Ontario Power Generation

Pickering Fuel Channel

Fitness for Service

August 2014

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.

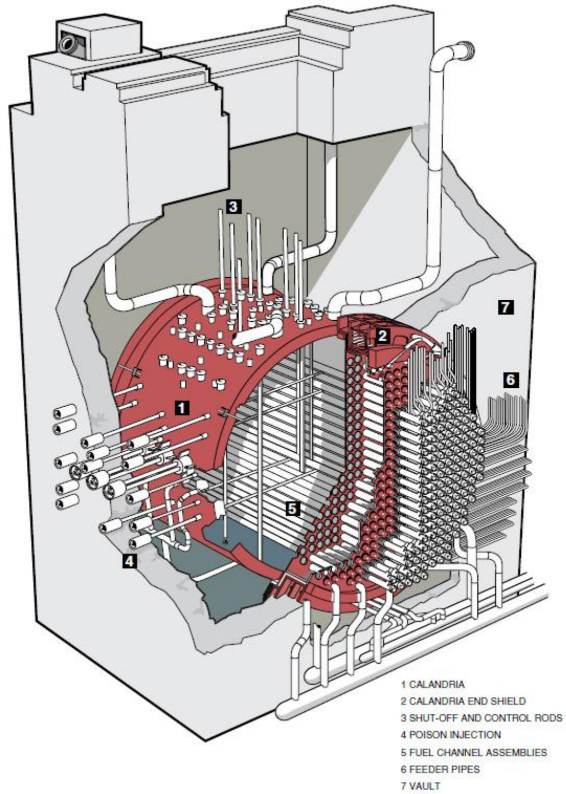

Figure 1 – Section View of CANDU Calandria Assembly

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 Pickering NGS, Units 1&4 contain 390 fuel channels while Units 5-8 contain 380 fuel channels. All fuel channels at Pickering NGS are made of a zirconium alloy. Figure 2 shows a reactor face of a typical CANDU reactor core.

Pressurized heavy water coolant is pumped through the fuel channels, 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. Dry gas flows in the annulus space between the pressure tube and the calandria tube, which provides moisture detection capability in the unlikelihood of a pressure tube leak. A detailed view of the Pickering 5-8 fuel channel is illustrated in Figure 4. The pressure tube forms the primary pressure boundary containing the fuel bundles and heat transport system coolant.

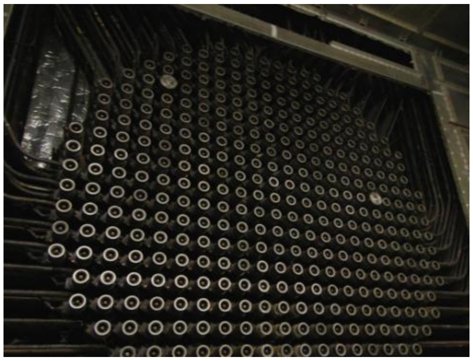

Figure 2 - Reactor Face showing Fuel Channel End Fittings

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 Channel 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 N285.4 [1] and CSA N285.8 [2] standards. The CSA standards, as well as the FCLCMP, are discussed in detail in Section 2 (Periodic Inspection and Aging Management Program) of this report.

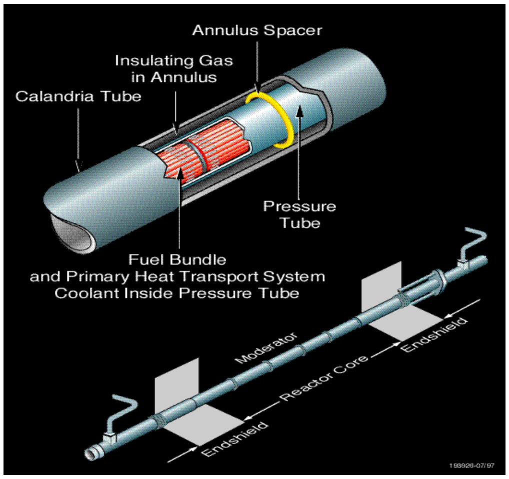

Figure 3 - Section View of Fuel Channel Assembly

Exposure to high temperature, pressure and neutron irradiation during operation results in changes to pressure tube dimensions and material properties. The changes are managed by the strategies provided in the FCLCMP. The plan includes in-service inspections, maintenance, engineering assessments, and research and development work. Based on the current understanding of the known aging mechanisms, strategic plans and mitigating actions have been developed to ensure the fuel channels meet the intended functions to end of target service life.

