UNENE
University Network of Excellence in Nuclear Engineering
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Benefit Report submission to UNENE

November 2013 - December 2016

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Executive Summary

This benefit report covers the period from November 2013 to December 2016 and reviews all UNENE aspects as they relate to its defined objectives. The objectives assessed are the establishment of research programs in key areas of importance to industry, supply of Highly Qualified Personnel (HQP) to meet industry needs and the creation of a pool of scientific experts for consultation by industry and government when required.

In addition to the three key objectives the report reviews the status of funding, additional funds leveraged, scientific publications. The work summarized in the report demonstrates how university based research plays a role in the evolution and support of the national policy of NPP design and continued safe operation.

Industry research funding is 100% leveraged by NSERC to the level of $1.67M per year. Additional leveraging of research funds continues amounting to an additional $2.9M through individual efforts by researchers at various UNENE universities (e.g. McMaster, RMC, UWO, etc.). These grants are from many organizations noted in section 2.1

Research programs in UNENE universities bring a wealth of knowledge to industry and advances in the following knowledge areas:

1- Nuclear Materials: Research data from the Nuclear Materials IRC Program (Queen's University) is used by industry for validation of the Fitness for Service Guidelines (FFSG) codes used for Fuel Channel Inspection

2- Fuel channel creep: Creep models are also updated by industry (Kinetrics) based on newly developed understanding of the Queen's program

3- Modelling of Severe Accident (SA) phenomena in Candu cores along with analysis &validation through experimental results (McMaster). This work continues in support of substantiating limits of In Vessel Retention (IVR) for CANDU cores. The IVR is the basis of severe accident mitigation in current and future CANDU plant designs and licensing. Ongoing research in this area leads to optimization of SA heat sinks for post-accident mitigation guidelines, operator grace period and optimized heat sink mitigation strategy while crediting and confirming current plant heat sinks

4- Restoration of plant operating margin and its quantification is ongoing through the application of advanced Thermalhydraulic modelling and experiments, also at McMaster. Experiments to date from the CHF (Critical Heat Flux) facility are yielding data for full characterization of CHF under high pressure and high temperatures transients and other reactor operating conditions. Data validation continue to improve modelling in support of margin quantification. Technical support is ongoing by the IRC on Advanced Thermalhydraulics towards validating new computational toolsets/methodologies in support of Refurb/ Long Term replacement planning by industry

5- The application of a probabilistic based methodology continue to derive a risk based inspection and maintenance program for critical NPP equipment. This methodology is developed under the UNENE Research Chair program at the University of Waterloo and has been successfully applied to other key plant components industry wide. This methodology integrates actual component inspection data and mechanistic models on component degradation mechanisms into a probabilistic based methodology to derive a risk based approach to component replacement or maintenance

In addition to the above knowledge transfer from the Waterloo IRC to utility staff has also been successfully done through the delivery of advanced training courses on Risk and Reliability. This knowledge and technology case has been one of the key successes of this IRC program.

Other ongoing research that will result in advances in knowledge with potential benefit to future operations and refurbishment are:

a) A new methodology is developed for generating Floor Response Spectra (FRS) resulting in reduced time and effort to generate & analyze in a preliminary design. A complete methodology is being completed for producing a probabilistic based set of FRSs for detailed seismic analysis design

b) Development of mixed field dosimetry for TEPCs including its redesign for manufacturing and simplicity. New research has also started in 2015 for improved understanding of long term radiation impact on non-human biota. This is based on current research on fish species undertaken by the Research Chair on Radiation Physics and Environmental Safety at UOIT

   Attention has also been directed to the recently emerging issue of eye dosimetry resulting from the expected lowering by the CNSC of the annual eye-dose limit from 150 mSv to 20 mSv

c) ALARA (As Low As Reasonably Achievable) improvements for equipment maintainability is expected based on an ongoing development of a robot (at UOIT) equipped with radiation detectors and 3D mapping of rooms/areas along with a capability of identifying hot spots in such areas to reduce /optimize dose and durations during maintenance

d) Recommendation on the corrosion susceptibility of Steam Generator Tubing (Alloy 800 and 600) under various operating and shutdown conditions for avoidance of potential corrosion during shutdown and layup conditions (University of Toronto)

e) Development of a Transient Eddy Current (TEC) probe technology for inspection of equipment internals with tight configurations such as Steam Generator (SG) Tube - Tube support area, Pressure Tube/ Calandria Tube gap (PT/CT gap) and CT/ LISS (SDS2) nozzle gap (RMC)

f) Research continue the applications of wireless communication technologies to NPPs. If successful this will reduce cable runs and their installation and will reduce commissioning of plant control and instrumentation. Testing and development of robust radiation resistant wireless instruments continue through the I&C IRC Prof. Jiang at Western University

The previously reported leveraged funding of $43M in 2007-2009 has been used in this period towards the establishment of new research facilities in universities and acquisition of modern equipment to sustain an increased scope of research and number of graduate students. Below are some notable examples with additional details in section 2.2 of the report:

a) The Queen’s University Reactor Material Testing Lab (RTML) building at Queen’s University
b) A new Center for Advanced Nuclear Systems (CANS) at McMaster

Training and development of HQP for potential deployment by industry is one key objective of UNENE. The complement of graduate students in the various UNENE research programs has been steady during this reporting period to a typical level of nearly 130 students who are at various phases of their research programs. Some of the past graduates have been successfully recruited by industry, national labs, government and academia within Canada and internationally. Details are depicted in section2.3 of the report.

Publishing of the “The Essential Candu” a textbook that document the scientific basis of the Candu-HWR technology. The project was funded under a Candu Owners Group (COG) Joint Project with contributions from Candu utilities in Canada and offshore.

Researchers/industry interactions/consultations and technical exchanges continued during this period through workshops, meetings and COG technical committees. Details are noted in Section 3 of the report.

An increased national and international profile of nuclear research in Canada is noted from the sustained level of journal publications and conference papers. Details on various publication types are noted in section 4.3.

The UNENE Education program continued to offer both an M. Eng. and a Diploma program in Nuclear Engineering. The latter program was introduced in 2015 with a four course for a shorter path for professionals interested in enhanced knowledge in their respective core competency area

This review confirms that to date, more than a decade in existence, this partnership has grown and steadily progressed to become a mature and well respected partnership with notable achievements in both program areas; Research and Education. Review of aspects of UNENE shows continuing trends of additional secured funds leveraged from industry /NSERC funding of UNENE research.

Development /training of Highly Qualified Personnel (HQP) continue to be key in addressing demographic gaps experienced by industry and shortage of scientific personnel and engineers for currently planned Refurbishment /licensing.

1.0 Introduction

This report examines the value derived by industry partners from UNENE research and education programs with focus on the last three years from November 2013 to December 2016.

UNENE was established in 2002 as a partnership between industry and universities with the objectives of:

- Sustaining university research in key areas of interest to industry
- Developing a sustainable supply of HQP to address industry needs
- Providing independent scientific expertise for public and industry consultation

The report will examine the value of research with regard to advancement of knowledge, and its benefit to industry and supply of Highly Qualified Personnel to meet industry needs.

The education program for an M. Eng. and Diploma degrees in Nuclear Engineering will also be reviewed.

2.0 Value of Research

UNENE research programs in the last three years were undertaken by the following IRCs and their teams of graduate students, Post-doctoral fellows and senior undergraduates. Current research programs under the leadership of IRCs are in the following area of the nuclear technology:

- Nuclear Safety Analysis & Thermal hydraulics (McMaster)
- Nuclear Materials (Queen's)
- Corrosion and Material Performance in NPP systems (Toronto)
- Risk-Based Life Cycle Management (LCM) of NPP systems (Waterloo)
- Control& Instrumentation and Electrical systems (Western)
- Health Physics and Environmental Safety (UOIT)
- High Temperature Chemistry of D2O aqueous solutions (Guelph)
- Radiation induced corrosion in reactor Materials (Western)

The establishment of Industrial Research Chairs (IRCs) serve as an anchor /nucleus for well-established research programs, teams and facilities. The outcomes discussed below are advances in nuclear knowledge, training and development of highly qualified personnel (HQP) and leveraging additional funding used to establish state-of-the-art labs and equipment.

2.1 Leveraging Additional Funding and Knowledge

Industry research funding is 100% leveraged by NSERC to the level of $1.67M per year. Additional leveraging of research funds continues amounting to an additional $2.9M through individual efforts by researchers at various UNENE universities (e.g. McMaster, RMC, UWO etc.). These grants are from many organizations such as;

- Nuclear Waste Management Organization (NWMO)
- Candu Owners Group (COG)
- Canadian Fund for Innovation (CFI)
- Ontario Research Fund (ORF)
- Canadian Nuclear Safety Commission (CNSC)
- International ones such as EPRI

To support operation of the new facilities (RMTL&CANS) additional funding was secured from the CFI&IOF to the amount of $0.685M/year for operational support to the newly operational facilities; RMTL and CANS. The funds ensure a fully operational set of labs and equipment for the continuous progress of research programs and an increase in number of graduate students.

2.2 Equipment and Research Facilities

Leveraged one time funds (in 2007-2009) from federal and provincial agencies have been used towards the establishment of the two new research facilities increasing both the scope of research and number of graduate students.

