Written submission from
University Network of Excellence in
Nuclear Engineering

In the Matter of

Ontario Power Generation Inc.

Environmental Assessment pursuant to the
Canadian Environmental Assessment Act of
a proposal by Ontario Power Generation for a
Project that includes site preparation,
construction, operation, decommissioning
and abandonment of up to four new nuclear
power reactors at its existing Darlington
Nuclear Site located near Oshawa, Ontario,
in the Municipality of Clarington and a
Licence to Prepare a Site application for the
Project under the Nuclear Safety and Control
Act.

Public Hearing

March 21, 2011

Mémoire de
University Network of Excellence in
Nuclear Engineering

À l’égard de

Ontario Power Generation Inc.

L’évaluation environnementale, en vertu de la
Loi canadienne sur l’évaluation
environnementale, du projet d’Ontario Power
Generation qui inclut la préparation de
l’emplacement, la construction, l’exploitation,
le déclassement et l’abandon de jusqu’à quatre
nouveaux réacteurs nucléaires sur le site de la
centrale nucléaire Darlington près d’Oshawa
(Ontario), dans la municipalité de Clarington, et
une demande de permis de préparation de
l’emplacement, aux termes de la Loi sur la
sûreté et la réglementation nucléaires.

Audience publique

Le 21 mars 2011
UNENE Submission

To

Darlington Joint Review Panel Commission

Submission from UNENE

(University Network of Excellence in Nuclear Engineering)

February 2011

www.unene.ca
1.0 Purpose of Submission

The main objective of this submission is to make the panel aware of the new capacity in Canada created to support nuclear education and research required for the new build and thus supports the new build of NPPs on the Darlington site. UNENE in its entirety of research, education and staff feel privileged to work on a clean energy supply option for Ontario with a safe and economic performance. Current Darlington units continue to supply Ontario rate payers with reliable electricity at competitive rates.

University Network of Excellence in Nuclear Engineering (known as UNENE) was created in 2002 as a non-profit partnership between Industry and universities with the objective of establishing nuclear related research in universities in areas of importance to industry, developing a sustainable supply of Highly Qualified Personnel (HQP) for industry and creating a well respected pool of university based scientists for industry and public consultations.

UNENE has become over the past eight years a well established network for nuclear research and education and is pleased to submit this paper to the Darlington Joint Review Panel in support of the current plans for two future Nuclear Power plants (NPP) on the Darlington site.

2.0 Current Industry Status & Priorities

Canada’s nuclear industry is currently a $6B/yr industry with nearly 70,000 jobs in science engineering, manufacturing, construction and delivery of related products and services. It started in 1945 with experimental and research reactors and progressed to what is now the established CANDU - PHWR (Pressurized Heavy Water Reactor) technology – with a current market share of 8-10% of the world-wide commercial Nuclear Power Plants (NPP).

Nuclear power in Canada now provides 15% of the national electricity supply, with Nuclear Power Plants (NPP) in New Brunswick, Quebec and Ontario. More than half of the electricity supply in Ontario is from nuclear. Most of the plants are Generation II vintage, coming on stream from the mid-1970s (Pickering A Units 1 to 4) to the mid-1990s (Darlington Units 1 to 4). Some of the CANDUs have been life-extended beyond their original 30-year design life while others are being (or are planned to be) refurbished for a 50 to 60-year life. Such examples are, Bruce A Units 1&2 in Ontario and Point Lepreau in New Brunswick and Darlington 1-4 starting 2016.

Future nuclear construction of Generation III and Generation III+ plants are expected to replace retired nuclear capacity and to meet energy requirements as part of an integrated system of electricity supply (Figure 1).

Current industry status and the importance of knowledge preservation over two to three generations prompted attention to the role of research and education as key enablers to its
safe and economic performance over its entire lifecycle: design, licensing, construction operation, decommissioning and long term waste management.

The industry recognises the role of knowledge preservation and continuous competence-building in order to meet the following strategic priorities:

1. Maintain the safe and economic Long Term Operation of its current nuclear plant fleet.
2. Maintain knowledge of the design and licensing basis of current plants.
3. Advance knowledge and innovation towards successful design, licensing and delivery of future Gen III+ plants (such as the Enhanced CANDU 6 and the ACR-1000) in Canada and off shore.

3.0 UNENE; its role in technology sustainability

With these priorities UNENE (University Network of Excellence in Nuclear Engineering) was established in 2002 as a non profit partnership between the nuclear industry and universities with the objectives of:

1. Establishing university research in key areas of interest to the nuclear industry.
2. Developing a sustainable supply of Highly Qualified Personnel (HQP) to address demographic gaps in the industry.
3. Providing an independent university–based source of scientific expertise for public and industry consultation. UNENE members are listed in Figure 2
UNENE Members

- Atomic Energy of Canada Limited (AECL)
- Bruce Power (BP)
- Ontario Power Generation (OPG)
- Canadian Nuclear Safety Commission (CNSC)
- CANDU Owners Group (COG)
- Nuclear Safety Solutions (AMEC-NSS)
- CAMECO
- McMaster University
- Queen’s University
- University of Ontario Institute of Technology
- University of Saskatchewan
- University of Toronto
- University of Waterloo
- University of Western Ontario
- University of Windsor
- Ecole Polytechnique
- University of New Brunswick
- Royal Military College
- University of Guelph

Figure 2: UNENE Members (Government/Industry and Academia)

4.0 UNENE Programs
UNENE programs focus on two key aspects: Education and Research.

4.1 Education Program
A graduate level Master’s program was set up by UNENE in collaboration with the member universities. Graduate level courses from member universities, duly accredited in Ontario by the Ontario Council on Graduate Studies, allows UNENE to coordinate a joint course-based Master’s of Engineering Program in Nuclear Engineering. The courses cover key areas fundamental to nuclear plant design, safety, operation and other related topics geared to enhance the knowledge and competence of students and other professionals working within the industry. Courses are offered outside working hours; acceptance is according to the normal graduate-level admission prerequisites. The courses currently offered are noted in the Table below:

Table 1: Courses offered towards the UNENE M. Eng. in Nuclear Engineering

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<tr>
<th>Course #</th>
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<th>Course Code</th>
<th>Course Title</th>
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<td>UN0801*</td>
<td>Nuclear Plant Systems and Operations</td>
</tr>
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<td>UN0802*</td>
<td>Nuclear Reactor Analysis</td>
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<td>UN0803*</td>
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<td>Radiation Health Risks and Benefits</td>
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<td>UN0902</td>
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<td>UN1001</td>
<td>Reactor Chemistry and Corrosion</td>
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<tr>
<td>UN0800</td>
<td>Industrial Research Project</td>
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</table>

*Core M. Eng courses

The M.Eng Program continues to grow both in student enrolment and in the selection of courses offered, as shown below (Figure 3).
The UNENE education program has experienced an increased enrolment in the last two years. There are currently over 60 active students in the M.Eng program. The program is also gaining credibility as a means of competence building (for career advancement), and knowledge transfer to young industry professionals. To date over fifty (50) students have graduated from the M.Eng program out of 137 enrolled. New courses are being added to the program, along with an increased number of courses offered on a quarterly basis.

The UNENE M. Eng. also offers other benefits such as:

- Development of HQP to meet industry needs.
- Assisting industry in knowledge transfer and preservation.
- Professional/career development of employees towards an effective and highly skilled workforce.
- Lower cost than in-house training (employees take courses outside of working hours on their own time).
- Forum for employee’s interaction with industry and university peers.

One utility explicitly recognizes the UNENE M. Eng. as an advantage when an individual applies to become a shift supervisor. Also some of the M.Eng course material is now being proposed for high-calibre non-accredited enhanced training to utility professionals.

An e-learning tool is now routinely applied to all course deliveries through the use of the ELLUMINATE program to accommodate and attract students who work at distant sites from the greater Toronto area. Student feedback with distance learning has been positive, and even “live” students appreciate and use the recording feature.

Figure 3: Current enrolment in UNENE M. Eng Program

The UNENE education program has experienced an increased enrolment in the last two years. There are currently over 60 active students in the M.Eng program. The program is also gaining credibility as a means of competence building (for career advancement), and knowledge transfer to young industry professionals. To date over fifty (50) students have graduated from the M.Eng program out of 137 enrolled. New courses are being added to the program, along with an increased number of courses offered on a quarterly basis.

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4.2 Research Programs

Industrial Research Chairs (IRCs) and Collaborative Research and Development (CRD) projects were set up as the platforms for UNENE/NSERC nuclear research in Universities. World Class IRCs were endowed in prominent Canadian universities to become anchors for research in key areas of the technology, while developing Highly Qualified Personnel for industry hiring. The IRCs established are:

- McMaster University: Safety and Thermal hydraulics
- Queens University: Material Sciences
- University of Toronto: Corrosion and Material Performance in Nuclear Power Systems
- University of Waterloo: Risk and Reliability
- University of Western Ontario (UWO): Instrumentation and Control, and Electrical
- Royal Military College (RMC): Fuel Technology
- University of Ontario Institute of Technology (UOIT): Health Physics & Environmental Safety

Most programs focus on R&D areas of interest to industry such as safety analysis methodologies, phenomena and analytical codes; fuel channel material sciences; corrosion chemistry in nuclear materials; and probabilistic and risk modelling in support of Life Cycle Management (LCM) in current plants.

Some of the latest updates are noted below:

- In Radiation Physics and Environmental Safety (UOIT), current research focus on:
  1. Development /demonstration of a generic methodology for a 3D visualization of complex radiation fields. This is geared to achieve lower ALARA levels of radiation by inspection and maintenance workers in plants.
  2. Joint assessment with industry on neutron spectrometry systems for neutron detection and monitoring in plants

- In the Fuel technology area at RMC current research focus is on the development of a thermochemical model to provide an understanding of the chemistry of irradiated fuel .
In the Safety Analysis methodologies and advanced thermalhydraulics research. Progress has been achieved to date in the following areas:

1. An alternate approach to the current Best Estimate and Assessment of Uncertainty (BEAU) methodology has been developed through a developed set of analytical dynamic sensitivity functions. These can be used to propagate uncertainties in input parameters and evaluation of its impact on its associated output parameters. The approach has been applied to the fuel channel integrity problem in Large Break LOCA. The dynamic sensitivity method is then applied in a probabilistic uncertainty analysis to evaluate the probability of a pressure tube experiencing thermal creep strain deformation to contact its calandria tube during the early stages of a LOCA.

2. In 2011 further testing of the dynamic sensitivity function approach will be performed for the thermal-mechanical response of fuel elements subjected to power and cooling degradation transients. Verification will be performed against experimental data from LWR fuel elements subjected to rapid large power pulses in Reactivity Initiated Accidents (RIA).

3. Other projects are initiated to look at BEAU for large break LOCA and Loss of Flow event using a newly developed hybrid model using the RELAP code. The objective of this project is to demonstrate additional analysis margins in support of life extension of current plants and avoidance of premature power deratings of reactors.

Other safety research programs are ongoing into development of severe accident analysis methodology and mitigation strategies. This research will contribute to industry efforts in severe accident analysis that are being called for under modern nuclear safety requirements. Of particular importance to CANDU reactors is the issue of in-vessel retention of molten corium because of the inherent characteristics of CANDU which
facilitate this. Modelling is ongoing of high temperature fuel behaviour, quench front modelling and hydrogen generation. This work is undertaken in collaboration with Idaho National Labs in the US and using the QUENCH experimental facility and data for computer code validation. Additional experiments are also planned in a new test facility in McMaster U as part of UNENE /NSERC research involving hot molten material interactions with water aimed at studying the forces and interacting materials under these extreme hypothetical conditions. This new facility of the high temperature interaction experiments will be constructed over the next 2 years and will utilize ultra high speed videography acquired to study the behaviour of the vapour front formation with time resulting from hot water quenching high temp pressure tube.