OPG can confidently state the fuel channels are fit for service up to and beyond their intended design service life. This confidence is derived from adherence to all applicable codes and standards, years of operating experience, assessments, and extensive research.

Through extensive studies and research, including involvement of industry and utility experts, OPG has demonstrated the Pickering fuel channels will remain within their design basis and be safe to operate to the end of station operations in 2020. In fact, the results show pressure tube condition is better than was estimated 30 years ago. We continue to prove this on an ongoing basis through our extensive reactor inspection program. Canadian Nuclear Safety Commission staff has concurred with our findings.

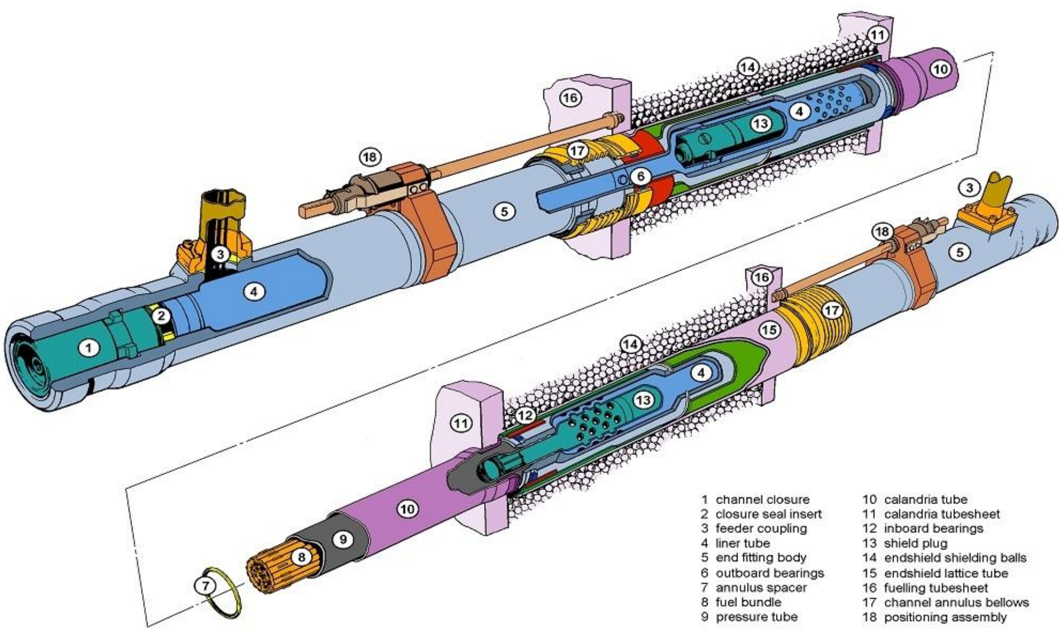

Figure 4 - Detailed view of Pickering 5-8 Fuel Channel

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 compliant 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.

