**AMP 140 CANDU/PHWR FEEDER PIPING (VERSION 2020)**

**Programme Description**

The main objective of this programme is to manage the effects of ageing related degradation of the feeder piping in the primary heat transport system (PHTS) of CANDU and PHWR in conformance with the guidelines, codes and standards applicable by the Member States, to ensure their integrity and functional capability through plant service life. Ageing management guidelines for nuclear power plants are also given in the IAEA safety guide [1].

An essential function of the feeder pipe is to transport heavy water (D2O) coolant to and from the Fuel Channels (FCs) to cool the fuel bundles in the pressure tubes. Each FC is connected at its inlet and outlet ends to feeder piping which join to the main headers of the PHTS circuit. Inlet feeder pipes deliver the coolant from the inlet headers to the fuel channels, and outlet feeder pipes take the coolant from the fuel channels to the outlet headers of the PHTS. Thus, there are twice as many feeder pipes as FCs; the total number of feeders can range from several hundred to nearly 1000 depending on the design and power rating of the reactor.

The feeders are small diameter carbon steel piping typically ranging from 4 to 10 cm (1.5 to 3.5 inches) nominal pipe size (NPS). Each feeder pipe is configured with a combination of bends (external angles from 21° to 90°) and straight pipe. Flow measuring elements made of Alloy 600 are installed on certain outlet and inlet feeders by dissimilar metal welds (DMWs) [2-3].

The feeder pipes operate in an environment of high primary coolant pressure, temperature and flow velocity. There are several ageing mechanisms affecting the feeder pipe, such as flow accelerated corrosion (FAC), and low temperature creep cracking and/or stress corrosion cracking, thermal cycling. This requires a comprehensive programme for inspection, monitoring, assessment, and maintenance to ensure fitness for service of the feeder pipes.

**Evaluation and Technical Basis**

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

The programme includes monitoring, inspection and assessments to ensure the fitness for service and reliable operation of CANDU/PHWR feeder piping, including supports, pipe bends, elbows and welds, and DMWs to ensure that:

* Wall thinning due to FAC does not reduce the feeder wall thickness below allowable limits (using data primarily obtained by periodic measurements and models developed for predicting this flow assisted corrosion);
* No failures caused by cracking occur at locations of high residual tensile stresses (i.e. at tight radius outlet pipe bends and field repair welds);
* No failures caused by outer surface contact and fretting / wear damage occur;
* Coolant chemistry is controlled to reduce the FAC rates and impingement of oxide particles; and
* Timely detection of SCC and leak before break (LBB) analysis to demonstrate a low likelihood of failure of DMWs at flow measuring elements installed in some inlet and outlet feeders.

Ageing degradation mechanisms included in this programme are [4-6]:

* Flow assisted corrosion (FAC);
* Low temperature creep cracking and / or stress corrosion cracking;
* Primary Water Stress Corrosion Cracking (PWSCC) on DMWs connecting flow elements installed at some inlet and outlet feeders; and
* Outer surface contact and fretting between adjacent feeders.

The objective of formulating the life management programme for the feeder piping is to address the various degradation mechanisms and their mitigation through research and development in the fields of design, manufacture, operation, in-service inspection and life extension. The programme also includes procedures or administrative controls to assure that the structural integrity of all feeder pipes containing high-energy fluids (two-phase as well as single-phase) is maintained.

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

The programme includes water chemistry (AMP 103) to monitor and control the primary coolant pH and O2 values in an optimal range to reduce the wall thinning rate and susceptibility to SCC. Cleaning of the internal surfaces of the steam generators tubes improves the steam quality leading to a decrease in temperature of the primary coolant at the inlet feeders which helps in reducing the wall thinning rate and SCC. The selection of appropriate feeder pipe material with higher chromium content and tensile strength, and in some cases the use of increased nominal wall thickness is applied for replacement feeders or new builds. Stricter controls and improvements in feeder fabrication methods, such as heat treatment of welds and the use of updated bend fabrication methods reduce the levels of residual stresses and improve the hydrodynamic conditions, is also be effective in reducing aging degradation in feeder pipes.

