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UNENE Benefit Report

2010-2012

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Rev.0
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Executive Summary

This version of the benefit report covers the period from October 2010 to October 2012 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 including additional funds leveraged and their benefits to the research program, contributions to industry, research publications made by various programs, their impact on current nuclear industry priorities and the extent of knowledge leveraged nationally and internationally for industry's benefit

Key highlights during this period are:

1. In the last two (2) years UNENE's industrial base increased through the joining of AECL-CRL as a full member, Candu Energy Inc. (replacing AECL-SP) and NWMO. The increase in industry base has resulted in some increase in funding. The joining of AECL-CRL has also enabled bilateral discussion for the potential of leveraging its facilities and expertise through research collaborations with UNENE making an overall impact and enhanced value to both entities. UNENE industrial funding for research continued at the level of $1.67M /year fully leveraged by NSERC funding. An additional one time grant of $1M was successfully leveraged by some IRCs in support of their current programs (such as; McMaster, RMC and UWO). Details are in section 2.1 and section 6.0 of the report.

2. The reported leveraged one time fund of $43M in 2007-2009 from federal and provincial agencies has been used 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:

    - The Queen's University Reactor Material Testing Lab (RMTL) building. The new facility will comprise a 4 MV tandem accelerator, two new electron microscopes and other testing equipment. These will be used to further research on CANDU pressure tube material and increased characterization of its irradiation induced degradation mechanisms.

    - A new Center for Advanced Nuclear Systems (CANS) has been approved but not yet built. This $24.5M regional facility will 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 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, and Kinectrics) as well as a number of leading international organizations (EPRI, EdF, Bechtel).

3. Ongoing research programs continue to advance knowledge in all areas of the technology, with some developed technologies successfully deployed by utilities in support of their safe and economic NPP operation;

- The probabilistic risk based methodology developed through the Waterloo IRC program continues to be applied to OPG critical systems and components for life cycle management and Generation Risk assessment of its Nuclear Plants. In the last two years such techniques have been applied by utility staff in applications such as; Generation Risk Assessment (GRA) for Darlington refurbishment project selection process, risk informed inspection of fuel channels to detect degradation of fixed spacers and many inspection and maintenance programs of nuclear components in the Heat transport system, conventional systems and electrical systems. Effective application of these techniques has yielded optimized inspection programs of critical components thus reducing forced outage rates and improving capacity factors of NPPs.

- 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 application has been one of the key successes of this IRC program.

- Advanced development of new safety analysis methodologies continues in the area of Best Estimate methodology (BEAU) as well as advanced Thermal hydraulics in support of phenomena characterization for Critical Heat Flux (CHF) under high and low pressure conditions, Post dry out (PDO) and code validation. Some of the achieved advances on the BEAU methodology have been used by utilities in their safety analysis

- Research results confirm assurance of fuel channel integrity for a wide range of expected conditions of hot spots during accident scenarios. This is of particular benefit to nuclear utilities in Canada in resolving reactor licensing issues. This was realized through coupled heat transfer and structural mechanics (COMSOL code).

- Research data reported by Queen's IRC on the effects of radiation on PT crystallographic structure, hydride properties, stresses and strain characteristics are now being compared against predictions of H3DMAP by AECL to provide advanced validation of the model predictions (under COG WP10166); this work continues. H3DMAP is used as input into fitness for service guidelines with relation to hydrides forming at flaws. It is used to predict the growth of hydrides at a crack tip under the influence of stress. Further experiments in this area are being carried out in collaboration with Kinectrics Inc. (COG WP 10197).

- The creep models used to calculate the relaxation of stresses at flaws are being updated by Kinectrics Inc. (COG WP 10618) based on the Queen`s IRC`s new understanding of the role of dislocation structures on creep anisotropy. Further experiments are being carried out in collaboration with AECL and Kinectrics (COG WP 10619) to obtain data to verify the creep manufacturing on PT properties, textures and creep characteristics, of current and future PT alloys.

- Advanced Fuel research by the IRC at RMC resulted in many outcomes to industry; the implementation of the fuel thermo chemistry model in the SOURCE-2 Industry standard toolset (IST) for fission product release analysis. This thermo chemical work has direct benefit for understanding alpha exposure from actinide contamination that may be experienced during reactor refurbishments and outages. Advanced development of a software tool COLDD (Candu On-Line Defected fuel Detection) for on-line defective fuel monitoring, assessment of I-SCC mitigation strategies in CANLUB additives to enable load following capability of nuclear plants in the future. Also research is ongoing (in collaboration with Cameco) to find an alternate material to replace or minimize the amount of Beryllium (Be) used for brazing in fuel manufacturing. All such results are readily transferred to industry via COG reports.

- The IRC on Control, Instrumentation and Electrical research at the UWO has effectively used its advanced Control and Instrumentation lab established in 2009 for application development /validation of numerous advanced diagnostic tools and control technologies. All are aimed at reducing the number of safety system channels and common mode failures. These programs have resulted in the following outcomes to industry:

    - Development &validation of a newly proposed fault detection /isolation strategy for fixed In-Core Flux Detectors (ICFD) using correlations with other proximate ICFD
    - Research on the applications of wireless communication technologies to NPPs. If successful this will reduce cable runs and their installation and will reduce commissioning costs of plant control and instrumentation. Current testing in Candu-like environments is ongoing at the ZED-2 Facility at Chalk River Labs
    - Advanced Shutdown Systems by applying analytically-based redundancy concepts to reduce common mode failure, improve reliability and avoid complex channel separation

- The research program at UOIT continues to focus on improving real-time detection methods for mixed radiation fields and tritium. These are additional to continuing to further understand risks of radiation exposures at low dose. In view of the importance of real-time tritium monitoring in CANDU plants the program continues to explore different detection systems. Gas ionization methods remain the most sensitive method for the detection of tritium in air.

- Another thrust of the UOIT program is the development of a versatile system for generating radiation maps on-demand for NPP areas in which completing a full sensor survey is impossible, and/or for which there is limited information available about the physical layout. 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 for optimizing in-reactor maintenance while achieving ALARA dose limits

4. Training and development of HQP for potential deployment by industry is one key objective of UNENE. The complement of graduate students in the UNENE research program remains steady at 130 students who are at various phases of their research programs. In the last 2 years thirty seven (37) HQP have graduated of which twenty five (25) have been successfully recruited by industry. The remaining graduates have been recruited by either academia or US National labs. Details are in section 2.3 of the report.

5. A notable highlight this year is the development of a CANDU Textbook to document the scientific basis of the CANDU-HWR technology. A business case was approved by the Board enabling such undertaking. The project is funded under a CANDU Owners Group (COG) Joint Project with contributions from CANDU utilities in Canada and offshore.

6. On the aspect of industry consultation over 90 industry interactions /consultations and technical exchanges have been reported in the last two years by UNENE universities. Most of these were on COG technical committees, industry technical panels and review teams, as well as with various federal and provincial departments and panels. Details are noted in Section3 of the report.

7. One notable benefit is the extensive coverage of the Fukushima events (March 2010) and the many interviews and publications made by UNENE's Industrial Research Chairs and their Associates in effectively addressing public concerns through TV and media interviews. Many of the UNENE IRCs such as: Profs. Luxat, Lewis, Novog and Waker have been interviewed on TV and the radio on numerous occasions following the Fukushima events. The interviews were timely in addressing public interest in the event, its impact on the public in Japan and its comparison with the Canadian CANDU design and safety features.

   This very incident confirmed UNENE's vision since inception and that is to provide an independent pool of university scientific experts for public consultation on industry related issues.

8. The M.Eng. education program has, during this reporting period (2011/2012), experienced an increase in the number of graduates from nearly 40 to 70 graduates (Figure 30 of the report). With this increase in M.Eng. graduates the number of active students enrolled has dropped to 49. This is expected to recover in the longer term driven mainly by the future Darlington refurbishment, Bruce unit 1 Return to Service and the recognition of the UNENE M.Eng. course work by industry members as a means of competency building and career advancement. In 2011-2012 a new course schedule was adopted with a mixed two/three year cycle of all UNENE courses. The new schedule offers 6 courses per academic year, with the core courses repeating every 2 years and the non-core courses every 3 years, thus giving student's predictability and leveling of their workload. Student feedback remains positive with specific examples of the benefits noted in section 5.0 of the report. A diploma program with four courses is being proposed by UNENE and is planned to be available for enrolment in the new fiscal year 2013/2014.

In summary the review confirms that UNENE continues to provide value to industry through its research outcomes and the derived knowledge transfer to industry professionals and through effective problem resolution. Such industry – university partnership has been a good strategic move and has served both parties well in so far as meeting all objectives set forth at the inception of UNENE. Research outcomes continue to advance knowledge in all facets of the technology and support continued safety and economic performance of NPPs in Canada. The supply of HQP has been proven effective in addressing the demographic gaps experienced by industry in the last few years.

1.0 Introduction

This report examines the value derived by the industry partners from the UNENE research and education programs with focus on the last two years from Oct 2010 to Oct 2012.

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 w.r.t. advancement of knowledge, and its benefit to industry and supply of Highly Qualified Personnel to meet industry needs.

The education program of graduate level course M. Eng. degree will also be reviewed and its role in enhancing nuclear knowledge and competency of industry professionals.

2.0 Value of Research

UNENE research programs were established by nominating well respected industry scientists to different universities to act as "anchors" for establishing research programs in the following areas of the nuclear technology:

- Nuclear Safety Analysis & Thermalhydraulics
- Nuclear Fuel technology
- Nuclear Materials
- Corrosion and Material Performance in NPP systems
- Risk-Based Life Cycle Management (LCM) of NPP systems
- Control & Instrumentation and Electrical systems
- Health Physics and Environmental Safety

The establishment of Industrial Research Chairs (IRCs) continues to serve as the nucleus of what are now 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

During fiscal years 2010 and 2012 UNENE research funding was 100% leveraged by NSERC to the level of $1.67M per year. Additional research funds were leveraged to the amount of $1M by some of the UNENE universities (e.g. McMaster, RMC, UWO etc.). Successful leveraging of additional funds amounting to a one time grant of $43M had been achieved through UNENE universities in the previous two year period 2007-2009 as noted in Rev 0 of this document. This one time grant was mainly from provincial and federal sources such as Ontario Research Funds (ORF), NSERC and Canadian Fund for Innovation (CFI). These additional funds enabled new facilities to be established, hence sustaining an increased scope of research and number of graduate students.

2.2 Equipment and Research Facilities

Research facilities and equipment available to UNENE programs continue to increase. Some acquired from successive UNENE/NSERC funding and others from additional leveraged funding from federal and provincial agency grants (e.g. CFI, ORF). Some of the recently established facilities are:

a) The High Performance Computing Centre (HPC) acquired in 2007-2009 by the IRC /AIRC in McMaster has been upgraded in 2010 using funds from the IRC renewal and NRCan and ORF-RE funding. Additional workstations and processors are used for CFD and safety analysis computing. Acquisitions made of many new safety codes (e.g. FLUENT, COMSOL, Multi physics, MATLAB, etc.) along with current CANDU safety codes from Industry Partners (OPG, AECL) are used in safety analysis code development for re-engineering of legacy software.

b) A new water CHF facility was also constructed at McMaster University to study steady state and transient Critical heat Flux in support of Industry efforts to disposition CNSC GAI -144. The high pressure CHF and PDO facility was used to carry out tests performed under steady state conditions. Future tests will include the study of the fundamental mechanisms in transient depressurization events. A PhD was also completed on high temperature quench behavior in cylindrical geometries and several publications generated in collaboration with the Department of Mechanical Engineering.

The second CHF facility has been installed for low pressure CHF on downward facing surfaces to study the behavior under these configurations.

Two new loops are planned to: a) examine geometrical effects on two-phase sub channel mixing and b) examine the fundamental behavior of liquid-liquid and solid-liquid high temperature heat transfer and momentum transfer and potential energetic behavior prior to steam explosion ignition. A new ultra high speed video camera will be purchased using CFI funds for these new loops, as well as a time-resolved PIV laser system (through joint funding between the IRC and some provincially funded Nuclear Ontario Program.

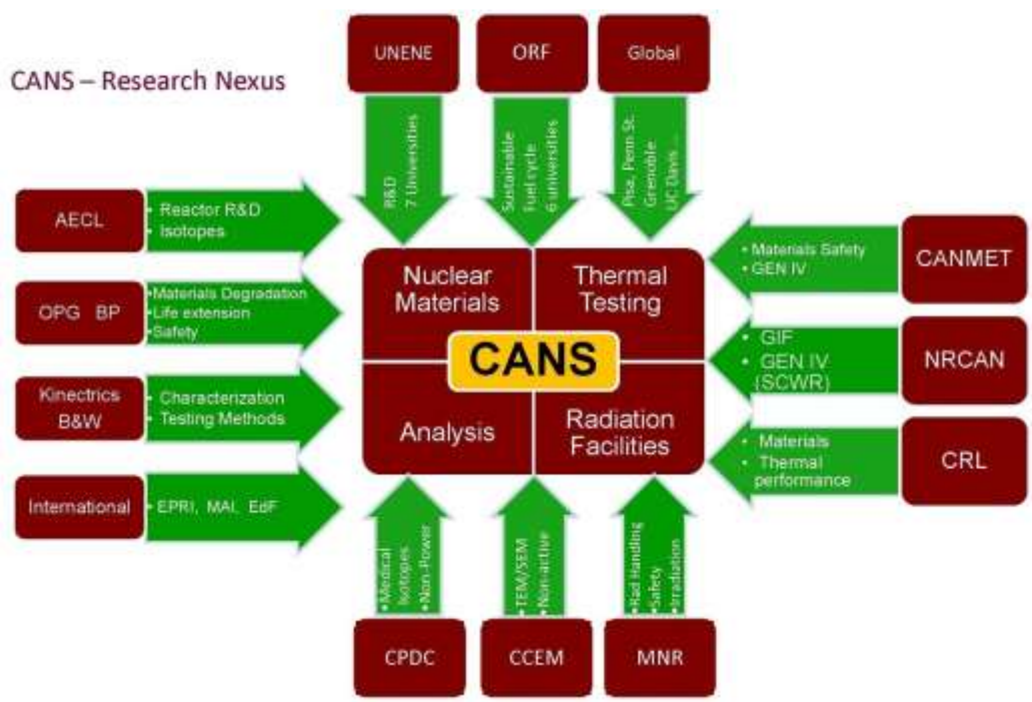


Figure 1: Centre of Advanced Nuclear Systems (CANS)

c) A new Center for Advanced Nuclear Systems (CANS) has been approved but not yet built. This $24.5M regional facility will 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 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, and Kinectrics) as well as a number of leading international organizations (EPRI, EdF, Bechtel) Figure 1.

d) Construction started in 2012 of the Reactor Material Testing Lab (RMTL) at Queen's University. The new building facility will comprise a 4 MV tandem accelerator, two new electron microscopes and other testing equipment. The tandem accelerator was ordered. The two new microscopes will be ordered this year. A medium sized computing cluster is being acquired to carry out molecular dynamics simulations of radiation damage. This is in addition to the creep laboratory established at Queen's during the first terms of the IRC program. The project to build the RMTL is funded mainly through CFI, Queen's and other provincial funding noted in section 2.1.

e) A new control and Instrumentation lab was established in 2009 at the University of Western Ontario (UWO) though its IRC (Professor J. Jiang). Six large projection displays and an operator console have been set up mimicking a full digital human machine interface of an NPP and with full connectivity to existing I&C systems, including smart sensor development systems and wireless monitoring modes for application development to CANDU plants.

f) Other new facilities were set up to support ongoing UNENE research programs that could be used in the future by Industry partners towards other research needs. These are: a scaled Lucite experimental header facility (both at McMaster), autoclaves for corrosion studies and state-of-the-art surface analysis and electron microscopy facilities (at UofT) and a Thermogravimetric Analyzer (TGA) for high temperature (2400C) nuclear fuel material studies at RMC.