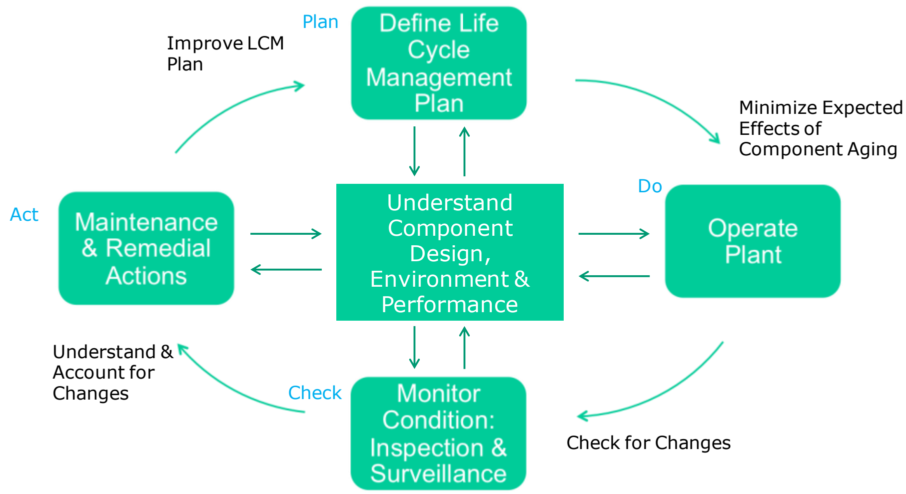

Figure 5 - Integrated Aging Management Process

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 will operate 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 Fuel Channel Life Cycle Management Plan (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 operation of the reactor to target end of life.

Managing and minimizing the impact of aging effects allows for adherence to safe operating envelopes. Understanding 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 must be fully understood.

A 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 assessments are performed and their findings reported to the regulator (CNSC). In the event that fitness-for-service acceptance criteria are not 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 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 Fuel Channel Life Cycle Management (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 (FFS) 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 N285.4 and N285.8 [1 and 2] standards. 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 extend the operating life of the components.

The life cycle strategy inspection and maintenance requirements are defined in terms of three time frames: short-term (two to three years), mid-term (five years) and long-term (to full service life) as follows:

- The main objective of the two to three year window (corresponding to the operating intervals between outages and planned inspections) is to demonstrate component fitness for service, safe operation, and to meet regulatory requirement.
- The main objective of the five-year window is to prescribe the required work that is integrated into business planning processes.
- The long-term strategy is to manage component aging to the end of commercial operations. The long-term strategy is mainly for asset management and economic forecasting.
- The fuel channel (FC) aging management strategy identifies and manages degradation mechanisms, generic issues and interfaces with other systems, structures and components.

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 the end of commercial operations to avoid hydride blister formation.
- Upgrade PT flaw assessment methodologies.
- Maintain PT integrity, fracture protection and Leak-Before-Break (LBB) assurance.

- Manage dimensional changes including PT elongation to assure FCs remain on bearing, and PT sag to prevent contact between CT and reactivity mechanisms (only applicable to Pickering Units 5-8).
- 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 refurbish.
- Analyses to support inspections and monitor trends.
- Performing Leak Before Break (LBB) assessments, fracture protection assessments 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 channels, 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 extremely unlikely.

The FCLCMP prescribes the inspection and maintenance requirements for each of the operating OPG nuclear units for a minimum ten-year projection. 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).

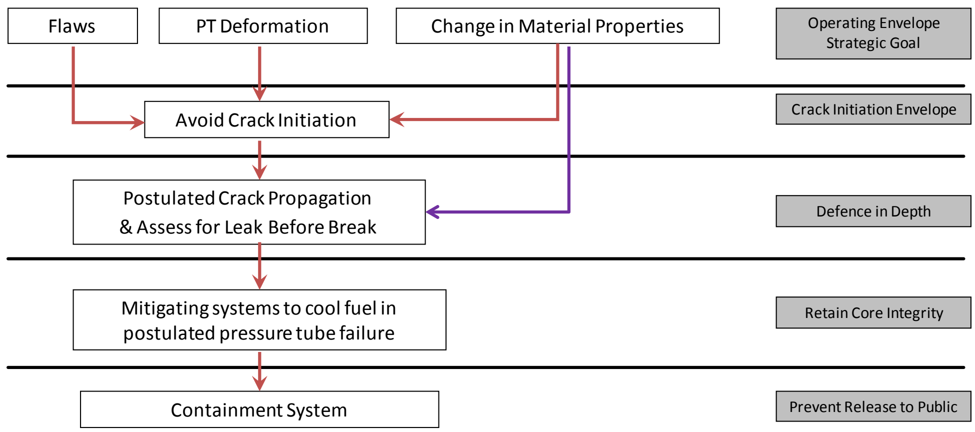

Figure 6 - Management of Fuel Channel Aging and Defense in Depth

Flaws in pressure tubes mainly occur early in the operating life of the units and appropriate measures are taken to ensure that new flaws will not be introduced. All known and postulated flaws 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 fitness-for-service 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 fitness for service assessments,

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

hydrogen isotope concentrations are measured for the body-of-tube and rolled joint regions of the pressure tubes.

