20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 8, Paper 1663

Considerations Related to Long-Term Operation for CANDU 6 NPP

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Keywords: LTO, PLiM Program, CANDU 6, Cernavoda NPP, INR Pitesti, R&D Support.

1 ABSTRACT

The safe and reliable long term operation (LTO) of a Nuclear Power Plant requires the systematic and proactive identification of degradation and aging mechanisms of critical SSC that are not addressed by the normal plant Preventive Maintenance strategies, and mitigation of these inherent major problems which will otherwise impact on the Plant assets. The LTO program, proposed to be applied at Cernavoda NPP, was developed based on WANO recommended best practices detailed in INPO-AP-913 and it is supported both by the experience of CANDU 6 owners and by the results of research conducted within INR Pitesti. Over the past 7 years, INR Pitesti has been working on R&D Programs to support a comprehensive and integrated Cernavoda NPP LTO Program.

2 INTRODUCTION

Long term operation (LTO) of a nuclear power plant may be defined as operation beyond an established timeframe set forth by, for example, licence term, design, standards, licence, and/or regulations, which has been justified by safety assessment, with consideration given to life limiting processes and features of SSCs. Managing physical or material ageing of SSCs important to safety aims to maintain their design safety margins above SSC specific requirements (see Figure 1.) and thus to minimize risk to public health, environment and safety, Kearney(2008).

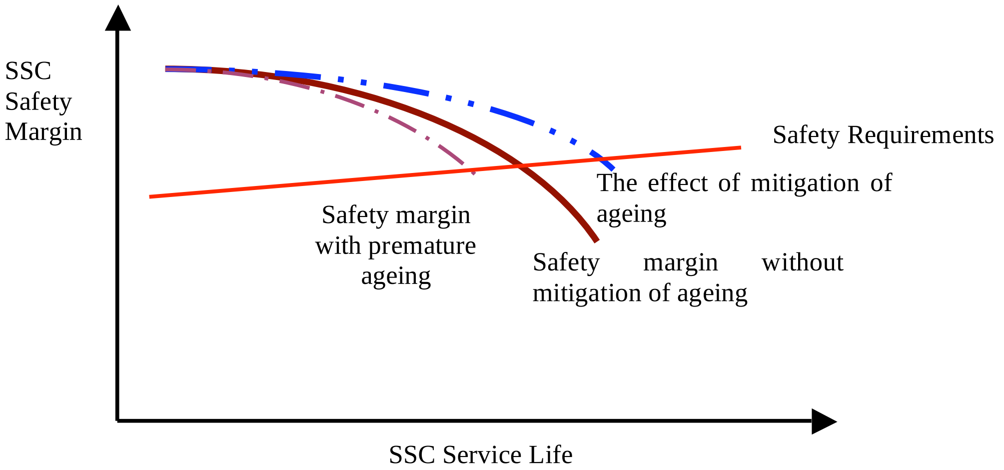

Figure 1. Relation between SSC safety margin and service life

Approximately 25% of the NPPs in the world have been operated for more than 30 years, and about 70% for more than 20 years. The first commercial CANDU® unit Douglas Point was put into commercial operation in 1968 (40 years ago) and the first CANDU 6 units operate for 25 years. Today, there are 11 CANDU 6 units in operation. The purpose of this paper is to present the LTO for PLiM Program which is now to be implemented at Cernavoda NPP, a CANDU 6 NPP, in order to develop and revise the approaches required for anticipating, identifying, preventing and resolving performance problems with Structures, Systems and Components (SSC) and to support safe and reliable plant operation at optimum costs.

3 CERNAVODA NPP - TWO CANDU 6 UNITS

The CANDU 6 power reactor is visionary in its approach, remarkable for its on-power refuelling capability and proven over years of safe, economical and reliable power production.

The first CANDU 6 plants- Gentilly 2 and Point Lepreau in Canada, Embalse in Argentina and Wolsong-Unit 1 in Korea have been in service for more than 25 years and are still producing electricity at peak performance and to the end of 2006, their average lifetime Capacity Factor was 83.25% (see Table 1). The newer CANDU 6 units in Romania (Crnavoda- Units 1 and 2), Korea (Wolsong- Units 2, 3 and 4) and Qinshan (Phase III- Units 1 and 2) have also been performing at outstanding levels. The average lifetime Capacity Factor of the 10 CANDU 6 operating units was 88.06 % to the end of 2006.