Figure 2: New Energy Research Centre at UOIT

g) UOIT also has dedicated laboratories for detector aerosol research and environmental radiation measurements. The aerosol research lab is designed for powder and liquid aerosol characterization and is fully equipped with research instruments such as particle sizers; portable aerosol spectrometers; cascade impactors; flow/volume simulator (breathing machine) and ball mills. Construction of the Energy Research Centre completed in 2011 now houses laboratories specifically designed to support IRC research including purpose built neutron and gamma irradiation facilities (Figure2). The installation of a Hopewell Designs G10 Cesium gamma irradiator will be carried out in mid 2012 and the addition of a thermo-Fisher P385 neutron generator is expected shortly after to complete the mixed-field irradiation facility. The IRC program also makes regular use of low energy neutron beams produced at the McMaster Accelerator Facility.

h) The research program undertaken by Professor P.Tremaine under the funded CRD on D2O isotope effects on Hydrolysis and Ionization equilibria in High Temperature Water is undertaken using a suite of high-precision instruments that have unique capabilities. The high-temperature platinum vibrating tube densimeter is one of fewer than six worldwide that provide the precision needed to measure standard partial molar properties of aqueous electrolytes up to 350C. Also the current UV-visible flow system has the stability needed for quantitative spectroscopic studies up to 275C, and is being upgraded for operation up to 400C.This work is relevant to the Supercritical water reactor (SCWR) technology to which Canada is a contributor as part of the international Generation IV forum .

i) Recent CFI and NSERC Strategic Grants, supported by AECL and UNENE, have added at the University of Guelph (Tremaine) a new high temperature (50 - 300 C) solution calorimeter and state-of-the-art Raman spectrometer. Cells suitable for use under CANDU-6, CANDU ACR 1000, and CANDU SCWR reactor coolant conditions are being developed. Cells suitable for use under CANDU-6, CANDU ACR 1000, and CANDU SCWR reactor coolant conditions are being developed.

j) A new recirculating water-air loop was designed and built at the U of Ottawa in support of the UNENE funded CRD on the proposed experimental and numerical investigations of two phase flows in nuclear reactor systems. This scope is in direct support of the AECL air-water header facility tests.

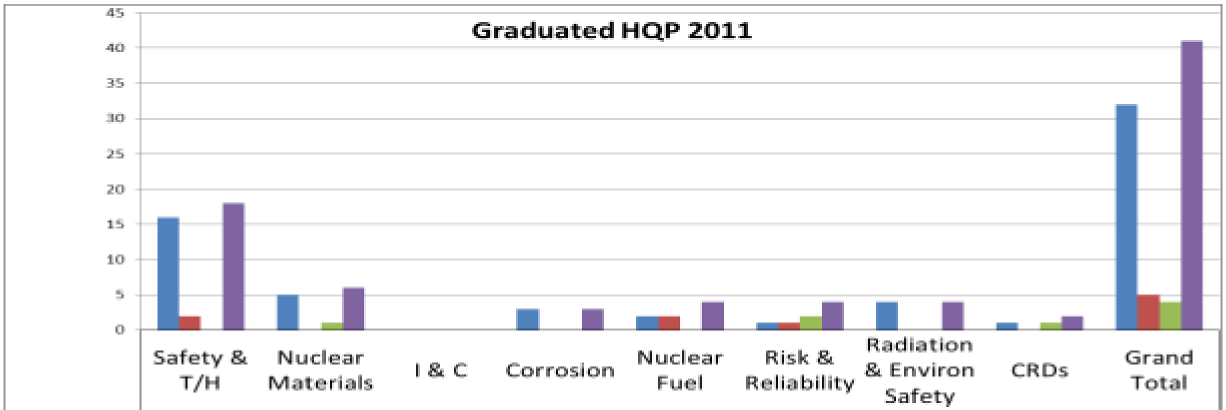
2.3 Training and Development of Highly Qualified Personnel (HQP)

Training and development of Highly Qualified Personnel (HQP) through nuclear research to meet industry needs is one key UNENE objective. Current UNENE universities report over 130 graduate students in different phases of completing their research towards a Masters or a PhD degree. This number of students has been consistent over the last few years and includes Post Doctorate Fellows (PDF) who, through their research experience and intellectual capability enhances the capability of research teams in their planned experimental and analytical activities. Figure 3 provides such details.

In 2011/2012 a total of thirty seven (37) graduated from various research programs; thirty two (32) with a Master's degree and five (5) with PhDs. Of the 37 graduates 25 have been hired by the nuclear industry achieving 68% success in attracting both types of graduates to opportunities within industry partners. It's also worth noting that of the five (5) PhD graduates three (3) have been hired by industry partners making the success rate for PhDs to be 60%. Although the PDFs are not counted amongst the graduates two (2) of them have been successfully recruited by industry and academic institutions. Figure 3 and Tables 1 & 2 provide additional details.

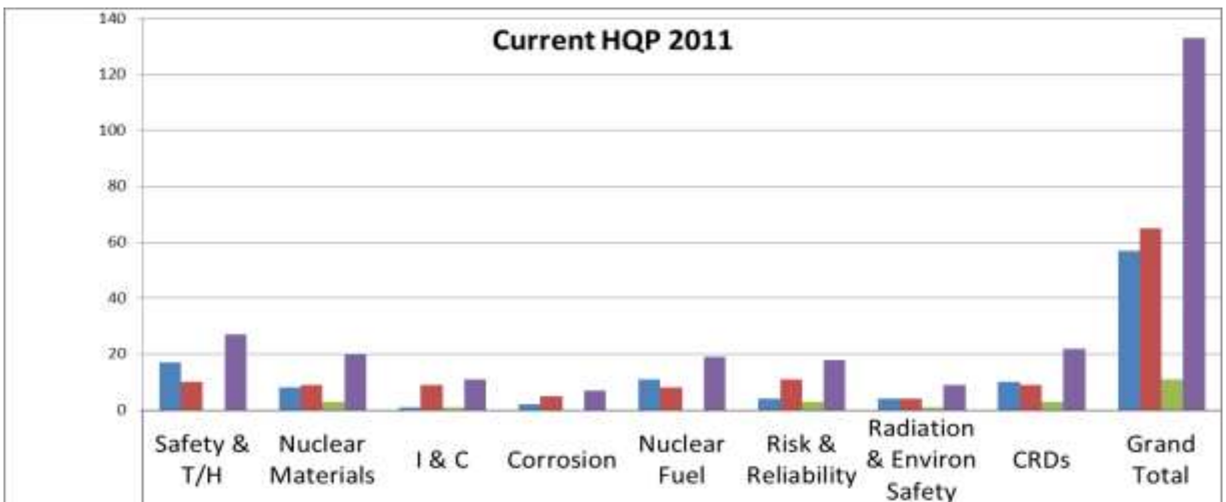
The remaining graduates and both PDFs have been successfully recruited in academia and US national labs with details depicted in Table 3 below.

Figure 3: Graduated HQP (2011) (by discipline by type)



	Safety & T/H	Nuclear Materials	I & C	Corrosion	Nuclear Fuel	Risk & Reliability	Radiation & Environ Safety	CRDs	Grand Total
MASc	16	5	0	3	2	1	4	1	32
PhD	2	0	0	0	2	1	0	0	5
PDF	0	1	0	0	0	2	0	1	4
Total	18	6	0	3	4	4	4	2	41

Figure 4: Current HQP (2011) by discipline and type



	Safety & T/H	Nuclear Materials	I & C	Corrosion	Nuclear Fuel	Risk & Reliability	Radiation & Environ Safety	CRDs	Grand Total
MASc	17	8	1	2	11	4	4	10	57
PhD	10	9	9	5	8	11	4	9	65
PDF	0	3	1	0	0	3	1	3	11
Total	27	20	11	7	19	18	9	22	133

Table 1: 2011 Graduated HQP & Hiring Data

	Nuclear Industry (Canada)			Academia / US National Labs& other			Total
Research Program	**MASc**	**PhD**	**PDF**	**MASc**	**PhD**	**PDF (not counted as graduate)**	
- Nuclear Materials (Queen's)	4			1		(1)	5
- I & C & Electrical (UWO)	---						---
- Nuclear Fuel (RMC)		1		2	1		4
- Safety & T/H (McMaster)	16	2					18
- Radiation Physics (UOIT)	2			2			4
- Corrosion & Nuclear Material Performance (UofT)				3			3
- Risk & LCM (Waterloo)	1				1	(2)	2
CRDs				1		(1)	1
Grand Total	23	3		9	2	(4)	37

Table 2: Graduated HQP Hired by Industry (by discipline)

	Safety& T/H	I & C & Electrical	Nuclear Materials	Radiation Physics	Nuclear Fuel	Risk & LCM	Corrosion & Materials Performance	CRDs	Total
AMEC-NSS	7		1	1	1				10
AECL-CRL	1								1
Bruce Power	6								6
Candu Energy	2								2
CNSC									
Kinectrics			1						1
OPG	2								2
Monserco				1					1
SNC-L Nuclear			1						1
Nutech Precision			1						1
Total	18		4	2	1				25

Table 3: HQP Hired by Non-Industry

Non Industry	Safety & T/H	I & C & Electrical	Nuclear Materials	Radiation Physics	Nuclear Fuel	Risk & LCM	Corrosion & Nuclear Material Performance	CRDs	Total
Academia			-	2	2	1	3	2	10
US National Labs					1	1			2
Grand Total			-	2	3	2	3	2	12

2.4 Advances in Nuclear Knowledge and Technology Transfer to Industry

Established research programs in member universities bring a wealth of knowledge to the industry, while expanding the R&D base beyond the currently established ones within industry. This framework of university/industry cooperation aligns Canada with other nuclear technology exporting countries such as the U.S., France, Russia, South Korea and China. It brings advances in the following knowledge areas:

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 and the mechanical behaviour of Ni alloy steam generator tubing (with additional funding). During the 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.

Program Highlights & Advances in Knowledge

In the past year significant advances have been made in understanding factors impacting on the phase stability of hydrides and on the impact of the condition of the hydrides (e.g. natural orientation vs. stress reoriented) on subsequent DHC during heatup, a relatively unexplored area. Significant progress has also been made in Queen's ability to carry out modelling of deformation and in particular twinning in zirconium. Work on understanding the basic deformation mechanisms operating in two phase zirconium alloys, exploring the relative influence of alloying and phases has also been reported. Finally, work is ongoing in the area of in situ irradiation of TEM foils.

Detailed Research Highlights

• Ion irradiation of spacer material
Ar ion irradiation studies in Inconel X750 spacer material have shown that the γ phase present in the as-manufactured condition disorders after a very low dose (0.07dpa) with no chemical redistribution. Stacking fault tetrahedra (vacancy defects) are also seen at low dose. After 5.4 dpa there was some chemical redistribution (Figure 4) but no cavities form. Cavities do form after higher doses if the material is first implanted with a few hundred ppm of He – the formation of cavities is thought to be the degradation mechanism in-service.

• *In-situ* measurement of stress relaxation at flaws
Synchrotron X-ray diffraction measurements have been made showing substantial reduction in stress at the notch tip of a fracture specimen due to creep (specimen held under load at temperature for different time intervals). This demonstrates that flaws produced in-service will be less likely to initiate cracks by delayed hydride cracking after reactor operation, and provides data for models predicting this. Arrangement have been made to repeat the measurements on neutron irradiated material; tests expected during 2012.

• *In-situ* determination of deformation mechanisms of Zr-2.5Nb with oxygen and strain rate
The deformation mechanisms of Zr-2.5Nb are being studied as a function of strain rate, oxygen content and temperature. This provides fundamental information about these mechanisms and what controls them, but also investigates the possibility of controlling the distribution of dislocations present in a reactor component to control its anisotropic properties (Figure 6).

• Determination of deformation mechanisms of irradiated Zr-2.5Nb pressure tube material
The very first in-situ neutron diffraction deformation experiments have been conducted on irradiated material (in this case Zr-2.5Nb) allowing determination of lattice strain development. The data will show how the different slip and twinning systems are affected individually by irradiation induced defects

Outcomes to Industry

Some of the earlier studies reported on the growth and stress state of hydrides are now being compared against predictions of H3DMAP by AECL to provide advanced validation of the model predictions (under COG WP10166); this work continues. H3DMAP is used as input into fitness for service guidelines with relation to hydrides forming at flaws. It is used to predict the growth of hydrides at a crack tip under the influence of stress. Further experiments in this area are being carried out in collaboration with Kinectrics Inc. (COG WP 10197).

The creep models used to calculate the relaxation of stresses at flaws are themselves being updated by Kinectrics Inc. (COG WP 10618) based on our new understanding of the role of dislocation structures on creep anisotropy. Further experiments are being carried out in collaboration with AECL and Kinectrics (COG WP 106190) using synchrotron x-ray diffraction to obtain data to verify the creep

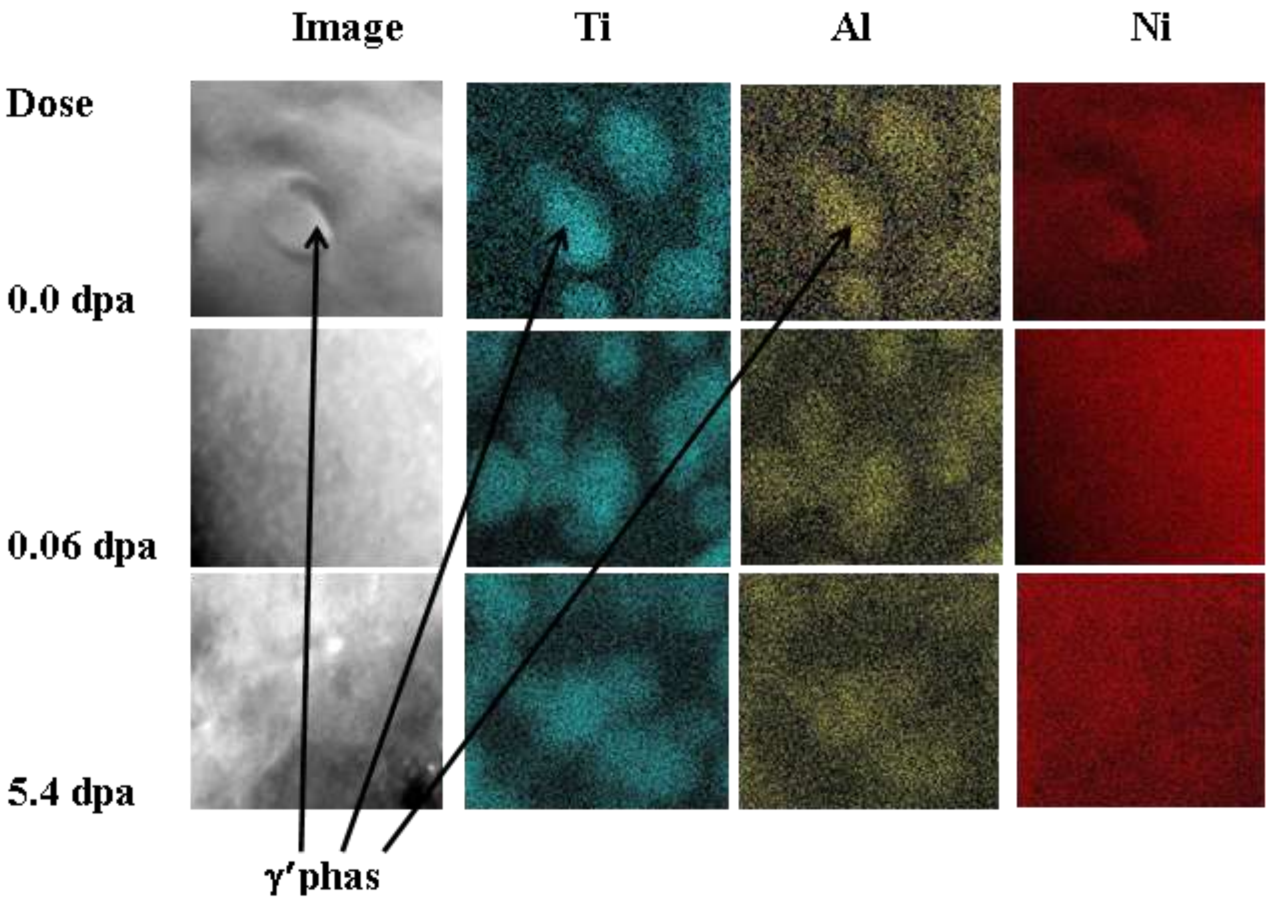


Figure 5: TEM Image of Inconel X750

TEM image and elemental maps of γ' in Inconel X750. The phase is disordered after 0.06 dpa, but there is no obvious chemical redistribution. Some migration of Ti and Al into the matrix is noticeable after 5.4 dpa

