CONSIDERATIONS RELATED TO CANDU 6 LIFETIME MANAGEMENT

M. COJAN, G. FLORESCU, M. ROTH, I. PIRVAN, D. LUCAN
Institute for Nuclear Research (INR), ROMANIA

Email address of main author: mihail.cojan@gmail.com

Abstract. The Plant Life Management Program, known as ***PLiM Program*** is concerned with the analysis of technical limits of the safe operation - from the point of view of nuclear safety - in NPP units, aiming at attaining the planned 30 years life duration and its extension to 40 or even 50 years of safe and economical operation. For the CANDU 6 reactors the so-called PLiM and PLEX Programs are just applied. These are applied research programs that approach with priority the current practices for assessing the capability of safe operation within the limits of nuclear safety (***fitness-for-service assessment***). Over the past 6 years, INR Pitesti has been working on R&D Programs to support a comprehensive and integrated Cernavoda NPP Life Management Program. A comprehensive R&D support to PLiM program applicable to CANDU 6 NPP has been proposed.

1. Cernavoda NPP - two CANDU 6 Units

The first commercial CANDU® units have already reached the planned 30 years life-duration, as is the case with 4 Units at Pickering “A”, while the four CANDU 6 units, considered as original for the CANDU 6 project (i.e. Point Lepreau, Gentilly-2, Wolsong-1 and Embalse) operate for 24 years. There are 10 CANDU 6 units in operation and 1 unit in commissioning – Cernavoda-2 (Figure 1). As in Canada and Korea where programs regarding lifetime management were implemented, the PLiM 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 will be in operation in 2007 (the first criticality was attaining on the 6th of May 2007). The Table I displays the evolution of the CANDU 6 reactors.

FIG.1 Cernavoda NPP Unit 2

Table I. Evolution of CANDU 6 Reactors

CANDU 6 Reactors	Unit	Location	Gross Output	Project Cod	In-Service Date	Age (Years)
Original Generation	Point Lepreau	Canada	680 MWe	87	Feb.01, 1983	24
	Wolsong-1	Korea	679 MWe	59	Apr.22, 1983	24
	Gentilly-2	Canada	675 MWe		Oct.01, 1983	24
	Embalse	Argentina	648 MWe	18	Jan. 20, 1984	23
	Cernavoda-1	Romania	706 MWe	79	Dec.02, 1996	11
Current Generation	*Cernavoda-2*	*Romania*	*706 MWe*	*82*	*2007*	-
	Wolsong-2	Korea	715 MWe	86	July 01, 1997	10
	Wolsong-3	Korea	715 MWe	86	July 01, 1998	9
	Wolsong-4	Korea	715 MWe	86	Oct. 01, 1999	8
Advanced Generation	Qinshan-1	China	728 MWe	98	Jan. 05, 2003	5
	Qinshan-2	China	728 MWe	98	July 24, 2003	4

2. CANDU 6 Lifetime Management

The main objectives of the PLiM program applicable to CANDU 6 NPP are [1], [4], [6]:

a) To maintain the long-term reliability and safety of the NPP during the design life (life assurance).
b) To maintain the long-term availability and capacity factors of the plant with controlled and reasonable generating costs during the nominal design life of (life assurance).
c) To "avoid surprises" through identification of potential ageing issues, ahead of its occurrence and provide means for monitoring and mitigation to ensure reliable component performance.
d) To preserve the option of extending the life of NPP with good safety and availability at reasonable cost, beyond the nominal design of 30 years, up to 50 years (life extension).

The strategy adopted in preparing the concept of a PLiM program applicable to NPP involves the following steps:

a) Identify critical components.
b) Undertake Ageing assessment studies of such critical components.
c) Implement Life Management Programs aiming to maximize component life, ensures good performances and monitor plant conditions.
d) Plan, scope and implement required programs attain the original design life.
e) Prepare economic case studies for rehabilitation and life extension (PLEX programs).
f) Implement rehabilitation and operate beyond the nominal design life.

Following the above strategy, the multiphase approach of a PLiM Program applicable to CANDU 6 NPP includes three phases in its structure, [1], [6]:

Phase 1: Detailed studies for the identification of critical SSCs, evaluation of ageing and definition of credible mechanisms of critical components degrading.

Phase 2: Definition, planning and implementation of detailed programs of ageing management (AMP) in view of attaining the planned life duration.

Phase 3: Upgrading, replacement and maintenance of critical components in order to ensure extension of the plant life duration.