These facilities are noted below:

1- The Reactor Material Testing Lab (RMTL) at Queen's University (Figure 2.2.1)

This new facility now built and operational has a 4 MV tandem proton accelerator, two new electron microscopes and other testing equipment. The proton accelerator will be used to introduce degradation into fuel channel materials at the microstructure level, simulating radiation and stress (creep, DHC, flaw etc.) introduced as a result of in-reactor conditions and to further characterize key degradation mechanisms experienced in materials, as well as investigating potential modification and improvements of materials. These results will be used to expand our understanding of CANDU fuel channel materials, and increase industry capability to characterize Fuel channel irradiation induced degradation mechanisms. Along with the accelerator and the two state of the art shielded test chambers other equipment are part of the facility these are:

a) a computer cluster for calculating the damage morphology in alloys
b) a sophisticated TEM lab built in-situ heating, straining, 3D construction and low background measurement capabilities, considered as unique equipment in Canada

Funding to establish the facility was obtained from the Canada Foundation for Innovation (CFI), the Ontario Ministry of Research and Innovation (MRI) and Queen's University.

Figure 2.2.1 Photograph of the Accelerator at the Reactor Material Test Lab (Queen's U)

2- The other major research Lab facilities built from grants and is currently operational is the Centre for Advanced Nuclear Systems (CANS). This centre is comprised of four primary facilities namely:

   a) Post Irradiation Examination of Nuclear Materials (McMaster University)

   b) Nuclear Materials Characterization Facility (McMaster University)

   c) Thermal Testing Facility (McMaster University)

   d) Health Physics Dose Response Facility. Located at University of Ontario Institute of Technology (UOIT) and is fully operational by the IRCs and their team

These facilities provide a suite of irradiated material handling and testing facilities and equipment; a thermal testing laboratory (at McMaster); and a radiation dose laboratory (at UOIT). This infrastructure, together with the McMaster Nuclear Reactor and the Canadian Centre for Electron Microscopy, provides a world class materials and thermal testing centre unique in North America. The project was supported by most Canadian nuclear energy related companies (OPG, Bruce Power, AECL, and Kinectrics) as well as a number of leading international organizations (EPRI, EdF, Bechtel). The McMaster Post Irradiation Examination (PIE) hot cell facility is the only one of its kind at a university world-wide (see Fig.2.2.2). This infrastructure, together with the McMaster Nuclear Reactor and the Canadian Center for Electron Microscopy, provides a world class materials and thermal testing center unique in

North America. The project was supported by a majority of Canadian nuclear energy related companies (OPG, Bruce Power, AECL, Kinectrics) as well as a number of leading international organizations (EPRI, EdF, Bechtel). In addition, Dr. Novog received a $275k CFI - Leaders Opportunity Fund grant for a Phase Doppler Anemometer System for thermalhydraulic experiments.

Figure 2.2.2 CANS PIE Hot Cell Facility nearing completion

3- The Control and Instrumentation IRC program under Professor J. Jiang of Western University has also established a suite of state of the art research facilities to support research activities and provide hands-on training for the team. some of the existing facilities before the 2013-2016 have been upgraded in support of new research. The main improvement in 2014 is the commission of the NPCTF, and fully instrumented with Wireless HART sensor nodes. A summary of the major facilities is listed below:

- Darlington NPP simulator (OPG in kind contribution)
- Tricon v9 safety system
- HFC 6000 safety system
- HFC non-safety DCS
- FPGA development systems
- Siemens PCS 7 redundant DCS control system

- Honeywell C-300 DCS
- Emerson DeltaV DCS with full fieldbus connectivity
- Hardware experimental test bench
- Wireless monitoring nodes with Wireless HART, ZigBee protocols, and
- Smart sensor development systems
- Nuclear Process Control Test Facility (NPCTF)

4- Under the IRC/AIRC (A. Waker/E. Waller) for radiation Physics and environmental Safety a considerable effort and funding was deployed to establish the following research facilities in support of a comprehensive program. the facilities established are:

- A Mixed Field Dosimetry Lab
- Aerosol Lab
- Animal Care Facility

5- A High Temperature furnace facility was built (at Western U) for the steam/H2 oxidation experiments simulating SG primary side conditions (conducted for a CRD research project). This steam/H2 facility is being used by Prof. Newman (IRC at UofT) in his ongoing research on internal oxidation of several nickel -based alloys and the potential for accelerated (galvanic) corrosion.

The same facility was used by CNL research for formation of oxide films under different humidity levels.

2.3 Training and Development of Highly Qualified Personnel (HQP)

Training and development of HQP for potential deployment by industry is one key objective of UNENE. The complement of graduate students in the various UNENE research programs grew from the early years to a typical level of nearly 130 students who are at various phases of their research programs. Some of the past graduates have been successfully recruited by industry, national labs, government and academia within Canada and internationally.

The bar chart below (2.3) depicts a typical distribution of HQP in different research programs.

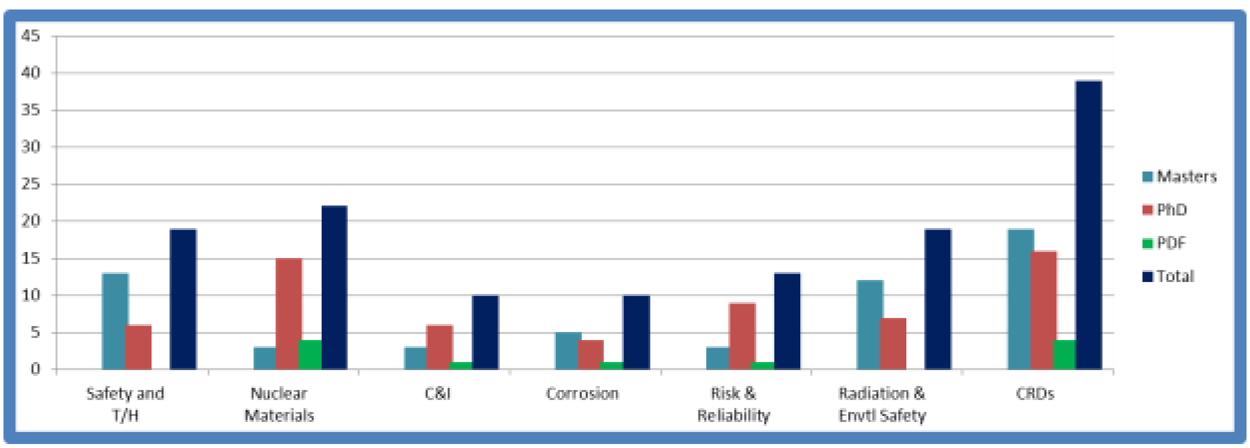


Figure 2.3 Current HQP 2013-15

2.4 Advances in Nuclear Knowledge and Technology Transfer to Industry

Research programs in UNENE universities bring a wealth of knowledge to industry. This framework of university/industry cooperation aligns Canada with other nuclear technology exporting countries (such as the U.S., France, Russia, South Korea & China) where university based research plays a role in the evolution and support of the national policy of NPP design and continued safe operation.

Such program brings advances in the following knowledge area:

2.4.1 Advances in Nuclear Materials

The focus of research at Queen's on Nuclear Materials is to understand the anisotropic behaviour of pressure tube material, over a wide range of crystallographic textures and microstructures and to relate this to the elongation of pressure tubes, their increase in diameter, their sag and their fracture characteristics. The research currently concentrates on the effect of manufacturing variables on the properties microstructure and texture of pressure tubes, the anisotropic creep of Zr-2.5Nb, the plastic anisotropy of Zr-2.5Nb, Zircaloy-2 and Excel alloy (Zr-3.5%Sn,1%Nb, 1%Mo), the behaviour of hydrides in bulk Zr-2.5Nb, delayed hydride cracking of Zr-2.5Nb.

During this reporting period, the focus continued on irradiation damage and its effects of properties of Zr alloys. This latter area will be a significant part of the Chair program in the future. Additional effort was extended to study of fuel channel spacer materials, as part of the understanding of overall fuel channel health.

Key highlights in this period are:

- Fuel Channel Spacers (Inconel-X750) degradation

Significant advances have been made in the past two years in the study of elemental segregation. This work has included Nickel X750 spacer materials, with a focus on understanding the contributing factors towards irradiation induced embrittlement, as well as elemental redistribution in Zr2.5Nb pressure tube material. Prof. Daymond and Yao continue to expand program expertise in the area of ion irradiation as a tool to explore the effect of neutron irradiation.

Recent crush tests on the ex-service spacers showed that a high dose of neutron irradiation in the CANDU flux spectrum reduces the strength and ductility of the material significantly compared to properties prior to insertion in the reactor. The underlying mechanisms remain unclear though it is undoubtedly associated with the radiation damage.

Heavy ion irradiation has been used as an analogue of neutron irradiation over a wide temperature range to understand the mechanisms involved in this property degradation. The irradiation was conducted not only with single ion-beam irradiation, but also with in-situ heavy ion irradiations with hot/cold pre-implanted helium to elucidate the effects of transmutation produced helium on irradiation induced cavity and dislocation microstructures.

TEM characterizations demonstrated that irradiations significantly altered the stability of the primary strengthening phase of the superalloy, and further that helium was found to play an important role in the irradiation-induced instability of the material. The most important defect structures induced from irradiation were recognized as stacking-fault-tetrahedra (SFTs), interstitial loops and cavities. The role of helium segregation to the grain boundary as an embrittling mechanism, and the conditions under which it occurred, were clarified.