Table 1. Evolution of CANDU 6 Reactors.

CANDU 6 Units	Location	Gross Output	Project Cod	In-Service Date	Lifetime Capacity Factor (%)	Age*** (Years)
Point Lepreau	Canada	680 MWe	87	Feb.01, 1983	82.4*	26
Wolsong-1	Korea	679 MWe	59	Apr.22, 1983	85.8*	26
Gentilly 2	Canada	675 MWe		Oct.01, 1983	79.5*	26
Embalse	Argentina	648 MWe	18	Jan. 20, 1984	85.3*	25
Cernavoda-1	*Romania*	*706 MWe*	*79*	*Dec.02, 1996*	*101.72***	*13*
Cernavoda-2	*Romania*	*706 MWe*	*82*	*Oct. 05, 2007*	*99.96***	*2*
Wolsong-2	Korea	715 MWe	86	July 01, 1997	94*	12
Wolsong-3	Korea	715 MWe	86	July 01, 1998	95.1*	11
Wolsong-4	Korea	715 MWe	86	Oct. 01, 1999	97.2*	10
Qinshan-1	China	728 MWe	98	Dec. 31, 2002	87.7*	7
Qinshan-2	China	728 MWe	98	July 24, 2003	86.1*	6

Note: *To the end of December 2006 ** In January 2009 ***To the end of December 2009

Cernavoda NPP was originally conceived as a 5 units Power Generating Station, out of which only 2 units are now operational, for another two (U3 and U4) a turn-key contract for construction and commissioning has been recently signed (in Nov. 2008). The electricity annually generated by the Cernavoda NPP Units 1 and 2 represents approximately 18% of the overall electricity production of Romania.

In January 2009, Cernavoda NPP Units 1 and 2 have produced 1,053.311 MWh out of which it delivered 972.037 MWh in the National Power Grid, at a capacity factor of 100%. In 2008, Cernavoda NPP, with both units in operation, produced a total quantity of 11.225.808 MWh, out of which it delivered 10.333.584 to the National Power Grid, at an average capacity factor of 84,83% for Unit 1 and 96,92% for Unit 2. The lower capacity factor of Unit 1 is due to the fact that during June 2008, Unit 1 was in planned shutdown.

As in Canada, China and Korea the LTO Program is already implemented in Romania where Cernavoda NPP Unit 1 was put into commercial operation on the 2nd of December 1996 and the Cernavoda NPP Unit 2 was put into commercial operation on the 5th of October 2007. The following actions have been performed, Delcea (2008):

- Fuel channel inspections using Ultrasound (US) & Eddy Current (EC) detectors were performed for Unit 1 into 1999, 2003 and 2008.
- For Steam Generators the periodic inspection program was started in 1998. The tubes (EC), the nozzles (US), internal supports and the walls (US) were inspected periodically.
- Feeder inspection program was started in 2003 for wall thinning measurement; elbows extrados cracks identification and welds monitoring.

4 PLiM PROGRAM SPECIFIC APPROACH AT CERNAVODA NPP

Shortly after Cernavoda NPP Unit 1 was put into commercial operation, on December 1996, the management became well aware of the advantages of implementing a strong Plant Life Management Program (PLiM is the name adopted for this Program) in the early stages of the plants life, Mocanu (2009), such as:

- Understanding aging mechanisms and contributors will help avoid accelerated degradation;
- Adequate countermeasures against degradation can be taken in a timely manner avoiding economic penalties;
- A systematic approach of ageing can sustain plant long term operation, as international experience demonstrates that the plant life extension beyond the design limit is feasible.

