INSTITUTE FOR NUCLEAR RESEARCH

Pitesti, ROMANIA

CONSIDERATIONS RELATED TO CANDU 6 LIFETIME MANAGEMENT

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AUTHORS CONTRIBUTIONS

Dr. M. Cojan:

- *"Introduction" & "CANDU 6 Lifetime Management"*
- *"Cernavoda NPP – two CANDU 6 Reactors"*
- *"NULIFE - the European Network of Excellence - Nuclear Plant Life Prediction"*

Drd. Gh. Florescu:

- *"Plant Life Monitoring by Identifying and Monitoring of Critical SSCs"*

Dr. M. Roth:

- *"Structural Integrity of CANDU 6 Pressure Tubes"*

Dr. I. Pîrvan:

- *"Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors"*

Dr. D. Lucan:

- *"Corrosion of the CANDU 6 SG Materials in High Temperature Water"*

OUTLINE

- Introduction
- Cernavoda NPP – two CANDU 6 Reactors
- R&D Support to CANDU 6 Lifetime Management
- NULIFE - the European NoE “Nuclear Plant Life Prediction”
- Conclusions

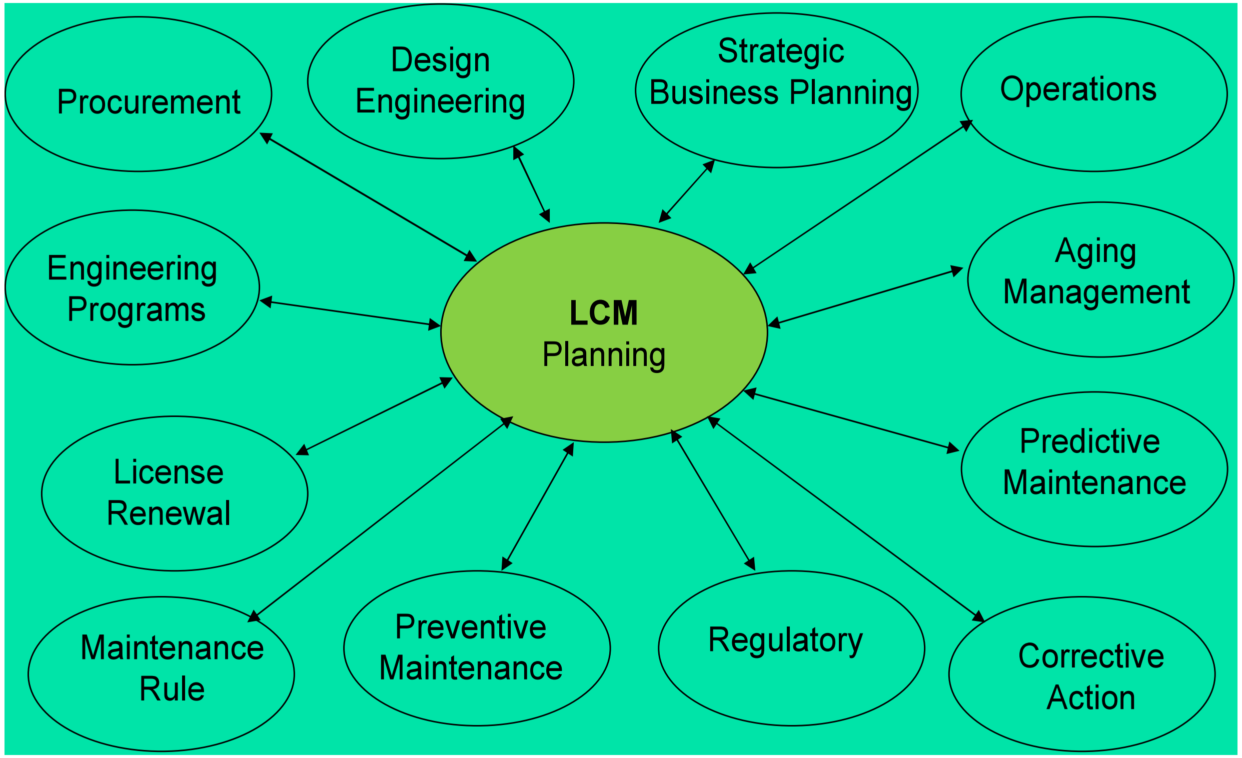
INTRODUCTION

LIFETIME MANAGEMENT

- **Maximizes the value and long-term profitability of the nuclear installation asset.**
- **Integrates ageing management with economic planning to optimise the service life of the nuclear power equipment.**
- **Identifies the components of the facility that are critical (screening SSC).**
- **Establishes a planned approach to maximize the life of those assets.**

INTRODUCTION

Integration of Life Cycle Management Planning with Plant Programs



Tafazzoli, M., Hager, M., *"Perspective of PLIM + PLEX in the USA",*
PLIM + PLEX 2003, New Orleans, Louisiana, USA, 13-14 October,2003.

INTRODUCTION

Role of R&D in Lifetime Management

Assessment	Understand degradation mechanisms and component behaviour
Monitoring	Develop surveillance monitoring technology
Mitigation	Develop and qualify maintenance, management activities, or improved components & systems

INTRODUCTION

Areas for R&D

good understanding of:

- Fitness-for-service assessment
- Design margins
- Degradation mechanisms and how to monitor them
- Mitigating measures and a plan of action in case margins become uncomfortable

INR Pitesti R&D Programs

Nuclear Power Programs:

- Nuclear Safety
- Nuclear Fuels
- Fuel Handling
- Management of Radioactive Wasted including Spent Nuclear Fuel
- Protection of the Environment
- Instrumentation and Control
- Analysis of NPP Operating Events, Aging, Environment Qualification and Life Extension
- Advanced Nuclear Reactors and theirs Fuel Cycles
- Heavy Water and Tritium

PLiM Programs:

- Fuel Channel
  (Dr. Maria ROTH)
- Steam Generator
  (Dr. Dumitra LUCAN)
- Process Systems and Equipment
  (Dr. Mihail COJAN)
- Chemistry of NPP Circuits
  (Dr. Ioana PIRVAN)

INTRODUCTION

FC Program	•Susceptibility of pressure tubes to delayed crack initiation at flaws; •Improved understanding of deuterium ingress, pressure tube deformation and the mitigation of hydride blister formation.
SG Program	•Establishing of the main corrosive degradation mechanisms which contribute at steam generator structural materials failure; •Mitigation of the corrosion steam generator material by chemical parameters optimization for primary and secondary circuits and / or selecting of adequate materials.
PS&E Program	•Increase of the NPP Unit utilization factor by reducing the unavailability of PS&E; •Assessing and increasing of performances, reliability and maintenance of PS&E in relation with the NPP Life Management.
CM Program	•Corrosion of structural materials from primary circuit in normal and abnormal conditions of CANDU 6 reactor operation; •Structural materials corrosion of components and equipment from the secondary circuit of CANDU 6 reactor.

Evolution of CANDU Reactors

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**	**Oct. 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

Cernavoda NPP – two CANDU 6 Reactors

Cernavoda NPP Unit 1 Characteristics:

- Reactor: Cernavoda U1 CNE-PROD
- Reactor type: CANDU 6
- Electrical power: 706 (MW)
- Start of construction: 1982
- First Criticality: 16.04.1996
- In-Service Date :
  2 December 1996
- End of design life: 2026
- Life extension: 2046

Cernavoda NPP – two CANDU 6 Reactors

Cernavoda NPP Unit 1

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.

Cernavoda NPP – two CANDU 6 Reactors

Cernavoda NPP Unit 2

Characteristics:

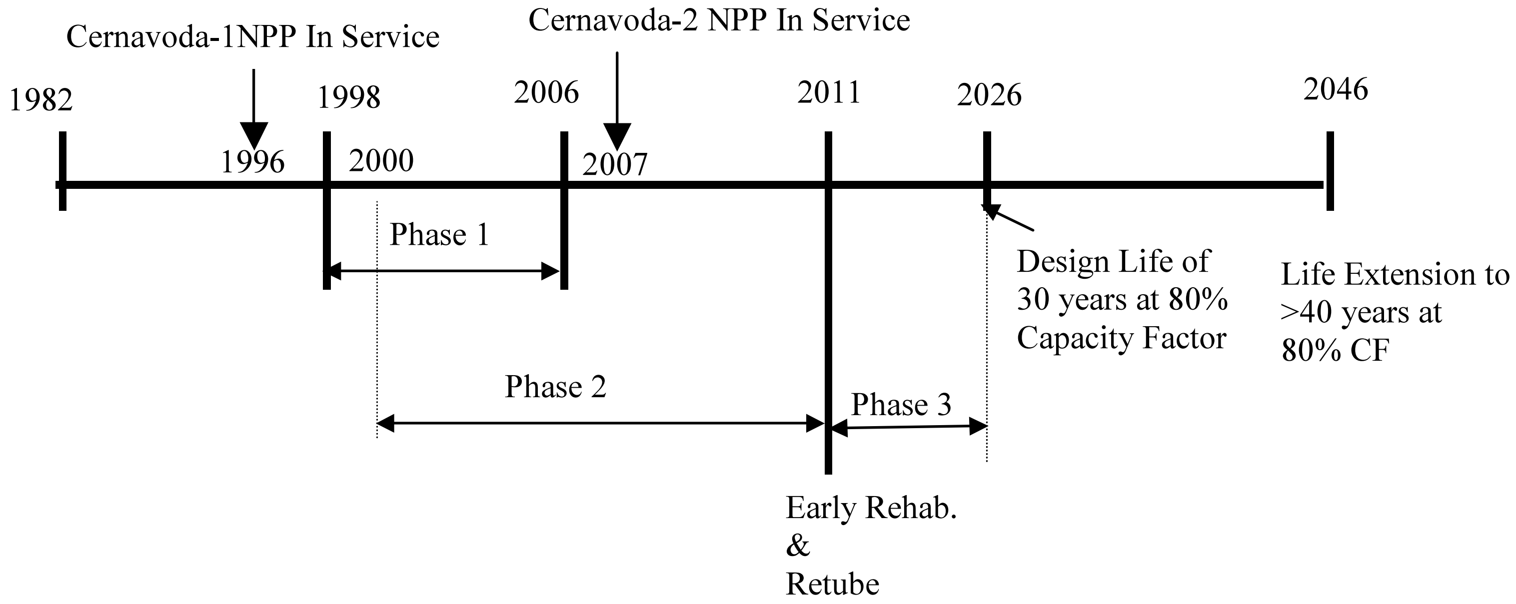
- Reactor: Cernavoda U2 CNE-PROD
- Reactor type: CANDU 6
- Electrical power: 706 (MW)
- Start of construction: 1982
- Restart of construction: 1997
- First Criticality: 06.05.2007
- In-Service Date: October 2007

Cernavoda NPP – two CANDU 6 Reactors

Cernavoda NPP Unit 2

- Cernavoda Unit's 2 commercial operation will mark an important contribution to the security of supply of Romania and EU, saving expense imports of primary resources from outside of Europe.
- The two units of Cernavoda NPP will cover together almost 18% of the country's total energy production and contribute to the significant reduction of Greenhouse Gasses to the environment by producing clean and environmentally friendly power to Romania.