This work complements the study of ex-service spacers and neutron irradiation studies in helping to elucidate the mechanism of degradation of Inconel-X750 CANDU spacers.

- Effect of hydrides on irradiation of pressure tube material.

The pressure tube (PT) being the primary pressure boundary for coolant in the CANDU design is susceptible to delayed hydride cracking (DHC), reduction in fracture toughness upon hydride precipitation and potentially hydride blister formation. The morphology and nature of hydrides in Zr-2.5%Nb with 100 ppm hydrogen was investigated using transmission electron microscopy (TEM). The high-quality images available in modern TEMs has enabled greater understanding compared to what was available using older tools. It was also found that the presence of hydrides changed the irradiation induced decomposition of the β phase; this is the first time that this has been observed, and is believed to be due to the interaction between H and vacancies. A particularly interesting effect is that of hydrogen on the irradiation induced redistribution of Fe; Fe is widely redistributed from the β phase into the α phase in the un-hydrided material, however, the loss of Fe from the β phase and subsequent precipitation is retarded in the hydrided material. These effects appear to be due to the interaction between alloying elements and vacancies produced during irradiation. This work suggests that there are differences in the irradiation induced microstructural evolution of Zr based alloys when Hydrogen is present. Figure 2.4.1 below depicts some details

Queen's is working with Kinectrics on studying DHC in high (>100wppm) hydrogen content pressure tube material, as well as alternative approaches to hydrogen solubility measurement. This has impact on end-of-life pressure tube conditions, and in our ability to predict how long the pressure tubes can continue to operate. In addition, we are working with Kinectrics to provide mechanical test data on proton irradiated Ni X750 spacer material. This has significant impact in understanding potential for spacer embrittlement, and hence in predicting maximum life for fuel channels.

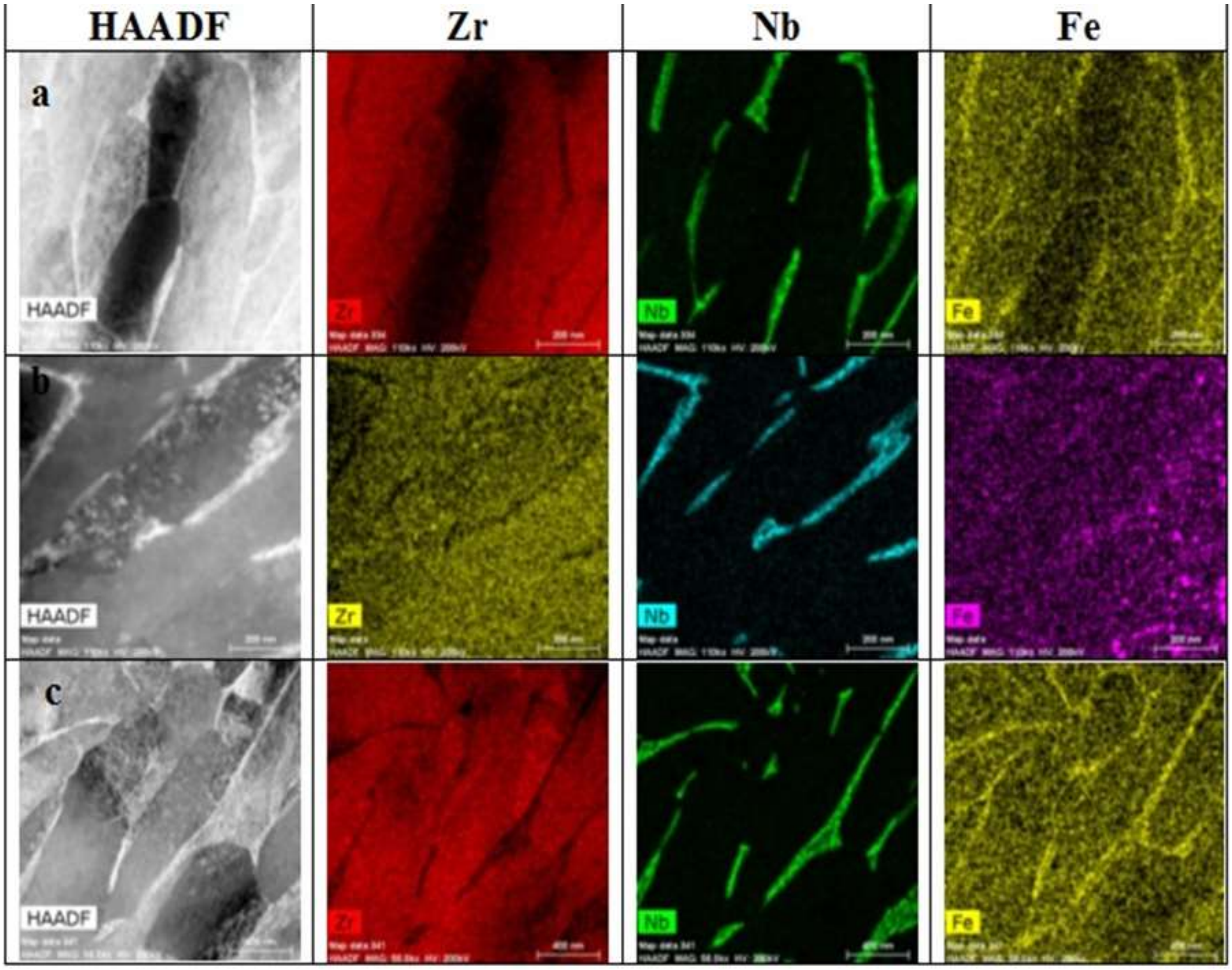


Figure 2.4.1 Grain boundary structure and chemistry of (a) unhydrided unirradiated Zr-2.5Nb, (b) unhydrided Zr-2.5%Nb irradiated to 10 dpa (by heavy ion irradiation), (c) Zr-2.5%Nb-100ppmH irradiated to 10 dpa. Of particular note, the Fe in b) is redistributed by the irradiation, while it remains in the beta phase in the presence of hydrogen c)

The Queen's RMTL TEM has also been used by CNL for a number of COG projects. These take advantage of the unparalleled chemical mapping capabilities of the Queen's TEM, and include:

- Chemical characterization of elemental distribution at crack tips in stainless steel alloy 800 after Stress Corrosion Cracking (SCC). Alloy 800 (Fe-35Ni-21Cr) is currently used for steam generator tubing The TEM EDX characterization is in particular trying to study the mechanism of minority element assisted stress corrosion cracking by using FIB milled thin foils containing cracks
- TEM characterization of neutron irradiated pure Ni and Inconel X750. The materials have been irradiated at low and high temperatures at the NRU reactor in Chalk River. Neutron irradiation induced defects (dislocation loops, stacking fault tetrahedrals), and voids were observed to see the effect of temperature on their size

and distribution. The effect of temperature on the disordering of gamma prime precipitates in X750 was also characterized.

2.4.2 Advances in Safety Analysis Methodology, Codes, Model Development and Understanding of Phenomena (McMaster University)

The research program under Drs. J.Luxat and D.Novog (IRC/AIRC) at McMaster is multidisciplinary in nature and has two key technical focus areas:

- Enhancing Nuclear Safety and Nuclear Safety Analysis and
- Support the Development of Severe Accident Analysis Methodology and Accident Mitigation

Prof. Luxat's program continued with modelling of Severe Accident (SA) phenomena in Candu cores along with analysis &validation through experimental results.

Knowledge derived from the current severe accident research program is key to designing mitigating features in current and future plants. The fundamental knowledge_base for understanding severe accidents has been broadened by the chair program through the generation of new heat transfer data and mechanistic models. A key outcome in this regard is to demonstrate sufficient confidence in severe accident conditions that govern the 'in-vessel retention' (IVR) phenomena in Candu type reactors.

Prof. Novog's experimental facilities are aimed at restoration of NPP operating margin and its quantification. This is undertaken through the application of advanced Thermalhydraulic modelling and experiments. Experiments to date from the CHF (Critical Heat Flux) facility are yielding data for full characterization of CHF under high pressure and high temperatures transients and other reactor conditions. Data validation continue to improve modelling in support of margin quantification. In 2013/14 research outcomes from this program confirmed assurance of fuel channel integrity for a wide range of expected conditions of hot spots during accident scenarios. Experimental research on Critical Heat Flux and Post Dryout heat transfer under transient conditions provides needed data to support the safety case for operating power reactors

Experimental and theoretical research is driven by these two key ones in so far as addressing knowledge gaps and the need to quantify uncertainty in various thermal hydraulic and physics models & calculations. All aimed at formulating a validated set of mechanistic models governing different accident analysis

Other supporting research is also ongoing such as water quenching of hot horizontal tubes, molten corium-water interactions (steam explosions) and a separate effect CHF test facility to obtain CHF data for downward facing metal surfaces (representative of the bottom of the calandria vessel). All of those are of significant benefit in establishing severe accident mitigation and its key elements.