2.2 Periodic Fuel Channel Inspections

CSA N285.4 – Periodic Inspection of CANDU Nuclear Power Plant Components is the standard, which defines the fuel channel inspection requirements in CANDU reactors, and compliance is required by the Canadian Nuclear Safety Commission 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 Standard [1] 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 confirm 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, the Canadian Nuclear Safety Commission, 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 [1] 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.

CSA N285.4 [1] 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.

In 2012, OPG revised inspection and maintenance plans to reflect continued operations at Pickering Station. For Pickering Units 1&4, this included plans to perform rolled joint deuterium sampling to confirm that deuterium uptake behaviour is as expected, as well as volumetric and dimensional inspections. For Pickering 5-8, rolled joint deuterium sampling was increased significantly for the remainder of life, including a specific plan to address when and where repeat measurements would be acquired. Spacer location and relocation (SLAR) scope and pressure tube to calandria tube gap measurement plans were adjusted to reflect continued operations. Full-length volumetric and dimensional inspections and maintenance were adjusted to reflect continued operations as well, including channel shifting and/or reconfiguration to maintain channels on bearing for their full service life.

3.0 Demonstrating Fitness for Service

In-service inspection requirements are governed by CSA-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. This information is required as inputs for core assessments for degradation related to flaws and to determine if the flaw population due to degradation mechanisms is changing.

The Fuel Channel Life Cycle Management Plan (FCLCMP) includes inspection scope that exceeds the CSA N285.4 standard minimum requirements. If a flaw, dimensional condition or material surveillance result that is detected by in-service inspections does not satisfy the acceptance criteria, it is necessary to engage in the component disposition process. This evaluates the component to demonstrate fitness for service (FFS) for the next operating interval.

Predictive models are required to demonstrate pressure tube fitness for service. These are required 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 is ongoing.

Tools have been developed to support PT fitness for service. These include models to determine PT core rupture frequency for a reactor unit via core assessments, probabilistic contact assessment to address post-SLAR spacer movements, deuterium ingress models, and diametral strain models to address flow by-pass 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.