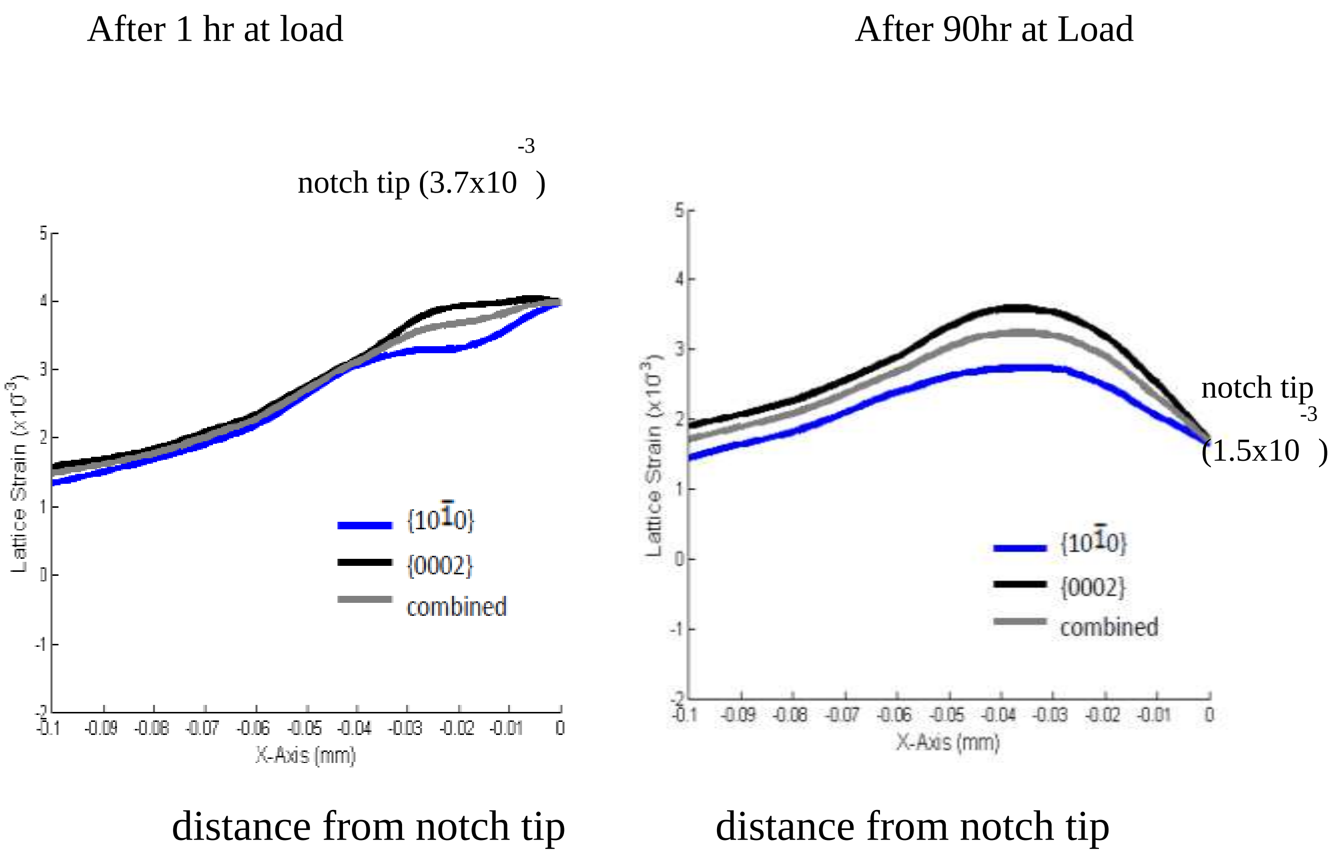


Figure 6: Stress Profiles of Curved Fracture Specimens

Stress profiles under load at notch tips of curved fracture specimens after 1 hour (left) and 90 hours (right) creep relaxation (under load) at 310° c. Note significant reduction of notch –tip stress due to creep

Strain rate = $4.8 \times 10^{-6}\ s^{-1}$ Strain rate = $1.5 \times 10^{-2}\ s^{-1}$

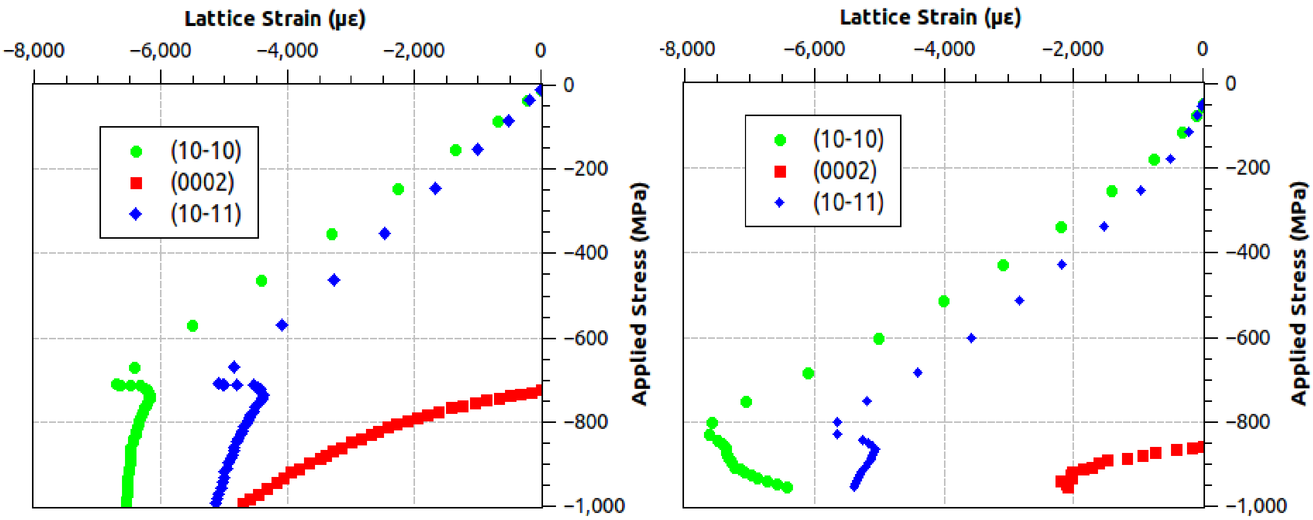


Figure 7: Lattice Strain

Development of lattice strain for different crystallographic planes at two strain rates. The changes in the relative positions, shapes and slopes of the curves with strain rate indicate changes in the importance of different slip systems. This will in turn change the anisotropic behaviour of the material if subsequently used in a reactor application

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

The research program at McMaster continues to be multidisciplinary in nature and covers a large number a projects. These projects address the following objectives:

- Development and enhancement of analysis methodologies in the area of nuclear safety analysis with a focus on improving nuclear safety, accident analyses and uncertainty estimation.
- Supporting the development of severe accident analysis methodologies and mitigation strategies.
- Perform fundamental and applied research and development in the areas of thermalhydraulics under normal and accident conditions and assessing the potential for improved reactor output.
- Train the next generation of Highly Qualified Personnel for the nuclear industry.

These objectives are formulated based on knowledge of industry priorities and current/future needs in the safety analysis area and severe accident mitigation measures.

Programs are aimed at enhancing safety analysis methodology by reducing dependence on empirical correlations and approximations. The program is based on a systematic approach of developing and validating mechanistic models for the key phenomena and processes. These phenomena and processes influence acceptance criteria under normal and accident conditions thus eliminating reliance on empirical formulas reduce uncertainty and conservatism.

A well-integrated research program between both Professors exists in all areas. Experimental test facilities are constructed to assist in characterizing numerous phenomena and to validate mechanistic models of key safety analysis parameters such as Pressure drop, Critical heat Flux, Post dry out etc. covering their behavior under various reactor conditions.

The program has two key focus areas:

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

Research in the other areas is driven by these two key ones in so far as addressing knowledge gaps and the need to quantify uncertainty in various thermalhydraulic and physics models & calculations. All aimed at formulating a validated set of mechanistic models governing different accident analysis scenarios

<u>Outcomes to Industry</u>

Some notable outcomes of this program have been:
1- Assurance of fuel channel integrity for a wide range of expected conditions of hot spots during accident scenarios. This was realized through coupled heat transfer and structural mechanics (COMSOL code).This work will be of particular benefit to nuclear utilities in Canada in resolving reactor licensing issues.

2- Knowledge derived from the current severe accident research program is key to designing mitigating features in current and future plants. This addresses current national and international nuclear safety requirements stipulated in nuclear regulatory standards. This supports the current development of mechanistic models of key processes occurring during severe accident conditions that govern the 'in-vessel retention' phenomena in Candu type reactors. 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 Candu calandria) . All of those are of significant benefit in establishing limits of in-vessel retention.

3- The adoption by industry of the Best Estimate and Assessment of Uncertainty (BEAU) methodology in some Large Break LOCA scenarios. In this area the IRC/AIRC work is yielding new computational methodologies referred to as dynamic sensitivity methodology aimed at fully characterizing key accident parameters and assessing their uncertainties under different accident scenarios.

4- The A-IRC program has also focused during this reporting period in participating in OECD-NEA international benchmarking exercises using Canadian safety and T/H codes. These are aimed at increasing confidence and validation of Canadian codes and showcasing our analytical safety analysis tools. Problem sets using PWR and BWR geometries have been carried out and documented in submissions. Current plans exist to apply these to Candu geometries. An outcome of this is a plan through COG (Candu Owners Group) to explore the possibility of using these advanced reactor analysis tools as a valuable contribution to the Canadian safety analysis technology development.

<u>Program Results / Highlights</u>

Projects in support of the key objectives are divided into the following R&D areas:

<u>Uncertainty Analysis</u>

- Developing and Supporting EVS (Extreme Value Statistics) Applications
- Uncertainty propagation in reactor physics simulations
- Best estimate and uncertainty analysis of SB LOCA
- Dynamic sensitivity and uncertainty analysis of fuel transients in accidents
- EVS applied to Loss of Flow events
- Application of New Software Tools to LBLOCA – RELAP BEAU Analysis of a 900 MW LBLOCA

In 2011 some outstanding research on uncertainty in reactor physics calculations was undertaken as a PhD thesis. The work, involved uncertainty propagation allowing the simultaneous examination of uncertainties on feedback mechanisms (including CVR), fuel composition (i.e., burn-up uncertainties), and initial fuel conditions (IFC – i.e., small changes in fuel lattice geometry). It was performed as part of the OECD-NEA international benchmark activities entitled Uncertainty Analysis in Modelling with some results depicted in Figure 8 below.

<u>Fuel and Fuel Channel Integrity</u>

- Modeling CHF on CT following PT contact
- Multiphysics investigation of PT hotspot due to localized fuel element-PT contact
- Modeling transient contact conductance following PT ballooning
- Experimental investigation of quench heat transfer on hot cylinders ;Fundamental experiments and visualization studies of heat transfer to cold water impinging on high temperature metal surfaces

- IBIF mechanistic modeling using GOTHIC
- CHF measurements in medium pressure water
- Mechanistic modelling of pool boiling CHF on calandria tube surfaces following
- PT/CT contact

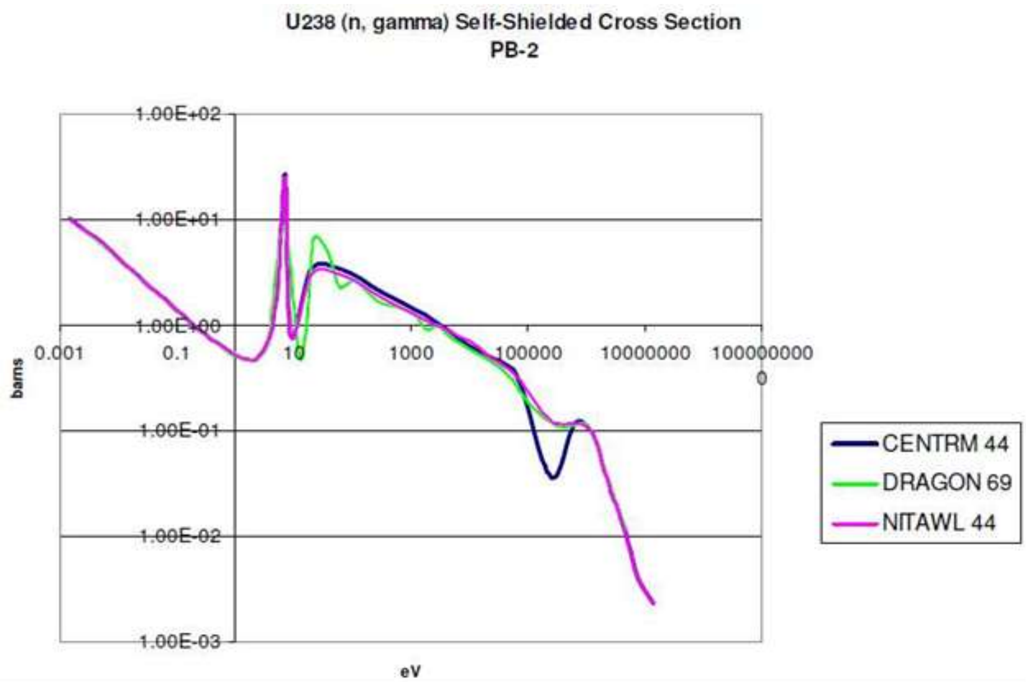


Figure 8: U238 (n, gamma) Self Shielded Cross Section (example of results from uncertainty analysis benchmark activities)

Current and completed research in the areas of Fuel and Fuel Channel integrity is aimed at improving the quantification of safety margins, helping to regain operating margins of nuclear operating units, improving the quality, efficiency and cost effectiveness of nuclear safety analysis and supporting the development of advanced CANDU designs.

Severe Accident Analysis and In Vessel Retention

- Mechanistic model of fuel channel disassembly
- Experimental investigation of CHF limits on downward facing surfaces
- Calandria In-Vessel Retention
- End-fitting/End-Shield Heat Transfer During a Severe Accident
- Validation of the QUENCH Experiments using RELAP

Under these programs several experiments were initiated with some completed in the last two years; A high pressure CHF and PDO facility was completed and tests performed under steady state conditions. Future tests will include the study of the fundamental mechanisms in transient depressurization events. A PhD was also completed on high temperature quench behaviour in cylindrical geometries and several publications generated in collaboration with the Department of Mechanical Engineering.

Another CHF facility has been installed for low pressure CHF on downward facing surfaces to study the heat transfer characteristics of molten corium and the bottom of the calandria under severe accident configurations. Details of the facility and experimental results to date are depicted in Figure 9.

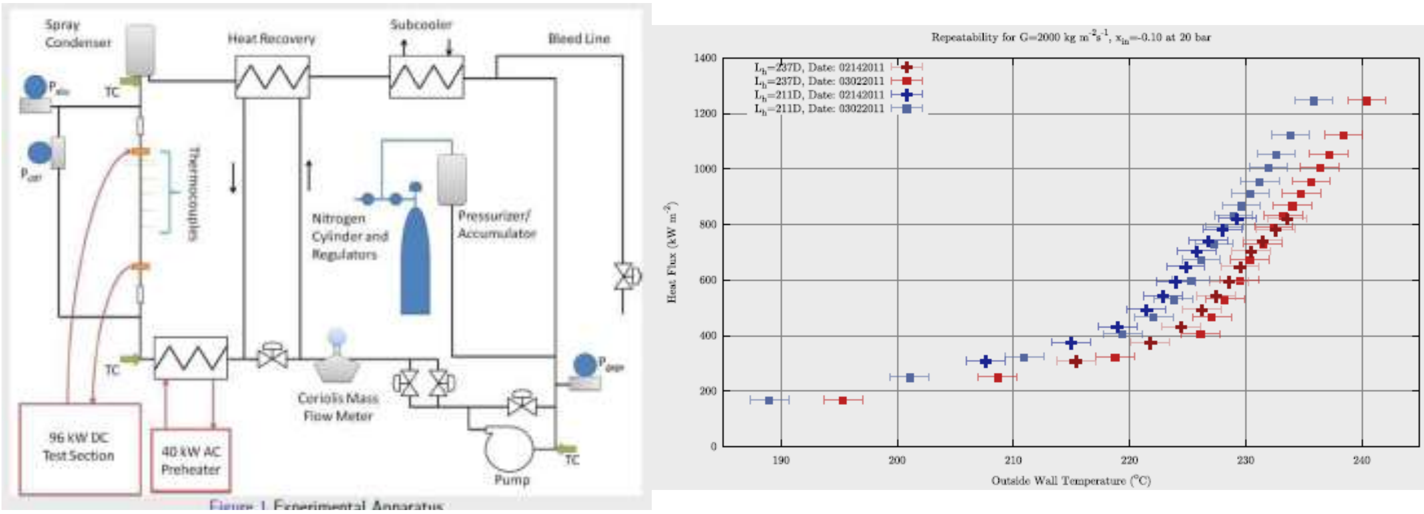


Figure 9: Subchannel CHF and Enhancement

Two new loops are planned or under construction in support of the subchannel CHF characterization under normal, abnormal reactor conditions and severe accident scenarios. The planned experiments aim to a) examine geometrical effects on two-phase subchannel mixing and b) examine the fundamental behaviour of liquid-liquid and solid-liquid high temperature heat transfer and momentum transfer and potential energetic behaviour prior to steam explosion ignition.