Technical support is also ongoing by the IRC on Advanced Thermalhydraulics (Prof. Novog) towards validating new computational toolsets/methodologies in support of Refurb/ Long Term replacement planning by industry

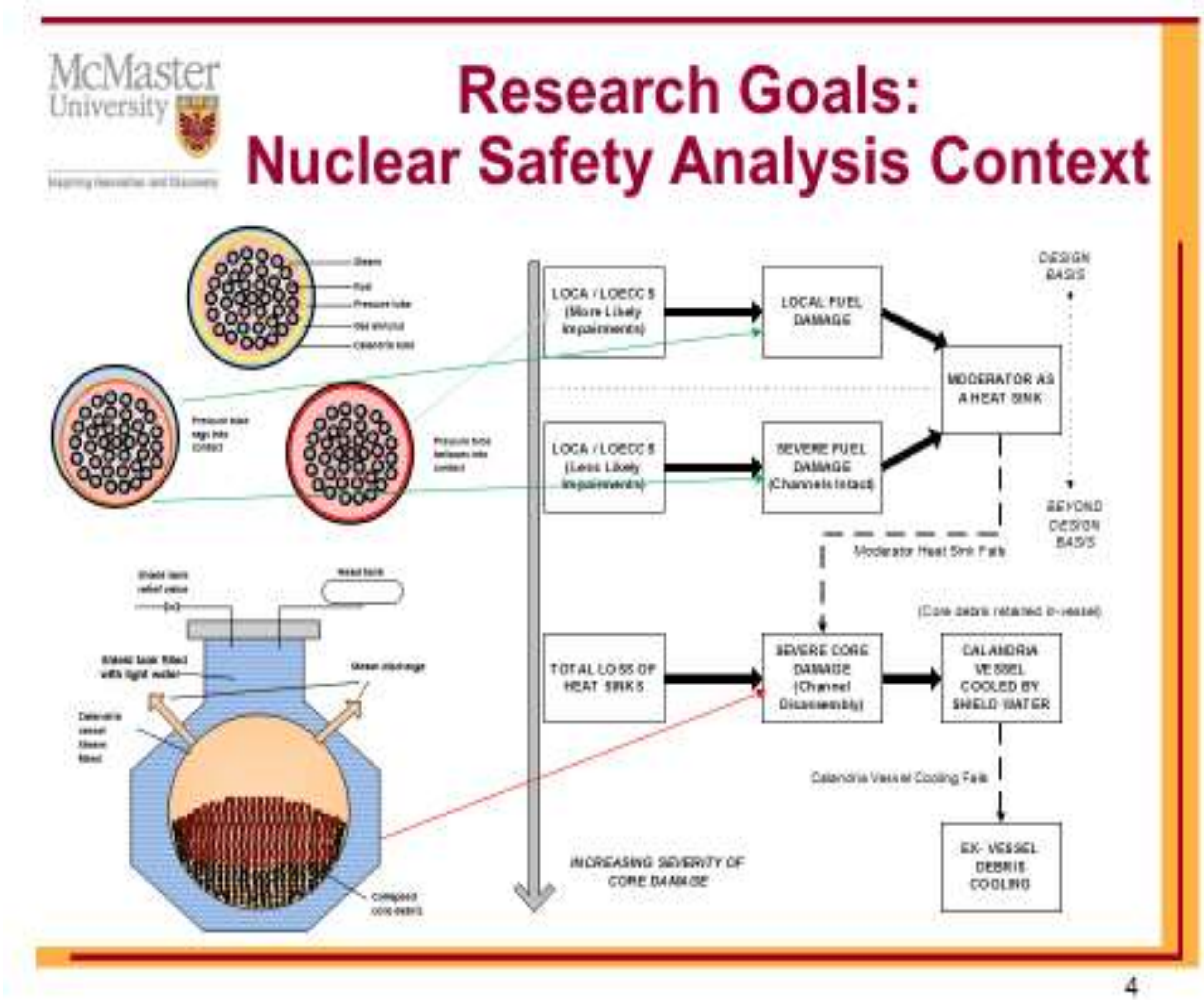


Figure 2.4.2 Severe Accident Research & Phenomena Characterization

2.4.3 Advanced Research in Control and Instrumentation Modeling, Simulation, Performance Monitoring and Diagnostics of Relevance to the Industry

This IRC research program has entered its third term of UNENE/NSERC research and covering a wide array of research topics related to instrumentation, control, and electric systems in nuclear power plants. With the financial support of UNENE and NSERC the research lab established under this IRC has become an internationally recognized centre of Excellence in Control, Instrumentation and electrical systems. To-date over 48 Highly qualified Personnel have been trained in this lab during their post graduate research, many of them are now playing important roles in the nuclear industry both in Canada and off shore.

One of the key areas that the IRC has been focusing on and is of interest to the Canadian industry is the post-accident monitoring and the applicability of wireless sensors inside containment post severe accidents.

Professor Jiang has developed a research plan to support progress in the development of a wireless based system for monitoring severe accidents in Candu NPPs. This plan also formed the basis of a proposal for additional funding submitted to ORF (Ontario Research Fund). The program covers John Luxat's portion on generated results & data for his severe accident phenomena research and Tony Waker on containment dose from SA releases.

In the last year, a standard based wireless sensor node (Wireless HART) was installed in the Nuclear Plant Control Test Facility (NPCTF), to acquire real time data for system performance monitoring purposes. this NPCTF facility is built to simulate the Nuclear island control system of boiler and pressurizer level control systems in response to conventional (turbine) side transients and vice versa. This facility has also been used for fault tree analysis, design for cyber security and insider attack, validation of a shutdown system based on HFC-6000 series instruments and development of a process fault diagnosis using wireless sensor network.

The overall research program of the IRC is depicted in Figure 2.4.3 below.

These research areas are divided into two themes: (1) Advanced Control Systems; and (2) Performance Monitoring, for NPPs. Monitoring systems are examined through the application of advanced technologies (fieldbus, wireless) for both normal and post-accident conditions Topics in this theme include: 1) wireless technologies for equipment health monitoring within a nuclear power plant, 2) smart devices for plant condition monitoring, 3) environment monitoring, and 4) radiation monitoring in a post-accident condition where radiation hardened wireless sensor technologies are parts of the investigation. The current wireless instrumentation research by Professor Jiang is formulated in response to post accident monitoring requirements inside containment in severe accident of interest to industry in Canada.

The scope of the program has also been extended with supplementary financial supports from CMC, CNL sponsored projects, an NSERC CRD grant, and the University Innovation Fund.

With this research, the IRC has maintained a presence through an IAEA related Coordinated Research Project (CRP). The CRP scope is to provide design recommendations for wireless technologies along with necessary tools for deployment in a NPP. The WSN system (Figure 2.4.3) of his research will be used to address the scope of the CRP.

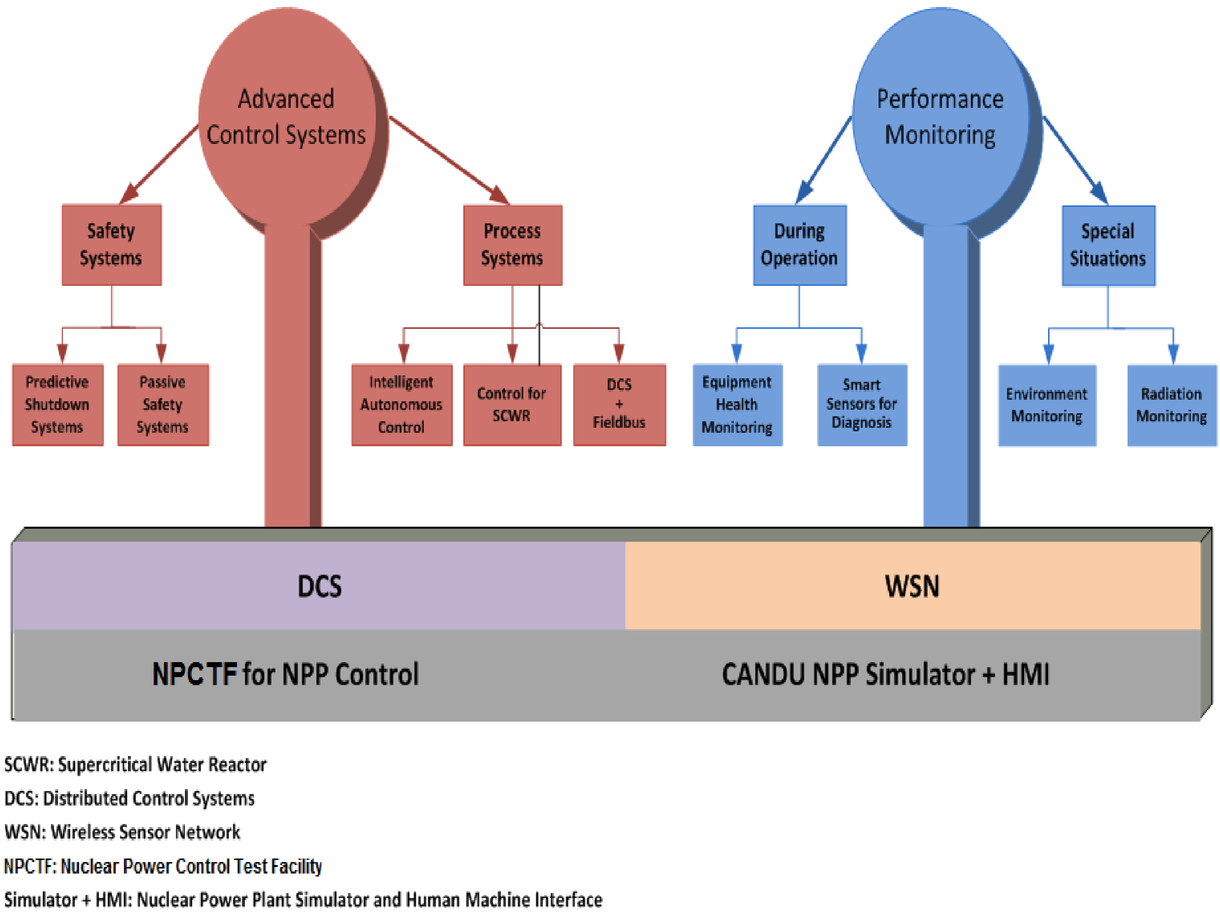


Figure 2.4.3 Research Activities under the IRC program for Control, Instrumentation and Electrical Systems