As Cernavoda NPP started the PLiM program before reaching a third of its design life, it was possible to prepare a strategy for “step by step” implementation. The step by step implementation strategy referred to:

- A number of programs were selected and developed as *pilot projects*;
- Methodologies and procedures for the PLiM program were developed as part of the pilot project. Also, the participating personnel received specific training for the PLiM program;
- Based on the experience gained from the pilot programs, a strong baseline for the mature PLiM program development was created;
- New programs will be added as necessary, with minimum impact on station resources.

The main phases of Cernavoda NPP Unit 1 PLiM Program are presented in the following time-table, Mocanu (2009):

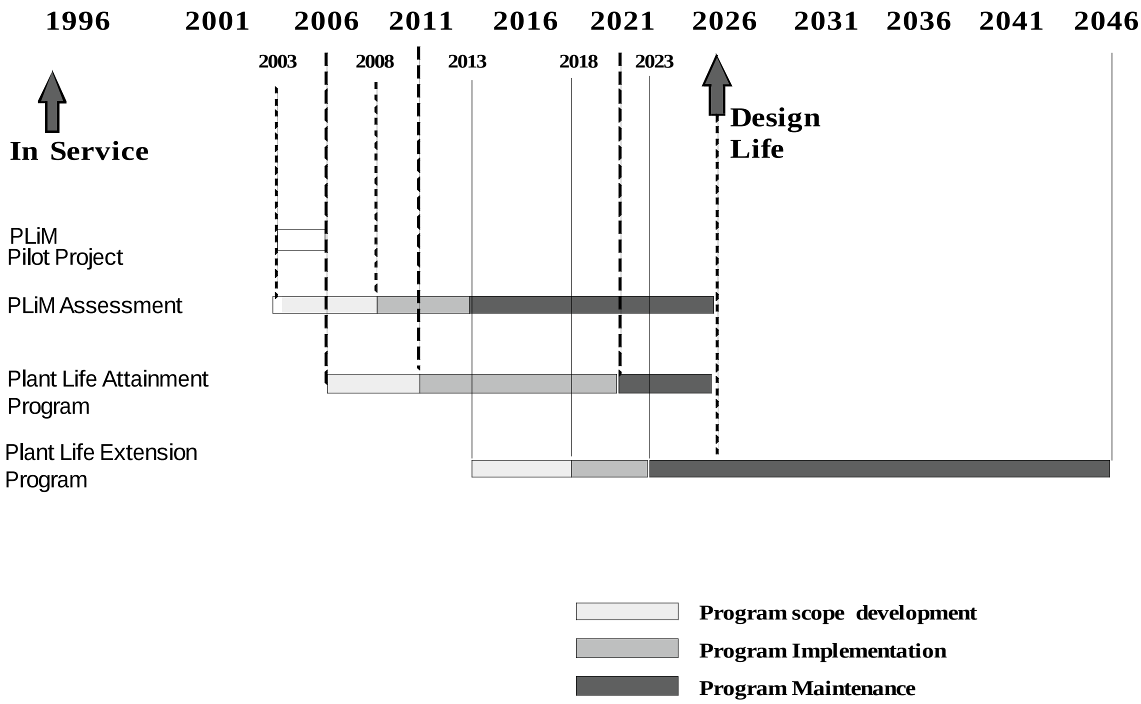

Figure 2. Time scheduling of the CANDU 6 PLiM Program applicable to Cernavoda NPP Unit 1.

Between 2001÷2005, Cernavoda NPP Unit 1 developed with the support of IAEA a technical cooperation project (ROM/04/026), based on which several PLiM programs have been initiated, in the form of a *“Pilot-Program”*. Upon placing into commercial operation of Cernavoda Unit 2 on October 2007 and based on the results and the experience achieved during the PLiM “pilot-programs”, the program entered the second phase: “*PLiM strategy Assessment*”.

It was the proper moment to assess and define the mature PLiM Program requirements in terms of procedural envelope and to reshape Technical Unit organizational chart, based on the human experience available and the future needs of PLiM Program development for 2 units in operation. So, beginning with

2008, Cernavoda NPP adopted the concept of *"Continuous Equipment Reliability"* (described in INPO-AP913) as strategic maintenance politics, which resulted in a dramatic change of duties inside the Technical Unit, as the Responsible System Engineers (RSE) retained the responsibility for maintaining the process systems within the design limits, but the expertise in maintaining the proper operation of generic components was transferred to Component Engineers (RCE).