Computational and Tool Development, Testing and Validation

1. OECD-NEA CFD Benchmark for Mixing Inside Tube Bundles (MATIS Experiment)
2. CFD analysis of CT thermalhydraulics following PT contact in LOCA
3. Modeling multiple parallel channel two-phase natural circulation in CANDU
4. Trip parameter maps for the McMaster Nuclear Reactor
5. MCNP analysis of the MNR Core: Measurement and computation of gamma ray fluxes in the McMaster Nuclear Reactor and Jules Horowitz Reactor (Cadarache)
6. OECD-NEA Benchmarks on PWR and BWR Bundle Thermalhydraulics

Also in the last year additional attention was given to the area of international thermalhydraulic benchmarking activities. This enabled exposure to international best practices and ensured that the Canadian nuclear industry is represented in these important activities. Examples of these activities include OECD-NEA UAM Benchmarks, OECD-NEA BFBT Benchmark, OECD_NEW, PSBT Benchmark, OECD-NEA CFD Benchmarks, OECDNEA Two-Phase Stability Benchmark, IAEA SCWR Heat Transfer Benchmark and IAEA SCWR Thermalhydraulic Stability Benchmarks.

A program is currently ongoing to explore the possibility of using these advanced reactor analysis tools to Canadian technologies is a valuable contribution to the Canadian safety analysis technology development.

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

The IRC research program covers a wide array of research topics related to instrumentation, control, and electric systems in nuclear power plants. Current research covers the following subject areas: modeling, simulation, advanced control, safety systems, performance monitoring and diagnostics, networks and smart devices.

Reactor Modeling, Control and Diagnosis (Figure 10)

Current modeling work focuses on the development of MATLAB/Simulink based models to facilitate the analysis and design of the control systems within CANDU reactors. The flux control loop model has been developed and can be extended to encompass larger subsystems and other types of reactors. Dynamic modeling of CANDU reactor using Modal Synthesis method leads to 3D models of the reactor core. This method will be integrated into the existing MATLAB/Simulink platform of CANDU reactor.

Also, a fault detection and isolation strategy for fixed In-Core Flux Detectors (ICFD) is proposed for CANDU reactors and is validated, where the correlations between proximate ICFDs are utilized. This proposed fault detection system requires review and validation by Candu Energy, OPG and Bruce Power for acceptance for potential application and approval by the CNSC. Advanced performance monitoring and diagnostic techniques are being developed for smart sensor applications.

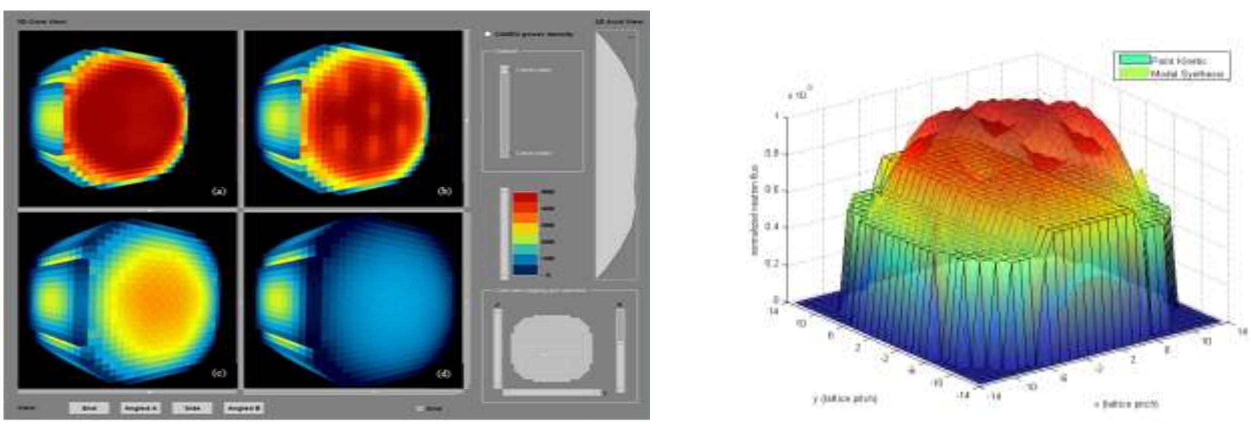


Figure 10: Reactor Modeling, Control and Diagnosis

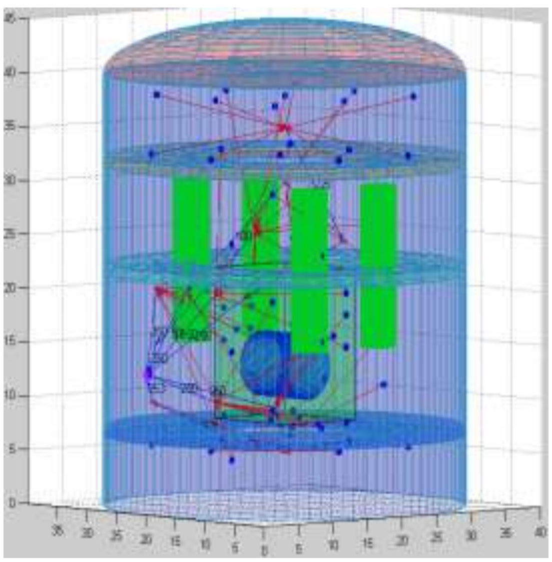
Advanced Process Control, Fieldbus and Communications

Evaluation is ongoing of Distributed Control Systems (DCS), fieldbus technologies, and advanced control algorithms for their potential applications in nuclear power plants. These evaluations are performed on a test-bench comprising commercial products, physical mock-ups, and an OPG desktop training simulator. Further, the development of smart sensors with advanced diagnostic capabilities is investigated. Smart sensor development involves the implementation of sensors, which are able to communicate through fieldbus protocols such as

Profibus and Foundation Fieldbus and are capable of performing additional functions in addition to basic control tasks. These algorithms can include diagnostic schemes and also cryptographic algorithms for security purposes. The suitability and performance of these algorithms are evaluated, and prototypes have been constructed.

Review and technical inputs on the potential of applying these alternate field bus technologies will be required for guidance on the future progress towards industry acceptance.

Research on wireless communications networks and sensors in nuclear power plant environment involves the design and implementation of wireless systems that conform to the electromagnetic compatibility (EMC) conditions and regulations in nuclear power plants. Wireless technologies can bring many potential benefits such as reduced cabling, lower installation and maintenance cost, and faster commissioning and upgrading. Tests have been carried out in Point Lepreau Nuclear Generating Station (Figure 11).



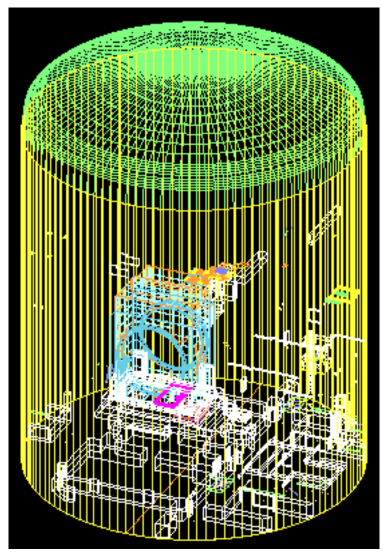


Figure 11: Conceptual Design of Wireless Networks in a Candu Reactor Building

<u>Design, Evaluation and Innovative Safety Systems</u>

Application of Field Programmable Gate Array (FPGA) technology to Shutdown System One (SDS1) involves converting SDS1 trip logics to digital system logics, and then implementing them into an FPGA device. FPGA technology provides a more reliable platform and faster execution rate of control logic and can potentially increase the safety margin of a plant. To validate and qualify FPGA implementation, simulation and safety analysis are being performed.

Similar to FPGA implementation, Programmable Logic Controller (PLC) implementation of SDS1 logic is performed. SDS1 logic is translated to function block diagrams and is implemented on a Tricon v9 triple redundant PLC. The performance of the system is evaluated against expected response from the nuclear power plant simulator. Simulation capabilities are established through incorporation of the advanced digital controller hardware (FPGA or PLC) into a hardware-in-the-loop (HIL) simulation environment. Through HIL simulation, new technologies can be qualified, verified and validated for specific applications. Advanced shutdown systems can be achieved by implementing the concept of analytic redundancy. Based on mathematical models of the dynamic systems within a NPP, the next expected values of shutdown parameters will be calculated, supplied to the shutdown system logic, and compared with the trip set points. This research aims to develop advanced shutdown systems, which can reduce common cause failures, decrease the mean time between failures and avoid complex channel separation (Figure 12).

<u>Realized Outcomes to Industry</u>

These programs have resulted in the following outcomes to industry:

- Development &validation of a newly proposed fault detection /isolation strategy for fixed In-Core Flux Detectors (ICFD) using correlations with other proximate ICFDs
- Research on 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
- Advanced Shutdown Systems by applying analytically-based redundancy concepts to reduce common mode failure, improve reliability and avoid complex channel separation

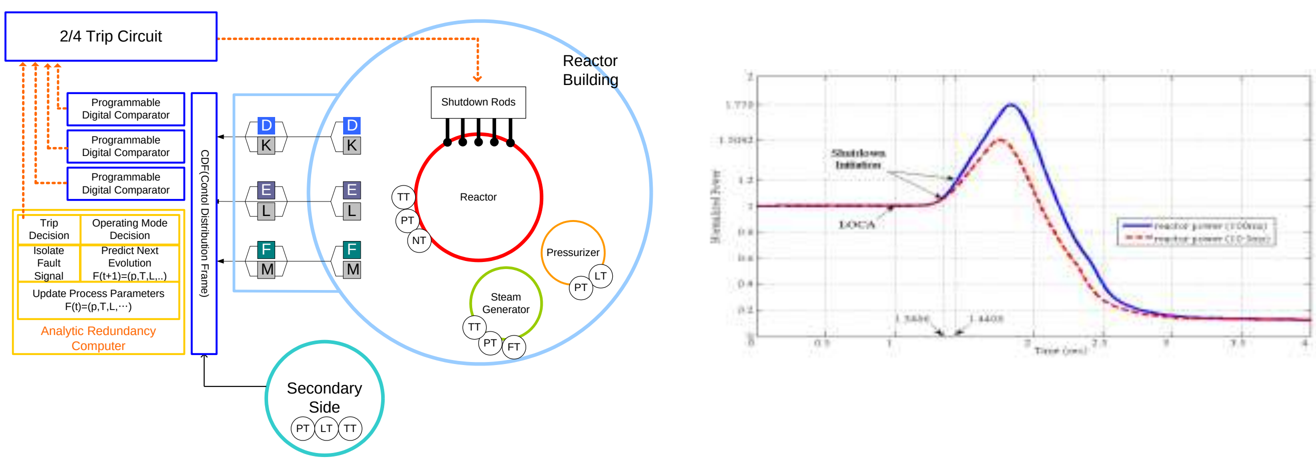


Figure 12: Advanced Safety System Design

2.4.4 Understanding of Nuclear Fuel Performance during Normal and Accident Conditions including Behavior of Advanced and Next-generation Fuel Designs

The main objectives of the IRC research program are to better understand nuclear fuel performance during normal and reactor accident conditions, including the behaviour of advanced fuel designs. This initiative involves a partnership with the CANDU Owners Group (COG), as part of their Safety and Licensing (S&L) research program on defective fuel behaviour and fuel chemistry.

Specific areas of research for this chair are:

Nuclear fuel chemistry; nuclear fuel and fission product release behaviour during normal and reactor accident conditions; fuel-failure monitoring techniques; and fuel performance prediction to improve operation and safety margins.

Program Results/Highlights

The advances in knowledge gained by this research effort over the given period include:

- Implementation and initial testing of a fuel thermochemistry model in the SOURCE-2 industry standard toolset (IST) for fission product release analysis. An advanced thermochemistry solver based on a novel partitioning of the Gibbs Energy was also developed as a standalone program. This solver is capable of handling a large number of chemical species for fission product and actinide analysis and includes a numerical checker to provide quality assurance of the code calculations. The thermochemical work has direct benefit for understanding alpha exposure from actinide contamination, which can be experienced during commercial reactor refurbishment and outages. The RMC fuel thermochemical model has also been benchmarked against other treatments as part of the international "Samantha" (Simulation by Advanced Mechanistic And Thermodynamic Approaches to nuclear fuels) network

- The current suite of fuel-failure monitoring codes (i.e. Visual_DETECT and STAR) are being advanced further for on-line, real-time, monitoring of defective fuel through coolant activity analysis with the development of the COLDD (CANDU On-Line Defected fuel Detection) software tool. The fission product release model in the STAR code has also been extended for delayed neutron (DN) monitoring applications to help assess ageing and degradation issues of the DN counting systems at commercial power stations. This model has been benchmarked against DN count rate data at a commercial reactor, where it has been demonstrated that the discrimination ratio can be optimized by selecting channels with the same transport time for both the suspect and background signals

- A "chemically-based" Iodine induced stress corrosion cracking (I-SCC) model has been used to determine I-SCC mitigation strategies with Canlub additives and pellet surface oxidation. Experimentation is continuing in collaboration with AECL-CRL to test these strategies in out-reactor laboratory-scale experiments. A fuel thermomechanical model has also been developed to account for fuel-pellet "hour glassing" phenomena to better assess sheath stress/strain at the pellet edges (with pellet-pellet and pellet-sheath contact). This thermomechanical model could be eventually coupled with the I-SCC chemical model in order to mechanistically model I-SCC phenomena, which is an important consideration with the possibility of future reactor load-following operations and the need for extended fuel burnups

- An out-reactor investigation has been carried out to assess the use of isotopic noble gas tags as a means to locate failed-fuel bundles. This work has determined detection thresholds of the gas tag in the primary heat transport system (PHTS) with mass spectrometry using a Varian 820 Inductively Coupled Plasma – Mass Spectrometer (ICP-MS). This technique could have possible application for demonstration irradiations with new fuel-bundle designs

- Research into Be-brazing reduction in fuel manufacturing (in collaboration with Cameco Fuel Manufacturing (CFM). With pending environmental and health considerations, a thermochemical analysis has been applied to help find candidate materials to replace or minimize the amount of be used for brazing in fuel manufacture. This collaboration with CFM investigated substitute Al materials and optimization of the brazing process to reduce Be volatility

- A fuel-oxidation model has been advanced to help in the design of an out-reactor instrumented fuel-defect test in collaboration with Atomic Energy of Canada Ltd. (AECL) and Stern Laboratories. This out-reactor experiment will provide information on the degradation of the thermal conductivity of oxidized fuel in defective elements at typical CANDU PHTS conditions. This experiment will be used to benchmark and validate the RMC fuel oxidation model developed for COG for defective-fuel behaviour analysis

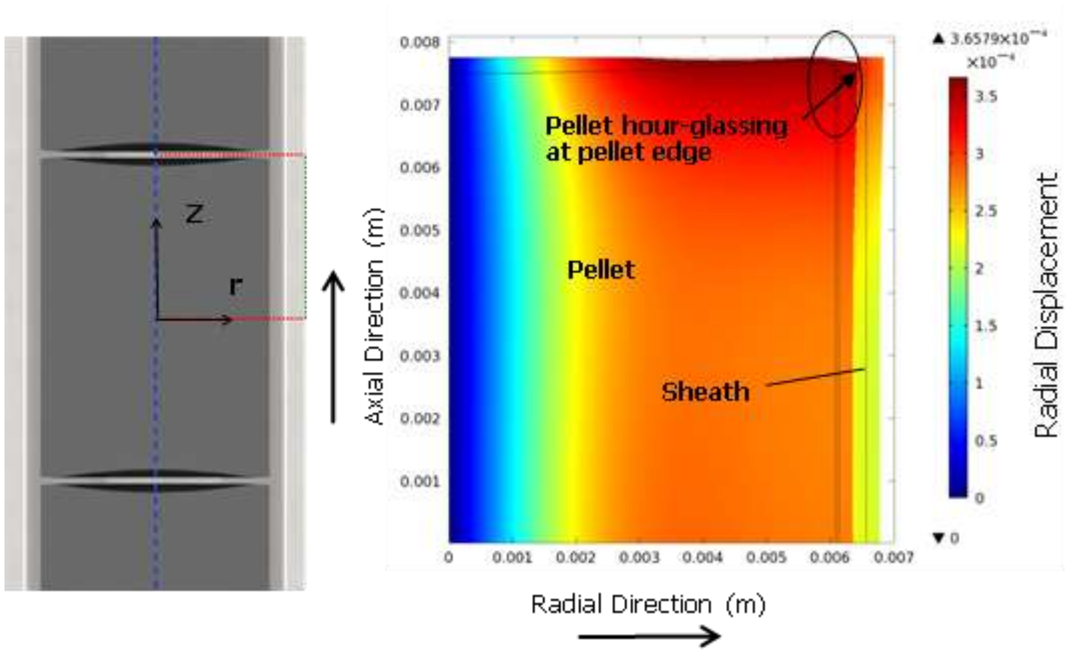


Figure 13: Prediction of 'pellet hour-glassing' phenomena with a multi-dimensional Comsol Multiphysics Analysis

- A multi-dimensional, thermomechanical model of a complete fuel bundle has been developed under a COMSOL multiphysics platform. This work is important to account for bundle-aging effects and its influence on the sub-channel thermalhydraulics during normal operation as well as bundle sagging/slumping during high temperature accident conditions. The current work has demonstrated that a composite beam approximation can be applied for the sheath, fuel pellets and end-plate webbing using a virtual work principle, which takes into consideration pellet/sheath interaction phenomena (Figure 13).