Over ten years of operation the Cernavoda NPP Unit 1 has been supplying 53 934 218 MWh to the national power grid. After 10 years of commercial operation the average capacity factor is 87.43%. Accordingly Cernavoda-1 NPP ranks 4th in the performance top of the similar CANDU 6 plants [2].

For a better timing of the Cernavoda NPP PLiM program there were considered both the framing of Cernavoda NPP in original CANDU 6 generation and the main instances of its completion and operation. The following moments related to Cernavoda NPP Unit 1 operation were considered:

1998 – The first inspection of turbo-generator;
1999 – Completion of the first inspection of the pressure tubes;

2001 – The first inspection of the steam generator;
2002 – Completion of the second inspection of the pressure tubes.

Besides, it is estimated that the Utility – "CNE-Prod" will benefit the AECL works and from the INR Pitesti and COG expertise and competences in application of the CANDU 6 PliM program, [3] ÷ [8]. Another prediction is that a period of 15 years, from the plant commissioning until the replacement of the first pressure tubes, is an optimistic one for Cernavoda NPP in comparison to the situation of pressure tubes at Wolsong-1, [6]. The fuel channels deformation may limit the useful lifetime of the pressure tubes [3], [4], [6]. The time scheduling of the Cernavoda NPP PLiM Program is presented in Figure 2.

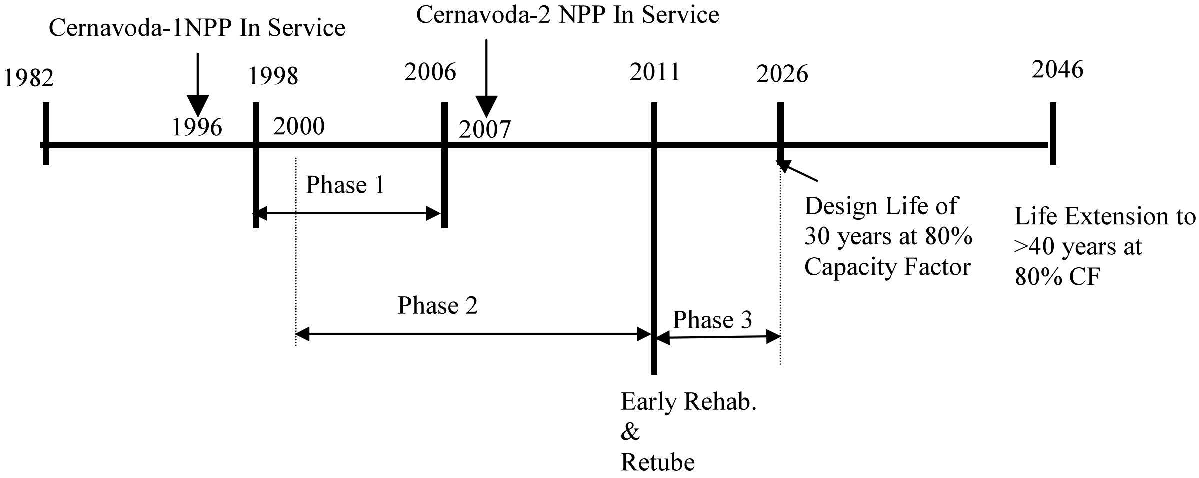


FIG 2. Time scheduling of the CANDU 6 PLiM Program applicable to Cernavoda NPP

3. R&D Support to CANDU 6 Lifetime Mmanagement

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. 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 [5], [7]. The works have been performed between 2000÷2006, within the INR R&D Program on ***"Process Systems and Equipment"*** [4], [6]. This program deals with the increase of performances of NPP systems and components; their upgrading based on the evaluation of their operation behavior. 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 PLiM Program phases are focused on [3] ÷ [8] :

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

3.1. Plant Life Monitoring by Identifying and Monitoring of Critical SSCs (CSSCs)

The specific tasks that must be performed in order to identify the CSSCs are:

- Processing/Ranking of the data/information/testing, maintenance, repairing, operational events.
- The risk significance associated with the operation events.
- Events ranking and critical components establishment criteria.
- Guiding of the testing, maintenance, repairing or operation activities at a NPP unit using risk studies (this task is important in order to perform first the right activities in order to prevent significant abnormal events).
- SSC safety, risk or reliability margin evaluation (to observe the departure from the severe accidents or major abnormal events).