Other Notable research outcomes

An earlier review of progress in research between 2007 and 2009 has identified advances of knowledge in other areas of the technology. Some of the developed technologies have been successfully deployed by utilities in support of their safe and economic NPP operation:

- A successful example is the application of risk-based methodologies to Life Cycle Management (LCM) issues. These, when applied to feeder replacement have reduced the number of feeders requiring replacement by nearly 70 feeders, reducing the cost of such replacement by many millions.[Note: There are 760 to 960 feeders in a reactor ]

- Research on effects of current manufacturing processes on Pressure Tube (PT) properties, textures and creep characteristics, on current and future PT alloys. If research outcomes succeed in this area this will be an international success for Canada in the field of nuclear materials.

- The IRC established in University of Western Ontario (UWO) has built an advanced Control and Instrumentation lab in 2009, with six projection monitors mimicking NPP human-machine interface with full connectivity to NPP control systems. The lab is used for application development/validation of numerous advanced diagnostic tools and control technologies aimed at reducing the number of safety system channels and common mode failures.

4.3 Development of Highly Qualified Personnel (HQP) through research and education continue to yield high calibre graduate students who, upon successful completion of their theses, have been recruited by industry, universities and government.
As of Sept 2009, the complement of graduate students in the UNENE research program was reported to be over 130 graduate students.

A large number of graduates (Masters and PhD) to date have been successfully recruited by industry, universities and federal government departments (e.g. DND etc.) while some proceeded further into PhD programs.

4.4 Industry/University consultation
Over ninety (90) industry–university consultation/interactions and technical exchanges have been reported in the 2007 to 2009 by all UNENE universities. Most of these were on joint industry technical committees, panels and review teams, as well as with various federal and provincial departments and panels.

4.5 Other outcomes
National & International collaborations are forged within the university itself across many engineering disciplines and scientific departments and among different universities, and with industry on specific research programs.

International collaborations are established with many US universities and the US Department of Energy (DOE) National Labs, and some European Union (EU) universities in areas such as thermal hydraulics (between McMaster / University of Pisa and Trinity College), and development of integrated fuel performance codes between Royal Military College and Oak Ridge National Laboratory.

- Equipment and Facilities:
  - A High Performance Computing Center (HPCC) set up at McMaster enabling Safety Analysis code coupling and code development. The HPCC is accessible by users University wide.
  - A Nuclear Materials Testing (NMT) Lab with state of the art equipment that is currently under construction at Queen’s University with commissioning expected in 2012.
  - A new Thermal hydraulic test facility; Water Quench Facility (WQF) to investigate heat transfer characteristics between the subcooled moderator and high temperature fuel channel surfaces during postulated accidents.

5.0 Summary
UNENE with its capabilities and achievements is ready to meet the research and professional education requirements associated with the Darlington new build.

UNENE through its various programs fully supports the planned new build at the Darlington site and will continue to support industry towards a successful delivery, safe and economic performance.
UNENE BI-ANNUAL REPORT 2007-2009

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Acknowledgement

On behalf of the Members and Directors of UNENE, I express our appreciation to the UNENE Officers, Committee members and Industrial Research Chairs for preparing this Report.

Funding from the Natural Sciences and Engineering Research Council (NSERC) is gratefully acknowledged. Without its enthusiastic support, UNENE would not be possible.

Dr. Peter Mascher
Chair
Board of Directors
University Network of Excellence in Nuclear Engineering (UNENE)
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CORPORATE PROFILE

University Network of Excellence in Nuclear Engineering (UNENE) is a not-for-profit Corporation incorporated by the Government of Canada with Letters Patent issued on July 22, 2002. The Head Office of the Corporation is located at the Department of Engineering Physics, Faculty of Engineering, McMaster University, 1280, Main Street West, Hamilton, ON, L8S 4L7.

UNENE is a unique industry - university alliance. Its current members are:

Atomic Energy of Canada Ltd. (AECL)
Bruce Power (BP)
Ontario Power Generation (OPG)
 Cameco
CANDU Owners Group (COG)
Canadian Nuclear Safety Commission (CNSC)
Nuclear Safety Solutions (NSS)

McMaster University
Queen’s University
University of Toronto
University of Ontario Institute of Technology (UOIT)
University of Waterloo
The University of Western Ontario
Ecole Polytechnique
University of New Brunswick
Royal Military College
University of Guelph
University of Saskatchewan
University of Windsor

UNENE was launched to ensure that the Canadian nuclear industry would continue to have a dependable supply of highly qualified and skilled professionals to meet its current obligations and emerging challenges. To this end, industry is investing significant funds in selected universities and is contributing in-kind to enable the universities to acquire and retain the highest quality of teaching and research professoriate. The industry is also assisting the universities in developing relevant research programs, attracting bright students, educating and training them to pursue safe and efficient use of nuclear technology. The universities secure additional funds from the Natural Sciences and Engineering Research Council (NSERC) of Canada, and elsewhere, to match investments made by the nuclear industry.
CHAIRMAN’S MESSAGE .............................................................

Peter Mascher

The last two years marked continued growth towards a stronger foundation on all facets of UNENE activities. In 2008 Cameco joined as an industrial partner making the industrial base stronger and more diverse. UNENE also attracted two new university members, Saskatchewan and Windsor, thereby increasing the current number of university members to twelve.

The research program grew both in size and scope with two new Industrial Research Chairs approved to the UNENE/NSERC base of IRCs, bringing the number of IRCs to seven. Professor Tony Waker of UOIT has been approved as an IRC in Health Physics and Environmental Safety along with an Associate IRC, Dr. Ed Waller. Professor Brent Lewis from the Royal Military College (RMC) has also joined as an IRC in Nuclear Fuel Technology Research. Both IRCs are positive additions to the breadth and wealth of nuclear research.

Education has also seen growth both in the number of students enrolled and graduating. To date the M.Eng. program has had 109 students enrolled, of which 39 have graduated. This success prompted a reconfirmation of Education as one key component of UNENE’s mandate at the Board of Directors retreat held to discuss UNENE’s future strategic directions, governance, director accountabilities and due diligence.

Towards the end of this reporting period two new (part time) officers have been recruited for UNENE, Dr. Victor Snell (as Program Director) managing all aspects of the M.Eng. program and Dr. Ben Rouben as Secretary /Treasurer overseeing UNENE’s day to day activities as well as its financial budget and obligations.

The board once again engaged chartered accounting firm Grant Thornton LLP to undertake the financial auditing of UNENE’s operations, balance sheet and bank statements. The outcome of the audit was to the satisfaction of the board and is reported herein in the biannual report.

On the topic of governance, Dr. Bill Garland’s announcement of his retirement in April 2009 prompted the set up of a board executive committee to oversee the hiring of his replacement. The search was successfully concluded with the appointment of B.A.Shabay in September 2009. Prior to joining UNENE, Basma worked for AECL where she was the Chief Engineer for the last eleven years. Her extensive knowledge of CANDU technology, the nuclear R&D program and the design and licensing basis of CANDU was considered by the board members as an asset to UNENE at this phase of its growth.
It has been a privilege to serve as UNENE board chair. My interactions with my university and industrial colleagues have been enriching and fulfilling. I look forward to my continued involvement with UNENE, representing McMaster University.
REPORT OF THE VICE CHAIR .................................................................

Dwight Willett

The outcomes of UNENE at the five year mark from its inception was of interest to the industry partners and hence one of the utility members undertook an assessment of the UNENE programs and their contribution to the utility’s objectives. The areas reviewed were the research program results, their applicability to current utility needs, the degree of expert consultations sought from university experts and the supply of Highly Qualified Personnel (HQP) to the industry. The results were encouraging and worth noting. The assessment concluded that a large percentage of the research program results were of relevance to the industry performance metrics, of which more than half were directly applied to the utility needs. The number of expert consultations across the whole industry was impressive, ranging from addressing regulatory issues, to reviewing new CANDU product designs, to risk-based life-cycle management of the generation assets.

Another contribution from UNENE, equally important to the industry, is the number of HQP developed through the R&D program. This has been impressive: approximately 100 HQP covering PhDs, Masters and Post Doctoral Fellows. A large percentage of these were recruited by companies providing services to utilities, with the remaining ones recruited by the regulator, government and universities.

In the international arena, Canada was the host country for the World Nuclear University (WNU) Summer Institute, which provided advanced nuclear training to some 100 international fellows (young nuclear professionals with a promising future). UNENE was the facilitator, and AECL (as a UNENE industry member) hosted the program contents at its sites. This has greatly enhanced Canada’s reputation as a well established nuclear country with a full spectrum of nuclear infrastructure: nuclear power plants, research reactors and many nuclear facilities, a fully established supply chain etc....

As UNENE continues to grow both in scope and in impact, the industry/university partnership will continue to play a key role in support of the industry success in both safe and economic performance, for the effective contribution to Canada’s economy.

Prepared by B. Shalaby
on behalf of Dwight Willett (retired from Bruce Power)
Membership of UNENE is available to Canadian universities, corporations, associations, government agencies or other entities. The Board of Directors and the Voting Members of UNENE approve an application for admission. Membership of UNENE is of two categories namely: Voting Members and Non-Voting Members. Each such Member, that is a corporation, nominates a representative in the dealings of UNENE.

Only those entities that fulfill the Annual Membership Fee and fund a significant portion of the overall UNENE Program and those universities that host UNENE funded Industry Research Chairs are eligible to become Voting Members. The current Voting Members of UNENE are Atomic Energy of Canada Ltd., Bruce Power, Ontario Power Generation, McMaster University, Queen’s University, University of Toronto, University of Ontario Institute of Technology, University of Waterloo and The University of Western Ontario.

Entities that are committed to UNENE objectives and as a minimum pay the Annual Membership Fee and universities that participate in research and teaching of UNENE programs may become Non-Voting Members if they apply and when the Board of Directors and Voting Members of UNENE approve their applications. Currently, CANDU Owners Group, Canadian Nuclear Safety Commission, Nuclear Safety Solutions, Ecole Polytechnique, University of New Brunswick, Royal Military College, and University of Guelph are Non-Voting Members of UNENE.

The UNENE Board of Directors, with each Voting Member represented by one Director, manages the property and business of UNENE. Each Voting Member nominates one Director for a renewable two-year term. The Directors representing Voting Members from universities elect the Board Chair; and the Directors representing industry Voting Members elect the Board Vice-Chair. The term of office of both the Chair and the Vice-Chair is two years. Effective September 2004, Dr. Tom Harris had assumed the position of Chair and Ms. Beth Medhurst assumed the position of Vice-Chair of the UNENE Board of Directors.

The Board of Directors sets policies and procedures not defined in the By-Laws of UNENE. It functions through two standing committees, the membership of which are drawn from the organizations of members of UNENE:

- Education Advisory Committee (EAC)
- Research Advisory Committee (RAC)

For administrative functions, the UNENE Board of Directors appoints a President and CEO, Secretary/Treasurer and Program Director as officers of UNENE, each for a two-year term. Current officers of UNENE for this reporting period are:

- Dr. Bill Garland, Secretary, Executive Director, combining the roles of President and CEO, Secretary / Treasurer and Program Director to June 2008, President and CEO thereafter.
- Dr. Ben Rouben, Secretary / Treasurer from July 1, 2008.
- Dr. Victor Snell, Program Director from June 23, 2008.

The financial year of UNENE is from April 1 to March 31 of the succeeding calendar year.
VISION AND STRATEGIC OBJECTIVES

Vision:

"An outstanding and effective university-industry-government partnership promoting university-based education and research in nuclear engineering".