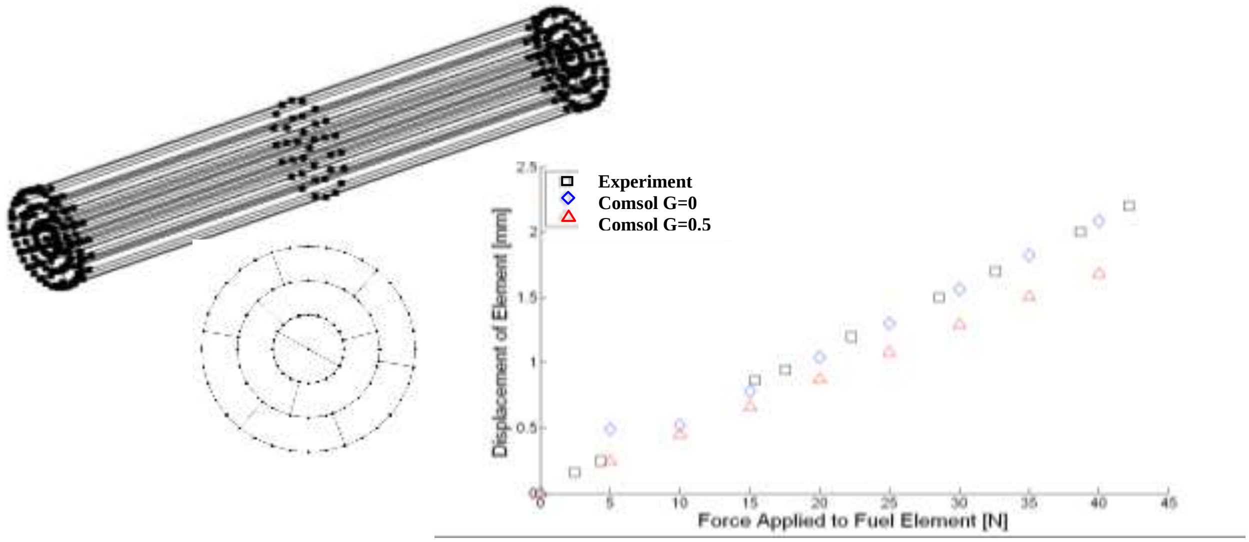


Figure 14: Model Simulation with an Out-Reactor 'Clamped-Bundle'

Comparison of model simulation with an out-reactor “clamped-bundle” experiment, where a load is applied to an outer fuel element at its mid-axial location. Agreement with experiment is seen when pellet-sheath gripping is ignored in the model (G = 0) as required for the out-reactor test simulation

Research at RMC has made use of the SLOWPOKE-2 nuclear reactor facility. Also work has involved the use of software for: i) Gibbs-energy minimization with the Facility for the Analysis of Chemical Thermodynamics/ChemApps, and ii) finite element modeling with COMSOL Multiphysics and ABAQUS performed on the High Performance Computational Virtual Laboratory (HPCVL) at Queen’s University. The IRC program supplements R&D activities in nuclear fuel technology carried out by COG. In particular, it directly contributes to three COG work packages on fuel oxidation and behavior modeling, fuel failure monitoring and fuel thermochemistry.

The IRC research has strong collaboration with AECL-CRL and Candu Energy on fuel studies for the ACR and with Bruce Power on gamma spectrometry, analysis of Gaseous Fission Product (GFP) and other chemistry data in support of fuel failure monitoring tools.

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

The main research objective of the Waterloo IRC program is the development and application of advanced risk and reliability models to support the life cycle management of a variety of nuclear plant systems, structures and components (SSCs). As such the key research areas are reliability analysis, statistical estimation, degradation modeling, inspection & maintenance optimization and generation risk assessment.

Advanced probabilistic based approaches have been applied to key NPP components such as fuel channels, feeders, steam generators and other components of the heat transport system. These applications continue to yield considerable benefits to the operation and risk based inspection & maintenance of NPP components.

Research Program and Outcomes

A number of research projects have been completed to support the industry's needs in risk assessment and life cycle management areas. Some of the key projects completed in the reporting period are summarized below.

1- Risk Informed End of Life Assessment of Feeder Piping Based on Flow Accelerated Corrosion (FAC) Inspection Data

Current mechanistic based assessment methods use a limited amount of feeder inspection data collected from a feeder, such as the minimum thickness of feeder bends. The new methodology developed under this research program utilizes the entire scan of the feeder bend wall thickness data and provides a risk-informed estimate of the FAC rate and the end-of-life of the feeder (see Figure 15).

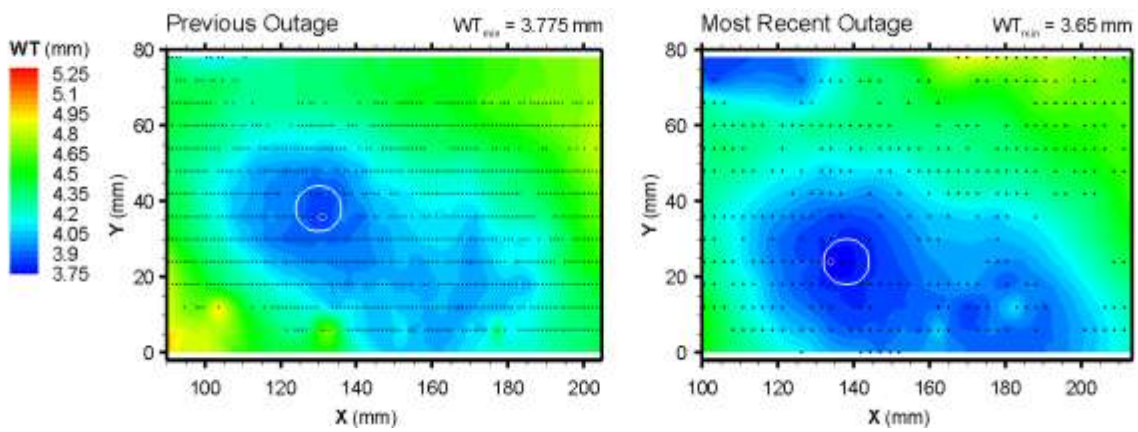


Figure 15: Detailed Risk-Informed Assessment of Feeder Bend and Weld Thinning

This method has been successfully applied to optimize the feeder replacement plans for a station. The new method provides a robust estimate of FAC wear rates by accounting for uncertainties associated with the ultrasonic inspection data. The method aims to determine the feeder end of life with minimal conservatism and high confidence, which is critical for the effective management of aging feeder systems.

2- Development of Visualization Tools to Support the Degradation Assessment of Nuclear Piping

Nuclear utilities collect a vast amount of in-service inspection data as part of periodic inspection plans and the detailed assessment and monitoring of various degradation mechanisms, such as corrosion, fretting and creep deformation. The development of data visualization tools allows the consideration of all of the in-service inspection data in the analysis, and hence supports a more comprehensive degradation assessment of systems, structures and components (SSCs).

A software tool has been developed to visualize the damage to feeder piping caused by the FAC process (Figure 16: Software for 3D visualization of FAC wall thickness loss in feeder piping). Inspection data, such as the wall thickness profiles of feeders from the 6-point and 14-point UT probes, can be contoured directly in Microsoft Excel using the method of Kriging. The data can also be visualized in three-dimensions from multiple outages, which is especially valuable for lead feeders and for feeders with complex bend geometries.

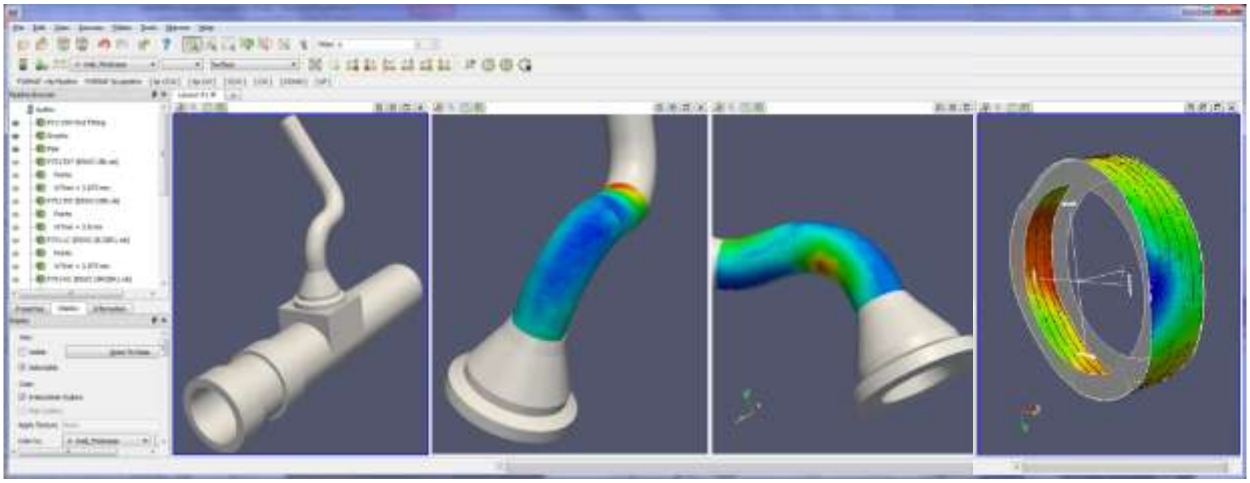


Figure 16: Software for 3D Visualization of FAC Wall Thickness Loss in Feeder

Other data, such as the sludge pile on the steam generator tube sheet, can also be visualized to assess the effectiveness of water lancing and chemical cleaning campaigns (Figure 17).

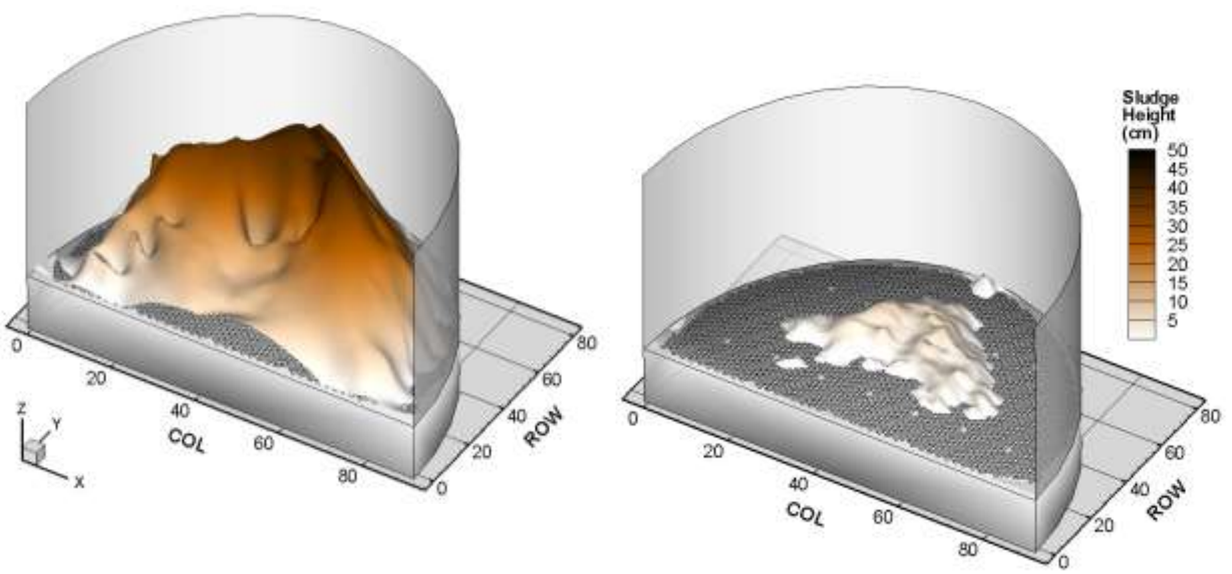


Figure 17: Software for Graphical Display of Sludge Pile in Steam Generators (e.g. before and after water lancing and chemical cleaning)

3- Risk-Informed Prioritization of Refurbishment Project Portfolio

The generation risk assessment (GRA) method has been developed to integrate risk and reliability information with the cost-benefit analysis of investment decisions. The GRA analysis increases efficiency and reduces ambiguity in the planning process and makes it easier to justify the project selections to all stakeholders.

We have developed an Excel based program, called WAT-LCM, for GRA of NPP systems and demonstrated its application to the primary heat transport system, and turbine/generator system at Darlington Station (see Figure 18). We are continuing to assist the OPG refurbishment group in implementing GRA within the refurbishment planning process.

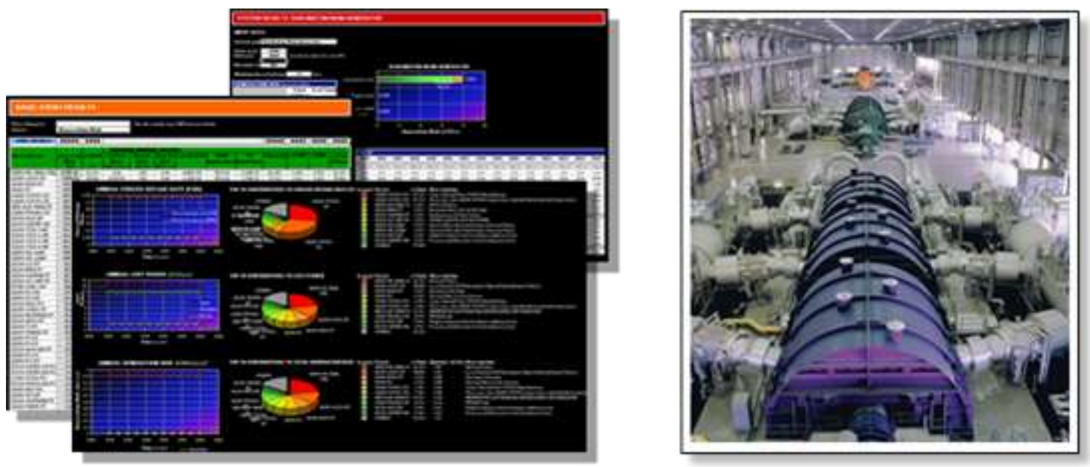
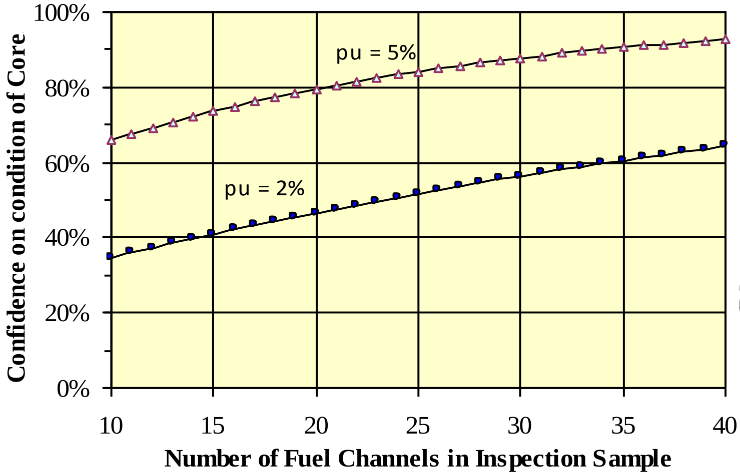


Figure 18: GRA Analysis of the Main Turbine/Generator at Darlington NGS (turbine hall image courtesy of OPG)

4- Risk-Informed Inspection of Fuel Channels

Inspections are carried out to measure the gap between the pressure tube (PT) and calandria Tube (CT) with the purpose of (1) ensuring adequate performance of spacers, and (2) precluding the possibility of contact between the tubes. Since the gap measurement is a fairly tedious and time consuming process, a careful planning of inspection campaigns is very important. A key problem here is how to determine the fuel channel sample size for inspection that would enable a meaningful inference about the condition of the reactor core. We have developed a risk-informed approach to quantify the statistical confidence about the condition of the core, i.e., probability of spacer degradation in the core, on the basis of inspection results.