<u>Processing/Ranking of the data/information/testing, maintenance, repairing, operational events</u>

Purpose of this activity is to *establish the criteria for ranking of the events.*

The process to create the events databases consists of the following ranking steps: *event selection; events sorting; events classification/categorization; events ranking.*

For the scope of this paper the events ranking process could be based on: *failure rate; system.*

Associated to ranking process could be evaluated the performance indicators, in order to reveal the importance of SSC, such as *plant availability, number of forced shutdown etc.*

<u>The risk significance associated with the operational events</u>

Steps to be performed in order to complete such activity are: *analysis of event impact; comparison of PSA impact events; estimation of event frequency; determination of reference* $(PDF)_{BL}$*.; estimation of updated* $(PDF)_X$ *value; calculation of - event significance* S_X.

$$Sx = \frac{PDF_x}{PDF_{BL}}$$

The event significance values could be greater then 0 and could be classified as very small (0.0-0.01), small (0.01-0.1), medium (0.1-0.30), high (0.30-1.0) or very high (> 1.0).

<u>Events ranking and critical components establishment criteria</u>

Such process could be based on:

- *The system from which the components originate (failure mode of these components generated the events);*
- *The importance of the system from which the components originate ((failure mode of these components generated the events);*
- *Event magnitude and complexity;*
- *Type of the component affected by the event;*
- *The modality by which the component participates to operation;*
- *Nuclear Power Unit (NPU) operating state;*
- *The causes that generated the initiating event;*
- *Reactor power state;*
- *Reactor shutdown type;*
- *Events occurrence;*
- *Components ageing;*
- *Events occurrence rate;*
- *Operating state restoration period of time of the affected component;*
- *The impact on the plant safety;*
- *Analysis type that will be applied to the events;*
- *The recurrence of the events;*

- *Equipments qualifying.*

<u>Guiding of the testing / maintenance / repairing / operation activities at a NPP unit using risk studies</u>

The scope of such activity is *to determine the critical/important SSCs by using sensitivity studies.* The purpose could be:

- *Integration of data bases/information/events and their presentation in a easy accessible form.*
- *Establishment of the main working/analysis tools necessary to the optimisation activities.*
- *Guiding for testing, maintenance, repairing or operation optimising activities of SSCs.*

The procedure steps necessary to perform such activities are:

- *Development of the NPP's probabilistic model (or safety, reliability or risk architecture model) assuming several initiating events;*
- *Identification of the dominant accident sequences from the event trees, for the abnormal plant states (using criterion and risk significance of the sequence or event);*
- *Establishment of the dominant contributors events (comparing with the criterion);*
- *Association of systems, equipments or components to these events;*
- *Determination of what type of activity generates the events (operation, maintenance, testing or repairing activity);*
- *Determination of the reliability parameters that have a major contribution to the event occurrence probability (comparing with the criterion);*
- *Optimisation the reliability parameters (comparing with the criterion);*
- *Determination of the optimisation effect (comparing with the criterion – using the risk significance of the sequence/event.*

The software codes that could be used in order to perform such activities (owned by INR Pitesti) *are OPTMOD, COGDB, PSAMAN, FTedit and FTexplorer computer codes.*

<u>SSC safety, risk or reliability margin evaluation</u>

Such evaluations are useful in determination of the critical situations where are necessary SSCs modifications, improvements or selection of SSCs configurations in order to prevent accidents or major events.

The necessary steps to be performed in order to perform such determinations are:

- *Specification of the installation, structure, system or component that is analysed;*
- *Selection of the analysis type;*
- *The process system to be analysed;*
- *The type of the abnormal event associated to the process system;*
- *Effects of the abnormal event in the nuclear installation;*
- *The analysed accident consequences;*
- *Identification and description of the analysed CSSC;*
- *Association of critical events as CSSC;*
- *Presentation of the risk type analysis, specifically to considered or analysed case;*
- *Identification of failure or damage state and level, for the considered case;*
- *Establishment of the safety limit, specifically for the considered case;*
- *Selection of the analysing or working method and modelling of CSSC;*
- *Selection of the analysing or working tools;*
- *Calculation of the risk, safety or reliability margins for the considered case;*
- *Interpretation of the results and considerations related to the measures to be followed to improve the safety/reliability in operations of a considered CSSC.*

The relative safety margin: $M_{sr} = \frac{V_r - V_{un}}{V_r}$, V_r *- reference safety value,* V_{un} *- safety value.*

The absolute safety margin: $M_{sa} = V_r - V_{un}$

Relative correction coefficient: $c_{cr} = \frac{1}{n_i}$, where, n_i is the *confidence level*.