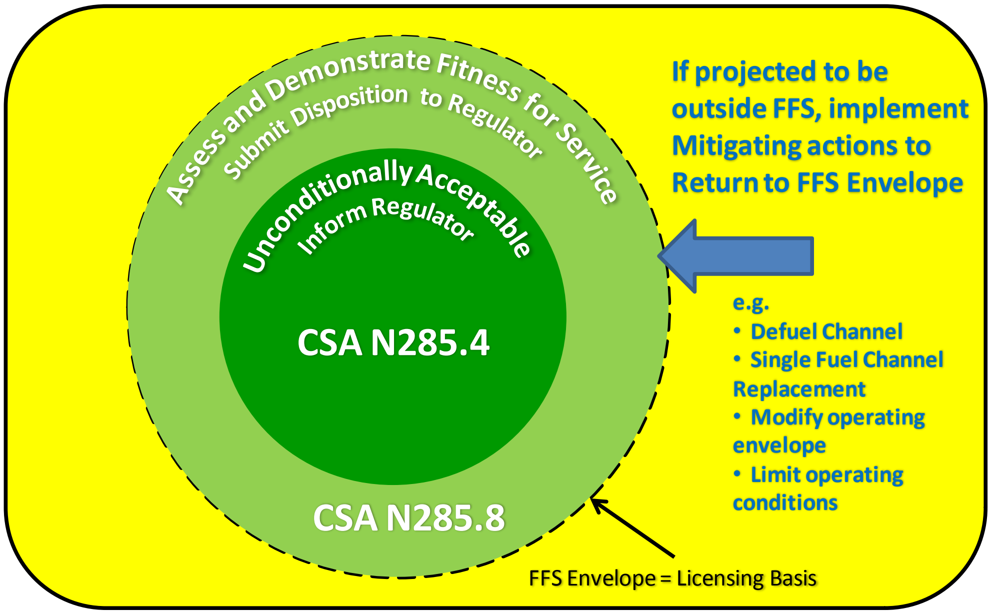

Figure 7 - Fuel Channel Fitness For Service (FFS) Assessment Approach

CSA N285.4 [1] forms the basis for the FFS envelope and in it, 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 satisfy the acceptance criteria of CSA N285.4 [1], OPG must demonstrate compliance with the technical requirements of CSA N285.8 [2].

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 FCLCMP.

The FFS envelope forms the licensing basis without which OPG cannot legally operate its reactors. The FFS framework ensures through periodic inspection, OPG continually understands the condition of the fuel channels, is able to predict fuel channel (FC) condition and ensure future operation remains within the acceptable FFS 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 (FFS) for planned future operation. For fuel channels, the method of condition assessment used is FFS assessments. 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 assessment of 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 unconditional acceptance criteria. In managing PT/CT contact, a key element is to ensure fuel channel annulus spacers maintain structural integrity and remain in location. Inspections have confirmed spacer material conditions are acceptable, and spacer locations are being managed through Spacer Location and Relocation (SLAR) programs, providing assurance of no PT/CT contact.

Scrape sampling and material surveillance examinations provide measurements of hydrogen content in body of tube, 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. Measurements have shown that hydrogen content is projected to remain within acceptance limits.

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 fitness for service assessment, thus satisfying CSA N285.4 [1] acceptance criteria and condition projections support continued operation to target end of life.

The increasing levels of hydrogen isotope concentration in the pressure tube 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 the new fracture toughness model that 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 new 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.

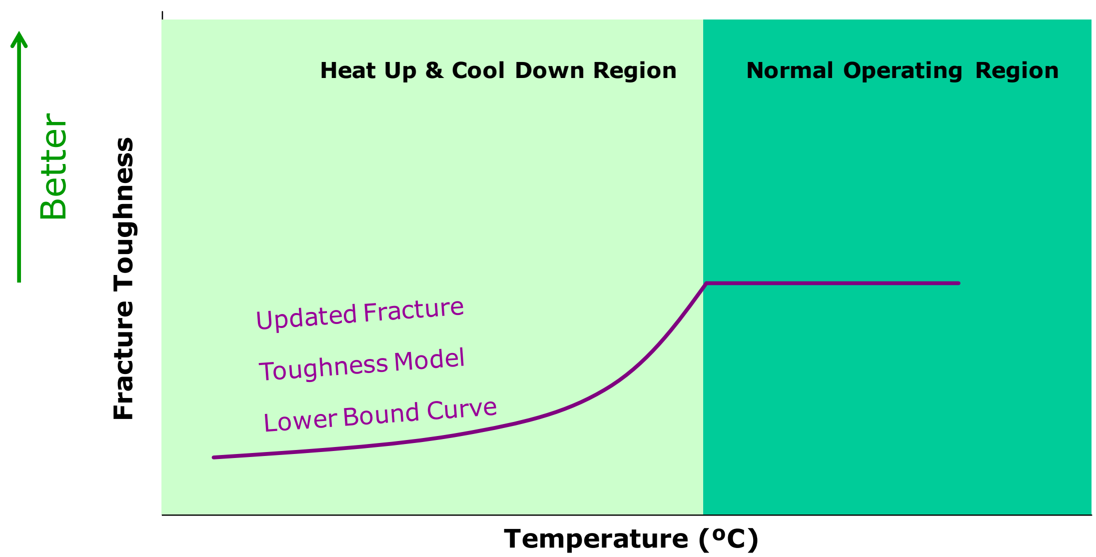

Figure 8 - Updated Lower Bound Fracture Toughness Curve accounting for high Hydrogen Content