The modification of the technical personnel organizational chart, as well as the new set of procedures related to the concept of "Equipment reliability" have been issued with the purpose of creating the conditions for the implementation of PLiM Program third phase: *"Plant Life Attainment"* (as presented in the previous flow-chart).

The main objectives of the PLiM Program at Cernavoda NPP are:

- Provide a clear image of the potential threats to plant safe and reliable long term operation to the Station Management, and the required Life Cycle Plan necessary to address them.
- Provide the necessary input for Plant Business Plan.

This means that after having identified all the ageing issues that might challenge plant operation and all the required measures to address and mitigate them, all the necessary PLiM activities identified shall be projected as time and expenditures into the Long Range Plan (extended on a 10 years horizon). During the implementation phase, based on the tests and inspection results, estimations of the remaining design life can be made, and adjustments of the initial PLiM program activities can be performed, in order to minimize the PLiM Program implementation costs, which are not negligible at all. The optimization of the PLiM Program in terms of mandatory activities and/or adapted frequencies is the most beneficial phase of the program, so the sooner it gets started the bigger the outcome can be as input for Plant Business Plan and, finally as economic efficiency of the power generation process.

The Cernavoda Top-Level business process diagram for the Integrated Equipment Reliability Process was developed based on WANO recommended best practices detailed in INPO-AP-913, Mocanu (2009). The main Reliability process is connected with the following key-processes:

- *Scoping and identification of critical SSC;*
- *SSC Performance and condition monitoring;*
- *Corrective action;*
- *Continuing equipment reliability improvement (CERP);*
- *PM implementation;*
- *Life cycle management.*

Within this framework, CERP has inputs from the first 3 processes: *Identification of critical SSC, Performance monitoring* and *Corrective action* and provides output to last 3 processes: *Long-term planning and life cycle management; PM implementation* and *Performance monitoring* (the loop is closed through performance monitoring which should confirm through data the adequacy of programs implemented).

The Long Term Operation (LTO) process will be developed and executed for SSC whose degradation or failure would not be adequately addressed by the normal PM Program (replacement could incur expenditures in excess of one million Euro or necessities very long outage), that could have serious safety or production consequences.

Figure 2 illustrates a number of mechanisms which have been experienced in CANDU 6 reactor systems as they are currently perceived in terms of ageing predictability.

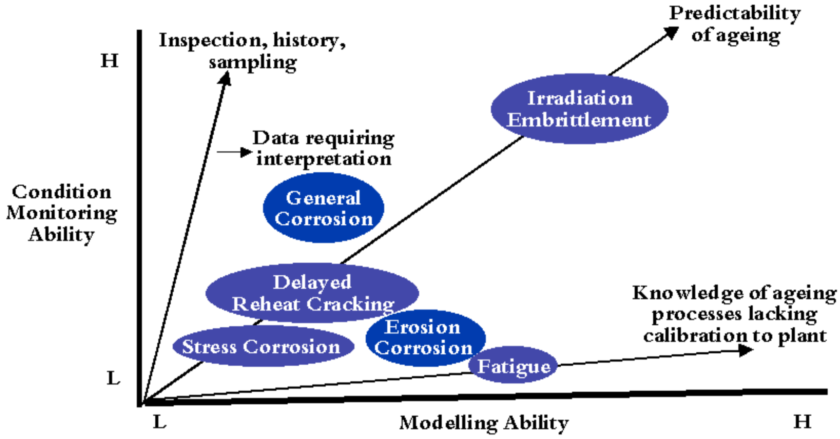

Figure 3. Illustration of modelling ability and condition monitoring ability for typical ageing mechanisms.

Such estimations indicate where R&D investment is required for predictability to be improved. It is clear that significant R&D expenditure is needed if modelling and condition monitoring technology is to achieve the required level for an effective ageing management based on predictability. This should lead to an increase in the use of mitigation measures that, if applied early enough, can prevent crack initiation and/ or further deterioration. Over the past 7 years, INR Pitesti has been working on R&D Programs to support a comprehensive and integrated Cernavoda NPP Life Management Program, Cojan et al. (2007).