Absolute correction coefficient: $c_{ca} = 1 - n_i$

$V_{una}^{-} = V_{un} - V_{un} \cdot (1 - n_i)$
$V_{una}^{+} = V_{un} + V_{un} \cdot (1 - n_i)$ *(Taking into account the confidence level)*

3.2. Corrosion Processes Monitoring in Primary System of CANDU 6 NPP

Surveillance of some structural materials corrosion from primary heat transport system (PHTS) of CANDU 6 reactor is performing by:

- 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. The following methods were used to evaluate the corrosion behavior of zirconium alloys, nickel alloys, stainless and carbon steel: gravimetry, optical and electronic microscopy, XRD (X-Ray Diffraction), XPS (X-Ray Photoelectron Spectroscopy) and EIS (Electrochemical Impedance Spectroscopy) analysis. An informative system was developed for the storage and the administration of data into database. “Corrosion” database contains the data describing corrosion behavior of some structural materials obtained in out of pile corrosion experiments, and “CNECorozi Test” database contains the data concerning the characterization and the corrosion analysis of coupons exposed, several periods of time, in PHTS autoclaves of CANDU 6 reactor (Figure 3).

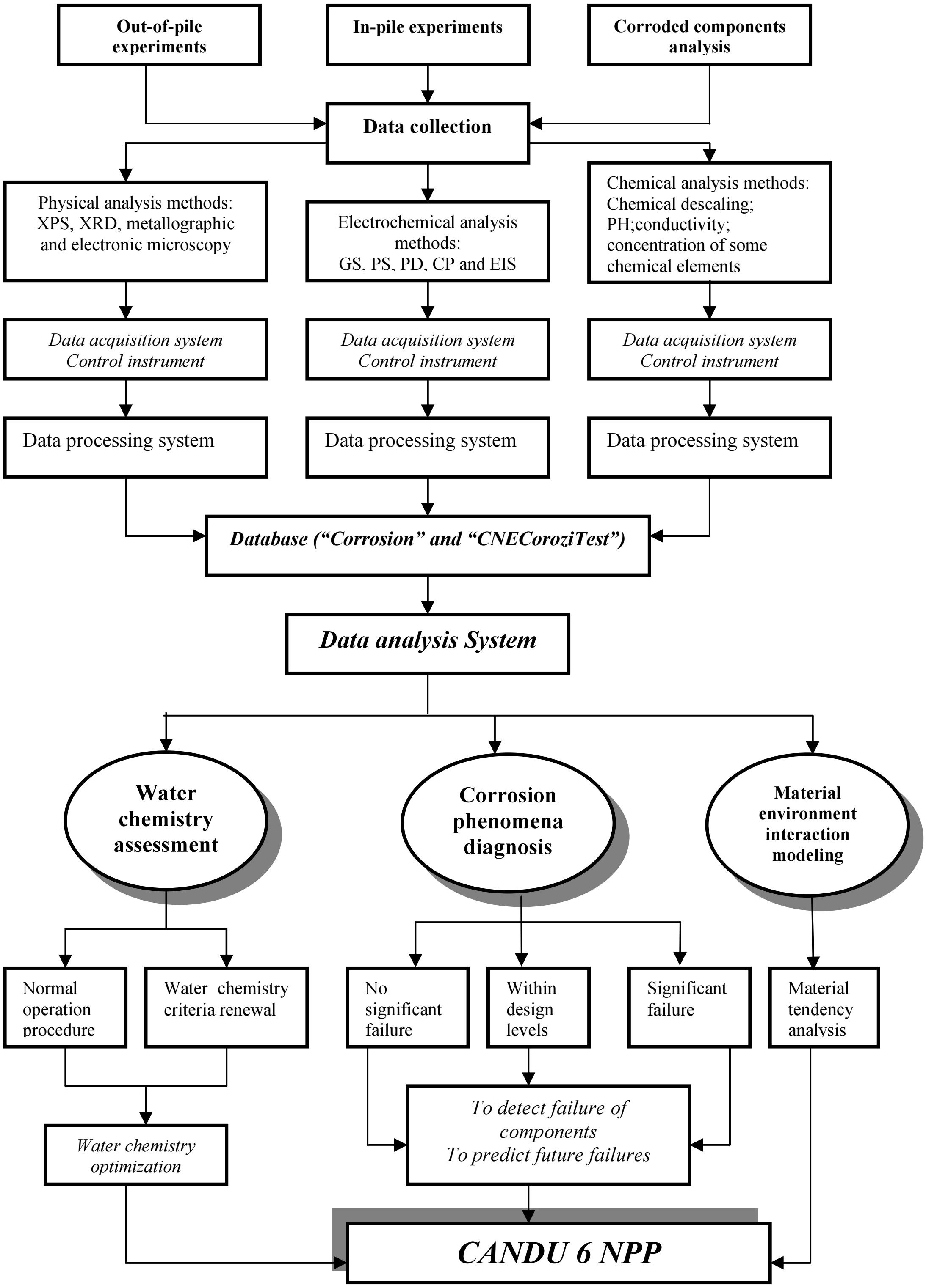


FIG. 3 Data flux in informative system for assessment corrosion

On the basis of data from "CNECorozi Test" database, the corrosion evolution of structural materials was performed (example-Figures 4, 5 and 6)

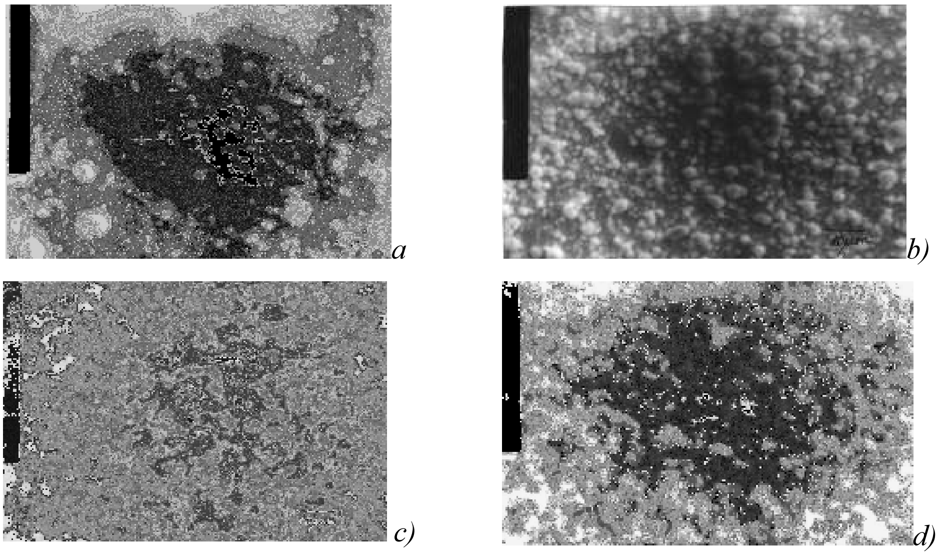


FIG. 4 Morphology of corrosion products on carbon steel SA 106 gr. B surface exposed: a) 197 days; b) 371 days; c) 568 days; d) 825 days (x 1000)

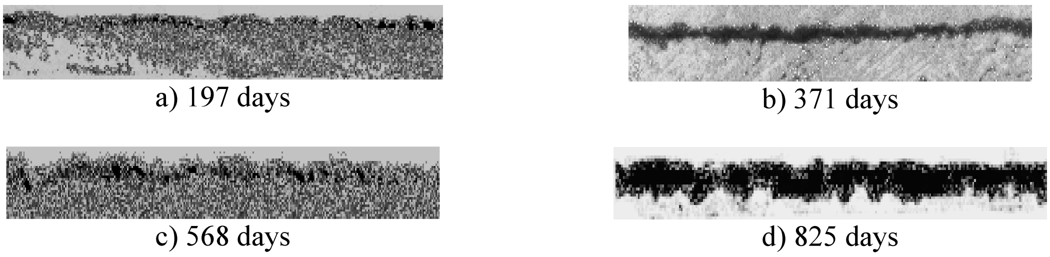


FIG. 5 Aspect of corrosive film (x250)