2.4.4 Advanced Application of Risk based Life Cycle Management (LCM)

The main objective of the Waterloo IRC research program is to

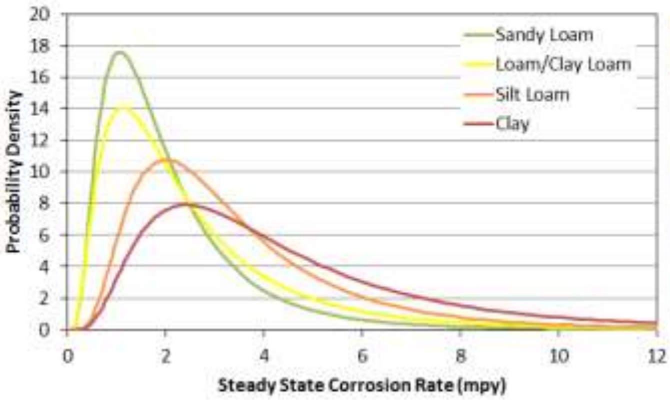
1- Improve life cycle management (LCM) of nuclear power plant (NPP) systems, structures and components (SSCs) through the application of advanced risk and reliability models developed under the IRC program. Develop probabilistic risk analysis models

2- Develop risk-informed approaches for FFS assessment

3- Solve a wide variety of practical problems related to reliability of nuclear plant systems Advanced methods of reliability analysis and statistical estimation are used to develop aging management for various plant components, site-wide hazard analysis and generation risk assessment. In previous years' applications have been developed for fuel channels, feeders, steam generators and other SSCs. Key industry projects completed during this period include NPP buried piping (cooling water pipes etc..), uncertainty analysis of Leak before Break (LBB) assessment of feeders and pressure tubes and fueling Machine reliability assessment based on OPG plant data. Details are noted below.

Probabilistic assessment of Corrosion of Buried Piping in Nuclear Plants

A sizable network of buried piping (cooling water etc.) in NPPS require detailed assessment studies as part of refurbishment planning.



	ALL	Clay	Silt Loam	Loam/ Clay Loam	Sandy Loam
Average	3.5	4.6	3.5	2.6	2.1
Median	2.7	3.7	2.9	2.0	1.7
%tiles					
80	4.9	6.5	4.8	3.7	2.9
90	6.8	8.7	6.3	5.2	3.9
95	9.0	11.1	7.8	6.8	5.0

mpy – mils per year

Figure 2.4.4.1 Distributions of steady state corrosion rates of carbon steel piping for different soil texture groups

The assessment done by the IRC included an analysis of existing long-term corrosion data from NPPS and other industries to estimate the probability distribution of corrosion rate in different environments and soil textures. Sample results for varying soil textures are shown in Figure 1. The key innovation in this work was the concept of steady state corrosion rate, which was fitted to the data using a two-step process involving a logarithmic transformation and regression analysis. The study results can be readily used for fitness for service assessment and structural integrity evaluation of buried carbon steel and cast iron piping in various soil types and conditions.

Uncertainty Analysis in Leak-Before-Break (LBB) Assessment

The leak before break (LBB) assessment of pressure retaining components, such as feeder pipes and fuel channels, is an important part of fitness for service assessment (FFS). In response to regulatory requirements, the nuclear industry has a great deal of interest in developing a consistent method for the uncertainty analysis of the output of LBB assessment. This IRC led project examined the currently available methods, such as two-stage Monte Carlo Sampling, and provided technically precise interpretation of results.

A sample analysis is presented in Figure 2.4.4.2, in which the uncertainty bounds are displayed for the probability of leak in a pipe. The bounds reflect epistemic uncertainty in the flaw growth rate.

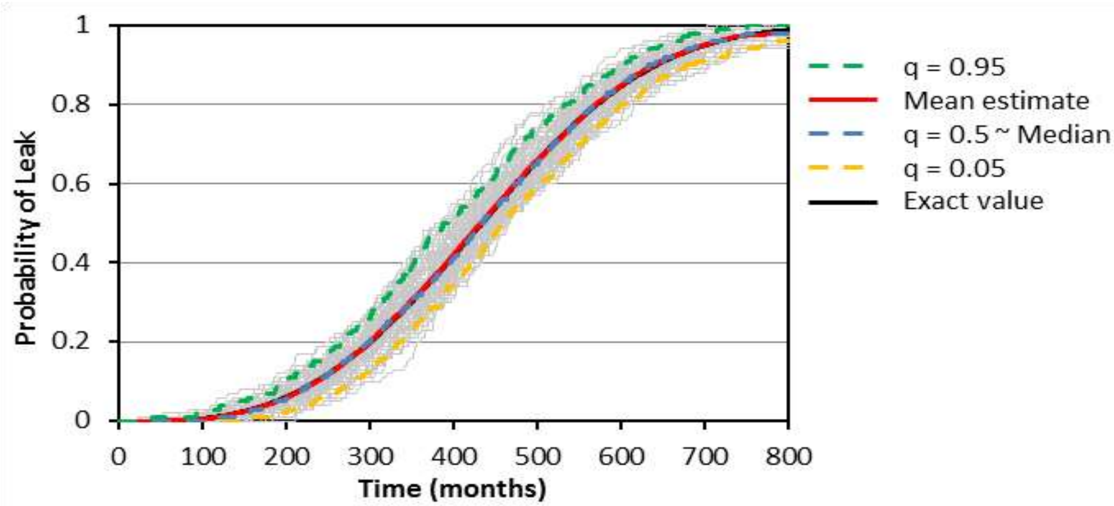


Figure 2.4.4.2 Sensitivity bounds on the probability of leak over time including the conditional mean, median and 5 % and 95 % limits, assuming epistemic uncertainty in the flaw growth rate

Other Industry Projects include:

- Probabilistic modeling of degradation of Inconel X750 spacers
- Reliability analysis of Fueling Machines
- Survival probability of fish eggs as a function of cooling water discharge temperature
- Prediction of creep deformation in CANDU 6 fuel channels
- Life cycle planning of Tritium Removal Facility

This chair program has particularly benefited industry in:

- Effective life cycle management of nuclear plant systems
- Risk-informed fitness for service assessment of reactor components and piping systems
- Improved communication with the regulator about managing the risk
- Minimize cost penalties associated with increased inspection and outage duration
- Overall improvement in operational efficiency and environmental compliance of nuclear power generation

2.4.5 Advancing the Understanding of Corrosion and Materials Performance in Nuclear Power Systems

A major part of the IRC research is focused on the mechanistic understanding of candu nuclear alloys and their behaviour at the atomistic level of their behaviour under in reactor conditions and during shutdown. in the last few years additional focus was given to corrosion of steam-generator tubing alloys 600, 690, 800 to support improvements in corrosion prediction and its mitigation in current plants. The long-term performance of, SG tubing Alloy 800 in most CANDU plants is the focus of numerous research programs; one at the IRC facilities and in conjunction with Western University (an ongoing CRD). These programs are focused on gaining insights into corrosion and cracking of that material have been carried out, including atomistic simulations of alloy corrosion. Such simulations, supported by appropriate experimentation are one of six areas highlighted in the IRC renewal proposals noted below.

1) Studies of stress corrosion cracking (SCC) in nuclear materials with current focus on a particular dissimilar weld in candu
2) Steam generator chemistry and corrosion
3) Surface modification for corrosion resistance
4) Science underpinning the monitoring of used fuel storage containers

This Chair program and the close collaboration resulting from it has been of significant benefit to OPG and the broader industry sector, through improved understanding of degradation mechanism in both new materials and in aging components. This has allowed OPG to better manage existing major components, such as steam generator tubing, feeders, pressure tube spacer springs and the calandria vessel. The Chair has also made significant contributions to the radioactive waste management program, including technologies for condition monitoring of dry fuel storage containers and other waste packages. The IRC continues to develop highly qualified personnel who have found employment within the industry. Through their participation with the IRC, significant knowledge transfer to OPG technical staff continues to accrue, for both experienced and more junior personnel.

In the last two years' work continued to progress in the area of mechanistic studies of stress corrosion cracking in steam generator tubing alloys and their model-alloy counterparts. The IRC along with his research associates have also achieved an improved understanding of the factors controlling the remarkably effective performance of Alloy 800 in high-temperature aqueous environments. This is timely, in view of the increased international interest in this material, with regular conferences being held in Toronto. In fact, the international interest is less concerned with steam generator tubing than with the potential of Alloy 800 to replace ordinary austenitic stainless steels for piping and ancillary core structures in pressure-vessel types of reactor. Canadian experience with this material is a major factor in this growing activity.