5 R&D SUPPORT TO CANDU 6 LTO

The LTO program, proposed to be applied at Cernavoda NPP, was developed based on WANO recommended best practices detailed in INPO-AP-913 and it is supported both by the experience of CANDU 6 owners and by the results of research conducted within INR Pitesti. Institute for Nuclear Research Pitesti (INR) is the main responsible RTD organization for development of national technical support of nuclear power in Romania. The activity of the Institute is oriented with priority towards applied and engineering research within RTD programs, connected to present and future specific issues of NPP, especially those using CANDU 6 type reactors.

At Cernavoda NPP Unit 1, the LTO implementation schedule known as the Life Cycle Plan will be issued, and reviewed. Each individual element (defined as a Major Problem in PLiM) will have its own specific implementing level 1 plan developed and corresponding budget documented, and rolled up into the Station Life Cycle Plan. The life cycle plan shall include but is not limited to the following elements, Mocanu (2009):

- Steam Generators;
- Pressure Tubes;
- Feeder Piping.

The multiphase program, proposed to be applied at Cernavoda NPP, is supported both by the experience of CANDU 6 owners and by the results of research conducted within INR Pitesti, Cojan et al. (2007). Thus, the first step of *Phase 1* has been covered, referring to the studies on the assessment of CSSCs operation, encompassing the methodology related to the definition of critical SSCs. The works have been performed between 2000÷2006, within the INR R&D Program on ***"Process Systems and Equipment"***. This program deals with the increase of performances of NPP systems and components; their upgrading based on the evaluation of their operation behaviour. Another objective of this program is assessing and increasing of reliability and maintenance of process systems and equipment in relation with the Plant Lifetime Management. In order to attain all the objectives of *Phases 1& 2*, INR has been initiated other R&D Programs for the evaluation of “ageing” and the capability to carry on safe operation within the limits of nuclear safety (“*fitness-for-service-assessment*”) of the key critical components in the Cernavoda NPP, such as: ***“Chemistry, Chemical Control”***, ***“Fuel Channel”*** and ***“Steam Generator”***.

The INR R&D Programs in support to LTO Program are focused on, Cojan et al. (2007):

- Understanding operating environment and degradation mechanisms, and developing models.
- Developing and applying inspection and monitoring technology.
- Applying models to field data to predict component behaviour and recommend maintenance and management activities, and/or develop and qualify improved components or systems.

5.1 Cernavoda NPP and INR R&D Experience on Steam Generator LTO Program

Steam Generators are one of the most critical equipment in CANDU nuclear power plants. The failure of the steam generator as a result of tube degradation by corrosion has been a major cause of CANDU 6 plants unavailability. Steam generator problems have caused major economic losses in terms of lost electricity production through forced unit outages and, in cases of extreme damage, as additional direct cost for large-scale repair or replacement of steam generators.

Following the general approach, the Cernavoda NPP developed an aggressive program to monitor the critical parameters, inspect and maintain the cleanliness of all these major equipments, since the early stages of operation. For Steam Generators the periodic inspection program started in 1998. The tubes (EC), the nozzles (US), internal supports and the walls (US) were inspected periodically, almost every year during the Planned Outage since then. Starting with 2007, when Unit 2 was placed into commercial operation, there has been adopted the strategy of a Planned Outage every 2 years for a unit. From this point of view, Cernavoda Unit 1 NPP adopted WANO recommendations related to Steam Generators' operating conditions, improving continually the chemistry on the secondary side (in fact, the unit is running with double of the blow-down design flow, although it affects unit thermal efficiency), Mocanu (2009).

The generalized corrosion is an undesirable process because it is accompanied by the deposition of the corrosion products which affect the steam generator performances. It is very important to understand the generalized corrosion mechanism in the purpose to evaluate the quantities of corrosion products which exist in the steam generator after a determined period of operation. The purpose of the experimental research consists in the assessment of generalized corrosion behaviour of the tubes materials (Incoloy-800) and tubesheet material (carbon steel SA 508 cl.2) at the normal secondary circuit parameters (temperature-260^{0}C, pressure-5.1MPa), Cojan et al. (2007).