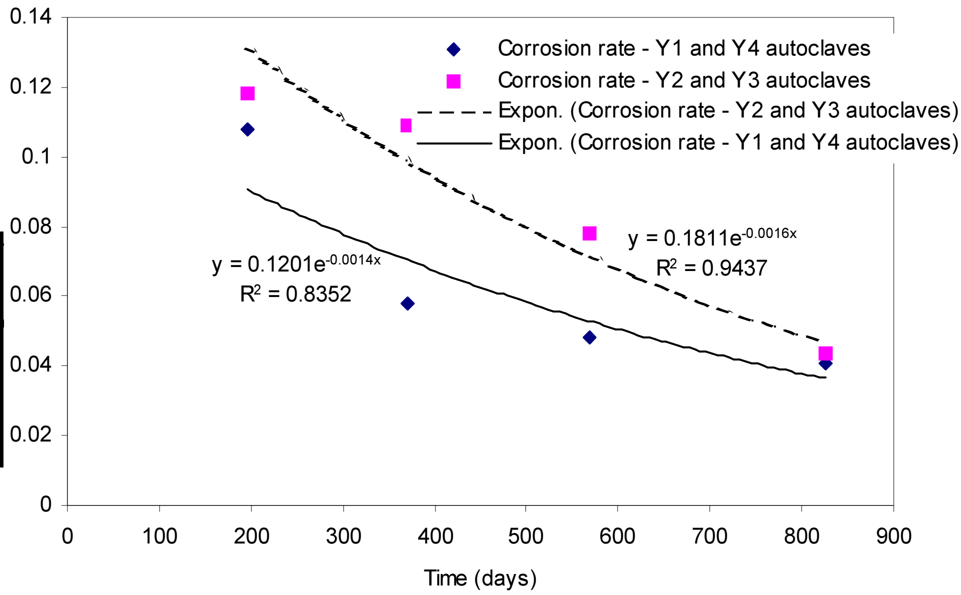


FIG. 6 Kinetics of corrosion rate on carbon steel SA 106 gr. B coupons exposed in Y1-Y4 autoclaves

3.3. Structural Integrity of CANDU 6 Pressure Tubes

"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 affecting 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.

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", [9]. 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 Figure 7, double melted or melted four times, suggests that the ingot preparation has no effect on the DHC velocity, [10].

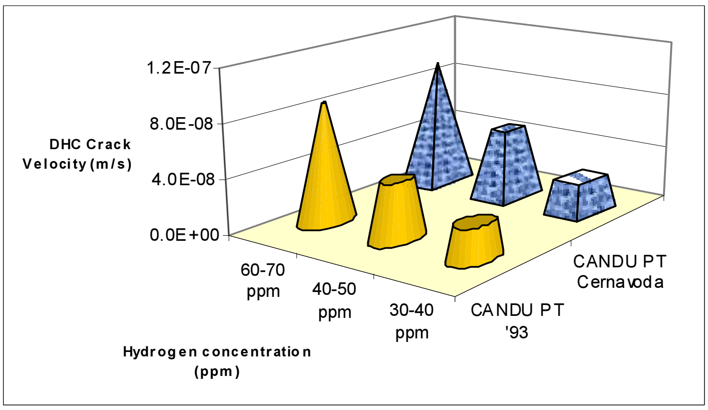


FIG. 7 DHC crack velocity on double melted and quadruple melted Zr-2.5%Nb alloy

From the theoretical point of view, DHC models have been investigated. Same improvements have been made on the Dutton-Nutton-Puls (DNP) DHC model after analyzing and verifying with the experimental data [11].

Taking into account of energy interaction of hydrogen in solution and the experimental TSS expressions for Zr-2.5%Nb alloy certain analytical expressions were replaced with available empirical correlations in order to improve the fit between theoretical predictions and experimental DHC data.
The comparative numerical results from different stages of simulation and experimental data are illustrated in Figure 8, [12].

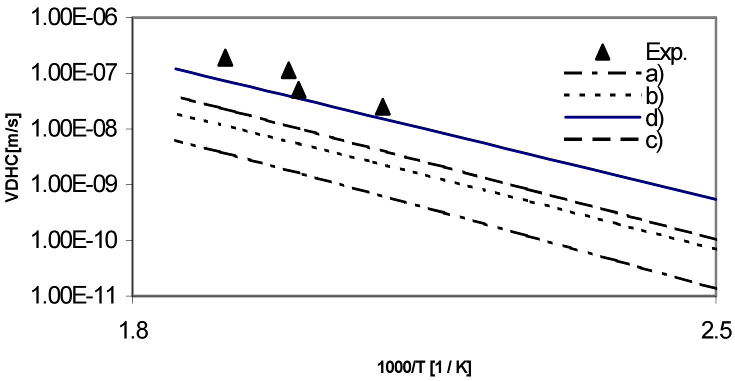


FIG. 8 DHC velocity vs. inverse temperature (K_I = 22 MPa $m^{1/2}$) in four cases:

a) DNP model without $\exp\left(\frac{p(r)\cdot \overline{V}_H}{R\,T}\right)$ *factor; b) DNP model with* $\exp\left(\frac{p(r)\cdot \overline{V}_H}{R\,T}\right)$ *factor;*

c) with TSSD and TSSP without $\exp\left(\frac{p(r)\cdot \overline{V}_H}{R\,T}\right)$ *factor; d) with TSSD and TSSP with* $\exp\left(\frac{p(r)\cdot \overline{V}_H}{R\,T}\right)$ *factor;*

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 of the mechanical testing results, the structural integrity of this type of material, using the Failure Assessment Diagrams has been evaluated. En detail, the experimental results and the structural integrity evaluation have been presented at the E-MRS Conference, [13].

