are periodically obtained to ensure that fuel channel condition is as predicted, and will remain fit for service and within design basis for the next inspection interval. One key area of deformation is PT sag and more specifically, PT sag that results in a condition of PT-CT contact. PT-CT contact is a condition that does not satisfy CSA N285.4 [1] unconditional acceptance criteria. In managing PT-CT contact, a key element is to ensure tight-fitting annulus spacers maintain structural integrity. The Long Term Darlington Life Management Plan for Inconel X-750 Annulus Spacers has been implemented to address aging concerns for tight-fitting annulus spacers. The spacer plan includes ongoing testing, additional in-service volumetric, dimensional and PT-CT gap inspections, and material surveillance activities to assure spacer fitness-for-service. These tests and inspections are proactive in nature and provide assurance of fitness-for-service for the next operating period as is the practice with all major components. Recent results from the inspection of Darlington fuel channels, specifically pressure tube to calandria tube gap measurements, and spacer location inspections, are consistent with the presence of integral spacers, and have shown that spacers continue to reside within design locations. Testing of spacers removed in 2013 and further analysis confirm that spacers continue to perform their design function. Periodic inspections will continue for the remainder of the pre-refurbishment service life of the Darlington units, in accordance with the CNSC accepted Long Term Darlington Life Management Plan for Inconel X-750 Spacers.

Scrape sampling and material surveillance examinations provide measurements of hydrogen content in body of tube (BOT), as well as rolled joint regions of the pressure tubes. CSA N285.4 [1] has established acceptance criteria for maximum hydrogen concentration values as well as maximum allowable rate of change in hydrogen concentration. A hydrogen equivalent concentration ([Heq]) exceeding the limit of Terminal Solid Solubility for Dissolution (TSSD) results in hydrides being present at operating temperatures, which increases the potential for DHC initiation and crack growth at normal operating temperatures. Exceeding TSSD in the body of the pressure tube requires demonstration of fitness-for-service and disposition as required by CSA N285.4 [1] Standard. For Darlington Units 1, 2 and 4, pressure tubes are not projected to reach TSSD in the BOT prior to the time at which they will be shut down for refurbishment. Using conservative assessment approaches, a small subset of the pressure tubes in Unit 3 are projected to have hydrogen content above TSSD solubility limit in the outlet end of the pressure tube prior to refurbishment. For this reason, Unit 3 will be refurbished earlier in its planned operating life, with Unit 3 now scheduled to be the second Unit to be refurbished. A strategy to disposition the small subset of channels which may have hydrogen content above TSSD, including demonstration of an acceptably low risk, has been developed consistent with CSA Standard N285.4. OPG will submit a disposition along with supporting documentation in accordance with CSA N285.8 and OPG's aging management processes, as needed, to mitigate this condition to the end of the pre-refurbishment service life of Darlington NGS.

Pressure tube material properties change due to the long-term exposure to high temperature, pressure and neutron flux. Pressure tubes experience changes to tensile properties, fracture toughness, delayed hydride crack growth rate, and threshold stresses related to delayed hydride cracking initiation. Monitoring to date has shown that pressure tube material properties are consistent with the properties used in FFS assessment, thus satisfying CSA N285.4 [1] acceptance criteria. Current projections support continued operation to the end of the pre-refurbishment service life of Darlington NGS.

The increasing hydrogen isotope concentrations in the pressure tubes result in changes in the fracture toughness (a measure of resistance to crack propagation in the postulated case of an active propagating crack). The increase of hydrogen isotope concentration (due to deuterium ingress) is a known aging mechanism that occurs slowly and predictably over the full operating life of the plant. Deuterium ingress is well characterized, with predictive models and routine monitoring via scrape sampling.

The changes in material properties of the pressure tubes are known and accounted for, and an updated fracture toughness model has been implemented at all OPG plants. Figure 8 illustrates a simplified version of the updated fracture toughness model, accounting for the effect of high hydrogen content on the lower bound fracture toughness values. The updated fracture toughness model has been integrated into standard OPG processes for managing reactor operations, fitness for service assessments, and continued demonstration of fitness for service.