Mission:

UNENE is committed to blend the strengths of industry and university and secure government assistance to deliver relevant nuclear engineering educational and research programs, and train highly skilled human resources for the current and future needs of Canada. The strengthened university-based UNENE expertise will be accessible to public, government and industry.

Objectives:

Nuclear industry, universities and governments in Canada have elected to work together to ensure that Canada continues to be among world leaders in peaceful and safe application of nuclear technology. UNENE concentrates its efforts to ensure that, in sufficient numbers, bright candidates are attracted, educated and trained as engineers and scientists to advance the state of the art in nuclear technology and find innovative solutions for challenges faced by the industry.

In specific terms, UNENE has three distinct objectives:

1. Enhance the supply of highly qualified graduates in nuclear engineering and technology
2. Reinvigorate university-based research and development in nuclear engineering and technology focusing primarily on mid- to longer-term research
3. Create a group of respected, university-based, nuclear experts for public and industry consultation.
PRESIDENT’S REPORT

Bill Garland

For the reporting period, UNENE continued to be a successful model of university, industry and government partnership.

UNENE was founded in 2002 to fulfill the following three objectives:
1. Reinvigorate university-based research and development in nuclear engineering and technology focusing primarily on mid to longer term research
2. Enhance the supply of highly qualified personnel in nuclear engineering and technology for future hiring by nuclear industry
3. Create a group of respected, university-based nuclear experts for public, government and industry consultation.

Starting in 2002, the initial surge in growth resulted in the establishment of five Industrial Research Chairs (IRC):
Prof. Rick Holt (Queen’s-2002), Dr. Jin Jiang (Western-2003), Dr. John Luxat (McMaster-2004), Dr Roger Newman (Toronto-2004) and Dr. Mahesh Pandey (Waterloo-2004). They are joined by the Associate Chairs, Dr. M. Daymond (Queen’s-2005), Dr. David Novog (McMaster-2006), Dr. Srim Narasimhan (Waterloo) and Dr. Amirnaser Yazdani (Western).

Three NSERC Collaborative Research and Development (CRD) projects have been completed with excellent results: Dr. Lynann Clapham (Queen’s), Dr. Peter Tremaine (Guelph) and Dr. Marilyn Lightstone (McMaster). All these successful projects secured NSERC-CRD grants to match the UNENE-industry grants for their projects. The projects of Dr. R. Klassen (UWO), Dr. M. Kawaji (UCF), and Dr. M. Daymond (Queen’s) are proceeding as planned. Tremaine’s 2nd CRD proposal has been approved by the UNENE Board. UNENE approved the conversion to an IRC of three additional CRDs awarded to Dr. Brent Lewis of RMC. In all UNENE has committed $900,000 to these projects.

UNENE has recognized new opportunities for participating with the Ontario Centre of Excellence in Energy and has supported UNENE funded researchers who applied for additional funds from the Ontario Research Foundation, several of which have been successful.

The newly appointed NSERC-UNENE Chairs and CRD researchers are busy supervising Master’s, Doctoral and Post Doctoral researchers adding to the available pool of expertise for future hiring by the nuclear industry. I am very pleased to report that the activities of the university researchers are very closely linked with industry. Industry advisory committees for each researcher meet frequently to keep the UNENE funded research relevant to industry. These committees also arrange, as and when needed, for the provision of industry data to researchers for the validation of research.
Senior researchers maintain active contact with industry experts and have provided input in arriving at important business decisions at various levels including to the Board of Directors of UNENE industry members. It is equally important to appreciate that, due to the complementary nature of the research among universities, an excellent network for frequent exchange of information among universities has emerged.

University-based nuclear research and development is, therefore, in good shape and UNENE is largely responsible for that.

From the perspective of the members of UNENE, industry is highly interested in the updated training of recently hired engineering staff through the part-time M. Eng. in Nuclear Engineering program, as well as, for future hiring, enlarging the pool of qualified personnel pursuing Masters, Doctoral or Post-Doctoral programs full time. UNENE has indeed made impressive progress in this regard. Although specific details of these activities will be found elsewhere in the Annual Report, it is important to observe that the M. Eng. in Nuclear Engineering is a part-time studies program jointly offered by UNENE member universities. There are currently 52 active UNENE M.Eng., students, and to date the programme has graduated 39 HQP.

Similarly, the enrollments in and the number of qualified personnel from the full time Masters, Doctoral and Post-Doctoral programs are strong. It is encouraging to note that for this reporting period there are 60 Master’s students, 53 Ph.D. students and 18 Postdoctoral Fellows in UNENE funded programs for a total of 131 Highly Qualified Personnel. Figure 1 provides a breakdown by program.
Figure 1 – UNENE sponsored research students currently in program (Industrial Research Chairs and Collaborative Research and Development grants)
EXTERNAL RELATIONSHIPS

Bill Garland

UNENE represents Canada as a founding member and actively participates in World Nuclear University (WNU) affairs. The World Nuclear University (WNU) was established on September 4, 2003, to promote nuclear education and training, safeguard quality standards internationally and enhance the mobility of nuclear professionals worldwide. World Nuclear Association (WNA), World Association of Nuclear Operators (WANO), International Atomic Energy Agency (IAEA) and OECD Nuclear Energy Agency (NEA) are founding supporters of WNU. Dr. Hans Blix is its Chancellor and Mr. Zack Pate chairs its Governing Board. Currently, 23 countries are members of WNU. UNENE’s role in WNU is significant as its officers and members are active in WNU activities and meetings and in particular serve on the WNU Academic Council.

UNENE also maintains an active liaison with the Canadian Nuclear Association (CNA), the Canadian Nuclear Society (CNS), several national governmental offices and the International Atomic Energy Agency (IAEA).

UNENE was represented at the IAEA Technical Meeting on “Development of Curricula in Nuclear Science and Technology” held in Vienna, December 2008. The purposes were to evaluate and analyze curricula in nuclear engineering, develop recommendations for the establishment of a reference curriculum on the subject and to otherwise provide recommendations on IAEA activities related to nuclear education, training and knowledge management. It was noted that there were already many forms of national and international cooperation among universities but the UNENE model was singled out for praise several times by the IAEA. It was also noted that most countries were experimenting with some forms of Distance Education, but the technology and methods are in the early stages.

UNENE was represented at the IAEA Technical Meeting on Status and Trends in Nuclear Education in Vienna, May 2009. The objectives of the meeting were to discuss the role of nuclear education in the development of human resources for national infrastructures for nuclear power, and to help draft an IAEA report entitled “Status of and Good Practices in Nuclear Education”. At the meeting, UNENE was again recognized and praised as an excellent model of collaboration between industry and academia.

At the request of the IAEA, a Canadian Country report was prepared in June, 2009 to summarize the nuclear education situation in Canada from the perspective of UNENE.
EDUCATIONAL ACTIVITIES

Joint Master’s of Nuclear Engineering Degree Program

Program Director’s Report

Victor Snell

Education and development of highly qualified personnel (HQP) is one of the principal objectives of UNENE. This objective is fulfilled through graduate level education at participating universities. There are two paths: 1) traditional research-oriented graduate degrees, or research assistantships, in nuclear-related disciplines; and 2) the Master’s of Engineering (M. Eng.) Degree programme in Nuclear Engineering, jointly offered by member universities with strong UNENE support and overall coordination. The M.Eng. programme is accredited by the Ontario Council of Graduate Studies (OCGS) and is aimed largely at people already working within the industry and wishing to upgrade their education within the discipline of an academic environment.

To accommodate students with a full-time job, the courses are given during weekends throughout the academic year, normally at the Whitby campus of Durham College. In 2008/9 a distance education technology was approved for use in the courses, so that staff at remote nuclear sites could avoid some of the difficulties of long-distance winter travel. It was implemented in 2009/10.

In order to deliver a full breadth of nuclear engineering courses, the program exploits professorial expertise residing at participating universities and draws specialist guest lecturers from UNENE industry members. The Education Advisory Committee (EAC) of UNENE controls curriculum matters, whereas the Programme 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 programme.

These past two academic years saw an increase in enrollment in the UNENE M.Eng., driven by the expected nuclear renaissance, and recognition given to the M.Eng. by some UNENE industrial members as a means of career advancement. At approximately the end of 2008/9 fiscal year (specifically as of May 6, 2009) there was an “active” enrollment (existing + accepted – inactive – graduated) of 52, with 4 more applications pending. With the increased enrollment, we have been able to commit a two-year cycle of all UNENE courses, with 6 offered per academic year. This simplifies course planning, and provides more certainty, on both the UNENE and the student side.
Figure 2 - UNENE Nuclear Reactor Safety Design Course – March 2008

Figure 2 below summarizes the *cumulative* throughput of students as of the same date, for the life of the UNENE M.Eng.

![Enrollment Chart]

**Figure 3 - Student Throughput**
Report of the Education Advisory Committee (EAC)

Roger Newman, Chair

The Education Advisory Committee (EAC) of UNENE met approximately quarterly in this reporting period. The Mandate of EAC is to advise the UNENE Board on education-related issues, including the curriculum for the M. Eng. Degree in Nuclear Engineering, admission standards, accreditation, course selection and delivery effectiveness and soliciting students for the programme. The EAC also reviews and dispositions proposals from the Programme Director on courses, and course delivery.

The Committee consists of one representative from each UNENE member. Roger Newman was the Chairman, and Katherine McCulloch was the Vice-Chairwoman, for most of the reporting period. At the end of the reporting period, the Committee Membership was as follows:

<table>
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<tr>
<th>Institution</th>
<th>Representative</th>
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<tr>
<td>AECL</td>
<td>Frank Yee</td>
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<td>Bruce Power</td>
<td>Jack Bingham</td>
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<td>OPG</td>
<td>Mary Duarte</td>
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<td>McMaster</td>
<td>John Luxat</td>
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<td>Queen’s</td>
<td>Mark Daymond</td>
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<td>Toronto (Chair)</td>
<td>Roger Newman</td>
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<td>UOIT</td>
<td>George Bereznai</td>
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<td>Waterloo</td>
<td>Mahesh Pandey</td>
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<td>Western</td>
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<td>Chary Rangachyulu</td>
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<td>CNSC</td>
<td>Magda Rizk</td>
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<td>COG</td>
<td>Martin Reid</td>
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<td>Ecole Poly.</td>
<td>Jean Koclas</td>
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<td>UNB</td>
<td>Derek Lister</td>
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<td>RMC</td>
<td>Brent Lewis</td>
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<tr>
<td>Guelph</td>
<td>Paul Rowntree</td>
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<tr>
<td>Nuclear Safety</td>
<td>John Mackinnon</td>
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Ex-officio

- Executive Director: Bill Garland
- Secretary/Treasurer: Ben Rouben
- Programme Director: Victor Snell

The committee oversees the course-based Master’s of Engineering programme in Nuclear Engineering, aimed at upgrading the knowledge of staff already working in the nuclear industry. The M. Eng. Programme is jointly offered by McMaster, Waterloo, Western, and Queen’s.
Candidates eligible for admission into the graduate program of a participant university enroll in the M.Eng. Program and complete 10 half-term courses, of which two may be replaced by a major engineering project, to earn their Degree. Three of the 10 courses can be Business Courses from Advanced Design and Manufacturing Institute (ADMI). The Education Advisory Committee recommends curriculum, course content and potential instructors. In addition, it assists the Programme Director in making arrangements for technical visits and selection of course delivery sites at member organizations.

Current offerings include the following courses:

UN0601: Control, instrumentation and electrical systems in CANDU
UN0602: Nuclear fuel waste management
UN0603: Project management for nuclear engineering
UN0701: Engineering risk and reliability
UN0702: Power plant thermodynamics
UN0801: Nuclear plant systems and operations
UN0802: Nuclear reactor analysis
UN0803: Nuclear reactor safety design
UN0804: Nuclear reactor heat transport system design
UN0805: Radiation health risks and benefits
UN0901: Nuclear materials
UN0902: Fuel management
UN1001: Reactor chemistry and corrosion

The four courses in red are compulsory core courses, taken by every student.