Also work on specific candu dissimilar metal welds in the outlet feeder orifices (Alloy 690 and Carbon Steel Alloy 82) in a similar environment revealed features which help explain the PWSCC resistance observed in these alloys at in- reactor conditions. Alloy 690 forms an external, protective Cr-rich oxide at grain boundaries which impedes intergranular oxygen diffusion; oxidation processes identified in Alloy 690 are shown in

. Similar work is currently underway on Alloy 800. Also, a recent proposal with CNL was accepted that will allow for exposures in a high temperature primary water loop for comparison with the simulated 480 °C hydrogenated steam environment. Initial TEM work supports the idea that the 480 °C environment is a valid accelerated simulation of extended primary water exposure, with very similar grain boundary oxide chemistries.

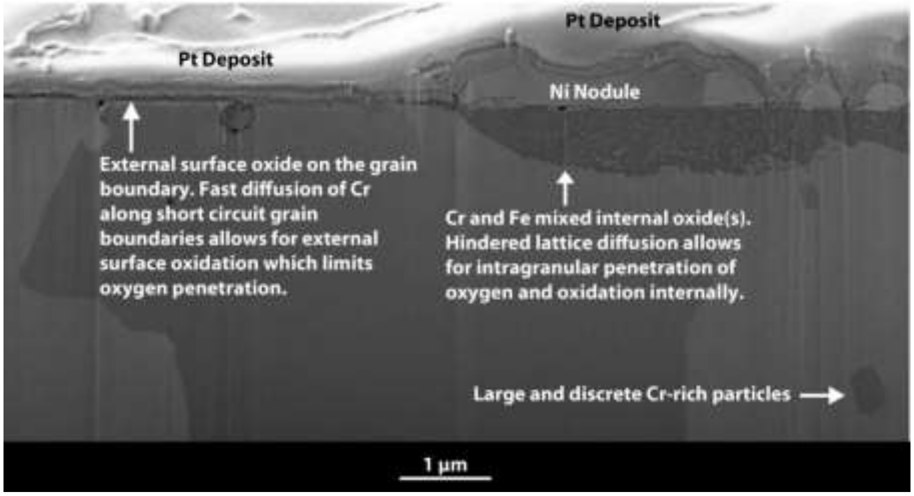


Figure 2.4.5 A high resolution SEM image highlighting the features of interest in a FIB trench in Alloy 690 after exposure to hydrogenated steam at 480 °C. The processes of external surface oxidation on grain boundaries and internal intragranular oxidation are described

As result of the recent course of the Chair program OPG has realized a number of significant benefits:

1- Identification of the mechanistic and microstructural basis for the resistance to cracking of dissimilar metal welds at the reactor outlet feeder flow orifice devices; this averted the need for extremely costly (>50 M$) inspection or replacement work.

2- Developed advanced methods to probe crack tips for the presence aggressive species (e.g. sulphur, halogen, lead); this is highly relevant to early detection (and mitigation) of potential degradation processes in steam generator tubing and so extend the service life of these major components 3) Provided insights into volumetric dealloying of Monel 400, which has recently emerged as a new, localized degradation mechanism in the Pickering steam generators; the causative factor(s) have not yet been definitively identified but some short-term scoping test in progress in Dr. Newman's laboratory are expected to help identify the cause.

2.4.6 Improved Dose Measurement, understanding and Communication of Dosimetry and Health Effects

This IRC is one of the last ones established in the first generation of IRCs (Sept 2008) at UOIT under the leadership of Dr. A. Waker (IRC) and Dr. E. Waller (Associate IRC).

In the last couple of years continued to develop its radiation research infrastructure. during 2014, additional equipment was installed. a nested neutron spectrometer was made under the Queen's RMTL accelerator (CFI grant) and expertise has been established in using this device for neutron spectrometry and dosimetry. Currently the research is made up of
A Mixed Field Irradiation facility, an animal care facility, an Aerosol lab and an Electron Paramagnetic Resonance (EPR) dosimetry lab.

Key industry benefits are the establishment of instrument testing based on neutron and photon dosimetry compliance, demonstrate compliance of environmental release pathway endpoints on non-human biota through studies of effects on fish and reference animal and plant (RAP).

Research Highlights/Outcomes

The IRC (Dr. Tony Waker) research program continues to focus on improving real-time detection methods for mixed radiation fields and tritium and developing methods for radiation field mapping and visualization as well as developing a greater understanding of the risks of radiation exposures at low dose.

Technical progress achieved to date are:

1- Redesigning the Tissue Equivalent Proportional Counters (TEPCs) for robustness and manufacturing simplicity for improved NPP dosimetry and monitoring. The capability of the TEPC is also being investigated under this research program for its potential for discriminating short range beta particle tracks (Tritium) from longer range Compton Scattered electrons from Gamma rays. To-date a new form of detector was developed that operates with a new thick GEM device designed at UOIT.

2- Radiation Quality; Regulatory and public concerns are continually raised about the appropriate radiation weighting

   Radiation weighing factor for use for low energy beta particles (tritium) often arises for human and non-human biota exposures. A low energy photon source was established at UOIT to mimic the tritium beta- particle spectrum and has successfully characterized the X -ray beam that fully mimics Tritium in its characteristics and dosimetric properties. this beam is currently used in investigations of radiation damage to fish eggs.

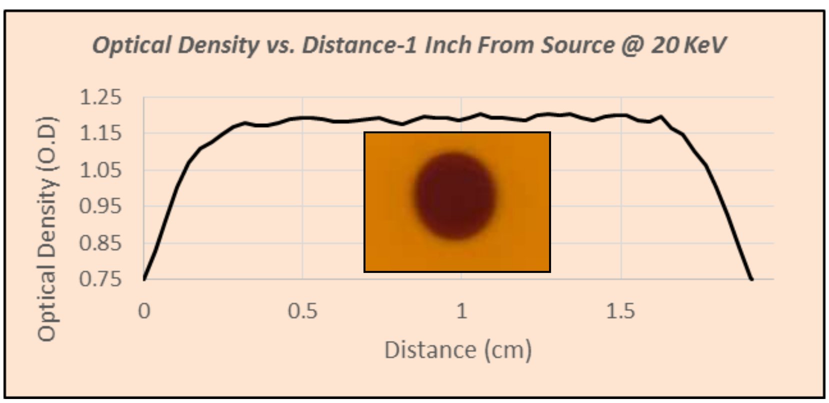


Figure 2.4.6 Radiochromic film image of X-ray beam at 1 inch from X-ray source at 20 kV and the associated film density across the beam image

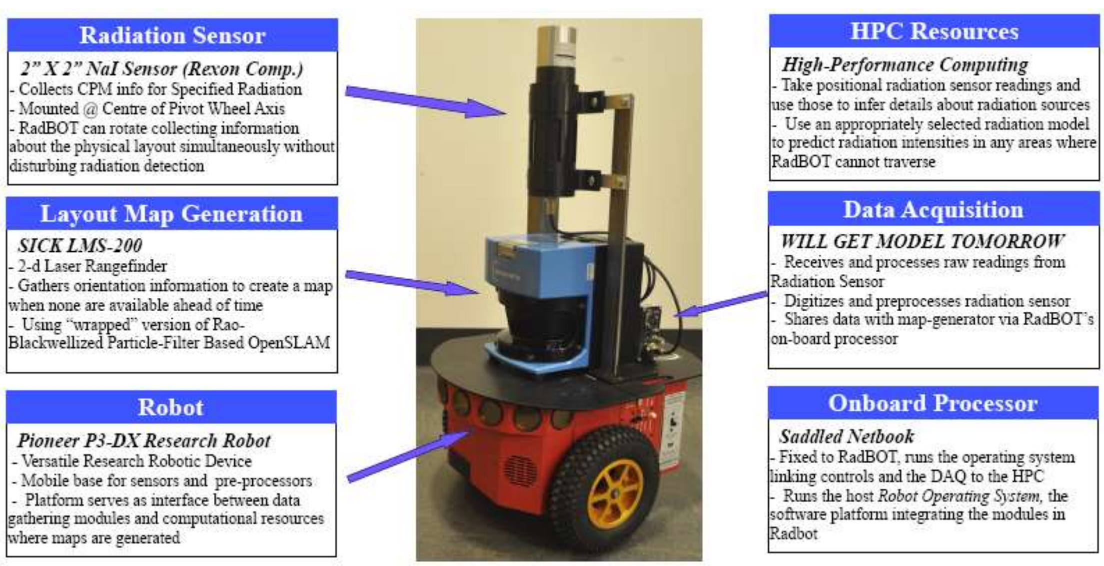
3- Research is also ongoing in support of industry for better operational values for Whole Body Counters (WBC). Models of WBC at Darlington and Pickering NGS were developed and simulation of efficiency curves were completed. Effects of external contamination (front to back ratios) and different chest wall thicknesses are being investigated

One key Research program undertaken by the Associate Research Chair (AIRC Dr. Ed Waller) in support of ALARA planning for maintenance and inspection activities is modeling, visualization and mapping of radiation fields in a 3D mode. These are being developed for inclusion in a Robotic tool currently under development to assist in minimizing total overall and acute radiation exposure in a variety of NPPs applications. Three active research projects noted below are being investigated by graduate students:

(i) radiation dose visualization
(ii) robotic assisted dose mapping
(iii) nuclear facility security simulation (not covered in this report)

Project (i) Radiation dose visualization is important especially if a continuous map of radiation field can be developed. In this way, a worker can navigate around radiation “hot spots” and therefore reduce their personal radiation dose. This research involves a novel technique for the creation of 3d visualizations of radiation fields. The initial stage of this work was completed by an MASc student and is being expanded with augmented reality and continued by a PhD student.

