### AMP 139 CANDU/PHWR Fuel Coolant Channels (VERSION 2020)

**Programme Description**

This programme manages ageing degradation of fuel coolant channels (FCs) of CANDU/ PHWR to ensure their integrity and functional capability throughout the plant service life. The AMP for FCs in CANDU/PHWR involves a comprehensive set of activities including in-service or periodic inspections, maintenance, surveillance, post-irradiation examination, engineering assessments for fitness-for-service and residual life estimation, research and development in the fields of design, manufacture, operation, in-service inspection and life extension. These activities are required to ensure that the effects of FC ageing will be managed with adequate margins on fitness for service (FFS) throughout the service life such that:

* Their deformation does not exceed allowable limits (using data primarily obtained by periodic measurements and research testing of pressure tube deformation and predictive models);
* Their characteristics and service induced deterioration does not exceed allowable limits, material properties remain bounded by surveillance and R&D data, particularly with sufficient fracture toughness (using data primarily obtained by periodically removing and testing surveillance pressure tubes);
* Leak Before Break (LBB) is assured; and
* Relevant (known and new) ageing mechanisms are understood, and effective actions and practices are in place for the prediction, timely detection, monitoring and mitigation of ageing effects.

**Evaluation and Technical Basis**

***1. Scope of the ageing management programme based on understanding ageing****:*

For the purposes of this AMP, the FC consists of the pressure tube (PT), calandria tubes, annulus spacers, and end fittings (EF) with associated hardware (including calandria tubes, grayloc connection to feeder, liner tubes, bellows, closure plug, shield plug, and positioning assembly hardware).

There are several hundreds of FCs in a CANDU/PHWR. The PTs support and locate the fuel within the reactor core as well as contain the pressurized heavy water coolant during all normal, transient and accident conditions (excluding single FC breaks) such that adequate fuel cooling can be maintained during operation within the licensing limits. The PTs are manufactured from cold worked zirconium alloy (Zr-2.5Nb, though Zircaloy-2 was used in early designs) which has a low thermal neutron absorption cross section, high strength and corrosion resistance, and are designed to meet the intent of Section III of the ASME code for Class 1 nuclear components [1]. The annulus spacers (4 per FC) are designed to maintain an insulating gap and prevent PT to calandria tube (PT-CT) contact from occurring. Each spacer is a close-coiled helical spring of Zr-Nb-Cu or Inconel X-750 alloy, formed into a torus which fits around the outside of the PT, either as “loose-fit” or as “tight-fit” depending on the design. The EF (2 per FC) provides interfaces between the FC and its inlet/outlet feeders, and between the FC and the fuelling machine.

The PT operates under the environment of high pressure and temperature, and fast neutron flux. Under this operating environment, the PT undergoes dimensional changes, material property changes, as well as other ageing-related degradation over time. The annulus spacers can also undergo a degree of degradation during operation, and spacer movement leading to PT-CT contact is of concern especially for earlier used “loose-fit” type spacers. Service experience indicates the EF and their associated hardware have not shown signs of significant ageing degradation; therefore, these components are not discussed further here.

Ageing effects and degradation mechanisms included in this programme are:

1. Deuterium (D) ingress;
2. Dimensional changes due to neutron irradiation creep and growth (PT diametrical expansion, PT axial elongation, PT sag and PT wall thinning);
3. PT fretting (bearing pad fretting, debris induced fretting);
4. Neutron irradiation, thermal and hydriding induced changes to material properties;
5. Delayed Hydride Cracking (DHC) initiation and propagation;
6. Fatigue crack propagation;
7. PT- CT contact and hydride blister formation;
8. CT contact with the liquid injection nozzle;
9. Other service induced degradation mechanisms:
10. PT wall thinning by corrosion;
11. Scratches in PT during bundle refuelling;
12. Crevice corrosion;
13. Commissioning damage;
14. Erosion;
15. Inlet roughness.
16. Spacer degradation:
17. Exposure to irradiation, rolling wear, D-ingress (zirconium-based spacers only);
18. Spacer movement due to pressure tube elongation, vibration (loose fitting spacers);
19. Loss of ductility (due to He void formation), and de-tensioning in Inconel X-750 spacers only [2].