Cernavoda NPP – two CANDU 6 Reactors



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

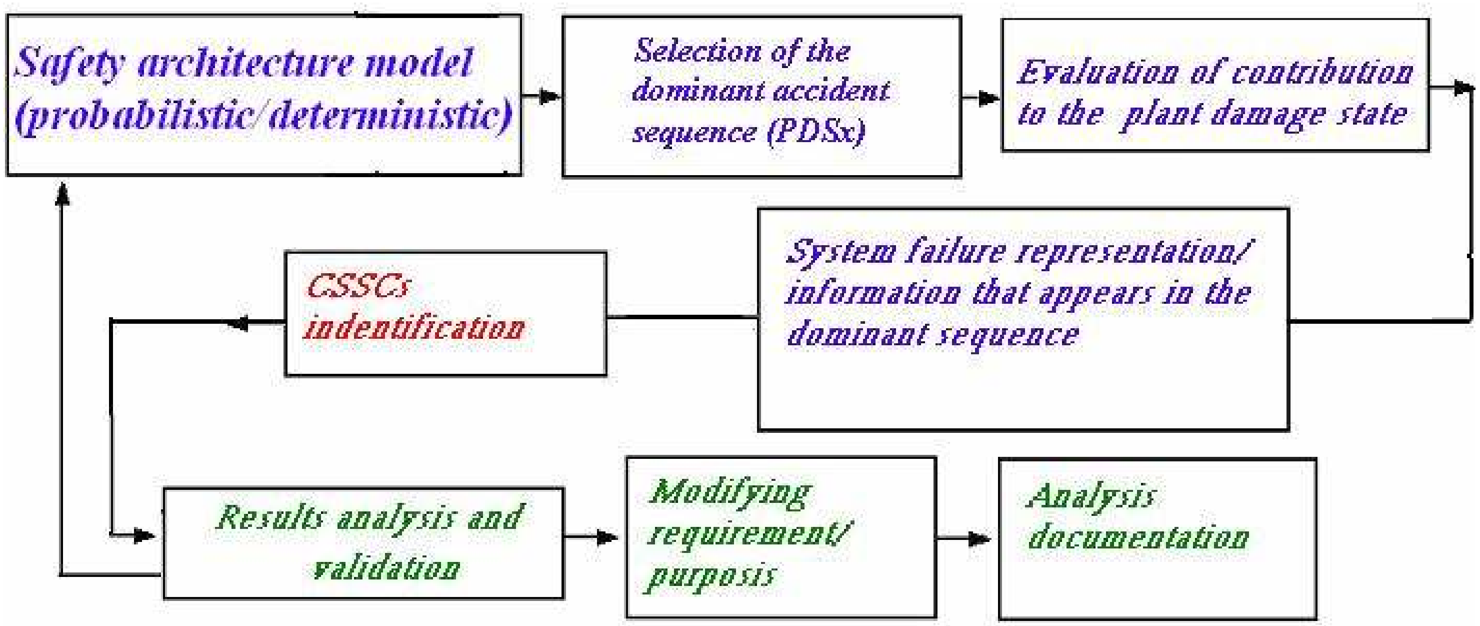
Plant Life Monitoring by Identifying and Monitoring of Critical SSCs

SCREENING SSCs SPECIFIC TASKS:

- *Processing/Ranking of the data/information/testing, maintenance, repairing, operation events.*
- *The risk significance associated with the operation events.*
- *Events ranking and critical components establishment criteria.*
- *Guiding of the testing / maintenance / repairing / operation activities at a NPP unit using risk studies.*
- *SSC safety / risk / reliability margin evaluation.*

Plant Life Monitoring by Identifying and Monitoring of Critical SSCs

STEPS OF CSSC IDENTIFICATION



Plant Life Monitoring by Identifying and Monitoring of Critical SSCs

THE RISK SIGNIFICANCE ASSOCIATED WITH THE OPERATION EVENTS

- Steps
- *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 SX*

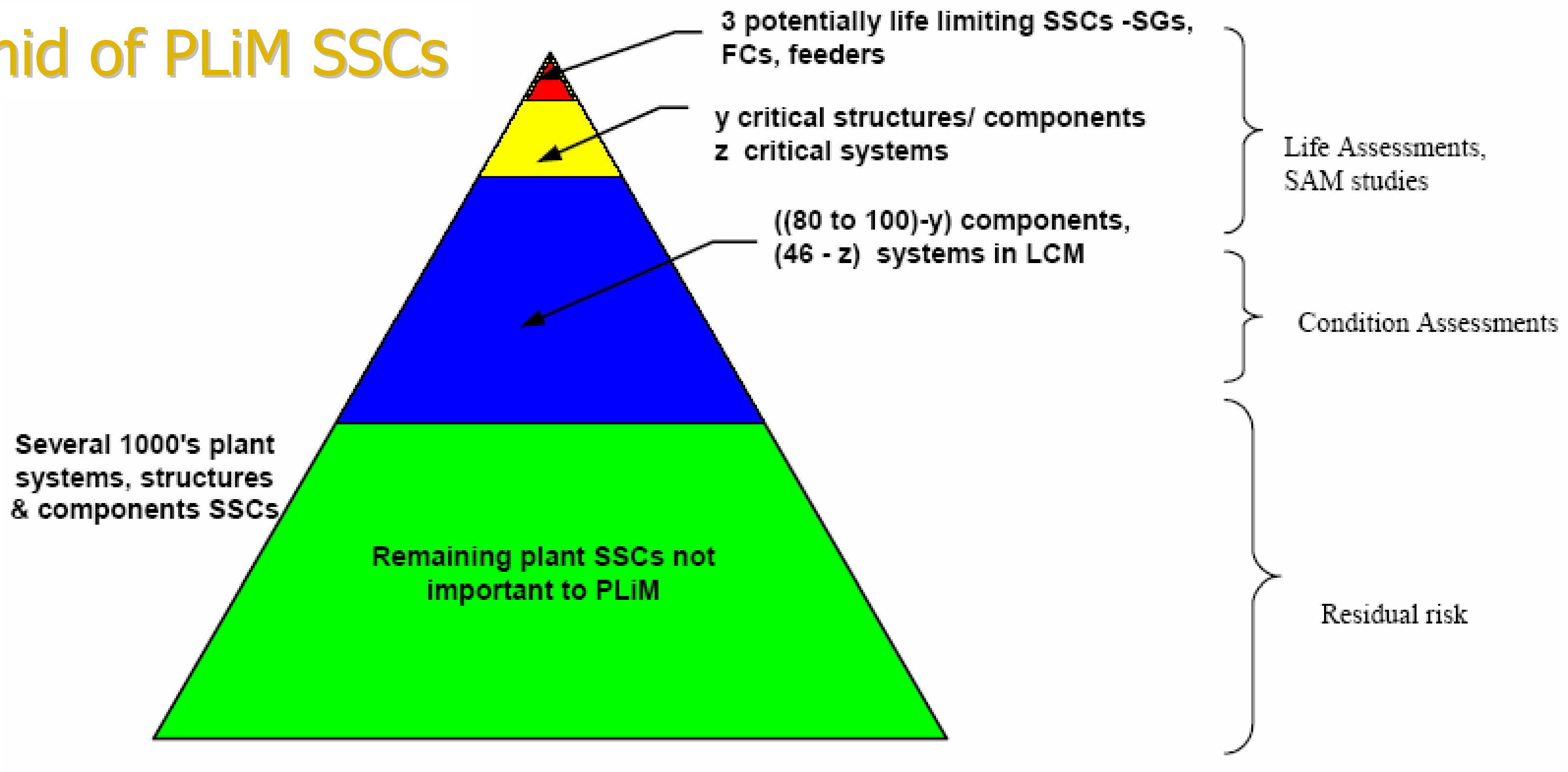
Plant Life Monitoring by Identifying and Monitoring of Critical SSCs

Ranges:

Event significance	*SX range*
Very small	*< 0.01*
Small	*0.01 - 0.10*
Medium	*0.10 - 0.30*
High	*0.30 - 1.0*
Very high	*> 1.0*

Plant Life Monitoring by Identifying and Monitoring of Critical SSCs

Pyramid of PLiM SSCs



IAEA Report, *"HWR PLiM / PLEx / Refurbishment – Processes and Technology"*, Vienna, Austria, 9-11 June 2004.

Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors

Inspection and monitoring activity:

- Development and qualification of NDE techniques for detection and sizing of defects in carbon and austenitic stainless steel piping;
- Development, qualification and implementation of measures and tools for monitoring of process relevant data, such as oxygen content, pH, conductivity, corrosion potential, radioactive crud, fission products, through sampling line;
- Development and implementation of the corrosion-monitoring program.

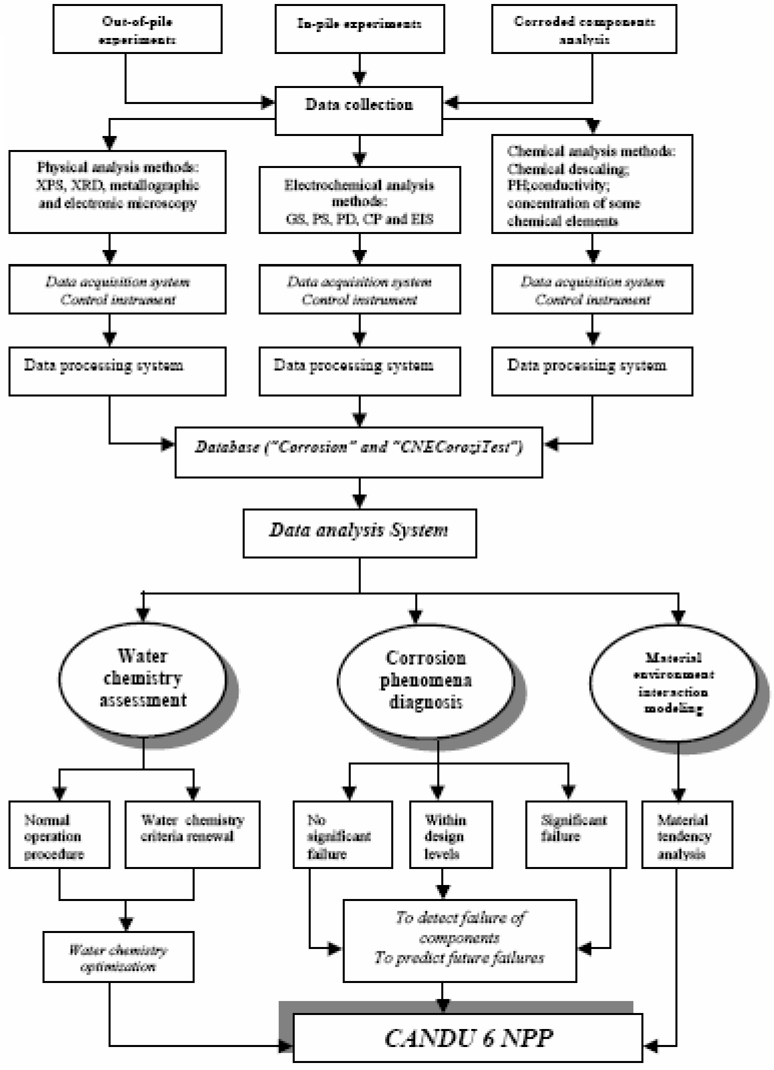
Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors

Corrosion – monitoring program:

- Out of pile corrosion experiments:
  - *appearance and evolution of the localized corrosion processes.*
- Corrosion experiments in autoclaves assembled in by-pass of CANDU-6 Reactor primary system:
  - *corrosion, deposition and releasing of the corrosion products, characteristics of the corrosive films and specific activity of different of radionuclides.*

Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors

Data flux in informative system for assessment corrosion



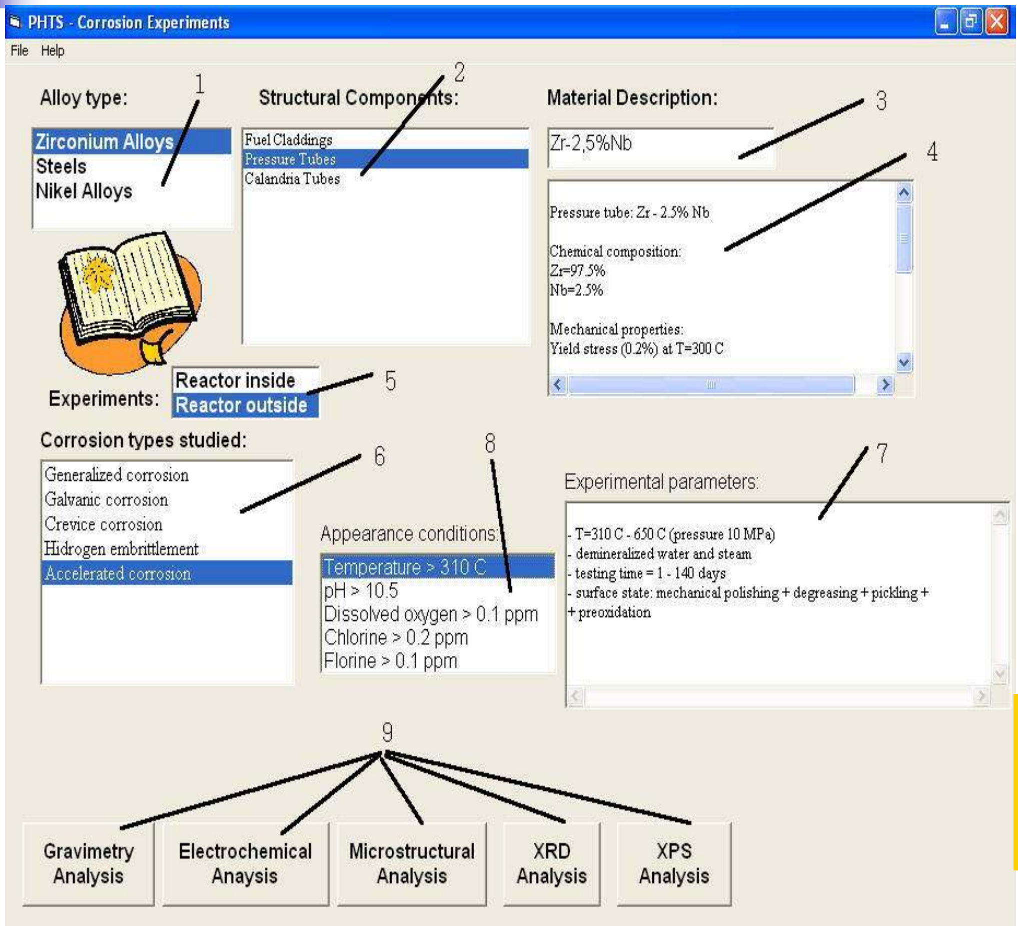
Objective:

- **Testing and evaluation of corrosion using physical and chemical methods.**
- **Databases development in an informatic system concerning corrosion of structural materials behavior:**

  "Corrosion" database

  "CNECorozi Test" database

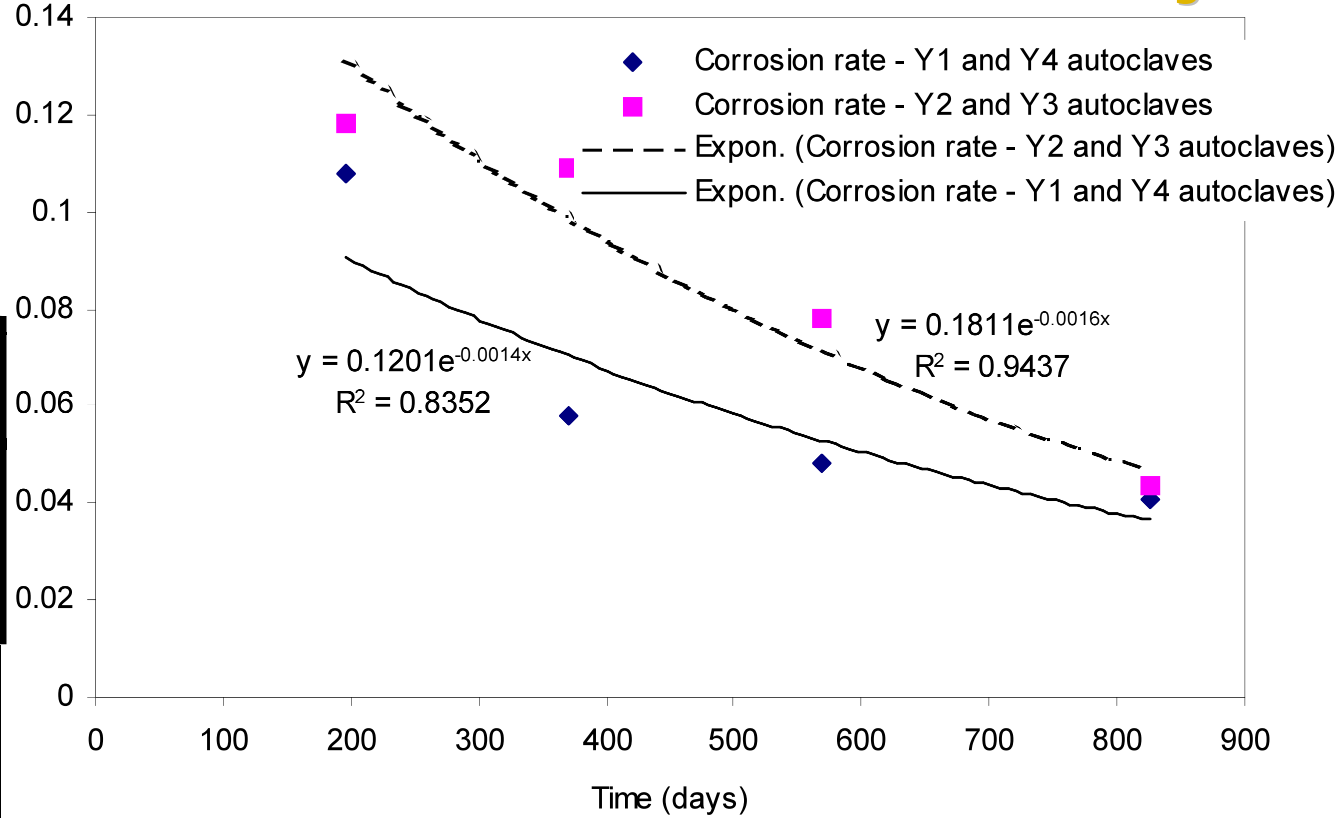
Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors



The principal form of the application "PHTS- Corrosion Experiments"

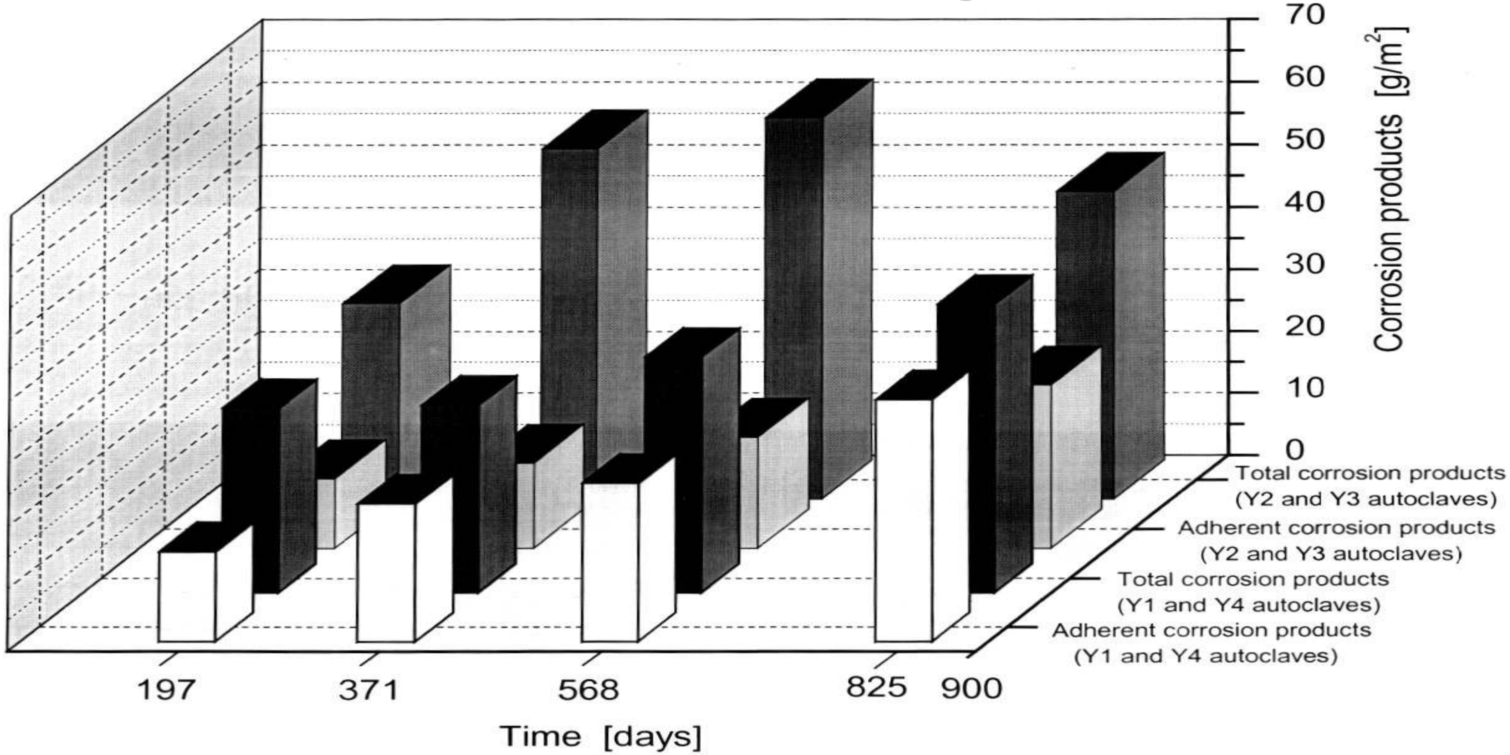
Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors

Generalized corrosion rate of carbon steel SA 106 gr. B

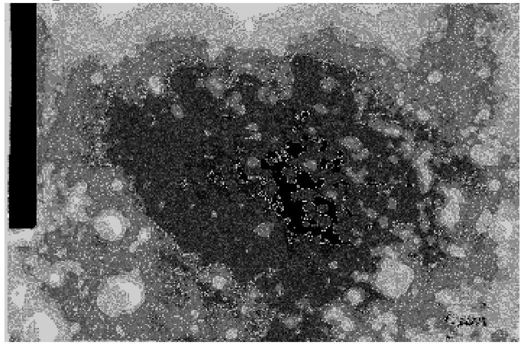


Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors

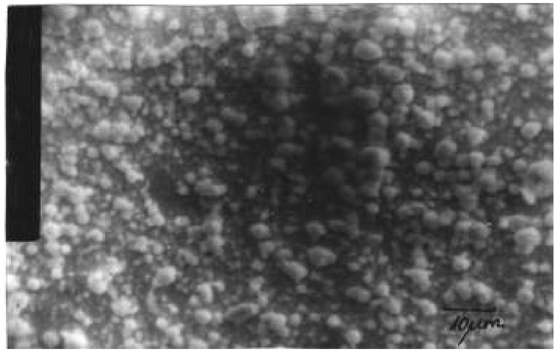
Total and adherent corrosion products formed on carbon steel SA 106 gr.B



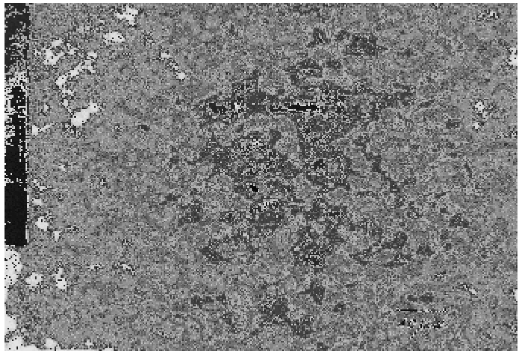
Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors



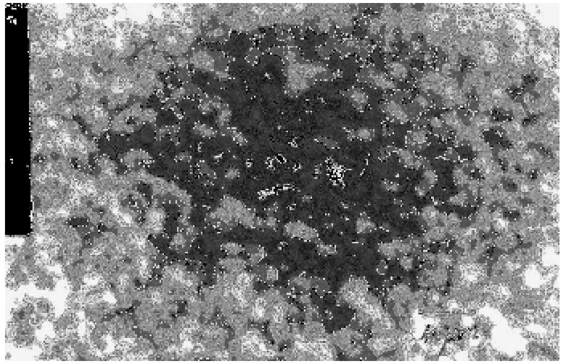
a) 197 days



b) 371 days



c) 568 days

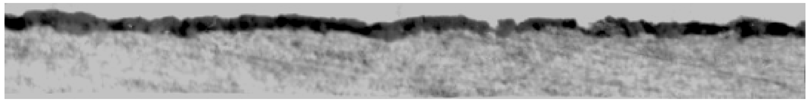


d) 825 days

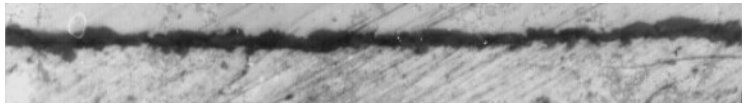
Morphology of corrosion products on carbon steel SA 106 gr. B exposed:
a) 197 days; b) 371 days; c) 568 days; d) 825 days (x 1000)

Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors

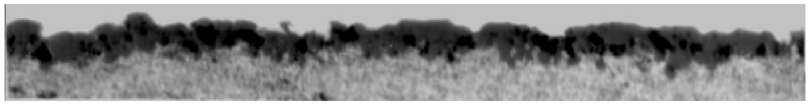
Aspect of the corrosion films on carbon steel SA 106 gr. B exposed different periods (x 250)



a) 197 days (1-4μm)



b) 371 days (2-5μm)

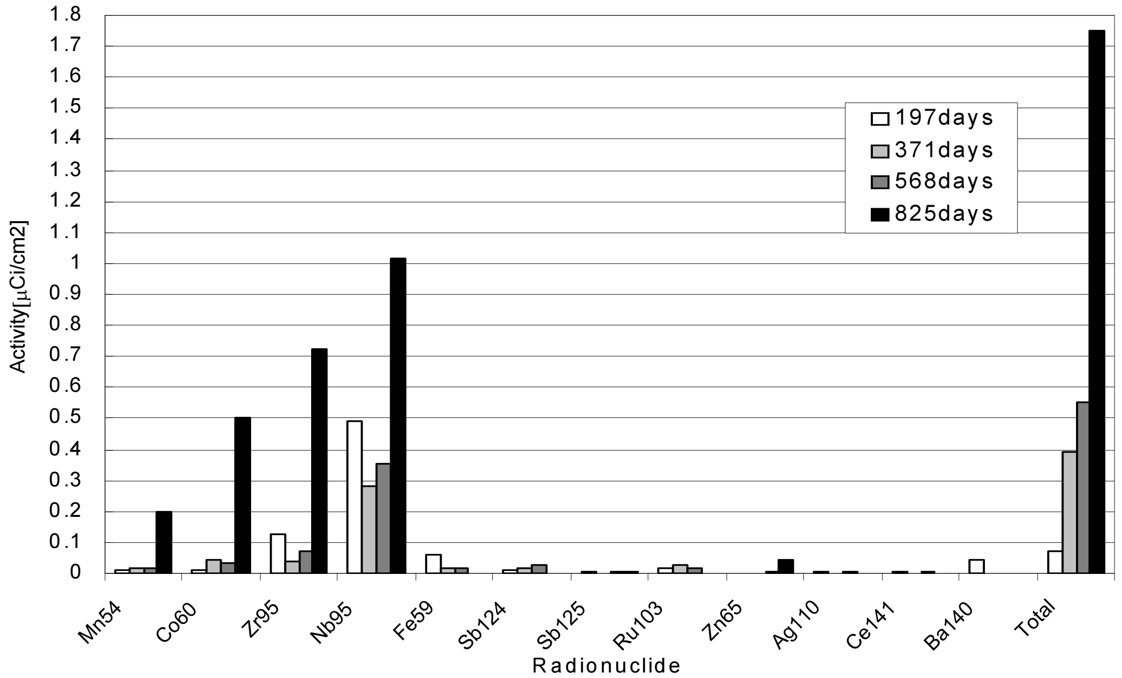


c) 568 days (3-8μm)

d) 825 days (5-12μm)

Corrosion Processes Monitoring in Primary System of CANDU 6 Reactors

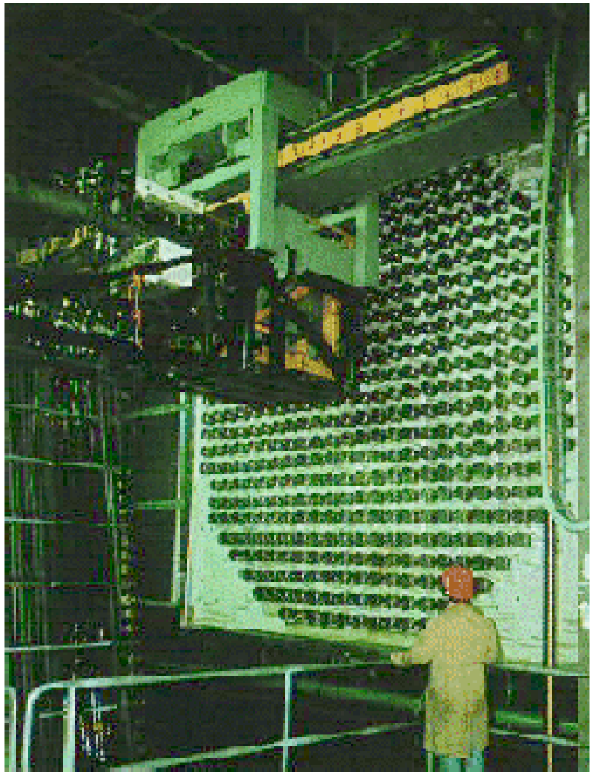
Activity of radionuclides of carbon steel SA 106 gr.B

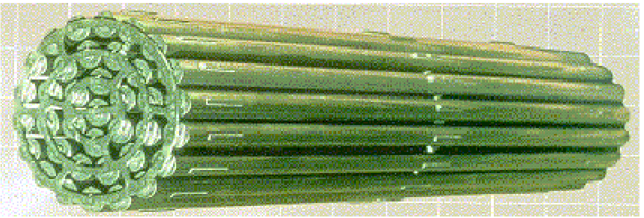


Structural Integrity of CANDU 6 Pressure Tubes

Pressure tube limitative factors:

- **Dimensional change**
- **Corrosion and Hydrogen ingress**
- **Change in mechanical properties**
- **Flaw development**