Project (ii) RadBot is a robotic tool to help minimize total overall and acute radiation exposure in a variety of industrial applications The goal of this research is to develop a versatile system for generating radiation maps on-demand for areas in which completing a full sensor survey is impossible, or for which there is limited information available about the geometrical layout. RadBot is in a proof-of-principle development stage currently. One PhD student involved in the robotics development is preparing to defend his thesis and one MASc is currently working on advancing the project.



Achieving these goals will require the integration of state-of-the-art techniques from a number of fields of research, including: mobile robotics, radiation detection, advanced systems modeling, and optimization. The successful integration of these topics should yield a robust radiation mapping tool capable of expanding the range for which radiation maps can be used.

2.4.7 Advances in Knowledge on the Long-term Effect of Radiation-Induced Chemistry and Corrosion of Materials from in-Reactor Service

This IRC (Prof. C.Wren of Western U) addresses research in irradiation induced chemistry and corrosion. The IRC program was approved in 2016 by UNENE Board of Directors and NSERC based on a defined scope of research in support of utility's current needs and NWMO's required research on the long-term corrosion behaviour of the NWMO modified used fuel container design. Prof. Wren was at the end of her 2nd term of an existing Chair program with CRL (now CNL) when the shift to UNENE took place thus leveraging established facilities, equipment and a team of researchers.

The aim of the research projects conducted in this first UNENE term of the IRC is to provide the scientific and technical basis for:

1) assessment of the integrity and longevity of the weld design of the proposed NWMO Mark II container for long-term disposal of used nuclear fuel, and

2) assessment of the corrosion performance of CANDU nuclear reactor structural components, in particular, End Shield Cooling (ECS) systems.

With many plant refurbishment/Life extensions being planned, accurate assessment of the integrity and longevity of the reactor structural materials is increasingly important. As such, current investigation into a leak in the End Shield Cooling (ESC) System in the Pickering Unit 6 nuclear reactor has raised a potential issue. Moisture from the ESC system leak could possibly reach a location in the annular air gap which exists around the periphery of the Calandria tank assembly and its supporting structures where corrosion would be problematic and needs careful evaluation. In particular, the potential for accelerated (galvanic) corrosion attack on carbon steel (CS) adjacent to the dissimilar metal weld between CS (SA36) and stainless steel (SS) (SA240, Type 304L) at the periphery of the annular gap (Fig. 2.4.7) must be addressed.

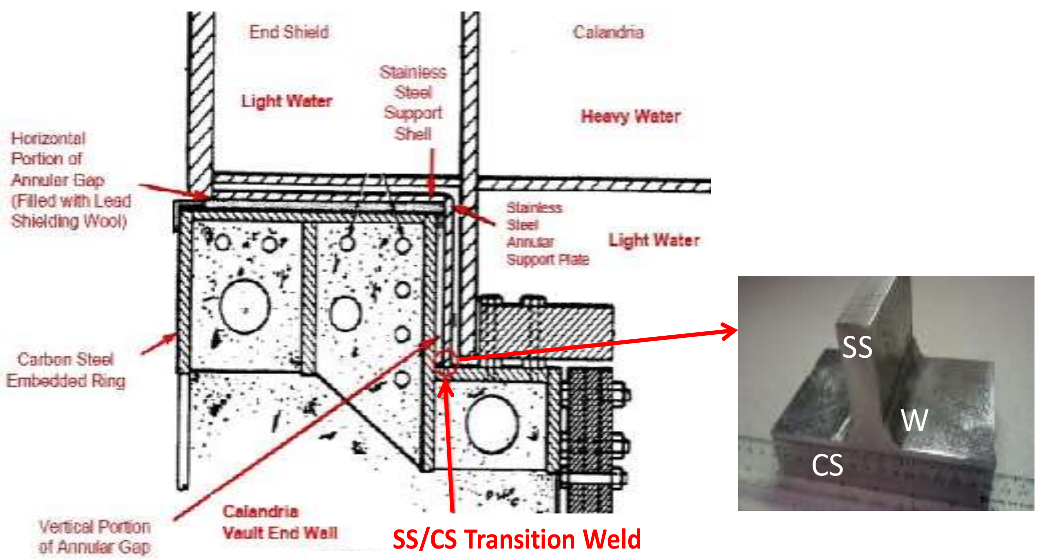


Figure 2.4.7 Schematic of the periphery of the calandria tank assembly and its supporting structures. The red circle indicates the location of the carbon steel (CS) and stainless steel (SS) weld joint

These corrosion studies are being conducted using off-cut samples from the weld block supplied by Ontario Power Generation (OPG). A combination of experiments with computational model analyses are being performed.

3.0 Interaction with & Consultation to Industry and Government

A key part of the scoping & undertaking of research is the interaction between researchers and industry representatives. This takes place through various activities such as an annual student Poster session where students present their research to industry in an interactive Poster session once a year. Definition of industry priorities takes place yearly during the annual research workshop after which a call for proposals are issued for research program (CRDs). The final set of approved CRDs are selected by industry to address such priorities.

Additional to the CRDs are the 5-year IRC terms cofounded by UNENE and NSERC. These are also approved by industry amid review and approval of defined objectives and planned outcomes of such research. Technical Advisory Committees (TAC) are used as the forum for continuous interaction between industry experts and researchers during the progress of research.

Additional to such interactions, agreement was reached with COG in 2016, through signed NDAs, to enable UNENE researchers that are not already members of their respective Technical committees to be part of those. This enables all UNENE researchers to attend their respective technical meetings, be apprised of ongoing COG research and seek input from other industry experts on their research during their update presentations to such groups.

Another objective of UNENE is to provide governments, public and industry with an independent source of scientific experts for input on matters relevant to government, public and industry policies. In the last three years' numerous consultations, technical exchanges and reviews were sought of the UNENE IRCs and Associate IRCs.

Some of these interactions/consultations are either continuing or new ones since last benefit reports:

- Prof. Holt (Queen's) engagement as an external consultant for Bruce Power and OPG (through Kinetrics Inc.), as a reviewer and a member of the COG Fuel Channels Technical Committee and the COG Fuel Channel Deformation Working Group

- Prof. Daymond (Queen's) continues to be a member of the COG Fuel Channel Working Group on Crack Initiation and Fracture, the COG Fuel Channel Deformation Working Group and the COG High Stress Creep Task Group

- Professor Yao is a member of the COG Fuel Channel Working Group on Crack initiation and Fracture. Profs. Holt, Daymond & Yao collaborate with AECL-CNL, Kinetrics and Nutech Precision metals on a number of research topic. Daymond and Yao collaborate with CNL AECL, Kinetrics and Nu-Tech precision metals on a number of research topics

- Prof. Luxat (McMaster) beyond some of his previously reported activities he is currently an appointed member &Vice Chair of CSA N290B Technical committee on; Reactor

Safety and Risk Management since May 2014. Developing nuclear standards CSA N290.16- Beyond Design Basis Accidents (BDBA) and CSA N290.17- Probabilistic Safety Assessment (PSA) and CSAN290.18-Periodic Safety Review (PSR)

- Prof. Luxat is also the Chair of CSA N290B, Technical Subcommittee developing nuclear standards CSAN290.18 -PSR

- Prof. Newman (UofT) has been continuing his consulting assistance to OPG in electrochemical monitoring in reinforced concrete. The contractor started site work in 2012 and data are being analyzed as they are produced

- UofT Laboratory test-development studies were carried out in support of a stress corrosion issue in the Canadian nuclear industry, as subcontractor to Kinetrics Inc.

- The U of T group has also hosted a one-day international meeting on SCC precursors organized by CNL and COG in November 2014

- Prof. Pandey (Waterloo) continues to transfer his risk and reliability knowledge to industry through active participation in COG projects with industry partners. This along with organizing workshops and training courses on Risk and Reliability for industry

- UNENE Chair holders Profs. Walker and Waller (UOIT) continue to interact with their nuclear partners on several levels on a regular basis. At the program level the senior Chair (Prof. Waker) continues to be a member of the COG Technical Committee for Health, Safety and the Environment and as such participates in the discussion and decision-making concerning the COG R&D program. Associated with guidance of the COG research and development program is the Health Physics Working Group for which the senior Chair is also a participating member

- The expertise of the UOIT Chair holders and that of the associate Chair, Dr. Waller, has been valued and used by the UNENE industrial partners to provide expert participation in a broad range of workshops and conferences on key emerging issues in radiation protection. Additional details are in the annual reports (2014/15/16)

- The UOIT Chair holders continue to be engaged in several nuclear community and educational initiatives such as, (i) Meetings with OPG Health Physics Department, Whitby on Health Physics and the Environment, Durham Nuclear Health Committee membership (& host location) (iii)Undergraduate Internship Programs (CNSC, Bruce, OPG)

- Dr. Tremaine, now an IRC on High Temperature D2O aqueous solutions (U. of Guelph) serves as a Member in the MULTEQ Database Advisory Committee, Electric Power Research Institute (EPRI). In this role, Prof. Tremaine provides input on Canadian nuclear industry needs to this international forum as well as currently within his research is addressing gaps in their data base w.r.t Heavy Water properties

4.0 Other Benefits

4.1 Integration of Research Programs among Universities and Industry

UNENE research addresses medium to long term industry priorities, and hence is aligned with ongoing programs at industrial research organizations such as AECL-CNL and Kinetrics. In such cases the scope of UNENE research is structured to provide additional experimentation and data aimed at leveraging both organizations strengths and knowledge for overall industry benefits. These collaborations continue to be explored and build on current ongoing ones such as:

- The ongoing one between Profs. Daymond & Yao (Queen's U), Kinetrics and AECL - CNL on PT life and Inconel X-750 irradiation embrittlement
- Current cooperation on future IST (Industry Standard Tool) Codes between Prof. Novog (McMaster), industry and the CNSC
- Cooperation in development of alternate brazing material to Beryllium for fuel bundles (RMC/CNL)
- Cooperation between Prof. Newman (UofT) and CRD Researchers at (Western University) on key experiments characterizing corrosion resistance parameters of SG tubing alloys (Alloy 600,800 & 690)
- Co-supervision of graduate students between RMC and CNL in the fuel area

Beyond such collaborations, the industry extends additional in-kind contribution to researchers as needed e.g. special equipment, material samples etc. Such contribution is equally critical to enable various research programs to achieve its expected results and outcomes.