3.4. Corrosion of the CANDU 6 Steam Generator Materials in High Temperature Water

Steam generators are crucial components of pressurized water reactors. The failure of the steam generator as a result of tube degradation by corrosion has been a major cause of Pressurized Heavy Water Reactor (PHWR) plant 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. 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 behavior 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), [14].

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 (0.50µm) and the chemical composition, which consists of Fe_3O_4 and NiO.

Potentiodynamic curves and Bode and angle phase curves for Iy-800 in demineralised water pH=9.5 (AVT), are presented in the Figure 9 ÷ Figure 11.

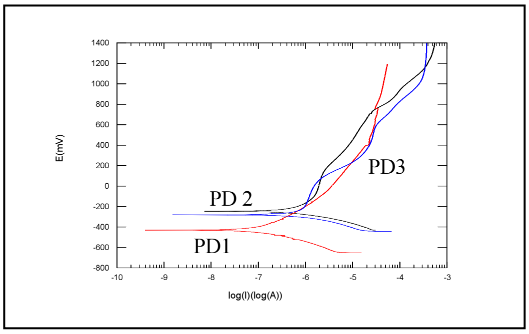


FIG. 9 Potentiodynamic curves for Iy-800 in demineralised water pH=9.5 (AVT): PD1- as received; PD2 – preoxidated 10 days; PD3 – preoxidated 150 day

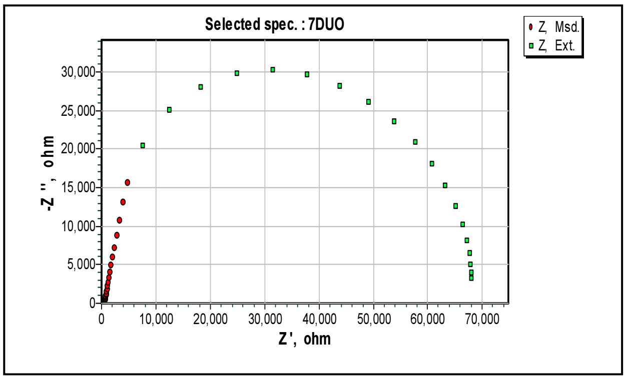


FIG. 10 Nyquist curve for Iy-800 – as received

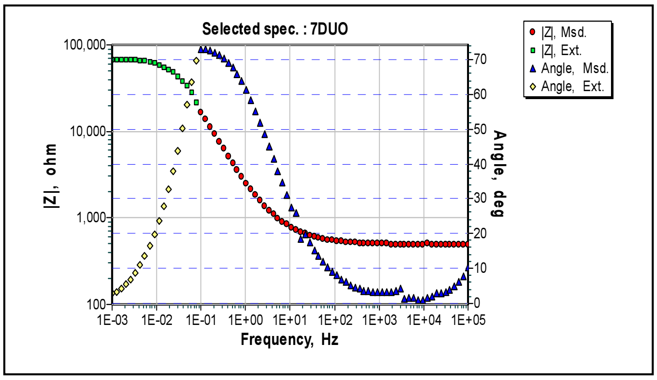


FIG. 11 Bode and angle phase curves for Iy-800 – as received

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 0.96µm up to 1.71µm, 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.

Potentiodynamic curves and Bode and angle phase curves for SA 508 in demineralised water pH=9.5 (AVT), are presented in the Figure 12 ÷ Figure 14.