Detailed teaching evaluations, conducted at the end of each course, provide opportunities for quality control. Examination of evaluation feedback assists the Committee in assessing the quality of teaching, and the teaching faculty in incorporating changes for improving the next offering and enhancing the students’ learning experience. The committee also recommends adoption of the latest computer and web-based course delivery tools to facilitate interaction between students and instructors. All course material is made available over the web. Where practicable, lectures are recorded and made available on the web for review purposes.
RESEARCH ACTIVITIES............................................................

Report of the Research Advisory Committee (RAC)

John Luxat, RAC Chair

THE PRIMARY OBJECTIVES OF UNENE are to conduct research and train personnel in CANDU technology through establishing Industrial Research Chairs (IRC) in Ontario universities and funding research at other Canadian universities. Since the creation of UNENE, seven IRCs and associate IRCs have been established, and three are pending. Several Collaborative Research and Development (CRD) projects have also been awarded to other researchers at Canadian universities. The established IRCs and ongoing CRD projects are currently facilitating research on more than 200 industry issues, where more than 228 researchers are being trained in specialized fields of CANDU technology to help replenish the eroding CANDU expertise in the industry.

The Research Advisory Committee of UNENE meet several times a year. John Luxat chaired the committee in this reporting period. Charles Kittmer (AECL) was the Vice-Chair until his retirement. The Committee membership for this reporting period comprised:

- AECL (Vice-Chair) Charles Kittmer
- Bruce Power Tevfik Kapaklili
- OPG Kazem Rassouli
- COG Frank Doyle
- CNSC Nanci Laroche
- NSS John MacKinnon
- McMaster University (Chair) John Luxat / David Novog (Alternate)
- Queen’s University Rick Holt / Mark Daymond (Alternate)
- Toronto Roger Newman
- UOIT Anthony Waker
- University of Waterloo Mahesh Pandey
- Western Ontario Jin Jiang
- Ecole Polytechnique Jean Koclas
- UNB Derek Lister
- Royal Military College Brent Lewis
- Guelph University Peter Tremaine
- UNENE Bill Garland

The main work of the committee has been:
1. Reviewing the progress of IRC research programs
2. Supporting the establishment of two new IRCs
3. Supporting grant applications for research funding that provide effective leveraging of UNENE funding.
4. Developing a list of industry approved research topics  
5. Monitoring progress of the CRD research proposals  
6. Recommendations supporting renewal of IRC’s to the Board of Directors.

CHAIR PROGRAMS: In this period two new UNENE IRCs were established, approved by UNENE and NSERC and initiated their research programs. In addition, four of the existing chairs were renewed and one is applying for renewal, as discussed below. The currently established UNENE/NSERC IRCs cover seven critical areas of CANDU technology as described below.

1) **Nuclear Materials** (Rick Holt (Senior Chair)/ Mark Daymond (Associate Chair), Queen’s University). This chair program focuses on CANDU Fuel Channels (FC) and primarily on improving the understanding of the basic mechanisms of Pressure Tube (PT) deformation and the effects of manufacturing variables, microstructure, and irradiation. The other focus of the Queen’s chair program is the understanding of hydrogen effects on PT integrity and the behavior of hydrides in zirconium to support research in Delayed Hydride Cracking and Fracture. Such degradation mechanisms threaten the structural integrity and end-of-life of the PTs in CANDU Nuclear Power Plants (NPP). The Chair and Associate Chair were successfully renewed in 2008.

2) **Nuclear Safety** (John Luxat (Executive Chair)/ David Novog (Associate Chair), McMaster University). This chair program focuses on Nuclear Safety Analysis Methodology and Nuclear Safety Thermalhydraulics. The Nuclear Safety Analysis area includes developing “best estimate” models of physical processes, plant conditions and failure events and methods to evaluate the propagation of uncertainty in accident analysis to ensure safety limits are met at a prescribed confidence level. The research has also focused on modeling severe accident phenomena. The other focus of the program is theoretical modeling and experimental studies in Thermalhydraulics. The objective in this area is to improve understanding of heat transfer behavior that influences both operational safety margins and the integrity of components during accidents. The Chair was successfully converted to a Senior IRC and both the Chair and Associate Chair were renewed in early 2009.

3) **Nano-Engineering of Alloys** (Roger Newman (Senior Chair), University of Toronto – U of T). The primary focus of research in this chair program is corrosion and protection of alloys used in CANDU systems. Model alloys are also used, along with atomistic simulation, to interpret the more complex behaviour of industrial alloys. A fundamental understanding of corrosion mechanisms is vital for plant life prediction, guidance for remedial measures, and materials selection for new and refurbished plants. The U of T chair has a particular focus on Steam Generator (SG) materials, and also covers some aspects of nuclear waste management such as dry storage. Research activities include mechanisms of stress corrosion cracking in high-temperature aqueous environments, intergranular corrosion of Monel, lead effects in nickel-alloy corrosion, theory of
alloy corrosion and stress corrosion, properties of nanoporous metals formed during corrosion, and electrochemical monitoring in concrete. The Chair was successfully renewed in 2009.

4) **NPP Instrumentation and Control** (Jin Jiang (Senior Chair), University of Western Ontario - UWO). The objectives of this chair are to: (1) investigate new control concepts and systems in refurbishing the existing plants; (2) develop new techniques to increase the reliability of neutron flux detectors; and (3) develop new techniques to relate probabilistic based risk analysis techniques to plant maintenance and outage planning. Methodologies being developed include: (1) establishing software and hardware experimental test procedures and environment for evaluating Distributed Control Systems; (2) using statistical and time-frequency based advanced signal processing techniques to detect abnormal conditions in the neutron flux signals; and (3) examining risk-based approaches to safety system analysis and relating risk to maintenance optimization using mathematical modeling and aging models. The Chair was successfully renewed in 2008.

5) **Risk-Based Life Cycle Management** (Mahesh Pandey (Senior Chair), University of Waterloo). The primary objective of this chair is to advance the life-cycle management of critical components of CANDU reactors, namely, FCs, SGs and feeders. In the FC area, the program will provide methodologies for risk assessment of PT-Calandria Tube contact, determination of optimum sample size for SLAR (Spacer Location and Repositioning) revisits, and a probabilistic model of D₂-uptake rate. In the area of SGs, the program is developing a risk-based model for optimizing SG inspection, maintenance, and repair activities. In the area of feeders, a probabilistic model of Flow Accelerated Corrosion (FAC) and wall thinning is under development, in order to optimize the aging management of feeders. The Chair is applying for renewal in 2009.

6) **Nuclear Fuel** (Brent Lewis (Senior Chair) Royal Military College). The primary objective of this chair is to advance knowledge of fuel behavior under normal operating conditions (NOC). This includes modeling of fuel defect formation; oxidation of defected fuel; development of defected fuel monitoring techniques; and advanced fuel designs in support of the CANDU industry. This Chair was established in 2007.

7) **Health Physics and Environmental Safety** (Tony Waker (Senior Chair), University of Ontario Institute of Technology). The primary objective of this chair is to advance health physics and environmental safety in support of operating CANDU reactors. This includes conducting research in such areas as: advanced tissue equivalent proportional counters for power plant neutron-gamma monitoring; ultra-thin scintillator counter for tritium in air monitoring; microdosimetry and radiation quality of low energy photons and beta rays; and, simulation of CANDU radiation fields and dose visualization. This Chair was established in 2008.
NON-CHAIR RESEARCH PROJECTS: A number of CRD projects have been awarded to other university researchers, as listed below.

2. D$_2$O isotope effects on hydrolysis & ionization equilibria in high-temperature water (P. Tremaine, U of Guelph). Application for renewal submitted to NSERC.
5. Delayed Hydride Cracking (M. Daymond, Queen’s University). Ongoing.

A number of additional CRD’s awarded to RMC were converted to the IRC program when the IRC at RMC was successfully established.

It is anticipated that a second round of CRD’s will be initiated in late 2009 based upon the success of the current program and the strong support for the program from the UNENE funding partners.

ADDITIONAL RESEARCH FUNDING: In 2008 UNENE investment in nuclear research through the IRC program was instrumental in the successful award of a $4.8M grant from the Ontario Research Fund (ORF) – Research Excellence (RE) program to establish “Nuclear Ontario: A University-Based Network Supporting CANDU Nuclear Technology in Ontario”. This multi-institution initiative, led by McMaster University, with John Luxat as the Principal Investigator, involves Queen’s, RMC, UOIT, University of Western Ontario and Carleton as collaborating institutions.

UNENE NETWORK OF NUCLEAR EXPERTS: UNENE chair and non-chair programs have created a wide network of nuclear experts in Canada. The industry has significantly benefitting from this network of expertise through numerous advisory and consultative exchanges. Examples of these consultations are presented in the reports of the IRCs.
Report on the NSERC-OPG-COG-Nu-Tech Industry Research Chair program in Nuclear Materials

Overview

The chair was renewed for its second term on February 1, 2007 with Prof. R.A. Holt as the chair and Prof. M.R. Daymond as associate chair. OPG and COG funding are now funneled through UNENE. In August 2009 a new faculty member Zhongwen Yao joined the group. Previously Zhongwen was a post-doctoral fellow at Oxford, studying radiation damage in materials for fusion reactors.

Research Program

The specific goals are 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).

Research Facilities

In addition to the creep laboratory established at Queen’s during the first term of the chair program, neutron scattering facilities and synchrotron radiation facilities in the UK (Rutherford Appleton Labs) and the USA (Los Alamos National Lab, Argonne National Lab, Brookhaven National Lab) as well as Canada (CRL) have proven very effective in pursuing the research goals, and profitable collaborations are continuing at these laboratories. In addition, facilities for strain measurement using both image correlation and laser speckle interferometry have been obtained via non-Chair research grants; these will be used for Chair research e.g. mapping of strain fields around crack tips. M. Daymond shared a combined CFI/ORF grant of $790k with K, Pilkey of the Mechanical and Materials Engineering department to purchase a micro-X-ray computerized tomography system, recently installed in Nicol Hall. This system is capable of imaging large hydrides in Zr alloys.

In June 2009, the Canadian Foundation for Innovation announced a ~$7M grant to Queen’s as part of a $17.5M project to build a Nuclear Materials Testing Laboratory, comprising a new building, a 4MV tandem accelerator, two new electron microscopes,
and other testing equipment. Provincial funding of ~$7M was unofficially announced in August. The remaining funds are provided by Queen’s (~$1.6M) and in-kind contributions from equipment suppliers (~$1.9M).

Research Team


Interaction with Industry, Universities and Other Organizations

Prof. Holt 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 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.

In January 2009, 18 members of the Queen’s Nuclear Materials group participated in the COG Fuel Channels Seminar in King City, Ontario. Students and post-doctoral fellows from the group made nine poster presentations describing their research.

In June 2009, Queen’s organized a session within the Canadian Materials Science Conference on the subject of Nuclear Materials, as well as an instructional workshop on Nuclear Materials the day before the conference. Both workshop (40+ attendees) and session (2nd largest specific subject area in conference) were extremely well received with 14 graduate students and postdoctoral fellows from Queen’s, RMC, UWO, McMaster and U. Alberta making oral presentations in the subject area.

The Chair-holders collaborated within Queen’s University, and with McGill University (where Holt co-supervises a Ph.D student), the Royal Military College of Canada, the National Research Council of Canada (NRC), Pennsylvania State University, Los Alamos National Laboratories (USA), the Open University (where Daymond co-supervises a Ph.D student) and the University of Manchester (UK). Experiments were been carried out in collaboration with NRC scientists at Chalk River Laboratories, and at
Rutherford-Appleton Laboratories (UK), the Los Alamos National Laboratory, Argonne National Laboratory and Brookhaven National Laboratory (USA) with several student visits to these laboratories.