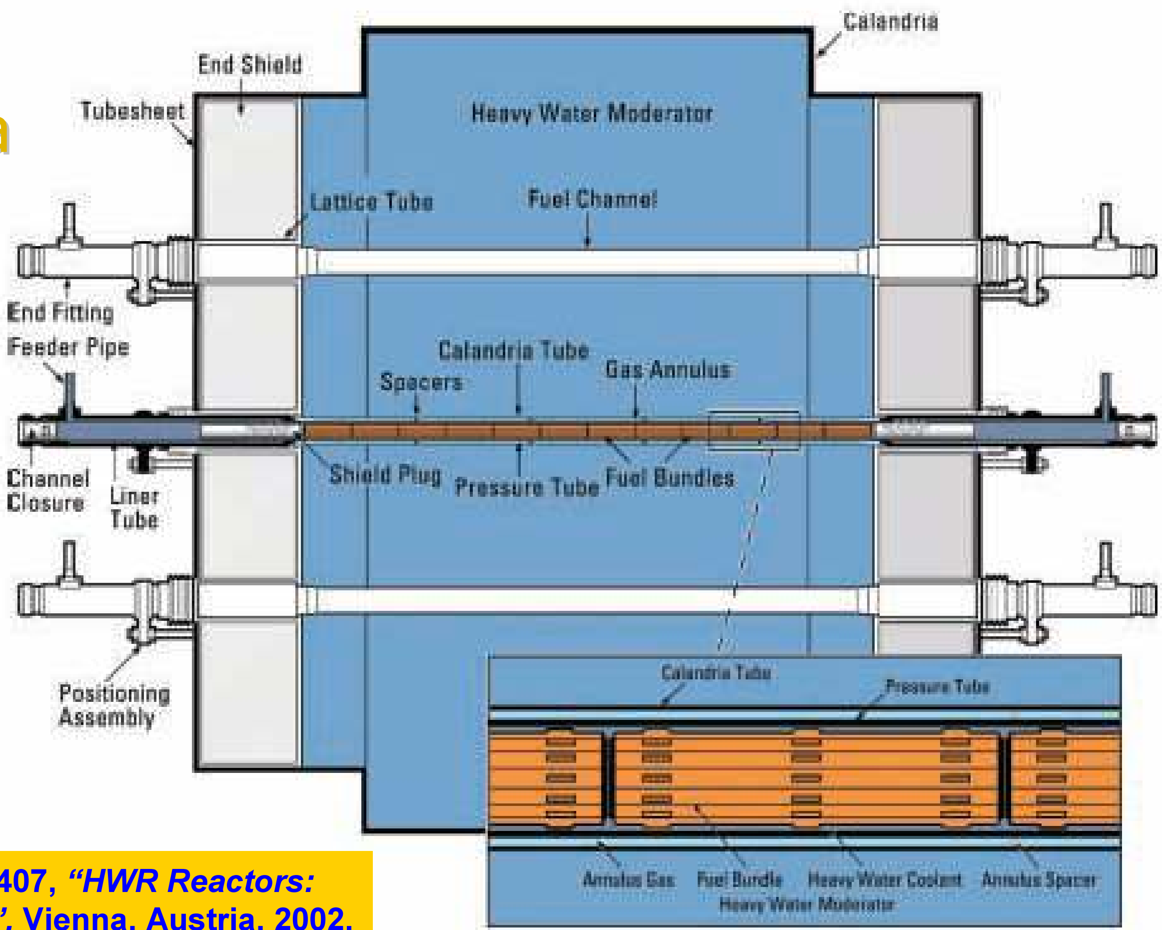


380 fuel channels
each channel-12 fuel bundles

Material: Zr2.5Nb,
Estimated lifetime : 30 years, Fluence: $3 \cdot 10^{26}$ n/m^2

Structural Integrity of CANDU 6 Pressure Tubes

Cross-section of CANDU 6 calandria



IAEA Technical Reports Series no. 407, *"HWR Reactors: Status and Projected Development"*, Vienna, Austria, 2002.

Structural Integrity of CANDU 6 Pressure Tubes

Structural materials - Zirconium based alloys:

- **Zr-2.5Nb for Pressure Tubes ;**
- **Zircaloy -4 for sheaths, bearing pads, end plates.**

Requirements - to operate under:

-specific thermo-mechanical, corrosion and irradiation conditions;

- low thermal neutron capture cross-section.

Disadvantage - hydrogen pick-up due to the water corrosion reaction, affecting theirs structural integrity and operating lifetime under certain reactor conditions like: hydrogen concentration higher than TSS, stress gradient, large tensile stress to fracture the hydrides.

Structural Integrity of CANDU 6 Pressure Tubes

- **Delayed hydride cracking (DHC) is a multi steps, diffusion-controlled crack propagation process.**
- **The DHC process consists in diffusion of the hydrogen (or deuterium) atoms to a high tensile stress region of the tube, such as at crack or notch tips loaded by tensile hoop stress.**
- **If the hydrogen concentration at these locations exceeds the TSS (terminal solid solubility) for hydride precipitation, hydrides with platelet normal parallel to the applied tensile stress direction will form and grow.**
- **When the crack/notch tip hydrides grow to a critical size, fracture of "radial" hydrides will occur and the described process would repeat itself.**

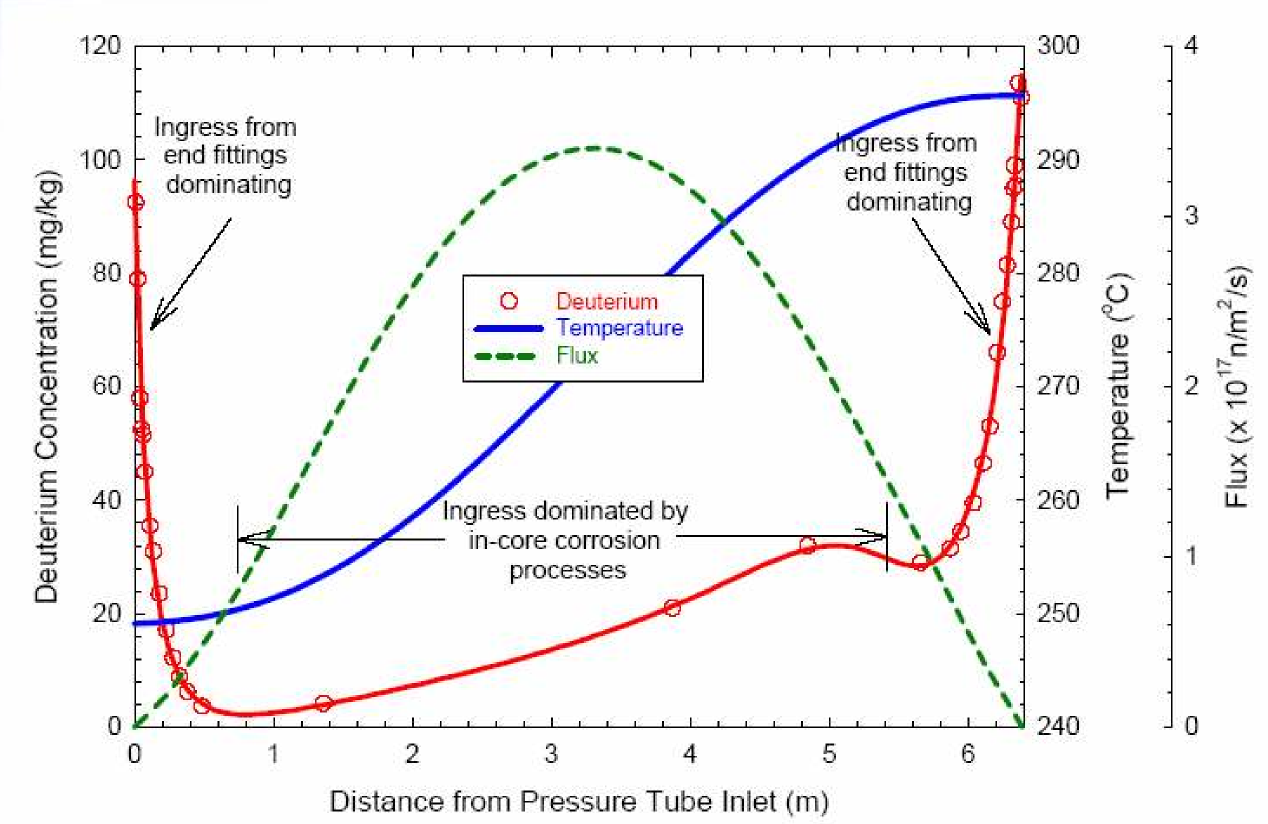
Deuterium Ingress - General

- Deuterium ingress rate is, in general, proportional to oxidation rate
- Oxidation rate increases with temperature and is approximately the same in fast neutron flux (*more recent results indicate it is greater in-flux*)
- % theoretical uptake of deuterium increases with fast neutron flux (but *more recent results show no difference in ingress; ie, oxidation rate is enhanced in-flux while D-ingress remains unaffected*)
- Hence:
  - Deuterium ingress increases along PT axis from coolant inlet to outlet with a small peak in accumulated pickup at ~5-m location from PT's coolant inlet (see next overhead)

Manfred P. Puls, *"Pressure Tubes– Continuous Improvements"*, 7th Fuel Channel Seminar, Toronto, Canada, January 15-16th 2007.

Structural Integrity of CANDU 6 Pressure Tubes

Profiles Along a CANDU Fuel Channel

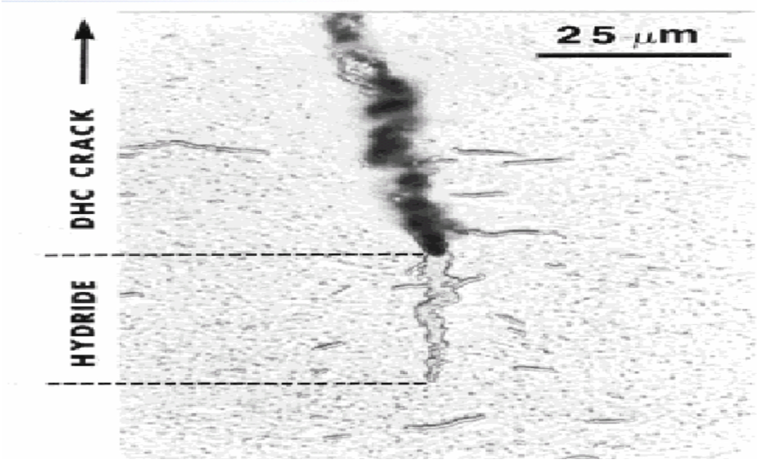


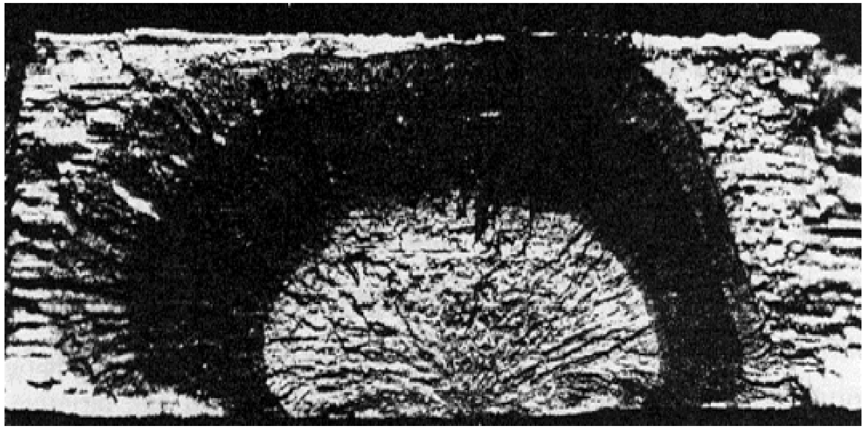
A.J. Elliot, *"A Review of Deuterium Uptake in Pressure Tubes at CANDU 6 Reactors"*, 7th Fuel Channel Seminar, Toronto, Canada, January 15-16th 2007.