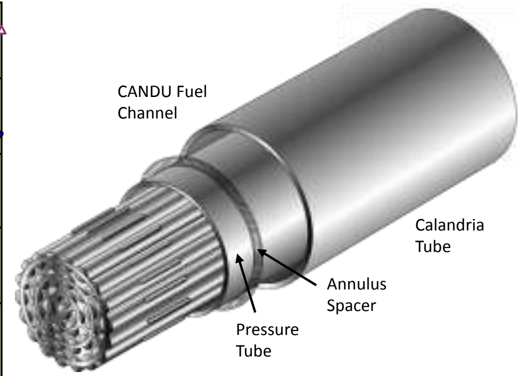


Figure 19: The Effect of Sample Size on the Confidence that Probability of a Defective Channel in the Core is Less than an Upper Bound Value, pu=2% and 5%

In Figure 19, The Effect of Sample Size on the Confidence that Probability of a Defective Channel in the Core is Less than an Upper Bound Value, pu=2% and 5%, the confidence that the potential level of degradation is less than a postulated upper bound probability (pu) is plotted as a function of sample size. These results can be used in the following way. If the inspection of a sample of 15 channels confirms an adequate gap, then it can be inferred with 75% confidence that the probability of spacer degradation in the reactor core is less than 5%. This approach is based on a modern concept of Bayesian hypothesis testing, and it is used here for the first time in the planning of reactor inspection. This approach will be applied to the inspection of other critical components, such as steam generators and welded joints in primary piping.

5- Prediction of Deuterium Ingress in Fuel Channels

In this study a large data set about deuterium ingress in pressure tubes collected from CANDU stations was analyzed using advanced statistical methods. A new probabilistic model for predicting D2 uptake in future service life has been developed. Our analysis shows that the currently used logarithmic regression (Arrhenius model) is quite conservative and conceptually inadequate to model the data, see Figure 20, Upper prediction limit (97.5% percentile) of the deuterium ingress as a function of hot hours (T=303°c). The proposed model is more in line with the data and will improve the risk-informed assessment of the reactor core.

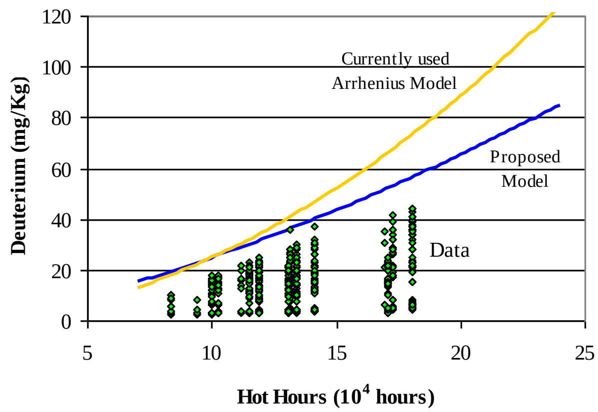


Figure 20: Upper prediction limit (97.5 percentile) of deuterium ingress as a function of hot hours (T=303° C)

6- Prediction of Creep Deformation in Fuel Channels

Diametral expansion of pressure tubes is the main life-limiting factor in CANDU reactors. The pressure tube deformation rates are directly influenced by material properties (e.g., texture and grain size) and operating conditions (i.e., stress, temperature, and neutron flux). Predicting the rate of diametral expansion is critical as it determines the maximum power level for reactor operation, and ultimately the useful life of the reactor.

We have developed statistical models for pressure tube diametral creep using inspection data from in-service pressure tubes. The model results can be used not only to make predictions for the inspected and uninspected pressure tube populations, but also to investigate the influence of material properties (microstructure) on the overall creep behaviour. Figure 21 illustrates the observed and predicted diametral creep rates for a selected pressure tube and the 95% prediction interval along the length of the pressure tube.

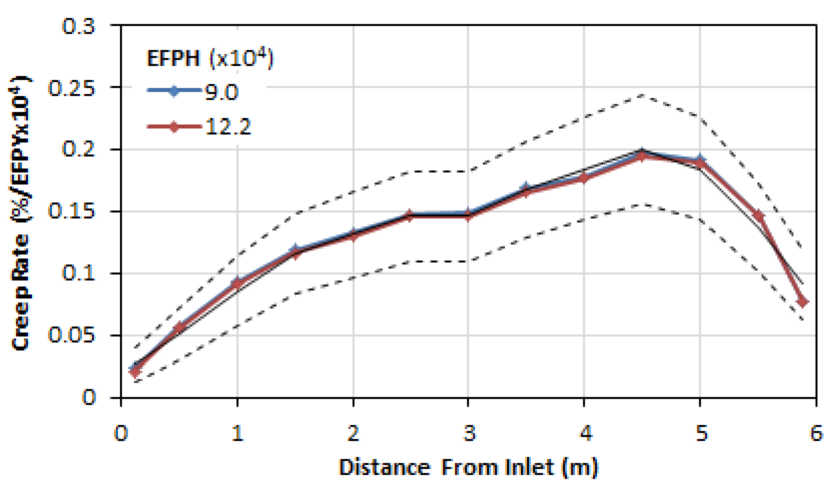


Figure 21: Observed Diametral Creep Rate vs. Model Predicted Mean (solid black line) and 95% Prediction Interval (dashed line) for a Selected Pressure Tube

7- Reliability Analysis of Eddy Current Inspection System

Eddy current (EC) inspection probe driving systems are extensively used during outages for steam generator tubing inspections in nuclear plants. For example, during an outage roughly 300,000 feet distance may be traversed by this system. The EC probe driving system has three major sub-systems; namely, take up reel controller (TURC) motor, pusher head and instruments (RDAU). The failure of the probe driving system results in the loss of time during inspection and has the potential to prolong the outage duration. Therefore, an accurate assessment of reliability of the EC probe driving system is necessary to forecast potential interruptions and prepare a “risk-management” plan by acquiring an appropriate number of spare parts and service crew. The in-service reliability of the probe system has not been analyzed in a formal manner.

The key objective of this project was to analyze the usage and failure history data provided by IMS and to develop a reliability prediction model for the probe driving system. We conducted probabilistic analysis of the data, estimated reliability of each of the three subsystems and then predicted the reliability of the probe driving system as a whole. A typical output of our analysis is shown in Figure 22 which shows the predicted number of failures of the probe driving system during a future outage that involves about 300,000 feet of coverage by this equipment. The reliability is estimated as 68%, and the probability of one failure is about 22%. This Figure also shows that by having two spare units, the interruption caused by the system failure can be minimized.

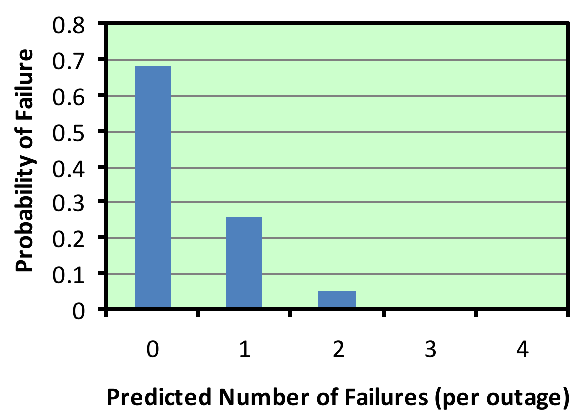


Figure 22: Predicted Probability Distribution of Number of Failures of the Eddy Current Inspection System (photo courtesy of Zetec)

8- Statistical Analysis of Fish Impingement at Pickering NGS

The primary objective of this study was to estimate the reduction in total biomass (i.e. fish) impinged at the Pickering Nuclear Generating Station (PNGS). This study was in response to the need to demonstrate to the regulator that a substantial reduction in biomass impingement has been achieved through a system of screens installed at the cooling water intake of PNGS.

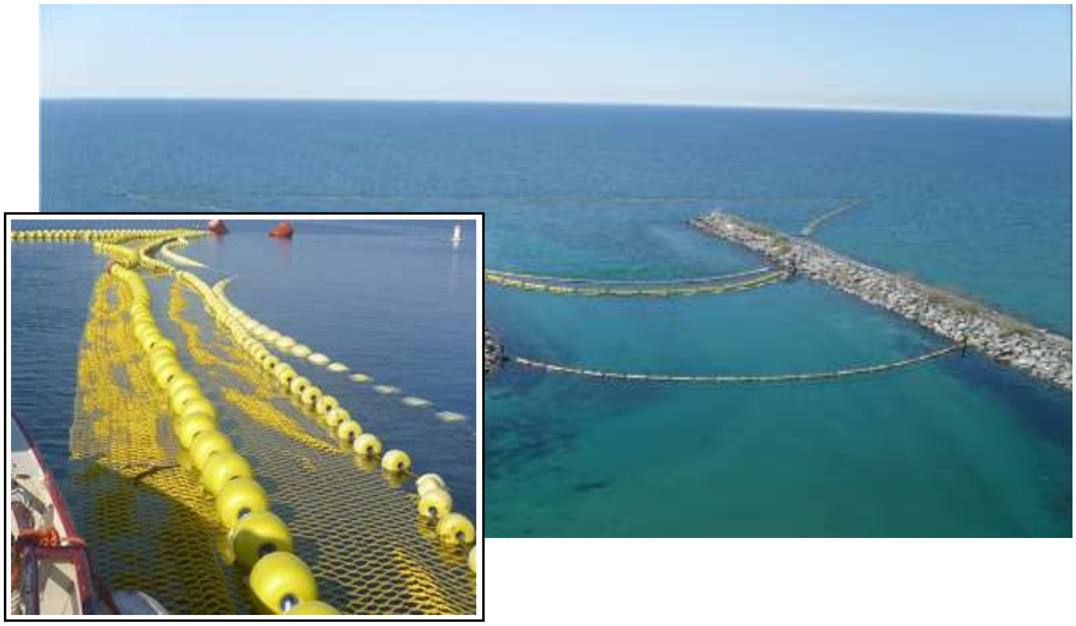


Figure 23: Fish Diversion Structure at the Inlet of Pickering NGS (image courtesy of OPG)

Key elements of the uncertainty in the data are missing observations from the time series and seasonal variations in biomass impingement. In this project, we developed a method to estimate of probability distribution of total biomass impinged in the reference period 2003/2004 and the year 2010, which led to the distribution of reduction in biomass impingement shown in Figure 24.

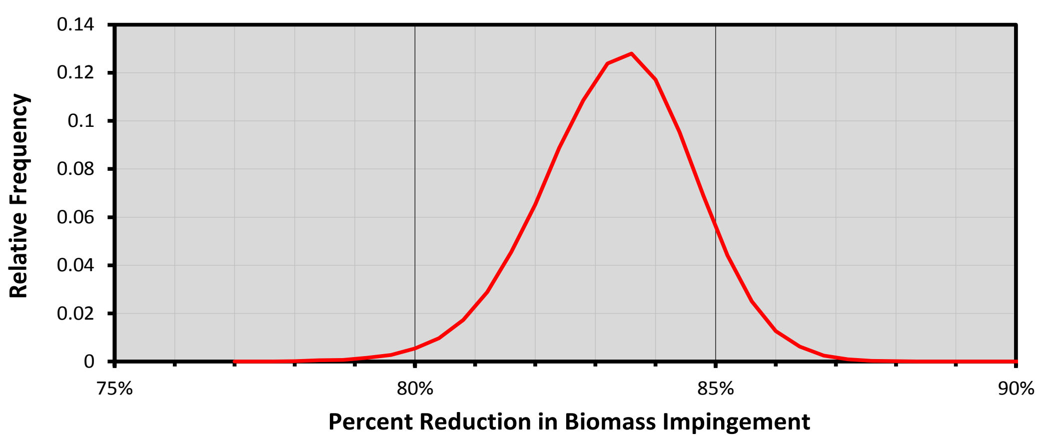


Figure 24: Reduction in Biomass Impingement at Pickering NGS

This study concluded that between 2003/2004 and 2010, a reduction in biomass by 80% was achieved with 99% confidence during the summer season.

This is a rather unusual application of probabilistic methods developed for life cycle management of engineering systems, however, it validates the inter-disciplinary and versatile nature of Waterloo`s research program.

Other applications included

- Estimation of the Material Improvement Factor for Alloy 800 SG tubing based on AECL incubation time test data
- Estimation of steam generator tubing degradation rate from noisy eddy current inspection data
- Probabilistic seismic hazard analysis of nuclear plant structures

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

A major part of the IRC research is focused on corrosion of steam-generator tubing alloys 600, 690, 800 to support improvements in corrosion prediction and its mitigation in current plants. A major issue in the latter area is the long-term performance of Alloy 800, a high-nickel stainless steel that is used as the SG tubing in most CANDU plants. Thus to gain insights into corrosion and cracking of that material fundamental studies of Alloy 800 corrosion 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. Fundamentals of engineering alloy behaviour in aqueous environments, including atomistic simulation
2. Studies of stress corrosion cracking (SCC) in nuclear materials
3. Steam generator chemistry and corrosion
4. Surface modification for corrosion resistance
5. Science underpinning the monitoring of used fuel storage containers
6. Zirconium hydriding project

Fundamentals of Engineering Alloy Behaviour in Aqueous Environments Including Atomistic Simulation

The significance of this fundamental research for the CANDU industry relates to the prediction of the long-term behaviour of Alloy 800 (a stainless steel with 32% nickel used for steam generator tubing at Darlington and in newly refurbished units). Figure 25 below shows a simulated result of a set of micrographs from recent research work, showing a new type of porous layer development in which dealloying bypasses regions of intact alloy; the surfaces of the porous structure are coated with a thin layer of nickel. The inset shows a simulation showing the same kind of bypassing behaviour.

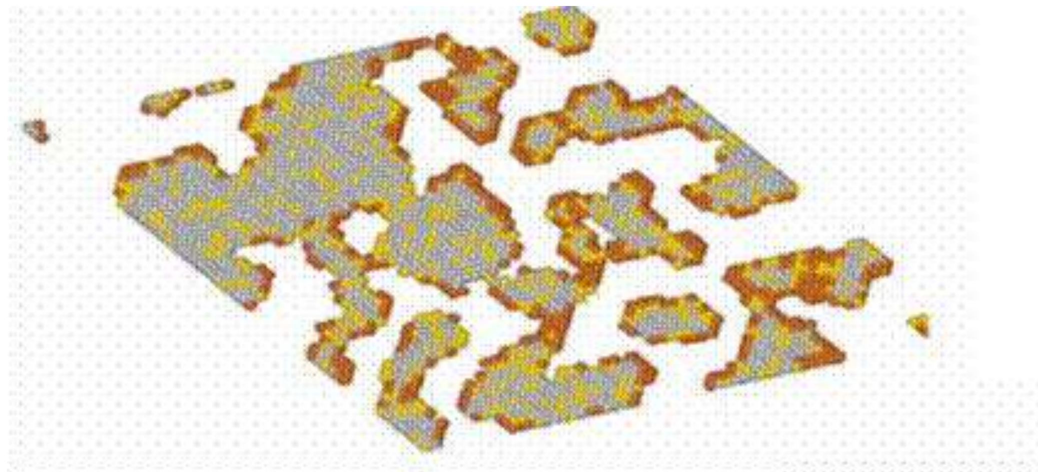


Figure 25: Section of a Simulated Lattice Shows an Analogous Structure

Section of a Simulated Lattice shows an analogous structure – gold-coloured 'nickel' atoms have never seen the solution, while brown ones have reorganized on the surface of the nanoporous structure. Studies of SCC in nuclear materials

Studies of SCC in Nuclear Materials

This project started in 2009, with the aim of understanding the detrimental effect of cold work (plastic deformation) on intergranular stress corrosion cracking (SCC). To date some advances in knowledge were made in the application of electron backscattered diffraction (EBSD) to stress corrosion cracking (SCC) using brass as a model material (collaboration – Queen's), alongside stainless steel and Alloy 600 (collaboration with UWO). Measurements were made of local strains before cold work, after cold work, and after subsequent SCC, all on the same microscopic area of the metal's microstructure. A relationship was derived between cold work and cracking, and critical tests remain to be done, but the main controlling factors (grain boundary character, local dislocation density, Schmid factor) are being teased out. In tensile testing the surface granular relief due to plastic deformation is being modeled (collaboration – Queen's). Figure 26 below shows measured local misorientation (greenish colour, related to local dislocation density) on the same area before and after deformation, and after SCC. White areas are unindexed crystallographically. The numbers refer to cracks.