Research Results

Research results were published in six theses, 24 refereed Journal papers, 13 presentations at international conferences, two COG reports and nine posters at the COG Fuel Channels Seminar, as follows.

Theses

1. Lattice Strain and Texture Evolution during Room Temperature Deformation in Zircaloy-2, F. Xu, December 2007 (Ph.D.).
2. Evolution of Interphase and Intergranular Strain in Zr-Nb Alloys during Deformation at Room Temperature, S. Cai, September 2008 (Ph.D.).
3. Initiation of Delayed Hydride Cracking in Zr-2.5Nb Micro-Pressure Tubes, R.K. Sundaramoorthy, April 2009 (M.Sc.).
4. Effect of Texture on Anisotropic Thermal Creep of Pressurized Zr-2.5Nb tubes, W. Li, August 2009 (Ph.D.).
5. Lattice Strain and Texture of Plastically Deformed Zircaloy-2 at 77K, C.D. Judge, September 2009 (M.Sc.).

Refereed Journals


International Conference Presentations


Reports


Posters at COG Fuel Channels Seminar (January 2009)

1. *Micromechanical Modeling of Twinning in Zirconium*, C. Mareau
2. *Thermal Creep of Pressurized Zr-2.5Nb Tubes with Different Textures*, W. Li
3. *Modeling of Anisotropic Creep of Pressurized Zr-2.5Nb Tubes*, W. Li and F. Xu
5. *Texture Evolution and Variant Selection in Zr-2.5Nb during the β′ Phase*
Transformation, P. Mosbrucker
7. Initiation of DHC in Zr-2.5Nb Micro-pressure Tubes, R. K. Sandaramoorthy
8. Proposed Experimental Analysis of Hydrides in Zr-2.5Nb Micro Pressure Tubes, S. Goldthorpe

Teaching

The senior/graduate level course in Nuclear Materials course was taught in winter 2009 by Profs. Holt and Daymond to the UNENE M.Eng program at Durham College, and by Holt to fourth year undergraduates and graduate students at Queen’s in the fall semester of 2007 and the winter semester of 2008. A shortened version of the course was given three times to a total of ~60 employees of AECL, OPG and Kinectrics in 2007 May/June, 2008 Jan/Feb and 2008 May/June.

Other

At the 14th International Symposium on Zirconium in the Nuclear Industry in June 2007, Prof. Holt was awarded the 24th W.J. Kroll Medal by the American Society for Testing and Materials for “unique and lasting contributions to the technology of zirconium”. The medal recognized his work identifying and describing in-reactor deformation mechanisms of materials and structures used in nuclear reactors.

Prof. Daymond was promoted to the rank of Professor, active 1st July 2008.
University of Western Ontario – Jin Jiang IRC

NSERC/UNENE Senior Industry Research Chair in Control, Instrumentation and Electrical Systems

The Control, Instrumentation & Electrical System (CIES) Laboratory at The University of Western Ontario was established in 2003 with the support of UNENE. CIES covers a wide array of research topics related to instrumentation, control, and electric systems in nuclear power plants. Current research encompass six major subjects including modeling, simulation, advanced control, safety systems, performance monitoring and diagnostics, networks and devices. Each of these subjects is addressed with respect to the short, medium and long term requirements of nuclear power industries.

Research Program
Reactor Modeling, Control and Diagnosis

Pressurized Heavy Water Reactor (PHWR) modeling focuses on the development of MATLAB/Simulink based models to facilitate the analysis and design of the control systems within CANada Deuterium Uranium (CANDU) reactors. The flux control loop model is developed and can be extended to encompass larger subsystems and other type of reactors.

Dynamic modeling of CANDU reactor using Modal Synthesis method, compared with Coarse Mesh Nodal method, is performed. This method will be integrated into the existing MATLAB/Simulink platform of CANDU reactor. This enhanced model will be used to investigate multivariable feedback control for reactor power regulating systems.

Super Critical Water Reactor (SCWR) is one of the six types of Gen IV reactors. The dynamic characteristics of a nuclear SCWR are quite different from other existing reactors. Therefore, it is important to develop adequate models for SCWR to facilitate design, analysis and controls.

A fault detection and isolation strategy for fixed In-Core Flux Detectors (ICFD) in CANDU reactors is proposed and validated, where the correlations between proximate ICFDs are utilized. Advanced performance monitoring and diagnostic techniques are being developed for safe operations of existing and future nuclear power plants.

Advanced Process Control, Fieldbus, and Communications

Evaluation of Distributed Control Systems (DCS), fieldbus technologies, and advanced control algorithms for potential applications in nuclear power plants are carried out. These evaluations are performed on a test-bench composed of relevant 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 also capable of performing additional functions on top of basis 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 are constructed.

Research on wireless communications and computer networks 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. Using wireless technologies can bring many potential benefits, for example, reduced cabling, lowered installation and maintenance cost, and fast commissioning and upgrading.

Design, Evaluation, and Innovative Safety Systems

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 evolution 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 failure down time, avoid complex channel separation and increase the pressure boundary integrity.

**Research Facilities**

Over the last seven years, we have developed some state-of-the-art research facilities to support the above research activities and training programs for highly qualified personnel. In 2009, we have moved into a new lab in green building. We have also acquired with six large projection displays and an operator console to mimic a full digital human machine interface station. This facility has full connectivity to existing I&C systems, which includes:

- Tricon v9 system
- HFC 6000
- HFC non-safety DCS
- FPGA development system
- Siemens PCS 7 redundant control system
- Honeywell C-300 DCS
- Emerson DeltaV DCS with full fieldbus connectivity
- RTDS real-time grid simulator
- Hardware experimental test bench
- Wireless monitoring nodes, and
- Smart sensor development systems.
Current Research Team
- Prof. Jin Jiang (IRC Chair)
- Dr. Xinhong Huang (Research Engineer)
- Dr. Qingfeng Li (Research Engineer)
- Mr. Mahmood Akkawi (MESc Candidate)
- Mr. Sungwhan Cho (PhD Candidate)
- Mr. Hash Hashemian (PhD Candidate)
- Mr. Jianping Ma (PhD Candidate)
- Mr. Drew Rankin (PhD Candidate)
- Mr. Jingke She (PhD Candidate)
- Mr. Peiwei Sun (PhD Candidate)
- Mr. Ahmad Osgouee (PhD Candidate)
- Mr. Lingzhi Xia (PhD Candidate)
- Mr. Quan Wang (PhD Candidate)

Publications (Selected)

Book

Journal Papers


Refereed Conference Papers


Other Activities
Dr. Jiang has maintained close ties with industry partners in AECL, OPG, and Bruce Power. He also actively participated activities in IEC standard committee on I&C systems important to safety. He has contributed to IAEA in developing technical guides for I&C systems and serve as technical expert on I&C system review missions in Korea.

In the last five years, Dr. Jiang organized UNENE Annual I&C Workshops every year at partners’ facilities to report the research activities in details and to interact with industrial partners.
He also served on the program committees for several key conferences in nuclear I&C area, such as ANS Topical Meeting on Nuclear Instrumentation, Control and Human Machine Interface Technology.

Dr. Jiang also collaborated with partners in Xi’an Jiaotong University, China, which results in a publication of a book on “Control of Nuclear Reactors”.
Overview

Prof. Brent Lewis was appointed the NSERC/UNENE/COG Industrial Research Chair (IRC) in Nuclear Fuel in the Department of Chemistry and Chemical Engineering at the Royal Military College of Canada (RMC) in September 1, 2007. The main objectives of the research chair are to better understand nuclear fuel performance during normal and reactor accident conditions, including the behaviour of advanced and next generation fuel designs. This research program developed from a previous partnership with the CANDU Owners Group (COG) and NSERC through a four-year Collaborative Research and Development (CRD) Grant in defective fuel behaviour from September 2004 to August 2008.

Research Program

Nuclear fuel is at the heart of any improved design for the CANDU reactor and is a key enabling technology for enhancement of reactor safety, performance and economics, as well as continued sales of Canadian nuclear technology worldwide. This research is of particular importance in light of the need for increased generation capacity and the realization of next generation reactors. The 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 in present, advanced and future reactor designs.

Research Facilities

The research made use of gamma spectrometry and neutron activation analysis capability at the SLOWPOKE-2 nuclear reactor facility at RMC. A high-temperature Thermal Gravimetric Analyzer/Differential Scanning Calorimeter has also been installed to support fuel studies. In addition, work involved the use of software for Gibbs-energy minimization with the Facility for the Analysis of Chemical Thermodynamics and finite element modelling with COMSOL multiphysics and ANSYS. The research group also collaborates with other groups at the national laboratory and international institutes.
Research Team

Both the COG/NSERC CRD and NSERC/UNENE/COG IRC involved collaboration with Prof. W. T. Thompson also at RMC in the area of fuel thermochemistry. From September 2007 to September 2009, the NSERC/UNENE/COG IRC research team was comprised of one research associate and two research assistants, as well as twenty-one graduate students (8 PhD, 13 MASc). Three PhD projects were carried over from the CRD investigation and involved research in fuel thermochemistry modelling of Advanced CANDU Reactor (ACR) fuel, fuel-failure monitoring and the development of a phase-field model for fuel melting. These three students graduated in the spring of 2009; two of these students are now employed at the Institute of Transuranium Elements and the Canadian Nuclear Safety Commission; Dr. Corcoran has joined the RMC as an Assistant Professor in support of this IRC activity. Two MASc students, who also graduated in the Spring of 2008 and 2009, were involved in a gamma spectrometry analysis of coolant activity at a commercial Nuclear Generating Station, and leaching studies of Low Void Reactivity Fuel (LVRF), and are now working in the Department of National Defence (DND). Four ongoing PhD projects involve the development of a defective fuel performance code, stand-alone Gibbs Energy Minimization tool for fuel thermochemistry computation, and development of an on-line fuel failure monitoring tool and design of an instrumented out-reactor test for defective fuel studies both in collaboration with Atomic Energy of Canada Limited (AECL). Seven on-going MASc projects involve the development of a hydriding model for defective fuel analysis, fuel-bundle modelling, fuel thermochemistry model for the SOURCE-2 industry standard toolset (in collaboration with AECL), noble gas tagging methods for demonstration irradiations, development of ultrasonic testing instrumentation for discharged CANDU fuel bundles, stress corrosion cracking model for the ACR, and a dissolution study of ACR fuel. In addition, one PhD student and four MASc students joined our research group in September 2009 in fuel-related projects including: actinide burning in multi-spectral CANDU reactors, high-temperature fuel-behaviour modelling, Be-brazing reduction in CANDU fuel manufacturing (in collaboration with Cameco Fuel Manufacturing), isotope identification in support of non-proliferation treaty (NPT) monitoring (in collaboration with Health Canada), and delayed-neutron monitoring techniques for defective fuel location in CANDU reactors (in collaboration with Candescos).

Two other MASc students and three PhD students are supervised by faculty also involved with this IRC that are further funded by NSERC Discovery grants as well as other government departments including the DND and Canadian Space Agency.

Interaction with Industry, University and Other Organizations

This chair program supplements research and development activities in nuclear fuel technology being carried out by the COG, which benefit the national laboratory, reactor designer and commercial utilities. In particular, the university research contributes directly to three COG work packages (WP) on fuel oxidation behaviour modelling (WP 22324), fuel-failure monitoring (WP 22303) and fuel thermochemistry (WP-22326).