Structural Integrity of CANDU 6 Pressure Tubes

DHC Start-up Steps

- Dissolving of hydrides with the first reactor start-up;
- Precipitation of hydrides due to mechanical and thermal gradients over the operation/steady state periods of the reactor;
- Increase of fragile hydride, their cracking, due to thermal and mechanical gradients over the operation/steady-state periods of the reactor;
- Dissolving of hydrides together with reactor restarting; end of crack development and oxidation of the crack surface;
- Continuous enlargement of the crack over the operation/steady-state periods of the reactor, until the penetration of the pressure tube wall.

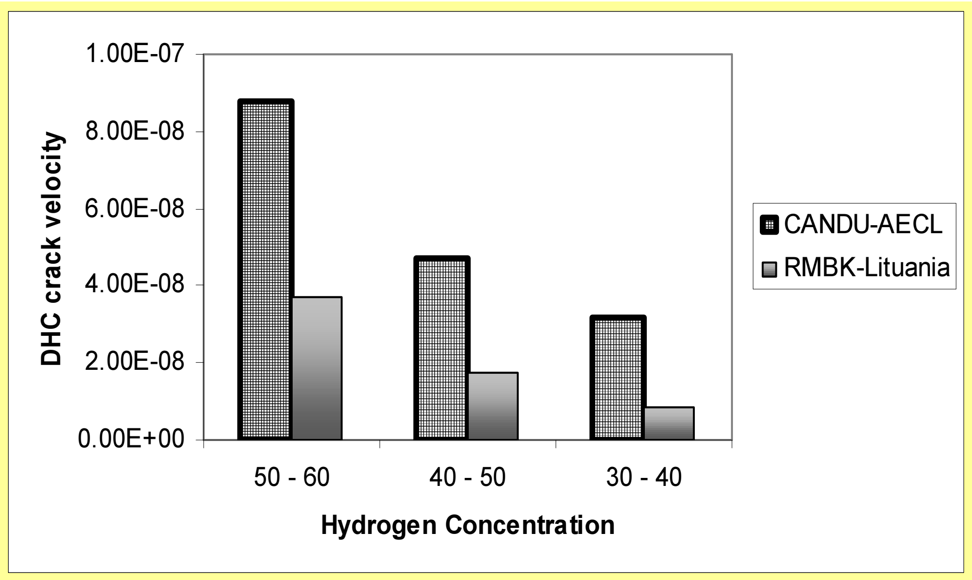




Structural Integrity of CANDU 6 Pressure Tubes

INR R&D activities concerning IAEA DHC project

Main Objective – DHC crack velocity measurements using a Round-Rubin exercise (10 countries) on CANDU and RMBK PT

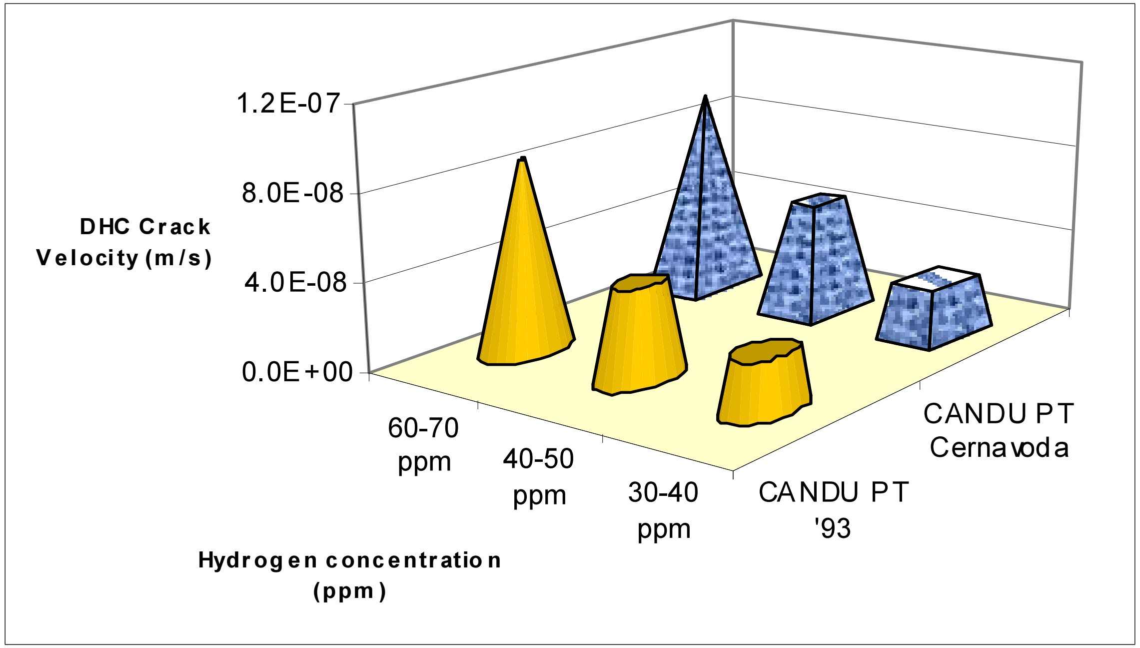


Advantages:

- **Developing of a experimental method useful to evaluate the PT structural integrity.**
- **Applying the DHC method to characterize the Cernavoda NPP PT.**
- **To demonstrate INR capabilities to participate in international Project.**
- **To participate in a new IAEA CRP on Zircaloy-4 sheaths.**

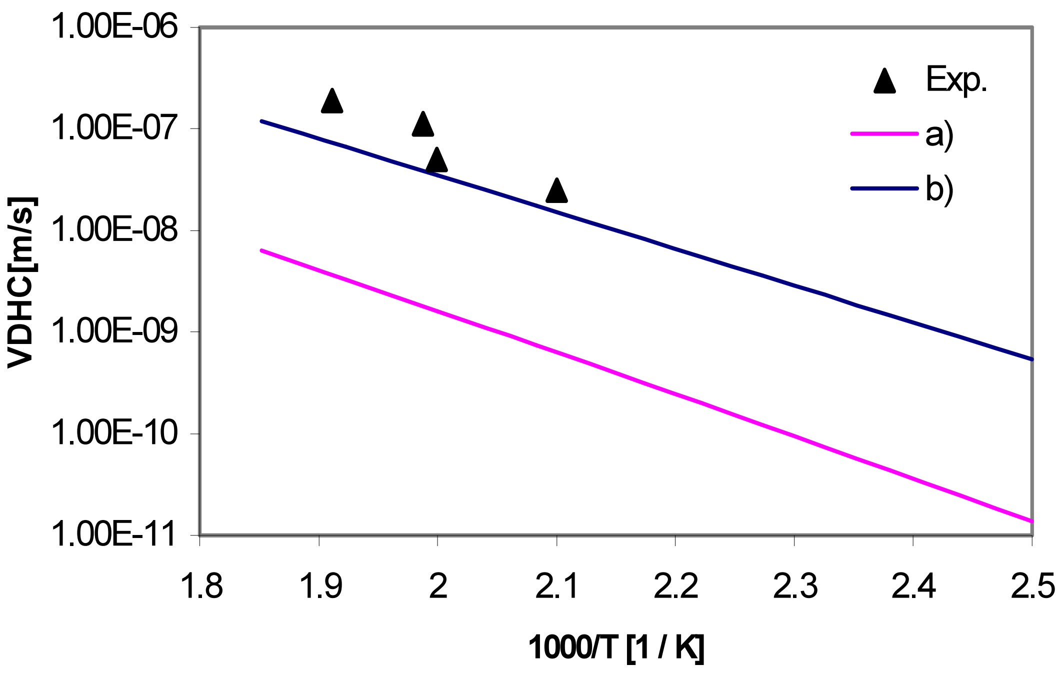
Structural Integrity of CANDU 6 Pressure Tubes

- The Cernavoda NPP pressure tubes were fabricated in the early 1980's and the material is comprising a mixture of sponge zirconium and recycled zirconium scrap material, that were melted twice, while current CANDU 6 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.



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

Structural Integrity of CANDU 6 Pressure Tubes



DHC velocity vs. inverse temperature (K_I = 22 MPa $m^{1/2}$)
(a) DNP calculated data
(b) modified model data

Corrosion of the CANDU 6 SG Materials in High Temperature Water

The experimental programme:

- **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)**

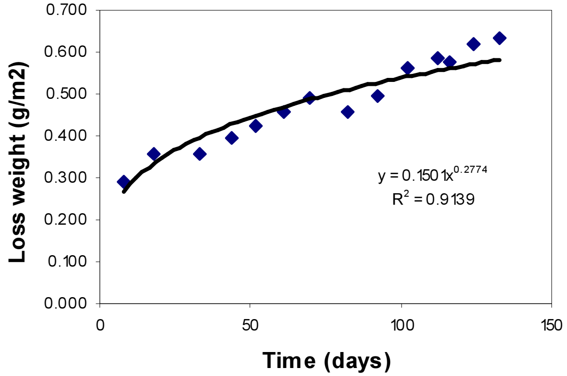
Corrosion of the CANDU 6 SG Materials in High Temperature Water

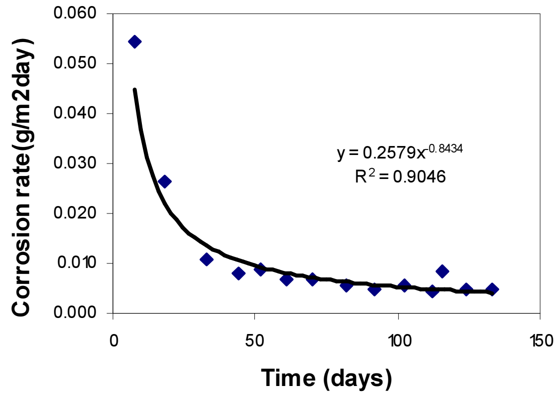
The principal goals of the experimental programme:

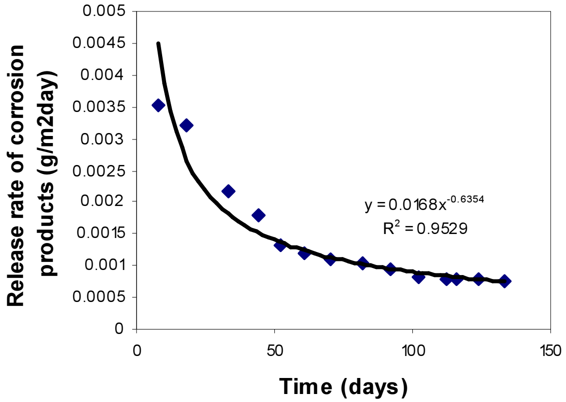
- The assessment of the corrosion kinetics;
- Corrosion testing of simulation devices of tube-tube sheet joint with and without deposits in normal and abnormal steam generator operation conditions;
- Chemical cleaning of deposits placed in the simulation crevice devices;
- The assessment of corrosion intensity at the operation resuming after the chemical cleaning;
- Concentration of impurities and corrosion products on simulated defects and the influence on the corrosion of tubes and tube sheet materials;
- The achievement of correlation between the presence of deposits and the intensity of crevice corrosion at tube-tube sheet joint.