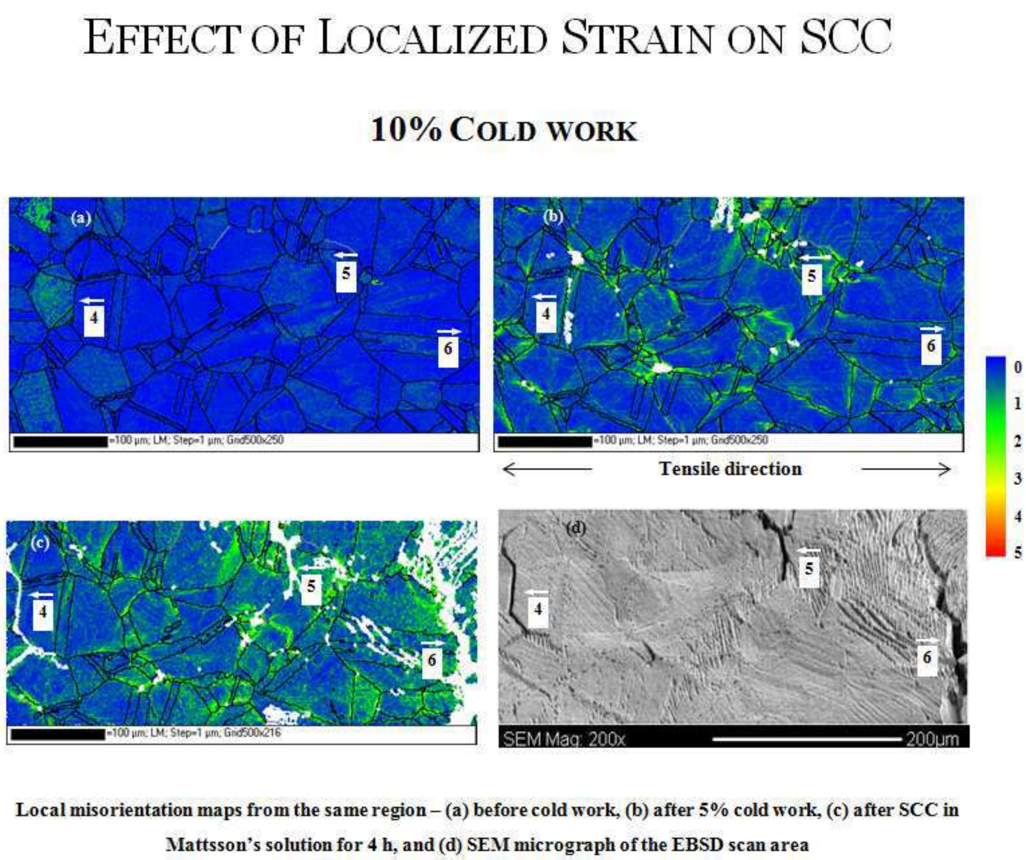


Figure 26: Effect of Localized Strain on SCC

Another research program in collaboration with Arizona State University) has been addressing the effect of local atomic arrangement on alloy corrosion.

Another SCC issue of dissimilar welds was identified by the industrial partners, and is currently the subject of research for a M.A.Sc. student. CANDU systems contain components made of Alloy 600 (Ni-16%Cr-9% Fe alloy) that are welded to carbon steel pipe using fairly similar Alloy 82. A known steam and hydrogen mixture was used to simulate the primary water SCC environment, and found that such welds are extremely diluted by carbon steel, to the point that the weld root surface is like a low chromium version of Alloy 800 (which does not suffer from primary-water SCC). Figure 27 shows the appearance of a cross-section of the component after steam/hydrogen exposure.

Figure 27: Cross Section of Dissimilar-Metal Weld

Cross-section of dissimilar-metal weld after steam/hydrogen exposure below the Ni/NiO equilibrium. The weld root forms an external Fe rich oxide owing to dissolution of carbon steel (extreme lower right) into the weld pool

A new SCC activity involves experimentation on Alloy 800 in acid sulfate solutions at 300ºC, and collaboration with UNENE Chair Dr. Mahesh Pandey of the University of Waterloo, an expert in probability and statistics. It is thought that SCC may only occur during brief startup periods, so cracking is being compared in Alloys 600 and 800 under conditions of continuous and intermittent immersion. Other SCC projects have been proceeding with funds from COG, OCE (Ontario Centre of Excellence) and others, in collaboration with UWO (McIntyre) and Queen's (Holt, Daymond) amongst others.

Steam Generator Chemistry and Corrosion

One of the most successful activities has been the elucidation of the effects of traces of reduced sulfur compounds on low-temperature corrosion of steam-generator tubing alloys. It is believed that sulfate is reduced to sulfide during operation, and then reoxidized to aggressive species such as thiosulfate during plant shutdown. A PhD research showed that the ratio of sulfate to thiosulfate concentration was a precise predictor of the aggressiveness towards Alloys 600, 690 or 800 over many orders of magnitude of ionic strength, but the same ratio argument did not apply when the predominant anion was chloride. A model has been created to explain these phenomena. The work has been published in major nuclear conference proceedings and submitted for journal publication. Another M.A.Sc. student created a simulation of the reoxidation step using beds of magnetite with layers of iron sulfide and other relevant materials such as metallic copper, and showed the importance of surface catalyzed reactions on the magnetite; thiosulfate and sulfate were monitored by ion chromatography and the results correlated with a finite difference model – Figure 28.

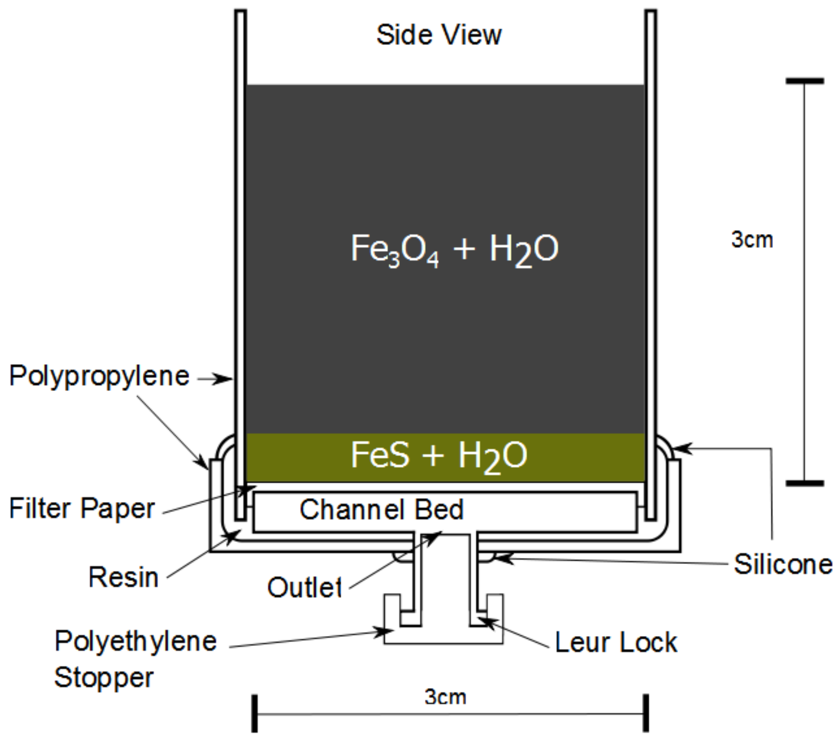


Figure 28: Arrangement for Studying Oxidation of FeS to Thiosulfate and Sulfate in a Simulated Steam-generator Sludge-Pile Environment with Well-defined Geometry

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

This IRC was established on Sept 2008 at UOIT under the leadership of Dr. A. Waker (IRC) and Dr. E. Waller (Associate IRC).

The 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.

<u>Research Highlights/Outcomes</u>

- Real Time Measurements

A novel design was developed of a compact multi-element tissue equivalent proportional counter (METEPC). The METEPC has been shown to provide very good estimates of the dosimetric quantities of interest, H*(10) and Q in low energy neutron fields typical of the nuclear power plant environment. The next stage planned for this work is to link the METEPC detector to a commercially available data acquisition system and test its performance as a hand-held device. To achieve this collaboration with the University of Regina and Far West Technology is ongoing to employ their data acquisition system; the REM500 device. The REM500 is the only commercial neutron monitor based on a tissue equivalent proportional counter detector. In 2011 a comprehensive study was completed of the response of the REM500 device in low energy neutron fields of relevance to nuclear power plant radiation protection in collaboration with AECL and McMaster University. The results of this work have been accepted for publication in the Health Physics Journal and in this publication we demonstrate a novel method of improving the low energy response of TEPCs by improving the algorithm used to derive the mean quality factor from real-time pulse-height data.

Also an investigation was completed of the relative response of thin plastic scintillators to beta particles and photons. Measurements were carried out using four different gamma sources with different energies ranging from 6 keV to 1.332 MeV and a Ni-63 beta source of maximum energy 66 keV. Scintillator thicknesses ranged from 10 μm to 2500 μm and the experimental results indicated that maximum discrimination between high energy gamma rays and beta particles could be achieved with a scintillator thickness of 250 μm. These results, in conjunction with the Monte-Carlo modeling have led to the conclusion that a system based on plastic scintillators will not be sensitive enough to measure a concentration of tritium in air of 1 DAC, while immersed in a background gamma field of a few hundred micrograys per hour. The system investigated however does have potential for the measurement of higher energy beta particles such as noble gases in a gamma ray background.

In view of the importance of real-time tritium monitoring in Candu plants we are continuing to explore different detection systems. Gas ionization methods remain the most sensitive method for the detection of tritium in air,

- Radiation Quality

Regulatory and public concerns are continually raised about the appropriate radiation weighting factor for low energy beta particles, particularly tritium, in the context of CANDU reactor radiation protection and environmental safety. To address this issue a study is underway to describe the dosimetry of low level exposures in terms of the specific energy probability distributions for single and multiple events in mammalian cells and sub-cellular structures (microdosimetry). This work showed that absorbed dose is related to the product of the mean specific energy deposited in a cellular target per charged particle track intersection, the mean number of hits received by such cellular targets during an exposure and the fraction of such cellular targets in a tissue receiving at least one such hit. From this analysis three regions of absorbed dose were identified where the microdosimetric quantities change in a manner that could be significant for a systems biology approach to radiation protection risk assessment.

- Radiation Field Modelling and Visualization

The goal of this research will be to develop a versatile system for generating radiation maps on-demand for areas in which completing a full sensor survey is impossible, and/or for which there is limited information available about the physical layout. The general concept of this system comprises three main stages as shown in the accompanying (Figure 29).

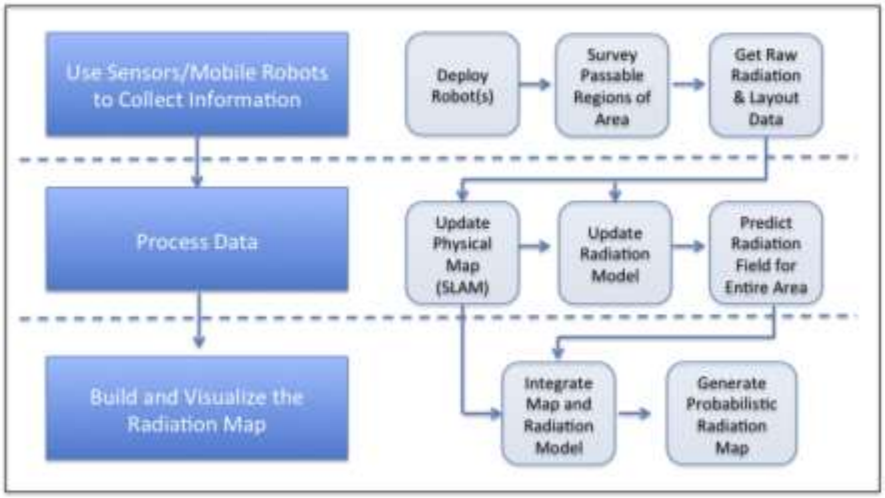


Figure 29: Radiation Field Modeling Visualization

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. Based upon needs identified by the Bruce A alpha event a multi-faceted research thrust was initiated, including research in (a) risk from radiological aerosols, (b) rapid triage and treatment from inhalation of radiological insults, and (c) exposure assessment from accidentally contaminated personnel in nuclear power plants. The research program focus is on protection of the public and workers in the event of a radiological accident or other emergency. This research seeks to generate rapid estimates of actinide levels in urine through liquid scintillation counting. The research will have great significance to the health physics and emergency response community for rapid determination of actinide intake. It will be of equal interest to industrial and government agencies that have requirements to protect the health and security of personnel. The research will benefit the scientific community by adding to the knowledge base of rapid actinide determination from bioassay samples, and by training a number of highly qualified personnel (HQP).

3.0 Consultation to Industry and Government

One of the objectives of UNENE is the availability of scientific experts for independent consultation by government, public and industry. To date this has proven to be a valuable asset to all stakeholders and has been extensively used by all. In the last two years over 90 consultations, technical exchanges and reviews were sought of the UNENE IRCs and Associate IRCs.

One notable benefit is the extensive coverage of the Fukushima events (March 2010) and the many interviews and publications made by UNENE's Industrial Research Chairs and their Associates in effectively addressing public concerns through TV and media interviews. Many of the UNENE IRCs, namely: Profs. Luxat, Lewis, Novog and Waker have been interviewed on TV and the radio on numerous occasions following the Fukushima events. The interviews were timely in addressing public interest in the event, its impact on the public in Japan and its comparison with the Canadian CANDU design and safety features. This very incident confirmed UNENE`s vision since inception and that is to provide an independent pool of university scientific experts for public consultation on industry related issues.

Other notable consultations and inputs to industry and governments are:

- Prof. Holt (Queen's) continues a strong interaction with the industry sponsors as an external consultant for AECL, Bruce Power and OPG (through Kinectrics 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) is a member of the COG Fuel Channel Working Group on Crack Initiation and Fracture, as well as acting as an external consultant for AECL. Both Profs. Holt and Daymond collaborate with AECL, Kinectrics and Nu-Tech precision metals on a number of research topics.

- Prof. Lewis (RMC) has provided consulting activities on; (i) an evaluation of fuel release and actinide fuel chemistry for Bruce Power to better understand alpha contamination during reactor refurbishment, (ii) instant release fractions for the Nuclear Waste Management Organization (NWMO), and (iii) an Independent Technical Panel (ITP) to assess Candu trip acceptance criteria for the nuclear industry (COG) and the regulator (CNSC).

- Prof. Luxat (McMaster) was an Independent Expert Reviewer on numerous industry reports; (i) Containment Scaling Approach to Multi-Unit Accident Simulation using MAAP-CANDU – AMEC NSS (2011), (ii)Severe Accident Analysis Consequence Assessment supporting Containment Event Tree Quantification for Level 2 Probabilistic Risk Assessment of Bruce A&B – AMEC NSS/Bruce Power (2011), (iii) Level 3 Probabilistic Assessment of Darlington NGS – AMEC NSS/OPG (2011), (iv) Severe Accident Analysis Consequence Assessment supporting Containment Event Tree Quantification for Level 2 Probabilistic Assessment of Darlington NGS – AMEC NSS/OPG (2010).

- Prof. Luxat is a member of AECL Board of Directors, (2008-present) and was a Member, Science, Technology and Nuclear Oversight Committee of the Board of Directors, Atomic Energy of Canada, Ltd. (2008 – 2011).

- Prof. Newman's ongoing work (at U of T) in the nuclear waste area is being used in decision making by relevant entities worldwide (Canada, Switzerland, and Sweden). Prof. Newman continues to provide consulting assistance to OPG in the area of electrochemical monitoring in reinforced concrete in support of concrete used in dry storage containers for used nuclear fuel This included a visit to a supplier in Oxford, UK in September 2011.

- The UofT Department of Chemical Engineering and Applied Chemistry (where Prof. Newman resides) organized a conference on Alloy 800, with representation from major nuclear corrosion specialists worldwide. The proceedings are available as a CD, with some restrictions.

- Prof. Pandey (Waterloo) continues to transfer his risk and reliability knowledge to industry through active collaboration and consultation on critical LCM issues related to critical systems, components and structures. Many risk based assessments were carried out on feeder thinning, PT/CT spacers and gap assessments and many others leading to a risk based inspection and maintenance in support of ongoing planned inspections. Other interactions with the IRC continue on conferences, workshops, and working groups. Prof. Pandey participated in a COG project on "Identification of Crack-Susceptible Feeders".

- UNENE Chair holders Profs. Walker and Waller (UOIT) have interacted with their nuclear energy partners on a number of levels regularly through the year. At the program level the senior Chair is a member of the CANDU Owners Group (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. Examples of industry-partner activity at the technical and research level are collaboration with AECL scientists on neutron spectrometry and dosimetry and a review of alpha particle internal dosimetry dose-assessments with Bruce Power.