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

This programme includes identification of susceptible locations, as indicated by operating conditions or special considerations. The following types of inspections are used to detect degradation mechanisms in feeders:

* Ultrasonic test (UT) to measure remaining wall thickness and detect cracking of feeder pipe;
* Visual inspection (VT) to monitor changes in support condition and outer surface of feeder pipe;
* Liquid penetrant test (PT) and magnetic particle test (MT) to capture outer surface cracking of feeder pipe.

A representative sample of components is determined based on operating experiences (OPEX) and inspection results to ensure the structural integrity of feeders up to a next planned outage.

The selection of outlet/inlet feeder pipes including pipe bends for carrying out monitoring for wall thinning can be based on:

* High flow velocity and mass flow rates criteria;
* High stress intensity criteria;
* High survey factor criteria (product of maximum flow velocity and stress intensity in feeder);
* Thinning experience based on review of inspection data and / or OPEX of other plants (locations of greatly reduced wall thickness, greatest rate of change of wall thickness); and
* High seismic load contribution.

The selection of feeders for volumetric inspections for other degradation mechanisms is based on:

* The component design (i.e., material, configuration, applied loads, and stresses);
* The component manufacturing/fabrication processes affecting residual stress level (i.e., bend manufacturing process, weld repair, post weld heat treatment);
* Environmental conditions (i.e., coolant chemistry and flow condition); and
* Industry operating experience.

The guidelines [7-8] specify the inspection scope and intervals for feeder piping, if localized wall thinning or cracks are detected, the inspection scope and interval is adjusted to ensure timely detection of wall thinning or cracking before the loss of intended function.

The location and high radiation levels at the DMWs make it very difficult to perform inspections, and the qualified inspection tool/technology is still under development. Leak before break (LBB) of the DMWs is demonstrated to exempt them from periodic inspection. Both deterministic and probabilistic LBB approaches are conducted to ensure sufficient time from detecting leakage to a safe shutdown of the plant. This hybrid-type of analysis process is similar to LBB approaches used in the DMWs in the USA [12].

Inconel 690 flow elements have been used in recently replaced feeders under refurbishment projects in Canada for the purpose of enhancing the resistance to initiation and growth of Primary Water Stress Corrosion Cracking (PWSCC) on DMWs between the Inconel 690 and the carbon steel feeder.

According to OPEX, localized wall thinning rates can be high at the tight radius bends and the Grayloc weld locations, and the inspection plan includes inspections for wall thinning at these locations.

Visual examination is performed of external surfaces of readily accessible feeders and their supports. Inspection results are evaluated to determine if additional inspections are needed to ensure timely detection of wall thinning, fretting and support integrity.

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

Inspections [8-9] are carried out as consistent with attribute 3. The wall thicknesses are trended, against equivalent full power operating hours or flow velocity, to predict wall thinning rates and time before minimum wall thickness is reached.

When susceptible components are replaced with resistant materials, such as high Cr content material, the downstream components should be inspected timely to monitor for wall thinning.

Primary heat transport leak rate is monitored, which ensure the timely detection of feeder pipe..

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

The mitigation methods include chemistry control, support adjustment, material and design modification, etc.

Chemistry control is the main method to mitigate the ageing effects of the feeder piping. Strict coolant chemistry control [10-11] is required to reduce the effects of flow assisted corrosion.

Replacement of smaller pipe size elbow by larger size (e.g. 32 mm NPS to 50 mm NPS) can help to reduce local flow velocity which will in turn reduce FAC rates in that section. Use of carbon steel material for replacement feeder piping with larger wall thickness, higher allowable stresses (e.g. Grade C) and 0.2-0.3 % minimum Chromium have also been used to mitigate FAC.

Fretting can be mitigated by adjusting the feeder support to avoid the feeder to feeder contact and feeder to support contact. Stainless steel sleeves can be installed at the area that fretting occurred.

***6. Acceptance criteria:***

Acceptance criteria, subjected to acceptance by regulatory authority, adopted to address different safety concern are available in the appropriate Code case [7], periodic inspection standards [8] or fitness for service guidelines [12] for feeder pipes in member states. For example:

The minimum allowable wall thickness is 75% of tmin\_ASME (e.g., the minimum wall thickness permitted by the ASME Code) [2, 12]. Canadian utilities have performed several feeder tests in order to demonstrate the structural integrity of the feeder under various feeder operating conditions. Test results indicate that 75% of tmin\_ASME still retains margin against burst under internal pressure loading.