For further information on these ageing effects and degradation mechanisms, see references [3-4].

***2. Preventive actions to minimize and control ageing degradation:***

This programme attribute includes preventative actions that can be taken in the design, material selection and manufacturing practices, commissioning, and operation and maintenance practices aimed at slowing down potential degradation mechanisms.

Actions that can be taken in the design, material selection and manufacturing practices to minimize or control some of the ageing degradation mechanisms include:

* Quadruple melting of ingots to reduce volatile impurities like hydrogen, chlorine and phosphorus etc. (H, Cl and P) concentration, thereby improving fracture toughness;
* Relocating PT burnish mark further inboard to increase time for hydrogen equivalent (Heq) exceeding the terminal solid solubility of deuterium (TSSD) limit (Heq > TSSD);
* Increasing bearing travel available for FC elongation;
* Optimizing PT carbon and iron (C and Fe) concentrations to limit deuterium uptake [5];
* Reduction of initial PT hydrogen concentration;
* Using tight fitting spacers and improved spacer installation procedures;
* Lowering of the liquid injection nozzle (by de-tensioning) to gain more tolerance for the CT contact due to sagging of fuel channel caused by axial creep.

Actions taken in operation and maintenance practices to minimize or control some of the ageing degradation mechanisms include:

* Chemistry control of pH, D and dissolved oxygen (DO) content in primary coolant to minimize PT corrosion and D pickup;
* Chemistry control of annulus gas – O2 addition to dry CO2 gas to maintain a protective oxide on PT external surface as a barrier to H/D ingress into PT;
* Parameters monitored: coolant flow-rates; crud levels; coolant chemistry parameters: pH, Li, conductivity, dissolved D2, dissolved O2, Cl, F, carbonate;
* Maintain safe pressure and temperature (time-dependant) envelope during operation as well as during start-up and cool-down.

Primary coolant chemistry can affect corrosion and hydrogen uptake in zirconium alloys. Hydrogen is added to the coolant to suppress the production of radiolytic oxygen. High dissolved oxygen levels have been shown to increase the corrosion rates of zirconium alloys. Dissolved hydrogen concentrations are maintained in the 3-10 mg/kg D2O range. There is some evidence that higher dissolved hydrogen levels may be associated with higher D uptake rates, although corrosion rates may be reduced.

Lithium hydroxide (LiOH) is added to the PHT coolant to maintain room temperature pH in the 10.0 - 10.3 range. LiOH is added primarily to minimize the corrosion of carbon steel components in the PHT circuit and to minimize activity transport around the core. Typical Li concentrations are maintained around 1 mg/kg D2O.

Controls for keeping debris out of the primary coolant circuit are maintained in order to prevent this contributing to PT fretting degradation.

***3. Detection of ageing effects:***

This programme attribute includes detection of any ageing effects of concern for the components within its scope. The total amount of inspection required is a key element of the strategy to provide timely detection and information on degradation. The scope and schedule for mandatory inspection and material surveillance of FCs for CANDU reactors are specified in CSA N285.4 [6]. Additional inspections are needed to manage detected degradation effectively [6-7]. While the susceptibility of modern (Zr-2.5Nb) PTs to DHC cracking is much lower than earlier (Zircaloy-2) tubes, the limited fraction of PTs subject to in-service inspection means that cracking cannot be ruled out. As a result, a well-designed, operated and maintained leak detection system (i.e. annulus gas system, AGS) is key to ensuring that the risk of break-before-leak remains acceptably low [[1]](#footnote-1).

In the pressure tube inspection and surveillance program, the following parameters are monitored:

* Irradiation induced dimensional changes, which include axial elongation and diametrical expansion;
* PT wall thinning and PT sag/ PT-CT gap and the presence of PT-CT contact if any;
* Location of annulus spacers [8];
* Service induced flaws;
* Deuterium / Hydrogen equivalent (Heq) concentration profile from PT scrape samples;
* Neutron irradiation and hydride induced embrittlement;
* Threshold stress intensity factor for DHC cracking;
* DHC velocity;
* Magnetite fouling on the inlet end fittings, liner tubes, and PTs; and
* Available gap between the CT and calandria vessel internals (i.e. Liquid Injection Safety System nozzles, and Horizontal Flux Detector tubes);
* Gap between the CT and the liquid injection nozzle.