The university research has involved strong collaboration with Atomic Energy of Canada Limited (AECL) – Chalk River Laboratories (CRL) and Sheridan Park (SP) on fuel development studies for the ACR, which have included X-ray diffraction studies at the university, fuel thermochemistry modelling of irradiated CANDU fuel and ACR burnable
neutron absorber material and use of coulometric titration (CT) equipment at the CRL for validation of the fuel thermochemistry model as part of COG WP-22326. The university has also worked closely with Bruce Power and other commercial utilities on gamma spectrometry analysis of gaseous fission product (GFP) and Chemistry Environmental Management (CEM) data in support of the development of fuel-failure monitoring tools for Nuclear Generating Stations (i.e., Visual DETECT and STAR). Additional collaboration with Bruce Power has also been carried out in which Cameco has provided fuel samples in support of LVRF defective fuel identification. In addition, neutron beam time was awarded and experiments carried out in December 2007 at the Los Alamos Neutron Science Centre (LANSCE) for scoping tests using neutron diffraction at very high temperature on doped CANDU fuel in support of the New Fuel Project for Bruce Power. This project was terminated with the announcement that Bruce Power was not pursuing LVRF development. The research group has also collaborated internationally with the Institute for Transuranium Elements, Commissariat à l’Energie Atomique and Oak Ridge National Laboratory. The Chair holder collaborates with other professors within RMC (i.e., Profs. T. Krause, D. Kelly and H. Bonin as co-supervisors of thesis projects), the Industrial Materials Institute of the National Research Council of Canada (NRC), and UOIT. In addition, Prof. Lewis has provided assistance for COG and AECL with the development of state-of-the-art reports on defective fuel behaviour, a strategic plan for fuel and fuel channel codes, an expert panel on fuel deformation, as well as reviewing activities for AECL, Journal of Nuclear Materials, Applied Radiation and Isotopes, Health Physics Journal, Nuclear Technology, NSERC, Chemical, Biological, Radiological-Nuclear & Explosives Research and Technology Initiative (CRTI) and the US National Institute for Occupational Safety and Health (NIOSH). The Chair holder is also a member of the Fuel Normal Operating Committee for the COG R&D Safety and Licensing Program.

Research Results

Published research findings from September 2007 to September 2009 are detailed below:

Journal Papers


Conference Papers


Technical Reports


Presentations


Teaching

An undergraduate course was taught by Profs. B.J. Lewis and L.G.I. Bennett, “Physics of Nuclear Reactors” at Queen’s University, September to December 2007 as an RMC outreach course. This course has led to two Queen’s students joining AECL and OPG. An undergraduate course, “Nuclear Science,” was also taught by Profs. Bonin and Corcoran in the fall term of 2008-2009. The Chair holder and Profs. Bonin and Bennett also taught graduate courses: “Nuclear Reactor Engineering”, “Nuclear and Radiochemistry” and “Nuclear Waste Management” in September 2007 to March 2008; and “Health Physics and Radiation Protection”, "Nuclear Fuel Engineering", “Nuclear Fuel Management” and “Nuclear Detection and Measurement,” in September 2008 to March 2009.
Awards

Recognition of the research work in 2007 include: (i) a best PhD paper award at the CNS Student Conf. for Dr. E. Corcoran, (ii) CF Lucks Award for the 29th Int. Conf. in Thermal Conductivity for Dr. J. Higgs, and (iii) RMC research prize for Prof. B.J. Lewis. Awards for 2008 include: (i) ‘Best Paper in the Nucl. Symposium’ at the Eur. Mat. Res. Soc. Conf. in Strasbourg, France for Dr. E. Corcoran; (ii) Jervis Award from the CNS for Dr. E. Corcoran; (iii) best paper (PhD) for M. Piro at the student session of the CNS; (iv) “Outstanding Poster Presentation” at the Gordon Conf. for Dr. M. Welland; and (v) Governor General’s Gold medal for D. Morgan for his MASc thesis on fuel performance code development.

M. Welland (PhD candidate) at the Los Alamos National Laboratory in December 2007.
Overview

The research focus of the NSERC/UNENE Industrial Research Chair and Associate Chair in Nuclear Safety Analysis at McMaster University is nuclear safety analysis methods and nuclear safety thermalhydraulics. The scope of the research covers many disciplines reflecting the multi-disciplinary nature of nuclear safety analysis. This requires academic knowledge and skills that can be found in the Faculty of Engineering at McMaster University. The Chair program enhances and extends this knowledge and skills base while providing an active link that supports the Canadian nuclear industry. The Chair program has enabled McMaster University to establish a robust, innovative and sustainable faculty research network during its first 5 year term, and with the approval of the second five year term the Chair and Associate Chair will make significant long term contributions to the Canadian nuclear industry and the international nuclear energy community.

The resulting knowledge, skills and innovation are applied to nuclear safety issues of critical importance to industry in improving safe operation and competitiveness of nuclear power generation. Novel research is aimed at improving the quantification of safety margins, helping to regain operating margins of nuclear generating units, improving the quality, efficiency and cost effectiveness of nuclear safety analysis and supporting the development of advanced CANDU reactor designs. This research continues to provide measurable contributions to operating power plants by improving the safety, reliability and competitiveness of generating units as an environmentally beneficial contributor to Canada’s energy supply and enhancing the competitiveness of Canadian nuclear technology in global markets.

Development of the Research Chair

The NSERC-UNENE Industrial Research Chair in Nuclear Safety Analysis was established in 2004 with John C. Luxat as the Executive IRC. Subsequently David R. Novog was hired as the Associate IRC Chair in 2006. Both chairs had a rapid growth of graduate students in Term 1 of the program and now have some of the largest research groups within the Faculty of Engineering. In addition both Dr. Luxat and Novog supervise and co-supervise additional students in the other Departments and Faculties at McMaster. In 2009 Dr. Luxat’s Executive IRC was converted to a Senior IRC and both he and Dr. Novog had their terms renewed for a further 5 year term following an NSERC site visit.
In 2008, McMaster University, along with five partner universities, was awarded an Ontario Research Fund – Research Excellence (ORF-RE) award entitled “Nuclear Ontario” with Dr. Luxat as the Principal Investigator. This new network establishes a research program aimed at developing concepts, materials and designs for existing and next generation power plants as well as examining options for the back end of the fuel cycle. This complementary program to UNENE provides an addition $5M of provincial funding to support nuclear research at six universities in Ontario. In 2009, Dr. K. Krishnan was contracted as Managing Director for Nuclear Ontario and research continues to accelerate under this program. In 2009, Dr. Luxat led a regional, multi-university, proposal to the Canadian Foundation for Innovation (CFI) and the Ontario Ministry for Research and Innovation (MRI) to establish the Center for Advanced Nuclear Systems (CANS). This $23M regional facility will provide a suite of irradiated material handling and testing equipment and a thermal testing laboratory (at McMaster), and a dose laboratory (at UOIT). This infrastructure, coupled to the McMaster Nuclear Reactor and the Canadian Center for Electron Microscopy, provides a world class materials and thermal testing center unique in North America. The project was supported by a majority of Canadian nuclear energy related companies (OPG, Bruce Power, AECL, Kinectrics) as well as a number of leading international organizations (EPRI, EdF, TEPCO, Bechtel). In 2008, Dr. Novog received a $275k CFI - Leaders Opportunity Fund grant for a Phase Doppler Anemometer System for thermalhydraulic experiments. Finally, in 2008 and 2009 the AIRC received additional funding from AECL for a CRD in SCWR analysis methods and from NRCan for a CRD in thermalhydraulic simulations of SCWRs totaling approximately $300k.

Research Facilities

Computational Facilities
A Linux-based Beowulf high performance computer cluster was acquired for the research group and is located in the Nuclear Safety Research Building. The cluster consists of a total of six nodes each with four high performance AMD 64-bit Opteron processors, providing a total of 24 processors. Each node contains, associated memory and local hard drives and the server node contains an additional RAID disc storage system. In addition, two new analysis stations (purchased with NRCan funding) add an additional 16 processors dedicated to CFD and safety analysis computing.

In addition to the hardware, FLUENT, COMSOL Multiphysics, Matlab and FlexPDE software packages have been purchased and installed. Other development software includes Fortran and C compilers. The source code software for nine legacy safety analysis computer codes, obtained under an agreement between Ontario Power Generation and McMaster University, have been used to introduce both graduate and summer undergraduate students to safety analysis methodology and reengineering of legacy software. Additional software license agreements have been signed with AECL and students are currently conducting research using the CATHENA, ASSERT, RFSP, WIMS suite of computer codes.
Experimental Facilities

a. The quench heat transfer experimental research facility has been established in collaboration with Dr. M. Hamed of the Department of Mechanical Engineering. Excellent qualitative, quantitative and high speed video image data have been acquired from thermal quenching experiments conducted in this facility.

b. Construction of a water CHF test facility has been completed and experiments have been performed to measure 2-phase heat transfer and pressure drop in water up to 2MPa. A new power supply was funded through Term 1 IRC funds and has provided accurate power up to 128kW. An additional 128kW will be order as part of the CANS facility. CHF and high pressure experiments will be completed in 2010.

c. A scaled Lucite experimental header facility was completed and experiments were performed to measure flow and pressure distribution in CANDU-type inlet headers. Phase Doppler Anemometer (PDA) measurements will be performed using a new facility funded by CFI through the Leaders Opportunity Fund grant to D.R. Novog.

d. A low pressure flow facility for flow and phasic distribution measurements in MNR, CANDU and PWR geometries has been designed and is being constructed by Stern Laboratories (funded by the McMaster Nuclear Reactor) and will be installed at McMaster in 2010.

Research Program

Rapid growth of the research group was achieved with the number of graduate students increasing from to six (6) students at the end of 2005 to twenty-nine (29) working on research projects in the areas of best estimate and uncertainty methods in nuclear safety analysis, heat transfer modeling, severe accident phenomena as well as GEN IV activities (funded separately through NUCLEAR Ontario, AECL, and NRCan programs) by the end of 2009. A total of 11 Masters students have already graduated from the IRC program with 29 students currently enrolled.

Difficulty persists in recruiting a post-doctoral fellow due to the strong employment opportunities in the nuclear industry. To compensate, a large number of undergraduate summer research students have been recruited into the research program which has proved to be of significant benefit in attracting more undergraduate students into the Nuclear Engineering option.

The students and their research topics are listed below.

Completed September 2006 and employed as a Reactor Physicist at AECL, Sheridan Park.

Research Topic: Best-Estimate and Uncertainty Analysis of Reactor Space-time Kinetic Transients in large LOCA.
Completed December 2006 and employed as a Reactor Physicist at AMEC - Nuclear Safety Solutions, Toronto.
Daryoosh Vashaee – Ph.D. Student, started November, 2004, Supervisor: J.C. Luxat
Research Topic: Parameter Identification of Space-time Dependent Reactivity in CANDU Reactors
This student withdrew from the program and has taken a junior faculty position at a US university.

Research Topic: Modelling the Onset of Critical Heat Flux on Horizontal Cylinders

Research Topic: Modelling the Quench Heat Transfer on Horizontal Cylinders
Completed April 2008 and employed at Bruce Power, Bruce site.

Currently employed at Bruce Power, Toronto office.

Fang Bao - Ph.D. Student, started September, 2006, Supervisor: D.R. Novog
Research Topic: Best Estimate and Uncertainty Analysis of Small LOCA in CANDU Reactors

Kifah Takrouni – Ph.D. Student, started September, 2006, Supervisor: J.C. Luxat
Research Topic: Experimental Study of Quenching of High Temperature Cylinders

Farshad Talebi – Ph.D. Student, started September, 2006, Supervisor: J.C. Luxat
Research Topic: Analysis of Fuel Channel integrity with Localized Hot Spots

Research Topic: Development of Trip Parameter Maps for the McMaster Nuclear Reactor
Completed December 2009 and continuing to doctoral studies with J.C. Luxat.