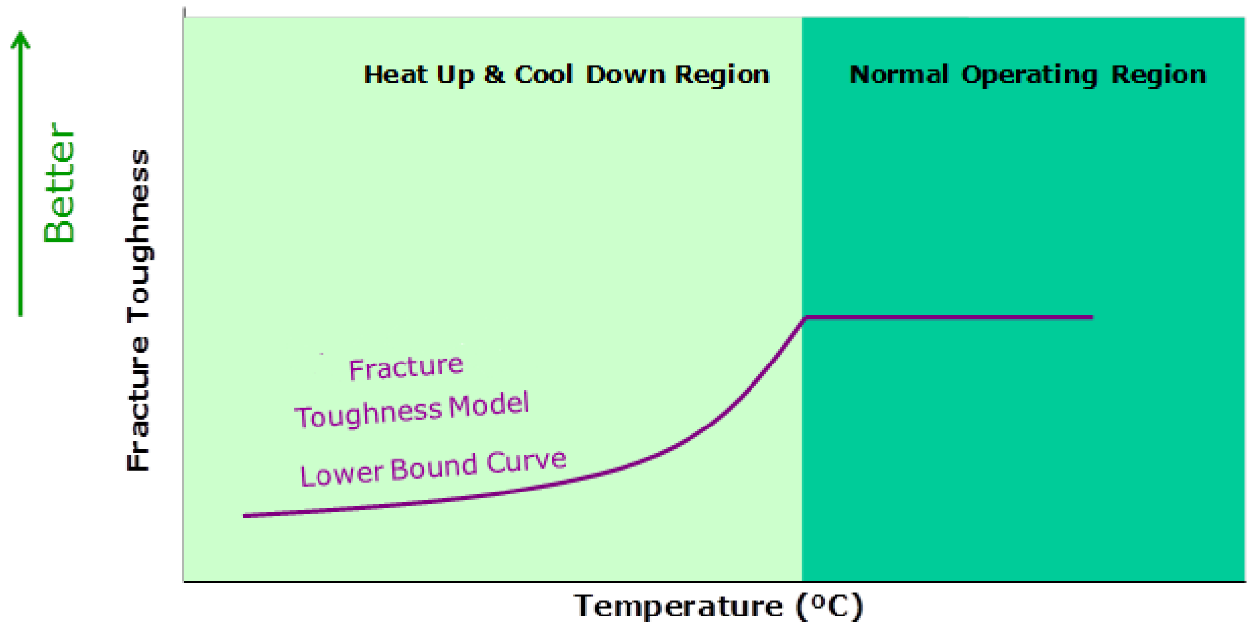

Figure 8 - Lower Bound Fracture Toughness Curve accounting for high Hydrogen Content

The fracture toughness material property change, due to increasing hydrogen isotope concentration, was used to define an updated pressure–temperature envelope for future reactor operation. The pressure-temperature envelope establishes a safe envelope for operating the plant to protect against pressure tube fracture for the case of a postulated severe flaw. OPG has implemented a more restrictive primary heat transport system operating envelope at Darlington, to maintain operating margins guided by the updated pressure tube fracture toughness model. OPG has also implemented the updated fracture toughness models in FFS assessments relating to pressure tube integrity for Darlington Units 1-4, specifically, probabilistic core assessments and leak before break (LBB), fracture protection, and flaw assessments.

It is important to note that the reduced fracture toughness at higher hydrogen content only affects the fracture toughness at temperatures below 250°C, and hence only has an impact during heat-up and cool down of reactor units. The fracture toughness test results at high hydrogen levels have revealed no reduction in fracture toughness at the higher temperatures for reactor operation at full power.

Volumetric inspection is performed to detect and characterize pressure tube flaws and to ensure that known flaws continue to satisfy the acceptance criteria defined in the standards. All detected flaws to date have been assessed and demonstrated to satisfy the acceptance criteria of CSA N285.4 [1] or the FFS criteria of CSA N285.8 [2]. Probabilistic core assessments, to assess the full core condition and project conditions over the next operating interval, continue to demonstrate an acceptably low potential for pressure tube rupture.

4.1 Fuel Channel Aging Mechanisms for Darlington NGS

Pressure Tube Axial Elongation - Available Bearing Travel

The consequence of PT axial elongation is the potential for a channel to no longer be supported on its bearings (an un-analyzed state). Axial elongation is currently not a life-limiting aging mechanism, as the time to reach maximum available channel bearing travel is beyond the planned refurbishment outages. Conservative projections indicate that the first channel to reach the end of bearing travel is in Unit 3 at approximately 241k EFPH.

Pressure Tube Axial Elongation - Burnish Mark Interaction

The consequence of interaction between the inlet fuel bundle bearing pad and inlet rolled joint burnish mark can cause accelerated pressure tube fretting if not properly managed. This mechanism is not a major concern, as the vast majority of channels will not reach burnish mark interaction (BMI) conditions prior to refurbishment. For the small number of tubes affected, known mitigating actions can be implemented in order to preclude BMI issues.