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 protection against fracture for the case of a postulated severe flaw, as a defense-in-depth measure. Based on projected hydrogen isotope concentration levels at end of service life and the new fracture toughness model, OPG has assessed the impact and implemented minor modifications to the pressure–temperature operating envelope, and associated operating procedures, for reactor heat up and cool down during start up and shut down. The modified operating procedures have been implemented to manage the very brief time period in transitioning from full power operation to reactor shutdown, and return from shutdown to power operation. It should be noted that in the vast majority of time (more than 99 percent of the time), the reactors are either in full power operation or in safe shutdown state at which time the fracture toughness of the pressure tubes are not of concern.

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 have been assessed and demonstrated to satisfy the acceptance criteria of CSA N285.4 [1] or the fitness for service criteria of CSA N285.8 [2] standard. 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 Pickering NGS

Pressure Tube Axial Elongation

The consequence of pressure tube (PT) axial elongation is the potential for a channel to come off bearing. Axial elongation is currently not a life-limiting aging mechanism, as the time to reach maximum available channel bearing travel is beyond the target service life for operation to December 2020, which is nominally 247k equivalent fuel power hours (EFPH) for Pickering 5-8. Note that selective channel shifting or selected defueling of a few limiting channels may be required. For Pickering 5-8, conservative projections indicate that with planned channel shifting/reconfiguration, the first channel to reach the end of bearing travel is in Unit 7 at approximately 264k EFPH. For Pickering Units 1&4, the bearing travel limits will not be reached within the service life of the plant.

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 (Pickering 5-8 only), and fuel passage issues. This mechanism is monitored by PT/CT gap measurements, PT sag measurements and CT/LISS nozzle gap measurement. Spacer Location and Relocation (SLAR) maintenance and re-visits to previously SLARed channels in Pickering 5-8 units with loose fitting spacers ensure the position of spacers is acceptable for maintaining gap between PT and CT. Inspections and assessments will continue to be performed. CT/LISS nozzle contact and PT sag is not expected to be an issue in Pickering units 5-8 until beyond 247k EFPH. Pickering Units 1&4 do not have LISS nozzles. Based on a conservative assessment performed in 2008, Unit 7 is currently not predicted to experience CT/LISS nozzle contact until 246k EFPH. Unit 7 is scheduled for repeat CT/LISS nozzle gap measurements in 2014. It is expected that operation to end of life will be bridged by repeat inspection to assess gap closure rate and/or mitigation strategies previously employed in the CANDU industry.

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 as life limiting (with minimum design values not reached until well beyond target service life). Periodic inspection will be carried out to validate assumptions and assessments. This mechanism is not considered life limiting; periodic inspection will provide confirmation that limits will not be reached through monitoring. Earliest projected time to reach design minimum wall thickness is beyond 300k EFPH.

Pressure Tube Diametral Expansion

The consequences of PT diametral expansion include reduced design margin, reduction in neutron overpower 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 PT gauging of diameter. The safety analysis of heat transport system (HTS) aging incorporates PT diametral creep and the impact on loss of flow, neutron overpower and small break loss of coolant accident (LOCA). PT diametral expansion will not limit the life of pressure tubes. Assessments show design limits and spacer nip-up will not be reached until beyond 300k EFPH.

Change in Spacer Material Properties

The material properties of Pickering 5-8 spacers (Zr-Nb-Cu material), are not considered a concern based on operating experience and testing of ex-service material. Inconel X-750 material is used for all spacers in Pickering Units 1&4, and a limited number of channels in Pickering Units 6, 7 and 8. The condition of the Pickering Inconel X-750 spacer material is bounded by the continued good performance of Inconel X-750 spacers at Darlington, which are subject to more severe operating conditions of temperature and accumulated neutron fluence.

Spacer Mobility

The consequence of spacer mobility is 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.

All Pickering 5-8 channels with Zr-Nb-Cu spacers have been SLARed (Spacer Location and Repositioning) to achieve a minimum 210k EFPH (with margin) service life, with most channels SLARed to 240k EFPH (with margin). Additional SLAR to 261k EFPH (with margin) is planned to support continued safe operation. Revisiting channels that have been SLARed to target service life is essential to verify the gap between PT and CT will be maintained. Some channels may need to be re-SLARed and this will be determined by ongoing inspections.