- The expertise of the UOIT Chair holders and in particular 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. Examples of these activities are the Bruce A Alpha Event and the Public Health and Radiation Emergency Preparedness Conference "Bridging the Gap "along with many Canadian and international conferences.

- The UOIT Chair holders are also engaged in a number of nuclear community and educational initiatives such as; (i) Meetings with OPG Health Physics Department, Whitby on Health Physics and the Environment (ii) Durham Nuclear Health Committee membership (& host location) (iii) Undergraduate Internship Programs (CNSC, Bruce, OPG).

- Dr. Tremaine, a CRD Principal Investigator (U of Guelph) serves on three industrial advisory committees for the nuclear industry and on several committees charged with nuclear education, organizing conferences, and preparing large project proposals.
  - Chair, R&D Advisory Panel Atomic Energy of Canada Ltd (to Oct 2011) The Panel reported to the Board of Directors through its Science Technology and Nuclear Oversight Committee.

- Member, MULTEQ Database Advisory Committee, Electric Power Research Institute (EPRI).
- Member, Advisory Committee NSERC/AECL Chair in Radiation Chemistry (2005 to present)

- Dr. Tremaine is providing input on Canadian nuclear industry R&D needs to the EPRI MULEQ Database Committee, which recently published and updated a database for magnetite and transition metal ferrite solubility. He is also a member of the Canadian National Committee of the International Association for the Properties of Water and Steam, which hosted its annual international meeting in Niagara Falls Canada, in 2010.

4.0 Other Benefits

4.1 Integration of Research Programs among Universities and Industry

UNENE research addresses medium to long term industry requirements. These are derived from joint discussions with dedicated Technical Advisory Committee members from AECL, BP, and OPG. Such interactions between industry representatives and researchers result in a confirmation of research directions and objectives. During 2012 collaborative discussions were held between research Chairs and AECL Chalk River Labs on the potential for access to some CRL facilities for experimental research. Such collaboration is aimed at leveraging both organizations strengths and knowledge for overall industry benefits. Such collaboration was initiated in Jan 2012 amid the change of AECL-Chalk River status as a National Lab. These collaborations continue to be explored and build on current ongoing ones such as;

- The ongoing one between Queen's U, Kinectrics and AECL CRL in the F/C area
- Current cooperation in the fuel cycle & physics for Thorium fuel cycle between McMaster, Candu Energy, AECL-CRL and EPM
- Cooperation in fuel performance modeling and analysis behavior (RMC/CRL)
- Co supervision of graduate students between RMC and CRL in the fuel area.

Additional to its financial support the industry extends some in-kind contribution to researchers as needed. Such contribution is equally critical to enable various research programs to achieve its expected results and outcomes.

4.2 CANDU Textbook

A notable item this year is the development of a CANDU Textbook to document the scientific basis of the CANDU-HWR technology. A business case was approved by the Board enabling such undertaking. The project is funded under a CANDU Owners Group (COG) Joint Project with contributions from CANDU utilities in Canada and offshore.

4.3 Publications

Advances in knowledge and technology are documented in Ph.D. and M.A.Sc., theses, as well as journal publications and conference papers. Over 200 publications (Table 4) have been issued in the last two years, advancing knowledge in all aspects of the technology and showcasing Canadian nuclear research. These documented advances are captured and documented nationally through IRC participation on COG technical committees and internationally through various exchanges such as student exchanges and ongoing validation of research and nuclear data.

Table 4: Publications by the UNENE IRCs and CRDs (2010-2012)

IRC Program	Journal Papers	Conference Papers	Miscellaneous (Industry Reports and/or Book Contributions etc.)	Total (excluding Posters)
- Nuclear Materials (Queen`s)	13	10	11 Posters in industry seminar (excluded)	23
-Safety & T/H (McMaster)	16	18		34
-Nuclear Fuel (RMC)	10	13	2 (Book Chapters) 7 (industry reports)	32
-I&C & Electrical (UWO)	21	9 (selected ones)		30
-Corrosion & performance of nuclear materials (U of Toronto)	12	Included in JP		12
-Risk &Reliability (Waterloo)	5 (selected ones)	9	5 (industry reports	19
-Radiation Physics & Environmental Safety (UOIT)	10	10	2	22
-CRDs	11	23		34
Total	98	92	16	206

5.0 Value of the M.Eng. Program and its Role in Knowledge Preservation/Transfer

A parallel path to research for training & development of HQP is the M.Eng. degree in Nuclear Engineering managed under the auspices of UNENE. This is a jointly offered degree by member universities, with strong UNENE support and overall coordination. The M.Eng. program is accredited by the Quality Council (equivalent to the previously known Ontario Council of Graduate Studies (OCGS)) and is mainly aimed at industry professionals for broadening work-related fundamental knowledge, academic advancement and overall competency building.

Courses are given during off-working hours throughout the academic year, normally at the Whitby campus of Durham College. Since November 2009 a Distance Learning (DL) technology (ELLUMINATE) was approved for use in course delivery and has been used since then during all course deliveries enabling staff at remote nuclear sites to enroll and participate "live".

The program uses professorial expertise residing at participating universities and draws specialist guest lecturers from UNENE Industry members. Most of the UNENE IRC chairs also give an M.Eng. course, providing the industry staff exposure to current, relevant and respected expertise. The Education Advisory Committee (EAC) of UNENE controls curriculum matters, whereas the Program Director appointed by UNENE is responsible for enrollment, logistics, educational quality and effectiveness, instructor selection, course delivery and liaison work with universities. The UNENE Administrator executes the UNENE- and university-administrative aspects of the program.

The past two academic years (2011/2012) experienced an increase in the number of graduates from nearly 40 to 70 graduates (Figure 30) decreasing the number of active students currently enrolled to 49.

Figure 30 below summarizes the cumulative throughput of students as of May 2012 since the inception of the UNENE M.Eng.

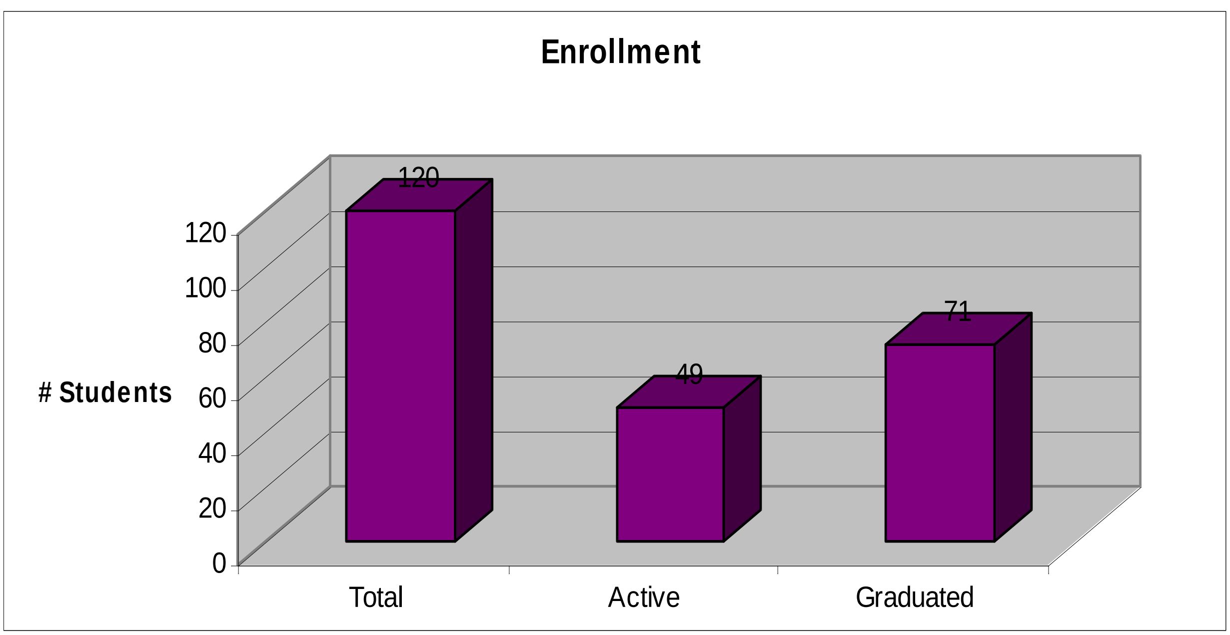


Figure 30: M.Eng. Student Throughput

Enrollment is currently fairly steady but is expected to rise in the longer term driven by the future Darlington refurbishment, Bruce unit 1 Return to Service and the recognition given to the M.Eng. by some UNENE industrial members as a means of competency building and career advancement.

In 2011-2012 a new schedule with a mixed two/three year cycle of all UNENE courses was adopted. The new schedule offers 6 courses per academic year, with the core courses repeating every 2 years and the non-core courses every 3 years, giving student's predictability and leveling their workload. Student feedback remains highly positive with specific examples of the benefit their increased knowledge has given back to industry. A diploma program with four courses is being proposed by UNENE and is planned to be available for enrolment in the new fiscal year 2013/2014.

The M.Eng. program offers the following benefits to industry:

- Development of HQP to meet industry needs
- Enhancement of young professionals' nuclear competency and their ability in 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

Two surveys of current and past M.Eng. students were undertaken during the period covered by this report.

The purpose of the first survey was to determine the benefit to the industry staff enrolled in the M.Eng., specifically:

- Determine students' overall satisfaction with the UNENE M.Eng. program
- Provide evidence of benefit (or otherwise) of the UNENE M.Eng. and its courses to the student
- Suggest improvements to UNENE in the way the program is run

The survey consisted of 14 statements on various aspects of UNENE which students were asked to rank (strongly agree to strongly disagree). Figures 31 a & b below depict responses to sample questions.

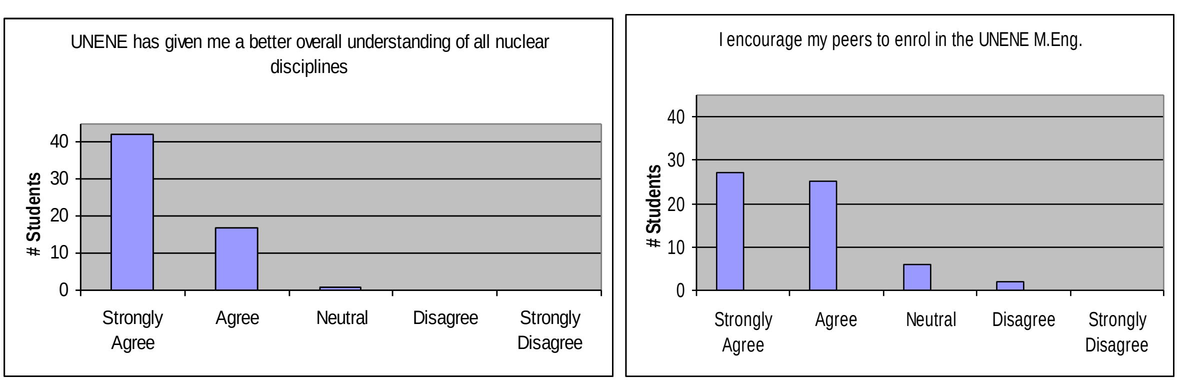


Figure 31: a & b: Sample of Results of Student Feedbacks on M.Eng. Program

Overall the responses showed that the M.Eng. was delivering good value with the following strengths:

- Broadening their knowledge
- Understanding the context of their work
- Effective Distance education & recorded lectures
- Effective UNENE Administration

and almost all would recommend the M.Eng. to their colleagues.

The purpose of the second survey was to determine the benefit to industry. Unlike the first survey, there were no structured questions - we asked for specific examples of benefits to the employer, and got a number of thoughtful replies, covering areas such as;

- Ability to prepare business cases for employer projects, including analysis of costs, benefits and risks
- Ability to take on senior roles, supervising others
- Success in Shift-Supervisor-in-Training program
- Performing shielding calculations on an urgent basis during an outage

Many replies stressed the long-term big-picture benefits of increased broad knowledge.

The UNENE Board of Directors had its strategic planning session in March 2012. Part of the ensuing recommendations on the Education program is to

- diversify its educational offerings
- develop an improved fee structure
- Offer a nuclear engineering Diploma as a supplement to the current M.Eng. degree. The diploma is currently under discussion at the EAC and Board of Directors. It entails two core courses + two non-core courses, given over four alternate weekends with Distance Learning and with identical course content to UNENE M. Eng. Approval by the Universities will be on the critical path.

6.0 UNENE Funding

In the last two fiscal years the three major industry members funding the program were OPG, BP and AECL-CRL. The CNSC contribution increased from $100k to $130k/year and AMEC-NSS, NWMO and Candu Energy each contributed $30k/year.

Table 5: UNENE Funding Details (2011/2012)

	FY11/12	Notes
Funding	**$**	
OPG	850K	
BP	300K	
AECL-CRL	300K	
CNSC	130K	
Cameco	30K	
AMEC-NSS	30K	
COG (for Daymond)	125K	
COG (for Lewis)	80K	
NWMO	30K	
Candu Energy Inc	30K	Funding starting FY2012/2013
TOTAL Funding	1905K	
Expenditure		
IRCs	1.4 M	Covering 7 IRCs until 2012
CRDs	270K	Covering 9 active CRDs
Mgmt/Admin	200K	excludes 13%HST

COG has been a funding member in UNENE, in addition to supporting some IRC programs through COG related Work Packages (WP). COG`s involvement and funding plays a key role in readily capturing some of the IRC research outcomes & knowledge into COG Industry reports.

7.0 Conclusion

In summary this review confirms that UNENE industry –university partnership has been a good strategic initiative and has, thus far, served all members well through successfully meeting all objectives set forth at the inception of UNENE. Research results continue to advance knowledge in all facets of the technology and support continued safety and economic performance of NPPs in Canada. The M.Eng. broadens the knowledge and abilities of industry staff and has direct payback to both the individuals and their employers.

The supply of HQP has been key in addressing the demographic gaps experienced by industry in the last few years.

Acronyms

CRD: Collaborative Research and Development Project

CFI: Canadian Foundation for Innovation

LCM: Life Cycle Management

GRA: Generation Risk Assessment

ICFD: In Core Flux Detectors

LBB: Leak Before Break

LCM: Life Cycle Management

OCGS: Ontario Council of Graduate Studies

USDOE: US Department of Energy

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Appendix A

OPG support to NSERC-UNENE Industrial Research Chair (IRC) Program: Risk-Based Life Cycle Management of Engineering Systems

On behalf of Ontario Power Generation (OPG), we would like to express our continued support for the NSERC-UNENE Industrial Research Chair in Risk-Based Life Cycle Management of Engineering Systems led by Dr. Pandey at the University of Waterloo.

We recognize the importance of Waterloo's IRC in the context of improving our risk-based decision-making tools for life cycle planning that would enhance our ability to make informed decisions about:

- the OPG power generation base,
- the CANDU nuclear reactor program, and
- the electricity generation support industry and infrastructure.

In the past eight years, we have developed a solid working relationship with Dr. Pandey and his research team at the University of Waterloo. This collaboration has increased our understanding of plant aging degradation processes and improved our plant management practices to enhance the safety and reliability of the commercial operation of our CANDU reactors.

Dr. Pandey and his research team continue to build on the success of the first phase of the IRC program. In the past three years, probabilistic life-cycle management techniques developed under this program have been extensively utilized by our engineers with some notable applications listed in the following:

- Generation risk assessment (GRA) of the heat transport system, turbine and generators at the nuclear station.
- Application of GRA to the Darlington Refurbishment project selection process.
- Prediction of deuterium ingress in rolled joints for the fitness for service assessment of pressure tubes.
- Reliability analysis of eddy current inspection probe systems used for steam generator tubing inspections.
- Risk-informed inspection of fuel channels to detect the degradation of fixed spacers.
- Probabilistic approach for optimizing the replacement of feeder pipes in a number of reactor units.
- Life cycle management strategies for main output transformers, air compressors and other important components.
- Risk-based model for the inspection of instrumentation tubing in the reactors.
- Statistical analysis of fish impingement at the cooling water intake of the Pickering Nuclear station.

Dr. Pandey and his team have been very responsive to our research needs. A number of our personnel and scientists are working closely with him and exchanging data to enable the development and practical application of the research methodologies. In the coming years, we expect to continue this cooperation and application of the research to our operating plants.

To meet our continued commitment to a high quality workforce, Dr. Pandey has developed and successfully delivered an advanced training course “Fundamentals of Risk and Reliability” to OPG staff and to M.Eng. students in the UNENE's Nuclear Engineering program. The technology and knowledge transfer to the industry has been one of the key successes of this IRC program.

We are confident that Dr. Pandey and his research team will continue to improve our capabilities in the risk assessment and life-cycle management area. Therefore, we will continue our collaboration and funding support for Dr. Pandey and his team as per the original research proposal.