Pressure Tube Sag

The consequence of PT sag is pressure tube-calandria tube (PT-CT) contact, calandria tube/liquid injection shutdown system (LISS) nozzle contact, and fuel/tool passage issues. This mechanism is monitored by PT-CT gap measurements, PT sag measurements and CT/LISS nozzle gap measurement. Ongoing PT sag measurements are scheduled and conservative assessments have shown that CT-LISS contact is not projected prior to at least 233k EFPH. Confirmatory CT-LISS gap measurements are planned for 2016. Testing has shown that fuel passage is not expected to be an issue during the pre-refurbishment operating life for Darlington fuel channels.

Pressure Tube Wall Thinning

The consequence of PT wall thinning is reduced tolerance to flaws in PTs. Periodic PT wall thickness measurements are used to monitor this mechanism. Wall thinning is not considered life limiting; periodic inspection will provide confirmation through monitoring that limits will not be reached. Earliest projected time to reach design minimum wall thickness is 295k EFPH at

Darlington NGS. Periodic inspections will be carried out to validate assumptions and assessments.

Pressure Tube Diametral Expansion

The consequences of PT diametral expansion include reduced design margin, reduction in neutron overpower (NOP) set point (may lead to power reduction) and spacer nip-up (condition when the spacer gets pinched between PT and CT around the full circumference). This mechanism is monitored by gauging of PT diameter. The current safety analysis incorporates PT diametral creep impact on loss of flow, NOP and small break loss of coolant accident (LOCA). The heat transport system aging model has been updated to incorporate the effect of 37M fuel bundles, a modified fuel bundle design to provide additional margin for safety analysis. The 37M fuel bundles have been accepted for standard fueling. Assessments show that Unit 2 (the first unit to be refurbished) will be the first to reach the design analyzed limit, as well as the onset of spacer nip-up, at 239k EFPH and 219k EFPH, respectively. Pressure tube diametral expansion will not limit the life of Darlington fuel channels as design limit, spacer nip-up and NOP penalty are projected to occur beyond refurbishment outages for all units.

Change in Spacer Material Properties

Inconel X-750 Annulus Spacer aging and resultant changes in spacer material properties can potentially lead to spacer de-tensioning and reduced mechanical strength, making PT-CT contact a possibility. The Long Term Darlington Life Management Plan for Inconel X-750 Annulus Spacers has been implemented to address aging concerns for tight-fitting annulus spacers. The spacer plan encompasses additional in-service inspections, spacer removal and an irradiated test program to provide assurance of spacer, and thus fuel channel fitness-for-service. As a living plan, updates to future inspection and material surveillance activities will be made based on new information as results become available, to ensure plans demonstrating fitness-for-service remain appropriate. Data from in-service inspections, material examination, and testing have demonstrated that Inconel X-750 tight-fitting spacers continue to perform their design function.

Spacer Mobility

The consequence of spacer mobility is potential PT/CT contact. Spacer locations are determined by in-service monitoring. The gap between the PT and CT is also measured as part of the regular fuel channel inspections. To date, in-service inspections have not found any tight-fitting spacers out of position. The final assessment of spacer mobility has concluded that tight-fitting spacer movement is a very low probability event for Darlington fuel channels. Ongoing spacer location inspections are scheduled in the FCLCMP.

Hydrogen Ingress & Fracture Toughness

Fracture toughness changes as a result of deuterium ingress, affecting the way the unit must be cooled down and warmed up. Reduced fracture toughness at high hydrogen equivalent concentrations also impacts upon the ability to demonstrate pressure tube leak-before-break (LBB) and fitness-for-service as pressure tubes age. Predictive ingress models are validated against in-service scrape sampling measurements and data from the ex-service pressure tube surveillance program. Based on R&D work, the mechanistic understanding of the material fracture behavior, and measurements from burst tests of artificially hydrided ex-service pressure tube sections (hydrided sufficiently to representative end-of-life hydrogen equivalent concentrations), a new fracture toughness model has been developed. The new fracture toughness curves derived from the model are being integrated into the 2015 edition of CSA N285.8 [2] Standard and will become part of the licensing basis once it is integrated into the Licence Condition Handbook. It should be noted that the reduced fracture toughness at higher hydrogen concentrations affects the fracture toughness at temperatures below 250ºC, and hence only has an impact on heat-up and cool down of reactor units. The impact of the new fracture toughness model has been integrated into standard OPG processes for managing reactor operations and continued demonstration of fitness for service. Updated FFS assessments incorporating the new fracture toughness model have been submitted to CNSC, as required by the operating licence.