A wall thinning assessment predicts that the wall thickness of a certain number of bounding feeders in some Canadian plants would reach to 75% of tmin\_ASME prior to large scale feeder replacements during a plant refurbishment to extend the operating life of feeders. The regulatory authority in Canada, CNSC, accepted a lower wall thickness than 75% of tmin\_ASME on a case-by-case basis based; the calculated safety margins from analytical assessment were confirmed by burst/cyclic tests of prototypical samples within bounding thickness profile.

***7. Corrective actions:***

Prior to return to service, components for which the acceptance criteria are not satisfied are reevaluated, repaired, or replaced. Long-term corrective actions could include adjusting operating parameters. If the wall thickness, or wall thinning rate, or crack dimension exceed the acceptance criteria, corrective action are taken, which can include:

* Local weld build-up of the wall thinning or fretting area, when accepted by the regulatory authority;
* Replace the degraded section of feeder pipe with high Cr content material and using improved fabrication technology;
* Replace or adjust the feeder pipe support, chafing shield or sleeve of the fretted feeder pipe.

***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 guideline documents such as “Feeder fitness for service guidelines” [12-14] have been developed based on operating experience and results of research which have been shown to be effective over time with their widespread use.

In Indian PHWR [15], reduction in wall thickness of the feeder elbows was observed in 1998 after 15 full power years of reactor operation. This was attributed to FAC. Out of 612 feeders which were inspected for wall thinning, the wall thickness of 70 elbows are less than the acceptable limit (0.875 times nominal thickness). These were mostly outlet feeders. The average corrosion rate was 100μm/year for outlet feeders and 50μm/year for inlet feeders [16].

The CANDU Owners’ Group (COG) [18] has observed that thinning occurs at outlet feeder elbows/bends and Grayloc weld region in all CANDU reactors. The thinning of the pipe is attributed to FAC. In 1996-97, Darlington plant reported the corrosion rate of 160μm/year CANDU industry has implemented rigorous inspection to control the thinning rate.

According to the COG OPEX, some of feeders are experiencing fretting damage due to contact between pipe and sling that is supporting the feeders. The extent of wall loss exceeds 12.5 % of the nominal wall thickness. In addition, contact has also been found between feeder pipes and support rods causing wear to the rods.

Due to different ingots used in manufacturing of coolant channels, neighboring channels were observed to have differential creep which had resulted in closing the design gap and in many cases contacts were noticed. Contacting caused fret due to constant vibration cause by the flow of coolant. Fretting wear, if significant, can bring down the operation life of feeders [17].

There have been three incidents of feeder piping leaks at Canadian CANDU stations: two from cracking at feeder bends, and one from a crack in a feeder field repair weld. After the identification of feeder bend cracking by leak detection system at one of stations in Canada, several part-through-wall cracks were detected during the expanded cracking inspection campaigns until refurbishment of this station at 2008. No bend cracking has been detected in the other Canadian stations since 2008.

In addition, leak at a field repair weld in another station in Canada was detected by the bulk leak detection system, and this leak initiated a comprehensive scope of inspection for the repair welds over all CANDU stations. However, no notable crack indications on repair welds have been reported after the first finding of the weld cracking [18].

When feeder pipe material was replaced with 0.2 % Cr content in the carbon steel pipes, wall thinning rates has been reduced significantly. For example, in a CANDU6 unit in China, the Cr content of feeder pipe is up to 0.33%, they screened the most susceptible feeder pipe by “high velocity criteria” [12]. The wall thickness of the extrados and intrados of the first and second elbow were monitored repeatedly. By now the maximum thinning rate is about 25μm/year, far below the acceptance criteria. Alternatively, in some plants higher schedule pipe elbow (with increased wall thickness) was used.

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) in India.

***9. Quality management:***

Administrative controls, quality assurance procedures, review and approval processes, are implemented in accordance with the different national regulatory requirements (e.g., CSA N286 [19]).

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