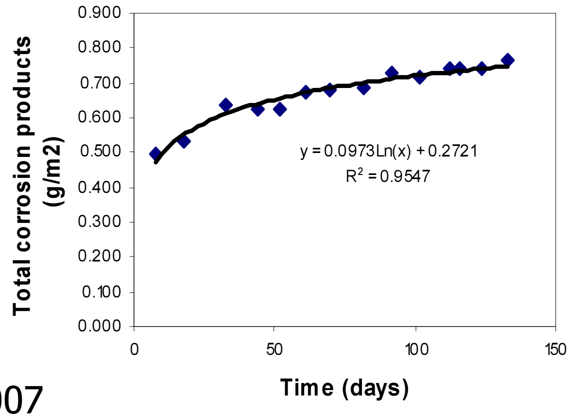
Corrosion of the CANDU 6 SG Materials in High Temperature Water

Incoloy-800 tubes samples tested in demineralised water pH=9.5

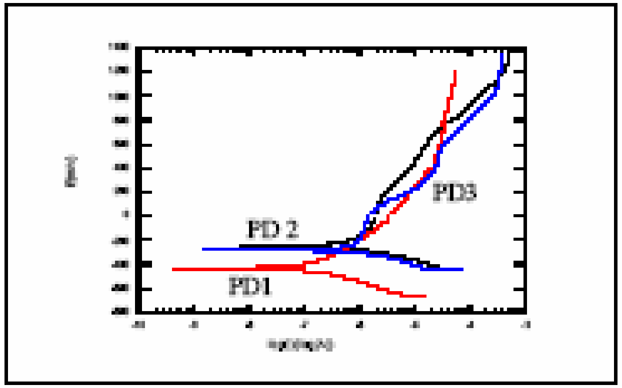




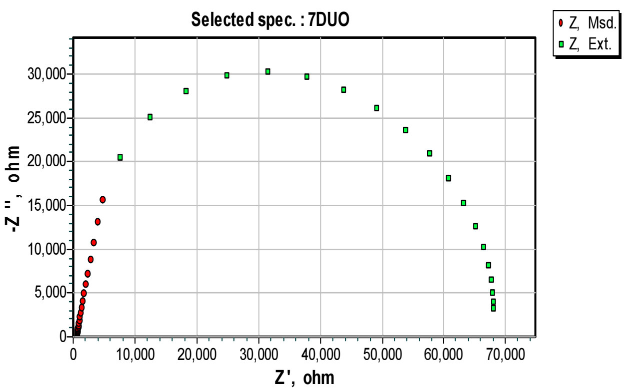




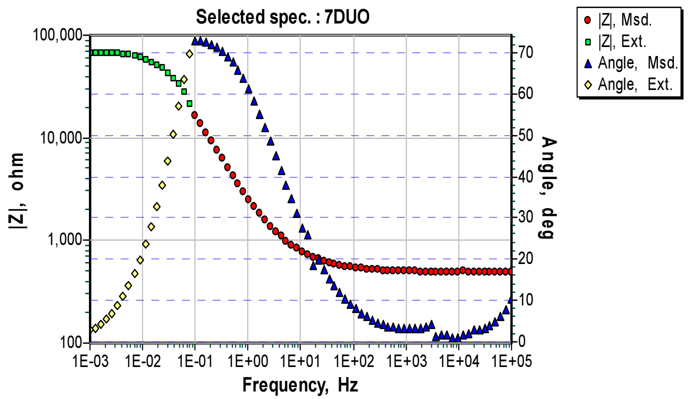
Corrosion of the CANDU 6 SG Materials in High Temperature Water



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



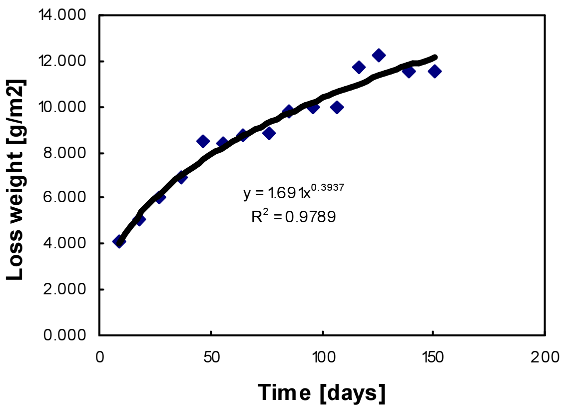
Nyquist curve for Iy-800 – as received

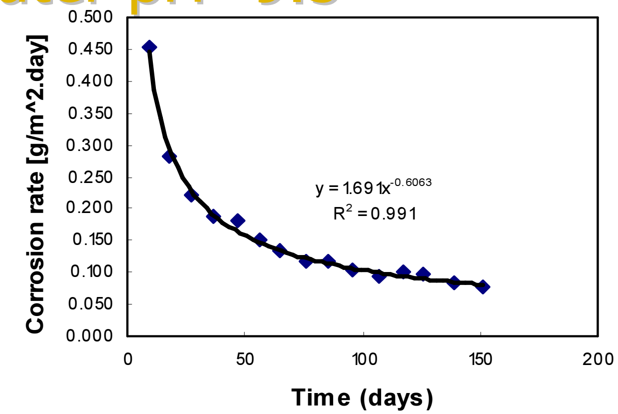


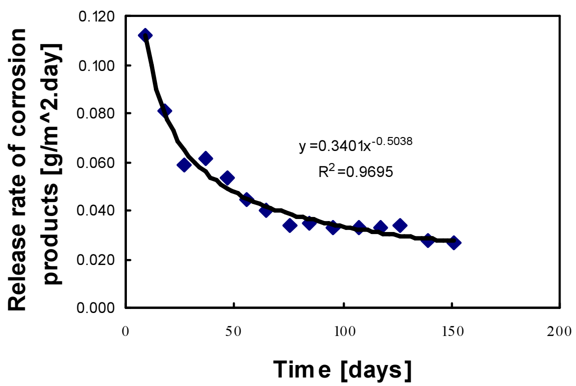
Bode and angle phase curves for Iy-800 – as received

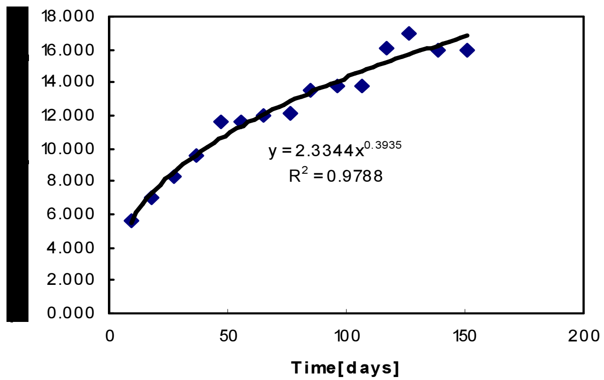
Corrosion of the CANDU 6 SG Materials in High Temperature Water

Carbon steel SA 508 cl.2 tubesheet material samples tested in demineralised water pH=9.5

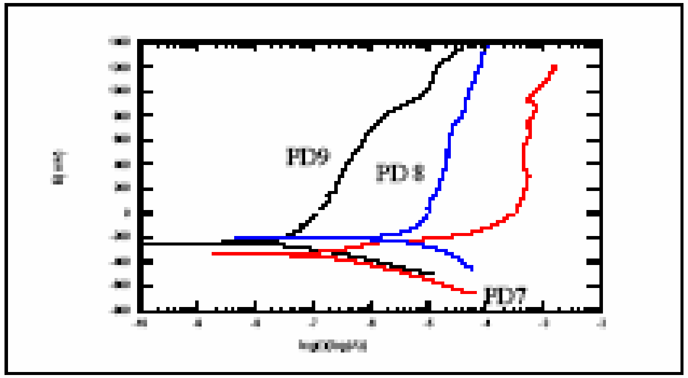




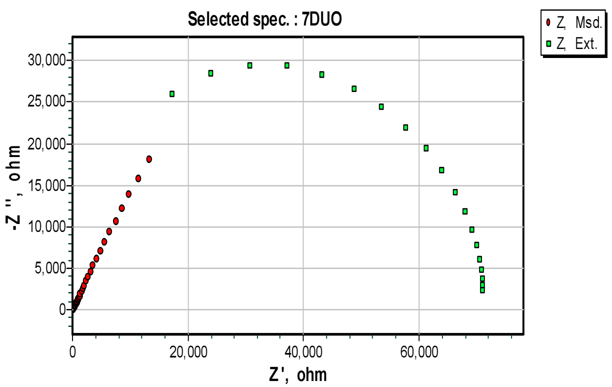




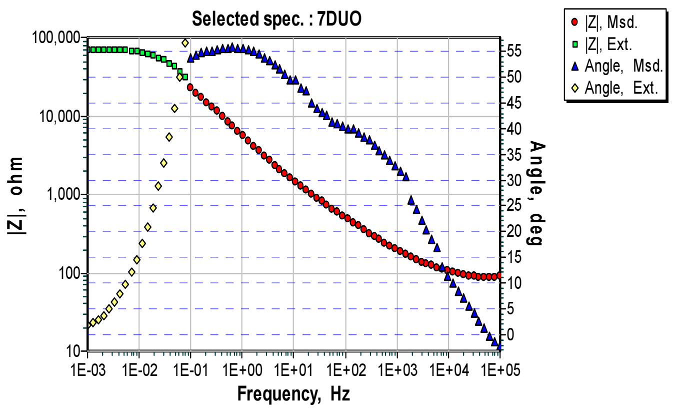
Corrosion of the CANDU 6 SG Materials in High Temperature Water



Potentiodynamic curves for SA 508 in demineralised water pH=9.5 (AVT)
PD7- as received;
PD8 – preoxidated 10 days;
PD9 – preoxidated 150 day



Nyquist curve for SA 508 – as received



Bode and angle phase curves for SA 508 – as received

NULIFE - the European NoE
"Nuclear Plant Life Prediction"

NULIFE

NUclear Plant LIFE Prediction
Network of Excellence

GOAL

Create a single organisational structure capable of working at European level to provide harmonised R&D in the area of <u>lifetime evaluation methods for structural components</u> to the nuclear power industry and the relevant safety authorities.