Flaw Assessments

Flaws are detected and characterized using ultrasonic examination and replication techniques. Flaws must satisfy acceptance criteria of CSA N285.4 [1] or be dispositioned in accordance with CSA N285.8 [2]. Known flaws are monitored. R&D is ongoing to better understand flaw behaviour and material properties to allow disposition of flaws for extended operation. Monitoring of known flaws, re-assessment, and disposition assure fitness for service for flaws.

Exceeding Terminal Solid Solubility for Dissolution

Hydrides present in the body of the pressure tube at operating temperatures increases the potential for delayed hydride cracking. Exceeding TSSD in the body of the pressure tube requires demonstration of fitness-for-service and disposition with the regulator in accordance with the CSA Standard N285.4 [1]. Darlington Units 1, 2 and 4 are not projected to reach TSSD before the time at which they will be shut down for refurbishment. Darlington Unit 3 however, contains a small subset of pressure tubes which are conservatively projected to have hydrogen content above TSSD in the outlet end of the pressure tube prior to refurbishment. A strategy has been outlined for demonstrating fuel channel FFS in Unit 3 when hydrogen content is projected to exceed TSSD. Mitigating options are available to ensure continued safe operation up to refurbishment outages.

5.0 Additional Considerations and Application of Operational Experience

Throughout the operating history of CANDU reactors, all plants have operated within the design basis as required by the Power Reactor Operating Licence (PROL). In the case of two prior pressure tube (PT) ruptures (early to mid-1980s, described in detail below), the events were contained to the affected fuel channel only and no special safety systems were required to be deployed in either case. The ruptures did not result in any nuclear safety issues and all known prior PT deficiencies were immediately addressed. Affected reactors were returned to service after repairs were made, or the full core of pressure tubes was replaced with improved fuel channel designs and material.

The issue of crack initiation (and subsequent crack growth and PT leakage) at rolled joints, as a result of very high stresses in over-rolled joints in fuel channel assemblies, has been eliminated. All reactors with over-rolled joints have now had their pressure tubes replaced and improved rolled joint assembly processes implemented, with no PT leaks having occurred with the improved rolled joint configuration.

In 1983, Pickering Unit 2 experienced a PT rupture (with Zircaloy-2 PT material) due to cracking of a critical-sized blister, which had sufficient hydrogen content at a location of PT-CT contact (which allowed a hydride blister to form and grow to a critical size). Following this event, all reactors were re-tubed with PTs manufactured using a superior zirconium alloy and all subsequently built reactors contain PTs of this type. The potential for pressure tube rupture due to blistering is now managed by ensuring that no PT-CT contact exists, or that contact only exists at locations of low hydrogen content. This is accomplished at Darlington through the use of tight-fitting annulus spacers and in-service inspections to confirm spacers continue to reside in design locations.

In 1986, a Bruce reactor experienced a PT rupture caused by a rare manufacturing flaw. The flaw initially propagated through the wall resulting in leakage that was detected, resulting in the safe shut down of the unit. The flaw was then aggravated by subsequent cold pressurization during leak search activities that were performed in the forced outage. Following this PT rupture, inspections were performed on all channels in the Canadian CANDU reactors identified as having a higher potential for manufacturing flaws. Additional improvements were made to the manufacturing process, including pre-service inspections, to further reduce potential for manufacturing flaws. Finally, operating procedures define a safe operating envelope for the pressure tubes, assuming the presence of through wall flaw, in compliance with CSA N285.8 [2], Clause 7.2.

The Canadian approach to reactor safety is about defense in depth, which directly applies to the fuel channels, as illustrated in Figure 9. Defense in depth involves creating multiple overlapping barriers to lessen the chance of an accident and reduce the possibility of harmful effects on people or the environment. Ultimately, the reactor design basis includes assumptions of PT rupture, and systems are in place to mitigate PT rupture and maintain low likelihood of severe core damage.