Research Topic: Parallel Channel two-phase natural circulation in CANDU reactors.
Completed September 2009 and employed at AMEC - Nuclear Safety Solutions, Toronto.

Research Topic: Mechanistic model of fuel channel disassembly in CANDU reactors.
Currently employed at AMEC - Nuclear Safety Solutions, Toronto.

Research Topic: Analysis of lattice cell physics of CANDU with actinide recycle.

Research Topic: Modeling the contact conductance between two contacting tubes.
Completed September 2009 and employed at AMEC - Nuclear Safety Solutions, Toronto.

Research Topic: Analysis of the thermalhydraulics around a calandria tube following pressure tube contact.
Completed December 2009 and continuing to doctoral studies with J.C. Luxat.

Research Topic: Hydraulic simulation of Shutoff Rod Insertion.

Research Topic: Experimental investigation of boiling heat transfer of downward facing surfaces with local obstacles.

Research Topic: Analysis of reactor kinetics of actinide burning CANDU

Minhaj Malik – Ph.D. Student, started May, 2009, Supervisor: J.C. Luxat
Research Topic: CFD Analysis of Advanced CANDU fuel channels.


Ala Muhana – M.Sc. Student, started September, 2007, Supervisor: D.R. Novog
Research Topic: Validation of CFD for Inlet Header Flows.
Completed: September 2009.

Brad Statham – Ph.D. Student, started September, 2007, Supervisor: D.R. Novog

Ken Leung – Ph.D. Student, started September, 2007, Supervisor: D.R. Novog
Research Topic: CFD of Advanced passive Moderator Systems.

Research Topic: On-line Compliance methodologies for Best Estimate.

Research Topic: Intermittent Buoyancy Induced Flow in CANDU channels.

Andrew Morreale – Ph.D. Student, started September, 2008, Supervisors: J.C. Luxat D.R. Novog
Research Topic: Coupled Thermalhydraulic and Reactor Physics Analysis of Small Break LOCA.

Matt Ball – Ph.D. Student, started September, 2007, Supervisors: D.R. Novog & J.C. Luxat

Research Topic: Probabilistic Level 2 PSA of a SCWR-CANDU Design (funded under NRCan program)

Research Topic: Consequence Analysis of a Severe Accident in a SCWR-CANDU (funded under NRCan program).

Research Topic: Coupled CFD-System Code Analysis.

Research Topic: IAEA Benchmark of a Heat Transfer in a SCWR CANDU (funded by AECL).

Research Topic: Best Estimate LBLOCA Thermalhydraulic Analysis Using RELAP

Research Topic: Assessment of Depressurization Transients with the USNRC Code TRACE.

Michael McDonald – M.Sc. Student, started September, 2008, Supervisor: D.R. Novog
Research Topic: Reactor Physics lattice Cell Analysis of a SCWR-CANDU Core (funded by AECL).

Sarah Mostafian – (AECL Employee, Part Time M.S.C), started September 2008
Supervisor: D.R. Novog
Research Topic: Application of Thermalhydraulic System Codes for CANDU-SCWR Designs (funded by AECL)

A total of twelve (12) undergraduate summer research students successfully completed research projects over the period August 2007 to September 2009 and supervised by the IRC or AIRC.

Interactions with Industrial Sponsors and Collaborations

Both the Chair and Associate Chair have maintained strong interactions with industrial sponsor organizations, UNENE Associate Member organizations, acting as an external consultant and technical reviewer to Ontario Power Generation, Bruce Power, AECL, CANDU Owners Group (COG), Nuclear Safety Solutions Ltd.(NSS), CANDESCO, Kinectrics, the CNSC, the International Atomic Energy Agency (IAEA) and other international organizations. These interactions include the following.
Chair (J. Luxat)

- Member of the COG Safety & Licensing Technical Committee, acting as an advisory resource. Participated in the Annual COG/CNSC Safety & Licensing Seminar and the Annual COG S&L program planning seminar.
- Member, OCGS Appraisal Visit Review, Department of Chemistry and Chemical Engineering, Royal Military College, 27-28 April 2009.
- Member, Science, Technology and Nuclear Oversight Committee of the Board of Directors, Atomic Energy of Canada, Ltd.,
- Member, Executive Committee, American Nuclear Society Thermal Hydraulics Division
- Member, Advisory Board, International Association for Structural Mechanics in Reactor Technology (IASMiRT).
- Member, Organizing Committee, SMiRT 20, Helsinki, Finland, 2009.
- General Conference Chair & Chair of Organizing Committee, 14th International Conference on Nuclear Reactor Thermalhydraulics (NURETH-14), Toronto, Ontario, (to be held in 2011)
- Reviewed NSERC grant research proposals and research proposals seeking funding for projects under Canada’s GPX program.
- Chair of the UNENE Research Advisory Committee (RAC) for a two year term.
- Bruce Power - Refurbishment of the Bruce A Units 1 and 2: Analysis of safety system performance under different impairment conditions, and provision of advice and assessments regarding safety design and CNSC licensing issues, 2008-2009.
- COG - Member of an Expert Panel reviewing the modelling of temperature induced deformation of CANDU fuel bundles, 2009.
- CNSC - Participated in an international panel of experts on a Phenomena Identification and Ranking Table (PIRT) process addressing the effects of component and system ageing mechanisms on the results of Probabilistic Risk Assessments (PRA).
- AECL - Reviewed ACR-1000 Severe Accident program and mitigating system design.
- AECL - External Licensing Advisory Group (ELAG) providing independent advice to executive management on licensability of the Advanced CANDU Reactor (ACR-1000) in Canada and in other international jurisdictions.
- AECL - Member, Nuclear Safety Review Committee (NSC) - reviewed the safety of ACR-1000 and providing advice to Chief Engineer.
AECL - Chair of the Independent Safety Review (ISR) Team - reviewed the acceptability of the safety analysis and the safety case for ACR-1000 and reported to the NSC.

AECL - External Reviewer, AECL R&D Program, 2008/09

Provided technical advice regarding nuclear safety and nuclear safety education and training to senior management of KANNUP, the Pakistan Atomic Energy Commission (PAEC) and the Pakistan Nuclear Regulatory Authority (PNRA).

Associate Chair (D. Novog)


Reviewer, Independent Safety Review (ISR) ACR-1000 safety analysis, 2008

Member, OECD Benchmark Team on Thermalhydraulic, 2008-present.

Lecturer, Canadian Nuclear Society Reactor Safety Course, 2008-present.

Member, OECD Reactor Physics Uncertainty Benchmark Team, 2008-present.

Member, OCGS graduate Scholarships for Ontario Students, 2008-present.

Consultant to CANDESCO on Deterministic Safety Analysis for NRU.


Organizing Committee, Canadian Climate Change Technology Conference, 2008.

Reviewer, NSERC and US DOE academic granting programs, 2008-2009.


Consulting services on Nuclear Safety Analysis Issues through NSS to Bruce Power and OPG (2006-present)


Member of COG Industry Team on Computer Code Strategic Direction, 2007-2008

Consulting services on Nuclear Safety Analysis Issues through NSS and CANDESCO to Bruce Power, AECL and OPG (2006-present)

Publications for 2007-2009


34. D.R. Novog and F. Bao, "Thermalhydraulic Parameter Ranking and Best Estimate Analysis of Loss of Forced Circulation Accidents in a CANDU


To be published


43. F. Bao, D.R. Novog, and J.C. Luxat, “Realistic Assessment of a Small Break Loss of Coolant Accident in a CANDU Reactor”, submitted to NUTHOS-10, Shanghai, China, October, 2010

Other Presentations

Chair (J. Luxat)

Invited


4. J.C. Luxat, “Thermalhydraulic Aspects of Progression to Severe Accidents in CANDU Reactors”, Invited Keynote Lecture, 12th International Meeting on


Associate Chair (D.R. Novog)

Invited


The primary focus of research in this chair program is corrosion and protection of alloys used in CANDU systems. Model alloys are also used, along with atomistic simulation, to interpret the more complex behaviour of industrial alloys. A fundamental understanding of corrosion mechanisms is vital for plant life prediction, guidance for remedial measures, and materials selection for new and refurbished plants. The UofT chair has a particular focus on Steam Generator (SG) materials, and also covers some aspects of nuclear waste management such as dry storage. Research activities include mechanisms of stress corrosion cracking in high-temperature aqueous environments, intergranular corrosion of Monel, lead effects in nickel-alloy corrosion, theory of alloy corrosion and stress corrosion, properties of nanoporous metals formed during corrosion, and electrochemical monitoring in concrete.

Overview

Prof. Roger Newman joined the Department of Chemical Engineering and Applied Chemistry in June, 2004, after spending 20 years in the Corrosion and Protection Centre, UMIST, Manchester, UK. He has pursued research in corrosion and nanostructuring of metals, and has interacted extensively with the UNENE partners through contract research and review as well as through the main UNENE research program.

Corrosion prediction and control are ever-present concerns in nuclear power generation, and cannot be achieved reliably and cheaply without a deeper scientific understanding of the mechanisms involved. Accordingly, the research program addresses corrosion mechanisms from the atomistic to the component level. The materials involved are mainly nickel base alloys used in steam generators, with some work on carbon steel in the context of CANDU feeder degradation, and stainless steel as a possible future feeder material. Model alloys are also being used, to idealize or simulate particular processes that occur on small length scales in engineering alloys. The chair-holder’s extensive experience of corrosion mechanisms in a wide range of metallic materials, from aluminum alloys to stainless steels to noble metal alloys, is providing novel and useful insights into the behavior of nuclear-industry materials. Such insights will lead naturally to improvements in corrosion prediction and control. Alongside these main themes of the research, smaller projects are being conducted, such as a study of electrochemical monitoring in concrete relevant to dry storage of used fuel, and a project on electroplating of exotic metals from ionic liquids.
Research Facilities

The group has excellent electrochemical instrumentation, autoclaves for corrosion and stress corrosion studies, slow strain rate testing, optical microscopy, electrochemical hydrogen sensing, and a state-of-the-art atomic force microscope system. The department, together with Materials and Chemistry, has state-of-the-art surface analysis and electron microscopy facilities.

Research Team

The following PhD holders worked in the group during this reporting period:

Dr. Anatolie Carcea – Senior Research Associate, 2004-present
Dr. David He – Postdoctoral Fellow, 2005-2007
Dr. Dorota Artymowicz – Research Associate, 2006-present
Dr. Steve Wang – Research Associate, 2007-present
Dr. Smruti Parida – Postdoctoral Fellow, 2008-present
Dr. Yin Huang – Postdoctoral Fellow, 2008-2009

As befits the wide range of disciplines needed to understand corrosion, these senior people have brought expertise in materials science, physics and chemistry to the group, as well as chemical engineering.

As of September 2009, the research group comprised Dr. Carcea, 2 Research Associates, 2 Postdoctoral Fellows, 4 PhD students and 5 MASc students, as well as MEng students and undergraduate thesis students.

The group’s research has been mainly funded by the NSERC-UNENE program, but also by other sources including NSERC (Discovery), NWMO, SKB (Sweden), COG, USDOE and OCE.