Coordinator: VTT

Participants:

<u>Contractors</u>
- VTT, Finland
- JRC, EC
- SCK-CEN, Belgium
- Serco, UK
- British Energy, UK
- EDF, FRance
- AREVA, Germany
- NRI, Czech Republic
- CEA, France
- Vattenfal-Forsmark, Sweden

<u>Associate Contributors</u>
- IMS, Bulgaria
- AREVA France
- IRSN, France
- EON, Germany
- IWM, Germany
- FZR, Germany
- GRS, Germany
- Siempelkamp, Germany
- MPA, Germany
- BZF, Hungary
- AEKI, Hungary
- ENEL, Italy
- LEI, Lithuania
- NRG, Netherlands
- INR, Romania
- CITON, Romania
- JSI, Slovenia
- CIEMAT, Spain
- Tecnatom, Spain
- OKG, Sweden
- Ringhals AB, Sweden
- Studsvik, Sweden
- Westinghouse, Sweden
- PSI, Switzerland
- Rolls Royce, UK
- Uni. Manchester, UK

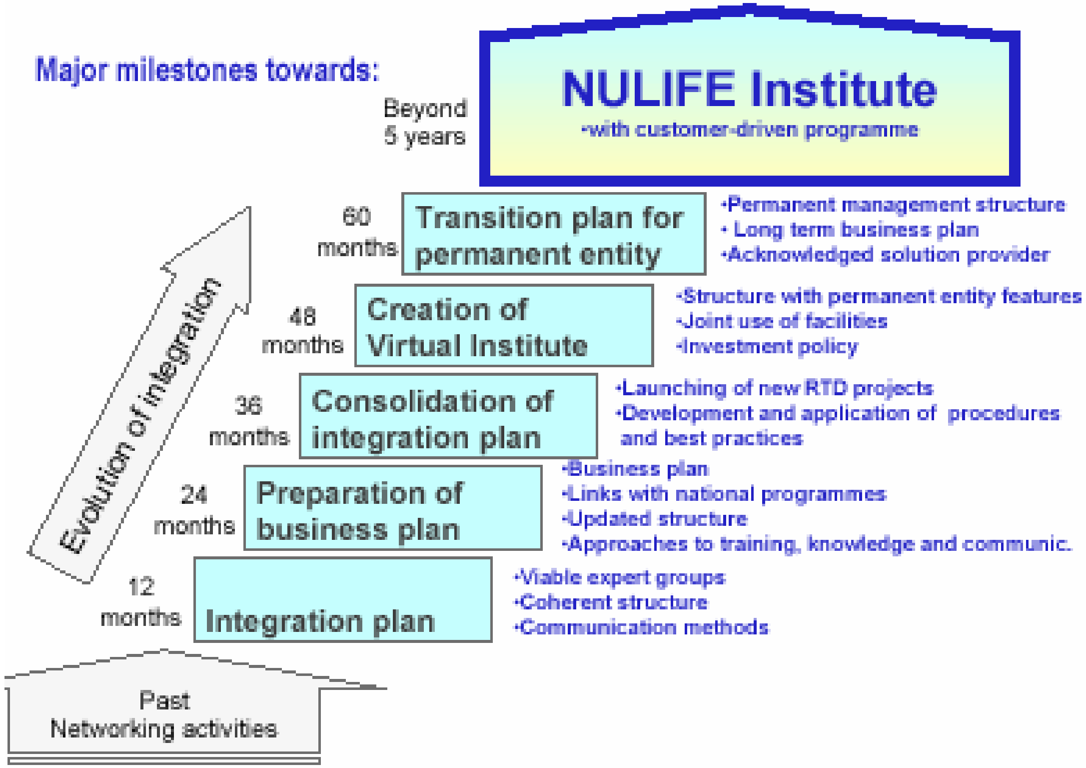
Aho-Mantila, R. Rintammaa, L. Heikinheimo, N. Taylor "*European research network aiming at harmonized nuclear plant life prediction procedures*", IAEA-CN-155/001, Shanghai, China, 15-18 October 2007.

NULIFE - the European NoE "Nuclear Plant Life Prediction"

INR Pitesti - Partner in NULIFE NoE

- **The Network of Excellence, Nuclear Plant Life Prediction (*NULIFE*) groups organisations of the EU member states, 1 Associated State and 2 new EU member Countries that are involved in nuclear power.**
- **The diversity of these organisations ranges from universities to power plant operators and from research institutes to designers and manufacturers.**
- ***NULIFE* is expected to impact the overall European skill base available in the area of residual lifetime technology.**
- **The network will provide a framework for continuing professional development of its personnel via targeted internal training, exchange of best practices and where appropriate mobility/exchanges.**

NULIFE - the European NoE "Nuclear Plant Life Prediction"



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

NULIFE - the European NoE "Nuclear Plant Life Prediction"

Process scheme of R&D priority identification

Target

Key expertise areas to be integrated

Materials and materials ageing	Assessment of integrity	Life Prediction	Safety and reliability	Design PLIM PSR
Needs Gaps Activities	Needs Gaps Activities	Needs Gaps Activities	Needs Gaps Activities	View of strategy: Discipline or Issue based approach
Results and Deliverables: -Ageing mechanisms -Ageing models -Degradation matrix	Results and Deliverables: -Assessment methods -Numeric -Data banks	Results and Deliverables: -Tools -Best practices	Results and Deliverables: -View of uncertainties -Acceptance criteria -Best practice concepts	Technical basis of qualified and harmonised set of procedures

Expertise and R&D road mapping

INR Pitesti – NULIFE

WP IA-1 “Mapping of partner RTD expertise and competences”

- Provide the INR expertise and competences in application of ageing management in CANDU 6 PLiM / PLEX programs

WP IA-2-3 “Lifetime evaluation”

- Provide advice on/develop the lifetime evaluation tools used by the INR
- Provide benchmarking of specific lifetime evaluation tools (experimental and analytical procedures, evaluation criteria...)

WP IA-2-4 “Safety, risk information and reliability”

- Review the practical applicability of various probabilistic methods for assessment of structural reliability, ageing and residual life of NPP components, and identify R&D needs in this area.
- Assess the limitations of structural component modelling in PSA and their importance for risk-informed decision making

CONCLUSIONS

- Over the past 6 years, INR Pitesti has been working on R&D Programs in support to CANDU 6 Lifetime Management.
- The INR R&D Programs in support to PLiM Program are focused on:
  - 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.
- NULIFE will be, in the future 5 years, the focal point for INR R&D activities in support to CANDU 6 Lifetime Management

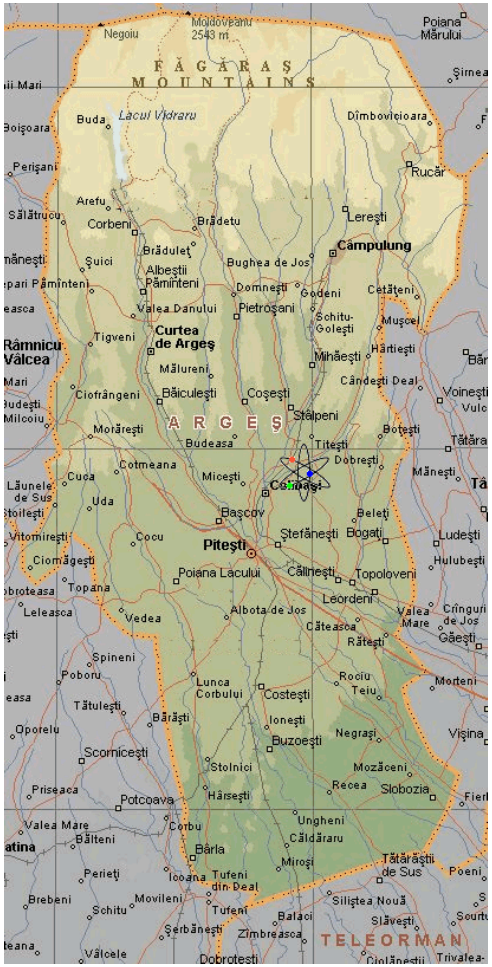
Institute for Nuclear Research Pitesti , ROMANIA

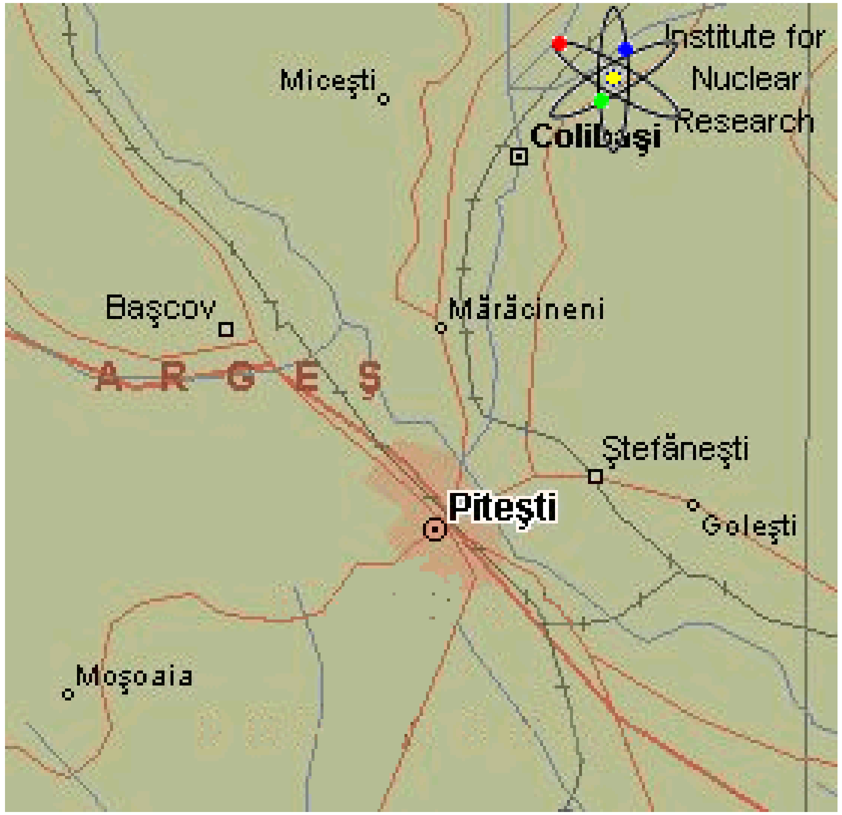
You are invited to visit our Institute for Nuclear Research – Pitesti , ROMANIA

Romania Map


HUNGARY
ROMANIA
MOLDOVA
BULGARIA
SERBIA
BESSARABIA
Black Sea
Miskolc
Nyíregyháza
Debrecen
Oradea
Arad
Timişoara
Reşiţa
Belgrade
Satu Mare
Baia Mare
Cluj-Napoca
Tîrgu Mureş
Suceava
Botoşani
Iaşi
Chişinău
Piatra Neamt
Bacău
Focşani
Galaţi
Brăila
Tulcea
Sibiu
Braşov
Petroşani
Rîmnicu Vîlcea
Tîrgovişte
Piteşti
Ploieşti
Buzău
Bucharest
Drobeta-Turnu Severin
Cernavodă
Constanţa
Mangalia
Ruse
Chernivtsi
INSTITUTE FOR NUCLEAR RESEARCH
CERNAVODA NPP

Arges Region Map





Thank You!