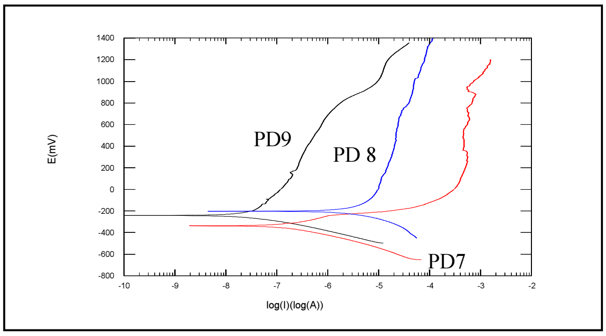
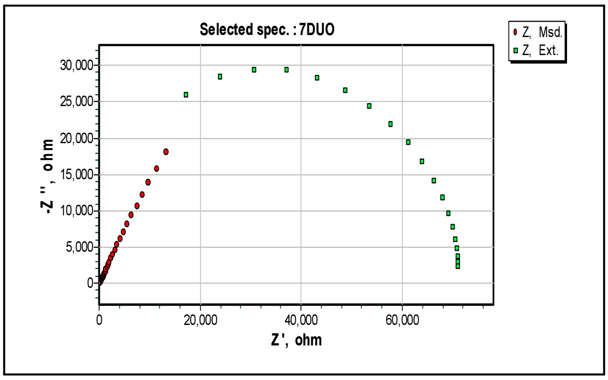


FIG. 12 Potentiodynamic curves for SA 508 in demineralised water pH=9.5 (AVT): PD7- as received; PD8 – preoxided 10 days; PD9 – preoxided 150 days



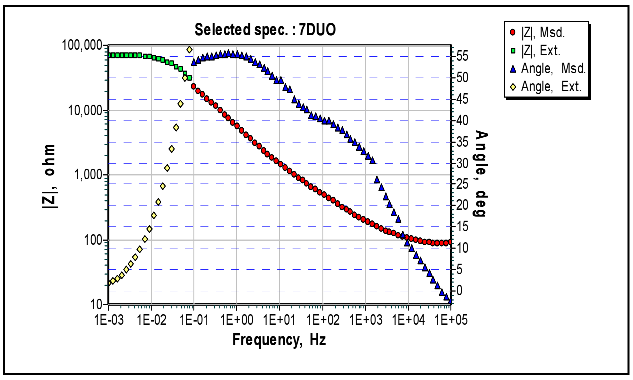


FIG. 13 Nyquist curve for SA 508 – as received

FIG. 14 Bode and angle phase curves for SA 508 – as received

3.5. NULIFE - the European Network of Excellence “Nuclear Plant Life Prediction”

INR Pitesti has become, on the 29th September 2006, a partner in the European **Network of Excellence Nuclear Plant Life Prediction (*NULIFE*)** coordinated by Technical Research Centre of Finland (**VTT**) http://nulife.vtt.fi [15]. The goal of this NoE is to create a single organisational structure capable of working at European level to provide harmonised R&D in the area of lifetime evaluation methods for structural components to the nuclear power industry and the relevant safety authorities.

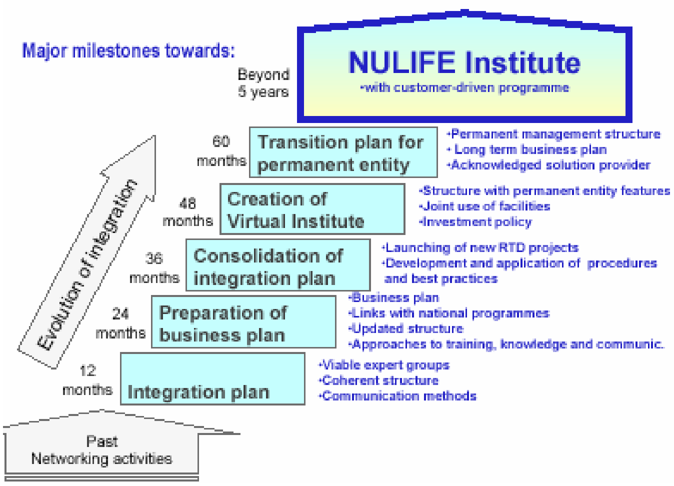


FIG. 15 The major milestones in evolution of the integration and finally reaching NULIFE Institute

INR Pitesti is involved in ***NULIFE*** for the following work packages:

- **WP IA-1** ***"Mapping of partner RTD expertise and competences"*** to provide the INR expertise and competences in application of ageing management in CANDU 6 PLiM / PLEX programs;
- **WP IA-2-3** ***"Lifetime evaluation"*** to provide advice on/develop the lifetime evaluation tools used by the INR and to provide benchmarking of specific lifetime evaluation tools (experimental and analytical procedures, evaluation criteria);
- **WP IA-2-4 "Safety, risk information and reliability"** to review the practical applicability of various probabilistic methods for assessment of structural reliability, ageing and residual life of NPP components, identify R&D needs in this area and assess the limitations of structural component modeling in PSA and their importance for risk-informed decision making.

NULIFE will be the future focal point and umbrella for INR R&D activities in support to CANDU 6 Lifetime Management Program.

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