Additional features in the Periodic Inspection Programme (PIP) [6] or In-Service Inspection (ISI) programme [7] for the pressure tubes include:

* Inspection of the full volume of the tube (by UT, ET or other qualified techniques) including the rolled joint region for the presence of flaws;
* Inside diameter measurements to ensure appropriate margins to fuel dry-out under (postulated) reactor upset conditions;
* Direct measurement of PT-CT annular gap to minimize the risk of PT-CT contact (in channels equipped with Inconel X-750 spacers);
* Characterization and sizing of the detected flaw by either taking replica or visual inspection, or by volumetric inspection (e.g. Channel Inspection and Gauging Apparatus for Reactor (CIGAR) or Advanced Non-Destructive Examination (ANDE) tool);
* Deuterium measurement in rolled joint (RJ) region and/or body of PT by removing scrapes samples. Removal of surveillance tubes to measure D and Heq concentration, hydride orientation, material tensile properties, micro-structure, texture, fracture toughness, and axial and radial DHC velocity.
* The Annulus Gas Leak Detection System is used for detection of PT or rolled joint leaks. It can also detect if there is any leak from CT or of end shield cooling water inside coolant channel assembly.

***4. Monitoring and trending of ageing effects:***

The ageing of the FCs is periodically assessed and monitored through a combination of periodic inspection, gauging / measurements, material sampling and surveillance testing. Continuous monitoring for (possible) FC leakage is carried out while reactors are on-power using the AGS. The parameters measured in PIP or ISI programme are evaluated to identify changes in PT behaviour or new indications of degradation and monitored or trended with respect to time of operation (equivalent full power hours) to ensure rates of degradation do not exceed the applicable acceptance criteria, and to validate or improve the predictive models. The results of the monitoring and trending activities are used as input for operational assessments and updates to the FC AMP.

FC elongation can be monitored either on an ongoing basis during on-power re-fuelling of each FC (CANDU 6 design reactors) or periodically, during inspection outages. Using elongation measurements as an input, operators can determine the remaining bearing travel for each FC.

D uptake can be measured in two ways: by scrape sampling or other methods in-service PTs, or during surveillance examinations of removed PTs. Data collected by either means can be trended and compared. Based on the trend from the measured data along with prediction for D uptake, operators can decide on the appropriate inspection programme for D measurements. Similarly, PT diametral expansion and sag (PT-CT gap) can be measured and compared with predictions. If the prediction and the measured data for creep deformation compares well, planned inspection programme can be followed else inspection interval can be modified depending upon the measured value and the margin available. Finally, these measured values for D uptake and PT creep are compared with the limiting value as mentioned in the design report or fitness for service standards, or per regulatory requirements of member states.

***5. Mitigating ageing effects:***

Techniques for mitigating pressure tube ageing effects have been developed and implemented, including:

* Perform fuel channel re-configuration to limit impact of axial channel elongation;
* Modify operating procedures (pressure and temperature limits) during start-up/shutdown to avoid DHC initiation and / or to remain below the flaw stability line ;
* Operate selected channels in a de-fuelled condition to minimize channel axial growth (avoid FC from going off its support bearings);
* Restricting the operating interval to the next inspection to reduce the risk of cracking due to DHC initiation from flaws and/ or hydride blisters if pressure tube is in contact with CT and the equivalent hydrogen concentration reaches the threshold for blister formation;
* Single/multiple fuel channel removal or replacement is also done, if necessary.

***6. Acceptance criteria:***

Acceptance criteria adopted to address different safety concerns are reviewed in the document IAEA TECDOC 1037 [8] and an overview of life management of coolant channels can be found in [9-12]. Clause 12 of CSA N285.4 [6] standard sets up the requirements for fuel channel periodic inspections also acceptance criteria for the results of inspections. When inspection indications do not meet the acceptance criteria, dispositions for those indications are required to demonstrate the affected channels are still fit for service for a period before the next planned outage. CSA N285.8 [13] establishes the procedures for conducting pressure tube fitness for service assessments, and provides the relevant acceptance criteria.