The Incoloy-800 tubes samples tested in demineralised water (pH=9.5), after a first period of exhibition (240 hours), visually present as a shiny aspect coloured in yellow-brown shades, while in steam they have a radiant aspect coloured in blue-green shades on a brown light background. Continuing the testing of the samples, their aspect becomes dark-brown to brown for those, which were tested in water, and light-grey with bluish shades for those tested in steam. The oxides obtained on the Incoloy-800 samples after the 1200 hours and 2400 hours testing are uniform, continuous, adherent and very thin. By X-ray diffraction there were determined the thickness of the oxides layer (0.50m) and the chemical composition, which consists of Fe_3O_4 and NiO.

The carbon steel SA 508 tested in demineralised water (pH=9.5) presents a grey toward black aspect, generally matted and comparatively uniform. The bulking layer values of oxides formed are thicker than those of the samples tested in water comparatively with those tested in steam. The thickness of the oxide layer determined by X-ray diffraction on the SA 508 samples tested in demineralised water 240 hours has the value 0.96 m up to 1.71 m, being also confirmed by metallographic determination. The experimental programme consisted in the testing of SA 508 cl.2 samples for 3550 hours in demineralised water environments with pH=9.5 (AVT –morpholine and cyclohexilamine) at the secondary circuit specifically parameters (temperature 260^{0}C and 5.1MPa pressure). The testing periods were 650 hours, 2050 hours and 3550 hours, Cojan et al. (2007).

Right now, Cernavoda NPP is tailoring a specific LTO Program, after having documented systematically the major ageing mechanism and contributors to Steam Generators' degradation. Taking into account the excellent inspection results up to date and the good behaviour of the Incoloy 800 Steam Generator tubes in CANDU 6 older plants, the first step in PLiM program implementation was deemed to be "a comprehensive Life Assessment study", planned for the near future (2009-2010). The "Life Assessment" study will allow the "fine tuning" of the Steam Generator PLiM Program, which should be beneficial for both units, especially when the PLiM program starts in the early stages of the NPP it provides enough time for optimization, Mocanu (2009).

5.2 Cernavoda NPP and INR R&D Experience on Fuel Channels LTO Program

Up to date, pressure tube ageing degradation mechanisms have been fully characterized through extensive R&D activities and inspections of the current reactors. “DHC and Fracture“is a distinct theme of the “Fuel Channel (FC)” INR R&D Program for a better understanding of the phenomenon and its consequences affects the structural integrity of CANDU 6 pressure tubes. Experimental and theoretical studies have been performed to put into the evidence the DHC phenomenon, to measure the main parameters responsible of the initiation and propagation of the DHC cracks. Testing set-up, experimental procedures and method has been developed at INR concerning: hydriding of Zirconium alloy samples using the electrolytic method; evaluation on mechanical properties on hydrided samples under uniaxial state of stress; threshold tensile stress determination, responsible of hydrides reorientation; measuring of K_I , K_{IH} parameters; measuring of DHC crack velocity in the longitudinal and axial direction of the pressures tubes, Cojan et al. (2007).

The research activities concerning DHC studies on Zr-2.5Nb alloys have been included not only as part of the INR R&D Program “Fuel Channel” but also as participation in the framework of International Project like IAEA Co-ordinated Research Project “Hydrogen and Hydride Induced Degradation of the Mechanical and Physical Properties of Zirconium-based Alloys”. The goals of this International Project were:

- To prove the capability of the INR Pitesti to perform DHC tests on Zirconium alloys used as pressure tubes material.
- To develop a consistent testing procedure for DHC crack velocity measurements on Zirconium alloys allowing reproducible measurements.
- To obtain a data base as regarding the susceptibility to DHC of Zirconium alloys.