Hydrogen Ingress & Fracture Toughness

Fracture toughness changes as a result of deuterium ingress affects the way the unit must be cooled down and warmed up. It also impacts upon the ability to demonstrate pressure tube leak before-break (LBB). PT scrape samples are acquired to monitor deuterium ingress and for development of models to predict ingress rates in the future. Research and development (R&D) has developed improved fracture toughness models that account for hydrogen content. The new models have been developed and are being incorporated in updated fuel channel (FC) assessments. OPG has made analytic and procedural changes to support continued demonstration of fracture protection and LBB for the full service life of the plant.

Flaw Assessments

Flaws are detected and characterized using ultrasonic examination and replication techniques. Flaws must satisfy acceptance criteria or be dispositioned. 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, and re-assessment and disposition will assure fitness for service for flaws.

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 1980's, 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 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 and no PT leaks or ruptures have occurred since 1986. All reactors with over-rolled joints have now had their pressure tubes replaced and improved rolled joint assembly processes installed.

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. This is done through monitoring SLAR programs.

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 the forced outage during the leak search activities. Following this PT rupture, inspections were performed on all channels 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 are compliant with CSA N285.8 [2] Clause 7.2 to define a safe operating envelope for the pressure tubes, assuming the presence of through wall flaw.

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 is about 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; systems are in place to mitigate PT rupture and maintain low likelihood of severe core damage.

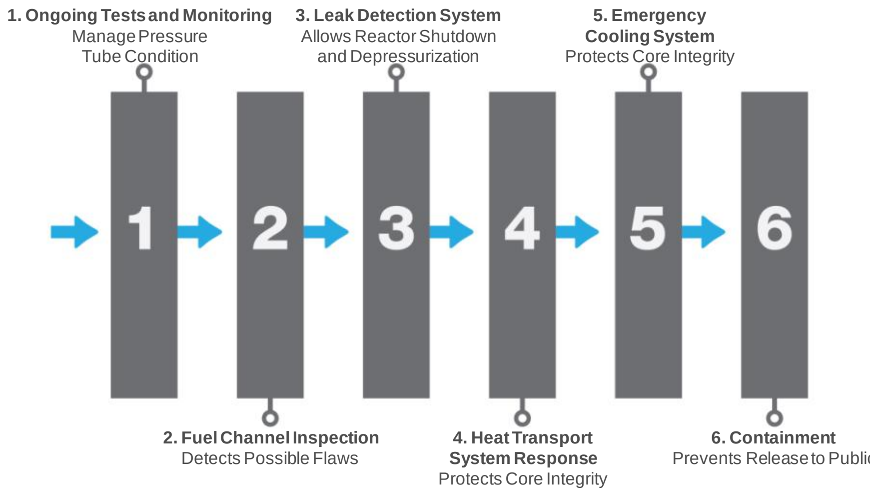

Figure 9 – Defense in Depth Framework

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 operation 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 to the targeted end of life. The Aging Management Program provides the basis to ensure the condition of fuel channels is fully understood and that required activities are in place to ensure their health as the plant ages.

The Fuel Channel Life Cycle Management Plan is developed as part of the Aging Management Program and helps to define which specific aging mechanisms need additional attention and monitoring. Fitness for service (FFS) assessments are carried out to ensure the fuel channels remain within the licensing envelope. 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 satisfy defined acceptance criteria, 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 confirming conservatisms in predictive models used in FFS assessments, is required.

Through extensive studies and research, including involvement of industry and utility experts, OPG has demonstrated the Pickering fuel channels will remain within their design basis and be safe to operate to the end of station operations in 2020. The CNSC staff has concurred with our findings. In fact, the results show pressure tube condition is better than was estimated 30 years ago. We continue to prove this on an ongoing basis through our extensive reactor inspection program.

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
SLAR:	Spacer Location and Relocation