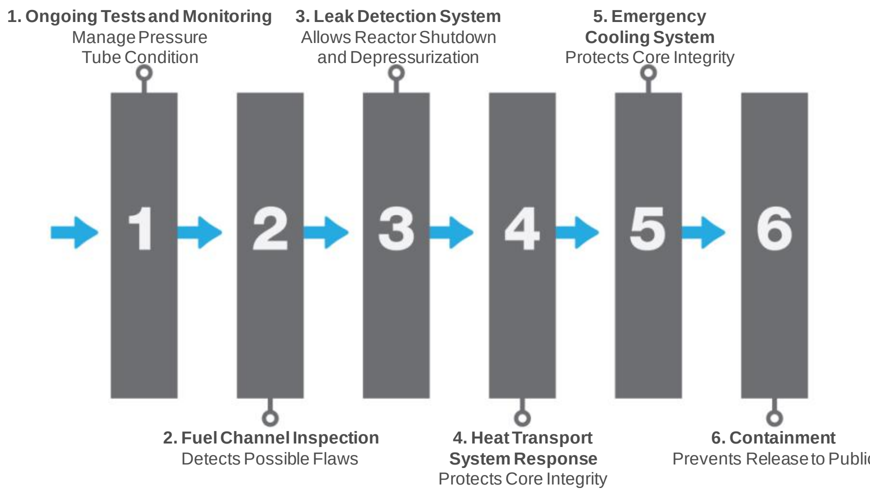

Figure 9 – Defense in Depth Framework

6.0 Summary

This report briefly introduces fuel channels and their vital role in CANDU nuclear reactors and describes how fitness for service is established and monitored throughout the operational life of a fuel channel.

Like all components in a nuclear power plant, the fuel channels are subject to proactive scheduled inspections to assess fitness for service, and confirm the component will function safely and reliably throughout the service life of the plant. The Aging Management Program provides the framework that ensures the condition of fuel channels is fully understood and that required activities are in place to ensure their health as the plant ages.

The FCLMP is developed as part of the Aging Management Program and helps to define which specific aging mechanisms need additional attention and monitoring. FFS assessments are carried out to ensure the fuel channels remain within the fitness for service envelope and licensing basis. CSA N285.4 [1] defines the minimum requirements for periodic inspection of CANDU nuclear power plant components including periodic inspection and material surveillance requirements for pressure tubes. When in-service inspection or material surveillance results do not initially satisfy defined acceptance criteria, the disposition process is engaged and appropriate corrective actions implemented. A fitness-for-service evaluation is performed in order to demonstrate acceptance of fuel channel condition and continued FFS for planned future operation.

The aging mechanisms affecting fuel channels are well understood and have been listed and described within this report. OPG understands and accepts that continued monitoring of fuel channel condition and research and development work focused on validating conservatisms in predictive models used in FFS assessments, is required.

OPG is confident of continued safe operation of the fuel channels to the end of Darlington's pre-refurbishment operational life for each unit. This confidence is based on OPG's operating experience, extensive research and development evidence, in-service inspection, as well as the use of predictive models and component condition assessments. Inspection and surveillance reports, used to establish component condition, are routinely submitted to CNSC, as required by the CSA Standards. The condition of the fuel channels is regularly monitored via inspection programs, consistent with the life cycle management approach used for all major components.

7.0 References

[R-1] "Periodic Inspection of CANDU Nuclear Power Plant Components", CAN/CSA Standard No. N285.4-05, Update No.1 June 2007.

[R-2] "Technical Requirements for In-Service Evaluation of Zirconium Alloy Pressure Tubes in CANDU Reactors", CAN/CSA Standard No. N285.8-10, Update No.1, June 2011.

[R-3] "Aging Management for Nuclear Power Plants", International Atomic Energy Agency (IAEA), Safety Standards Series, Safety Guide NS-G-2.12, (2009)

[R-4] "Aging Management for Nuclear Power Plants", CNSC Regulatory Document RD-334 (2011).

8.0 Abbreviations

BOT: Body of Tube
CNSC: Canadian Nuclear Safety Commission
CSA: Canadian Standards Association
CT: Calandria Tube
DHC: Delayed Hydride Cracking
EF: End Fitting
EFPH: Equivalent Full Power Hours
FC: Fuel Channel
FCLCMP: Fuel Channel Life Cycle Management Plan
FFS: Fitness for Service
IAEA: International Atomic Energy Agency
LBB: Leak-Before-Break
LISS: Liquid Injection Shutdown System
NPP: Nuclear Power Plant
OPG: Ontario Power Generation
PROL: Power Reactor Operating License
PT: Pressure Tube
RJ: Rolled Joint
SCC: Structures, Systems and Components