***7. Corrective actions:***

Tools have been developed to locate and (if necessary) reposition spacers whose movement could lead to potential early PT-CT contact. Pressure tubes that do not meet fitness for service or acceptance criteria in conformance with the applicable guidelines listed above, require replacement or reassessment subject to approval by the regulatory authority. Where unexpected degradation is observed, sample size and inspection frequencies may be increased. If required, a corrective action plan, which might include repair, replacement, operation with restrictions, or other mitigating actions per section 5, is developed and implemented.

***8. Operating experience feedback and feedback of research and development results:***

This AMP addresses the industry-wide generic experience. Relevant plant-specific operating experience is considered in the development of the plant AMP to ensure the AMP is adequate for the plant. The plant implements a feedback process to periodically evaluate plant and industry-wide operating experience and research and development (R&D) results, and, as necessary, either modifies the plant AMP or takes additional actions (e.g. develop a new plant-specific AMP) to ensure the continued effectiveness of the ageing management.

The overview of significant operating experience coming from the industry have been shown to be effective over time with their widespread use are described in References [2-4, 8-10, 12, 14-17].

Structural failures of coolant channels have occurred in a few instances due to failure of pressure tubes. Many of these failures came as a surprise, highlighting limitations in knowledge of the in-reactor performance of the materials used. Each of these failures were analysed in depth in various research labs to understand the associated degradation mechanisms. The programmes initiated for addressing these degradation issues have gradually grown mature with the feedback from the understanding of degradation mechanisms. Several hardware and software tools and technologies developed during these periods have contributed to the development of robust life management programmes for coolant channel components. They together help in modelling, monitoring, measuring and estimating the incidence and severity of various degradation mechanisms and in facilitating life extension programmes to maximise the safe operating life of these components. The details of some of the reported structural failures of the coolant channel components in the history of PHWRs along with the remedies suggested/implemented are provided in [12]. Further information on CANDU fuel channel components ageing degradation is provided in [3-4].

Two events involving leaks due to cracking in fuel coolant channels at NPP Kakrapar-1&2 were reported [18]. Following these events, some coolant channels were removed from KAPS-1&2 units and experimental and analytical studies were undertaken for the purpose of investigations. Based on all the investigations, it has been concluded that unlisted impurity (hydrocarbons) in the carbon dioxide gas used in the annulus gas system of these reactors, resulted in shallow localised corrosion spots on the outer surface of coolant channels and corresponding generation of hydrogen. Shallow localised corrosion spots led to gradual absorption of the hydrogen by the coolant channels, which affected the material properties. The deteriorated material properties caused the events of leak from the coolant channels.

In some early CANDU reactors, a few pressure tubes leaked through delayed hydride cracks. High residual stresses were produced when tubes were incorrectly rolled into end fittings, contributed to the cracking. The cracks were easily detected by their leakage into the gas annulus, the reactor was safely shut down and the leaking tubes were identified and replaced, thus providing a clear demonstration of LBB [19].

Research and Development programmes are required to develop a better understanding of the degradation mechanisms and consequently to develop models for materials degradation. With many CANDU/PHWRs approaching the original intended (nominal) design life for FCs, there is a particular need for research and development programmes to address safe operation of fuel channels for extended service life. This includes extending the knowledge base of ageing degradation mechanisms for longer FC life and their impact, as well as developing improved methodologies and analytical tools predicting-end-of-life degradation levels and fitness for service evaluation. Robust feedback mechanism from post-irradiated material testing results of surveillance fuel channels, rolled joints and spaces etc. taken at regular intervals also provides important irradiated material database for further material improvements and helps in optimizing overall ageing management, inspection and maintenance practices.

Sources of research and development activities relevant to this AMP include the CANDU Owners Group (COG), Canadian Nuclear Laboratories and CANDU Energy Inc. in Canada, as well as Bhabha Atomic Research Centre (BARC), India and CNEA, Argentina.

***9. Quality management:***

Site quality assurance procedures, review and approval processes, and administrative controls are implemented in accordance with the different national regulatory requirements (e.g., CSA N286 [20]).   
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1. Ageing management of the Annulus Gas System is covered in AMP150 CANDU/PHWR ANNULUS GAS SYSTEM. [↑](#footnote-ref-1)