In the same time, the Project offered the opportunity to characterize the Zr-2.5%Nb pressure tubes of CANDU 6 Cernavoda NPP Units 1&2. This structural material fabricated in the early 1980’s is comprising a mixture of sponge zirconium and recycled zirconium scrap material, that were melted twice, while current pressure tubes are made from ingots that have been melted four times. To ensure that the fracture toughness remains high and to confirm that their properties were similar to those of tubes quadruple-melted, DHC measurements on a typical Cernavoda NPP pressure tube have been performed. The small difference between the DHC behaviour, of the two pressure tubes, double melted or melted four times, suggests that the ingot preparation has no effect on the DHC velocity, Cojan et al. (2007).

To study the influence of neutron irradiation on cold–worked Zr-2.5Nb, used as structural pressure tube material in the CANDU 6 Cernavoda NPP Units 1&2, INR Pitesti started an irradiation campaign, taking more than 6 years. The irradiation has been performed in the Romanian TRIGA Steady State and Testing Materials Reactor, at a fluence of about 3.5 x 10^{24} n/m^2 (E>1 MeV). Based on the mechanical testing results, the structural integrity of this type of material, using the Failure Assessment Diagrams has been evaluated.

At Cernavoda NPP the Fuel channel inspections using Ultrasound (US) & Eddy Current (EC) detectors were performed for Unit 1 in 1999, 2003 and 2008. The inspections were performed with Atomic Energy of Canada Limited (AECL), using AFCIS (Advanced Fuel Channel Inspection System) - the latest technology developed for fuel channel non-destructive examination, Mocanu (2009).

During 2008 Planned Outage, a number of 10 Fuel channels have been inspected and the preliminary conclusion was that the degradation process was within the design limits. On the same occasion, material probes have been extracted from 6 pressure tubes in order to determine the condition of the pressure tube material and assess the evolution of H_2/D_2 accumulation, compared to the initial cut-offs values. The conclusion of this latest analysis, performed with AECL technical support, was re-assuring as flaws seen in Cernavoda NPP Unit 1 are typical of those seen in other operating CANDU 6 stations and the deformation of pressure tubes conforms to the normal behaviour expected of CANDU 6, Mocanu (2009).

The actual Cernavoda NPP Fuel Channels LTO Program was developed based on the requirements of the Canadian Standard CAN/CSA N285.4 “Periodic Inspection of CANDU Nuclear Power Plant Components”, which have been accepted by the National Regulating Authority (CNCAN). So far in program implementation, no Life Assessment study is deemed to be necessary until 2015, when Life Assessment/Condition Assessment studies shall be conducted on a large scale in order to determine the condition of critical major equipment to be addressed in the Extension Refurbishment Plan.

5.3 Cernavoda NPP and INR R&D Experience on Feeders LTO Program

CANDU 6 Reactors have experienced two types of feeder degradation, IAEA (2006):

- Pipe wall thinning due to Flow Accelerated Corrosion (FAC), and
- Cracking.

FAC wall thinning has been seen at most stations while cracking has only been observed in a few situations. The thinning rate of the feeder pipes has been shown to be dependent on water chemistry, particularly the pH and the electrochemical potential. The mechanistic understanding of feeder cracking is still limited. To date, inter-granular cracks have been observed on both the inner and outer surface of the first and second bends on the outlet feeder and on one repaired weld. Inner surface cracks are postulated to be caused by stress corrosion cracking. Figure 4 shows a schematic diagram of feeder pipe.