4.2 Candu Textbook

A notable item in this period has been the publishing of all chapters of the Candu Textbook, which started in 2012/2013. The "Essential Candu" textbook documents the scientific basis of the Candu-HWR technology. The project was funded under a Candu Owners Group (COG) Joint Project with contributions from Candu utilities in Canada and offshore. The technical Manager is Dr. Bill Garland (Ex UNENE President) and authored by many industry scientists and engineers, some of whom are current IRCs. The textbook is an e-based book and accessible from https://www.unene.ca/the-essential-candu-textbook

4.3 Publications

Advances in knowledge and technology are documented in Ph.D., M.A.Sc., theses, as well as journal publications and conference papers. A review of publications made by UNENE in the two-year period of 2015 &2016 records nearly 200 publications to a variety of scientific journal, conferences and industry fora. These range from submissions to scientific Journal, Conference Papers & Posters. Table 4 provides further details. UNENE has enabled Canadian Universities to play a role by contributing to nuclear industry research while advancing knowledge in all aspects of the technology and showcasing Canadian nuclear research. This has increased the profile of Canadian nuclear research worldwide and in Canada.

Table 4.3 Publications by the UNENE IRCs and CRDs (2015/2016)

IRC Program	Journal Papers	Conference Papers	Miscellaneous (Industry Reports and/or Book Contributions etc.)	Total (excluding Posters)
- Nuclear Materials (Queen's)	11	2	24 (Posters) in industry seminars	13
-Safety & T/H (McMaster)	22	24		46
-Radiation Assisted Corrosion (Western U)	9	2	5(Posters)	11
-I&C & Electrical (Western U)	10	10	One chapter contribution in Candu Textbook	20
-Corrosion & performance of nuclear materials (U of Toronto)	8	4	2 Posters	12
-Risk &Reliability (Waterloo)	9 (selected ones)	9	Many industry reports	18
-Radiation Physics & Environmental Safety (UOIT)	7	14	2	21
-CRDs	30	17	Many oral presentations and Posters	47
Total	106	82	33	188

5.0 Value of the M.Eng./Diploma UNENE Program

Another element of UNENE's programs is the training & development of HQP including young professionals in industry. UNENE offers a Diploma and an M. Eng degree in Nuclear Engineering. It's a jointly offered degree program with courses delivered by member universities, under the UNENE umbrella with responsibility for program management and coordination. The M. Eng. program is accredited originally by the Quality Council (equivalent to the previously known Ontario Council of Graduate Studies (OCGS) and recently as of November 2013 by an international /national team under IQAP.

The degree program is geared to young industry professionals for academic advancement in nuclear engineering generally, while enhancing their knowledge of the design and licensing basis of the CANDU technology. Courses cover the entire spectrum of the technology and are offered via different universities with Instructors, mainly UNENE research Chairs that are well recognized scientists in their field with most of them with significant experience in industry. A Graduate Diploma Program was approved by the Ontario Universities Council on Quality Assurance in March 2015 and introduced under UNENE in April 2015. Its intent is to increase the student base and provide another shorter track in nuclear education. The Diploma is a four (4) graduate course program enabling young industry professionals to acquire focused knowledge in a given core competency area as required by the individual in his/her current area of responsibility.

To deliver a full breadth of nuclear engineering courses, the M.Eng. and the Diploma programs use renowned professors from participating universities and senior specialists from UNENE industry members.

To accommodate students with a full-time job, the courses for both programs are given during weekends throughout the academic year, at the Whitby campus of Durham College. Synchronous interactive distance education is now a routine part of every course – it is used "live" by remote students, and the recordings provide all students a means of reviewing the material.

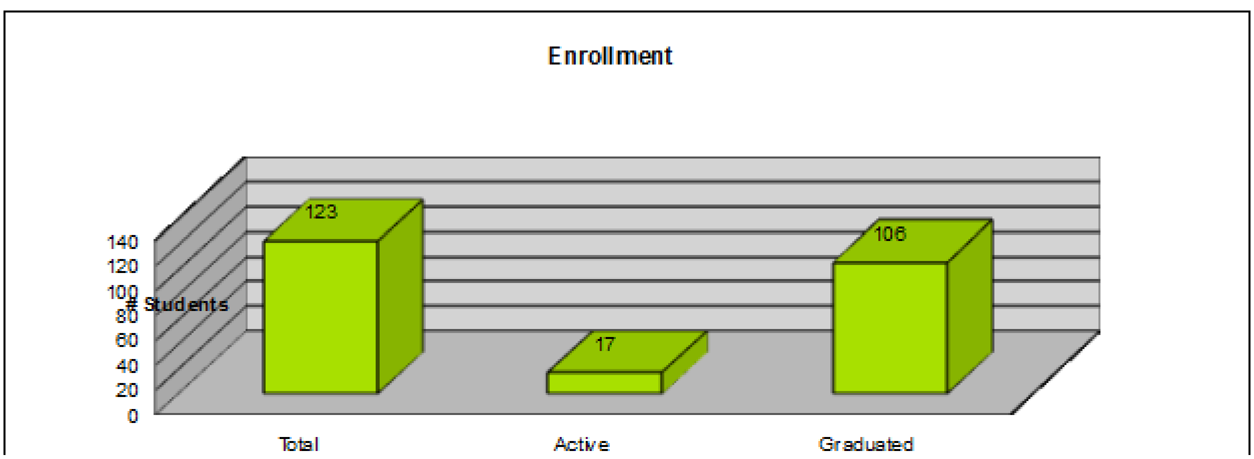


Figure 5 Cumulative M.Eng. Student throughput (from inception-Dec2015)

The M.Eng. and Diploma programs offer the following benefits to industry:

- Development of HQP to meet industry needs
- Enhancement of young professionals nuclear competency and their ability to cross discipline problem solving
- Assistance to industry in knowledge transfer and preservation
- Professional / career development of employees towards an effective and highly skilled workforce
- University courses cost lower than in-house training (employees donate their time)
- Provides a forum for employee's interactions with industry and university peers

6.0 UNENE Funding

In the last two fiscal years BP and CNL have contributed $300k per year along with the OPG contribution of $900k per year. The CNSC contribution has been $130K/year (increasing to $166k per year for 2017) while NWMO contribution has increased in the last fiscal year in support of additional research in support of the new used fuel container design. COG contributions are also shown as complementary to UNENE's in some areas of F/C and Chemistry. The remaining members baseline contribution is $30k per year. UNENE leverages this industry funding of UNENE programs through obtaining NSERC support at a level of approximately $1.67M per year. In addition, as noted, UNENE-sponsored research Chairs and projects also obtain additional external funding from a range of industry stakeholders.

Table 6 UNENE funding for 2015/16

Funding	**FY 2015/2016**	**Notes**
OPG	$900K	
BP	$300K	
AECL-CNL	$300K	
CNSC	$130K	
AMEC-FW	$30K	
SNL-Nuclear	$30K	
COG (for Daymond)	$125K	
COG (for Tremaine)	($90K)	Direct to IRC
NWMO	$30K	
NWMO (for Wren)	($110K)	Direct to IRC
NWMO (for Tremaine)	($50K)	Direct to IRC
Total Funding	**$1.845M**	
Expenditure - IRCs - CRDs - Operation&Admin	 $1.325M $0.324M $0.217M	 Excluding 13% HST
Total Expenditure	**$1.866M**	

7.0 Conclusion

This review confirms that, to date, and more than a decade in existence, this partnership has grown and steadily progressed to become a mature and well respected partnership with notable achievements in both program areas; Research and Education. Review of aspects of UNENE shows continuing trends of additional secured funds leveraged from industry /NSERC funding of UNENE research. An increased national and international profile of nuclear research in Canada is noted from the sustained level of journal publications and conference papers.

Development /training of Highly Qualified Personnel (HQP) continues to be key in addressing demographic gaps experienced by industry, and potential shortages of scientific personnel and engineers for currently planned major projects in Refurbishment /Plant Life Management and licensing.

Acronyms

CRD: Collaborative Research And Development Project

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