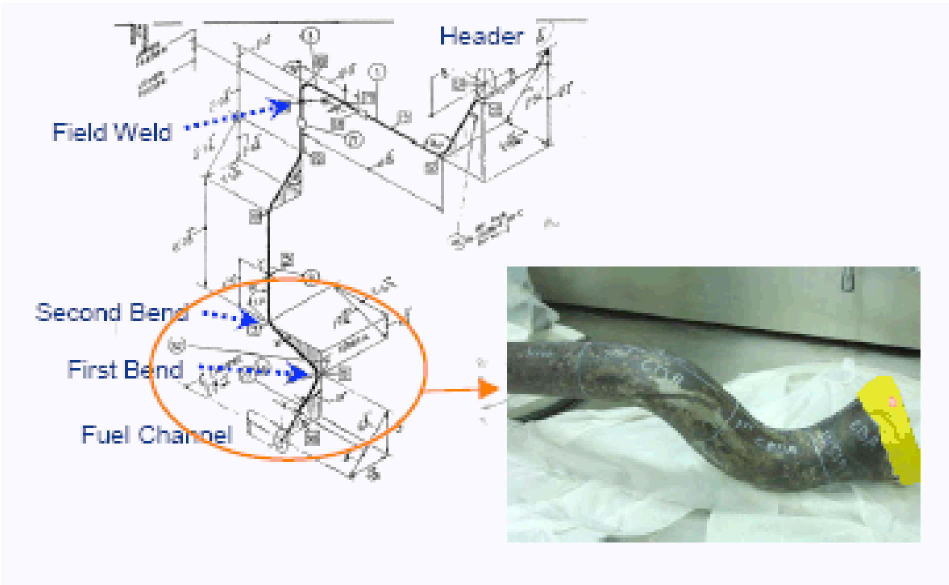

Figure 4. Schematic diagram of feeder pipe.

Outer surface cracks are currently believed to be caused by low temperature creep cracking, assisted by hydrogen ingress due to feeder thinning. The single crack on the repaired weld is currently believed to be an interrelation of both mechanisms. It is believed that all cracks are caused by unrelieved residual stresses induced during manufacturing or welding, plus other factors such as material susceptibility and chemical environment. Feeder Ageing Management Programs have been developed and are updated periodically to account for inspection findings and subsequent assessments. This program includes inspection plans at each planned outage and R&D plans. In addition, improved feeder inspection tools have been developed to inspect inaccessible sites. More reliable leak detection systems are also being considered.

Surveillance of some structural materials corrosion from primary heat transport system (PHTS) of CANDU 6 Reactor is performing by, Cojan et al. (2007):

- Out of pile corrosion experiments in different conditions of water chemistry and temperature;
- Corrosion experiments in autoclaves assembled in by-pass of CANDU 6 reactor primary system, and
- Corrosion analysis performed on some corroded components.

Accumulated data are stored in databases and a data processing and evaluation system allow us:

- Observation of plant water chemistry;
- To evidence the appearance and the evolution of some accelerated corrosion processes in primary circuit, and
- To determine the corrosion, deposition and releasing of the corrosion products, as well as the characteristics of the corrosion films formed on different structural materials.

The out of pile corrosion experiments were performed by: chemical accelerated tests in accordance with ASTM, static autoclaving and electrochemical methods (galvanostatic-GS, potentiostatic-PS, potentiodynamic-PD and cyclic polarization-PC). These experiments were performed on different structural materials in normal and abnormal operation conditions of water chemistry and temperature, being investigated several corrosion processes, Cojan et al. (2007).

The Feeders LTO Program was developed with AECL & COG support, Mocanu (2009):

- Starting with 2006, Cernavoda NPP adhered to several joint projects developed by COG as part of "COG Feeders Integrity Program" - (COG-FIJP), as well as to COG-R&D Project 407 "Reactor vessel and piping material degradation".
- CNE Cernavoda intends to develop the long term strategy and to define the LTO activities related to Feeders' ageing control with the support of COG/AECL.
- Feeder inspection program has started in 2003 for wall thinning measurement; elbows extrados cracks identification and welds monitoring.
- During the Planned Outage of Unit 1, in 2008, a series of 1336 inspections have been performed. Out of them, only one problem has been reported: the contact between the feeder N15A and nearby calandria tubes end fittings M21/M22. The problem was not new and all the required measures have been taken in order to resolve the issue through a Project modification, as previously done.
- Feeders' PLiM Manual issued recently identifies the need for periodic inspection of a series of components on each of the 4 sub-programs: THINNING (Feeder elbows downstream end fittings; and Grayloc Zone), CRACKING, CONTACT EROSION and SUPPORTS INSPECTION.

The inspection program contains the following type of activities, performed every 2 years on a specific selection:

- Feeder elbows thinning measurements downstream end fittings and in Grayloc zones;
- Detection of elbow or welding cracking;
- Feeder - end fitting inter-space checks;
- Supports inspection;
- Assessment of possible lower feeders' replacement

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