Projects under way during this reporting period included:

PhD
Stress corrosion cracking mechanisms in reducing hot water
Intergranular corrosion and pitting of steam generator tubing alloys
Localized corrosion in thin particulate layers (DOE funding)
Elucidation of the role of cold work in stress corrosion cracking
Catalysis by nanoporous metals (Discovery funding)

MASc
Simulation of low-temperature underdeposit corrosion of steam generator tubing
Kinetics of alloy corrosion
Properties and applications of nanoporous metals (Discovery funding)
Electroplating of exotic metals from ionic liquids
Small stress corrosion cracks and the effect of surface mechanical treatment (COG-EMK-OCE funding)
Modification of oxide films for improved corrosion resistance
Stress corrosion cracking of copper in sulfide solutions (SKB funding)
Electrochemical monitoring of dry storage containers for used nuclear fuel
Stress corrosion cracking prediction of nickel-base alloy weldments

Postdoctoral and Research Associate
Atomistic simulation of alloy corrosion
Anaerobic atmospheric corrosion kinetics of steel (NWMO funding)
Properties and applications of nanoporous metals (Discovery funding)
Stress corrosion cracking of copper in sulfide solutions (SKB funding)
Stability of localized corrosion in nickel-base alloys (DOE funding)

Drs Carcea, Artymowicz and Newman were active in a wide range of other research involving summer students, MEng students, and local and international collaborators.

Interaction with Industry and Other Collaborations

Interaction with industry is based around a Technical Advisory Group with representation from OPG, AECL and Bruce Power that meets several times annually.

Roger Newman led a number of short-term contract projects for industry, including OPG (Pickering Unit 7 return to service; hydrogenation of pressure tube material; monitoring of dry storage containers), AECL (aspects of NRU return to service) and Bruce Power (low-temperature corrosion in steam generators).

Collaboration is extensive worldwide. The most active collaborations during this period were with Johns Hopkins University and Imperial College.

Roger Newman serves on the Scientific Advisory Board of the Max Planck Institute for Iron and Steel Research and is a member of the Proactive Aging Management Committee, a nuclear materials expert group based in Tohoku University, Japan. He was a member of the ROCSE (Research Opportunities in Corrosion Science and Engineering) committee of the National Academies, Washington DC, whose report will be issued in 2010. He was Vice Chair of the 2008 Gordon Research Conference on Corrosion (aqueous) and will be the Chair of the 2010 Conference. He continues to chair the Education Advisory Committee of UNENE.

Students and postdoctoral staff have lively interactions with industry and with collaborators worldwide.

Research Results

Conferences, workshops and seminars

In 2008 Roger Newman was invited to address a special symposium in memory of Norman Hackerman, The Corroding of America’s Infrastructure, at the James Baker Institute for Public Policy, Rice University, Houston. Later he gave a plenary lecture at Eurocorr 2008 in Edinburgh. He and other members of the group have attended and made presentations at many other international and local events. William Zhang continued the tradition of winning a prize at the NACE student poster session.
Publications

The following list gives all papers published by the Chairholder, students and colleagues in the 2007-2009 period, to bring the list up to date from the last Annual Report. This list includes both UNENE and non-UNENE funded research and scholarship. Roger Newman made a significant contribution to the 4th Edition of Shreir’s ‘Corrosion’, including a major chapter on Stress Corrosion Cracking.

Journals


Conferences and book chapters


Teaching

Until 2008, Roger Newman taught introductory nuclear physics and basic reactor concepts in one half of the Nuclear Engineering 4th year Chemical Engineering elective course. He taught the second half of a 3rd year Materials course for Chemical Engineers, and teaches a graduate course in Corrosion, both of which have used many nuclear examples. He also teaches a 500-level course on Electrochemistry which has used examples such as pH measurement in high-temperature water.
This period was marked by a noticeable upsurge of interest among undergraduates in nuclear matters, and UofT began plans for new nuclear courses based in Mechanical and Industrial Engineering as well as Chemical Engineering and Applied Chemistry. It can be expected that by 2012 there will be 3-4 times the number of nuclear offerings in UofT that existed in 2007. As part of this renaissance of nuclear teaching, Roger Newman revived a graduate course on ‘Nuclear Chemical Engineering’ in 2009.
Overview

Life cycle management (LCM) is a process for timely detection and mitigation of aging effects in systems, structures and components (SSCs) important to plant safety, reliability and economics. It is also considered a decision making process to choose the best and balanced alternative for asset management. In the nuclear plant, LCM defines in-service inspection and maintenance programs, outage/generation plan and cost and investment planning.

“Risk-Informed Decision Making” has become a cornerstone of the regulatory framework worldwide. Uncertainties about the condition of existing assets and effects of aging are other significant confounding factors in life cycle management. Therefore, integration of techniques of risk and reliability analysis with LCM is important.

As many plants in Canada are approaching the end of life, cost-effective decisions are essential for the success of refurbishment projects. The balance between “fitness for service” and “asset preservation” is evolving over time. Fitness for service is important for operation in the short term, whereas asset preservation is important for refurbishment. This suggests that LCM should be a dynamic model involving all aspects of uncertainties.

The main research objective of the Chair program at the University of Waterloo is the development and integration of reliability models with LCM of NPP systems, structures and components. The program is focused on

1. Developing probabilistic models for risk analysis
   - Benchmarking existing standards and FFS methodologies
   - Solving a wide variety of practical problems related to reliability of nuclear plant systems

2. Supplying HQP to the industry
   - Graduate Students (PhD, MASc), Post-Docs
   - Education/Training of plant engineers (Undergraduates)

Fundamental research has focused on probabilistic risk and reliability modeling, stochastic processes, statistical estimation and extreme value analysis. Practical applications of the basic research include risk-informed LCM of fuel channels, steam generators, feeders and conventional systems, such as electrical generators and transformers. These applications have begun to yield considerable benefits to the operation and maintenance of nuclear power plants in Canada.
Research Program

The primary goal of the research program is to advance research in the area of life cycle management (LCM) of nuclear power plant systems and renewal of energy infrastructure as a whole. The core research capabilities are in the areas of reliability modeling, LCM and health monitoring techniques, as shown in Figure 1.

Figure 1: Core research capabilities of the IRC program

A number of research projects have been initiated and completed to address the effect of aging and improving life cycle management of major elements of the primary heat transport system, such as fuel channels, feeders and steam generators. Other conventional systems, such as main generators, transformers and piping in the balance of the plant have also been investigated.

These projects are not only relevant to the UNENE stakeholders in the short term, but also generate knowledge to improve life cycle management in the long term. Some of the key projects initiated or completed in 2007-2009 are summarized below:

Research Outcomes

**Feeder Projects**

**LCM Model**

The wall thinning of feeder piping due to flow accelerated corrosion (FAC) is a serious form of degradation affecting nuclear piping systems. We have developed probabilistic methods for estimating the corrosion rates taking into account probe measurement errors and other uncertainties. The models are now being applied to optimize the timing and sampling involved with feeder inspection and replacement at operating stations. The occurrence of leaks and ruptures of conventional piping in a plant have also been
modelled as a probabilistic process while considering the impact of plant vintage and increase in failure rate due to aging.

![Diagram of a feeder section](image)

**Figure 2: A schematic of a feeder section**

![Graph showing expected number of replacements](image)

**Figure 3: An application of feeder LCM model for predicting the number of feeder replacements**

**Feeder Cracking Susceptibility Analysis**

We have developed a variogram approach for statistical characterization of spatial distribution of Taylor factors in feeder bends. The research objective is to develop indicators to distinguish the susceptibility of feeder cracking in different stations. Samples of the Taylor factor distributions are shown in Figure 4.
**Fuel Channel Projects**

The performance of fuel channels in CANDU reactors are affected by pressure tube degradation mechanisms such as irradiation enhanced deformation (e.g., elongation, diametral expansion, sag, and wall thinning), delayed hydride cracking and changes in material properties. Due to large uncertainties associated with the degradation mechanisms, limited data, and high cost of inspection, the industry has emphasized the need for a prudent risk-informed framework for managing the reactor core in existing plants.

**Figure 5: A schematic of fuel channel**

Various sub-projects related to the LCM of fuel channels are briefly described below.
Probabilistic Leak-Before-Break (LBB) Assessment
The LBB assessment of pressure tubes is intended to demonstrate that in the event of through wall cracking of the tube, there will be sufficient time following leak detection for a controlled shutdown of the reactor prior to the rupture of the pressure tube. CSA Standard N285.8 (2005) has specified deterministic and probabilistic methods for LBB assessment. Although the deterministic method is simple, the associated degree of conservatism is not quantified and it does not provide a risk-informed basis for the fitness for service assessment. On the other hand, full probabilistic methods based on simulation require excessive amount of information and computation time, making them impractical for routine LBB assessment work. We have therefore developed a risk-informed approach by calibrating the existing criterion to specified target probabilities of rupture based on the concept of partial factors.

Delayed Hydride Cracking Assessment
CSA-Standard N285.8 recommends deterministic and probabilistic procedures for the assessment of potential for DHC initiation in planar flaws. We have proposed an innovative method in which the deterministic assessment criterion of CSA N285.8 Standard is calibrated to specified target probabilities of DHC initiation using the concept of partial factors. The main advantage of this approach is that it provides a practical, risk-informed basis for DHC initiation assessment while retaining the simplicity of the deterministic method.

Probabilistic End of Life (EOL) Assessment
Advanced random process models developed in the program have been applied to the analysis of inspection data regarding dimensional changes in pressure tubes and for predicting the end of life distribution. We have analyzed reactor specific data for diametral strain to estimate the distribution of remaining life of pressure tubes and the number of tubes unfit for service in a prescribed operating interval.

Material Variability Analysis
The nuclear industry has undertaken comprehensive experimental programs to determine the material properties, such as fracture toughness (Kc), DHC threshold toughness (Kih) and DHC rate using the samples taken from the in-service pressure tubes removed from the reactor core. We have developed in collaboration with AECL researchers multivariate statistical models to predict the distribution and bounds of material properties that are useful in the fitness for service assessment of pressure tubes.

Risk-Informed Inspection of Pressure Tubes: Optimum Sample Size
A key question in deciding the scope of pressure tube inspection is the sample size, as it affects the outage time as cost of inspection program. A case in point is the inspection for flaws that could become potential sites of DHC.
We have developed a risk informed model to estimate the sample size. For example, if we want to demonstrate through inspection that probability of DHC initiation is less than 0.01, then the optimal sample size as a function of statistical efficiency can be estimated using our model, as shown in Figure 6.

**Steam Generator Projects**

**Alloy 800 Lifetime Assessment**
Alloy 800 tubing has demonstrated excellent resistance to in-service degradation modes, in particular stress corrosion cracking (SCC). In planning refurbishment of a CANDU station, a key concern is the longevity of existing steam generators up to 60 year lifetime of the refurbished plant. We have developed probabilistic methods for estimating the lifetime distribution of Alloy 800 and 600 SG tubing using in-service experience and test data. We are also participating with a COG working group for experimental evaluation of Alloy 800 material.

**Impact of Inspection Uncertainties in the Assessment of SG Tubing**
In this project, we analyzed the influence of inspection uncertainties on the maintenance and replacement of SG tubing. Our analysis has shown that ignoring inspection uncertainties (such as POD and sizing error) will lead to highly biased decisions.

**Probabilistic Modelling of Pitting Corrosion**
We have developed a methodology to analyze all historically reported inspection data at Pickering B NGS and prepared a life cycle management approach. We have also correlated the extent of pitting with the distribution of sludge in the boiler (Figure 7)
**Generation Risk Assessment (GRA)**

The objective of the project is to integrate the results of the advanced degradation models of CANDU systems developed by the Chair into a system-wide assessment of generation risk. Key aging mechanisms affecting the availability of HTS systems are shown in Figure 8.

*Figure 7: Correlation of sludge distribution with pitting in a steam generator*

*Figure 8: Key HTS aging mechanisms*
The project includes a pilot study of the primary heat transport system at an existing nuclear station. We have developed degradation models using the station specific data and then quantified the forced loss rate for the station.

The GRA model has been applied to study a number of scenarios of plant maintenance and refurbishment, such as HTS pump vibration monitoring, extending testing interval of liquid relief valves (LRV) from 3 years to 6 years, aging of HTS pump seals, and the FAC of feeders. Figure 9 shows results of optimization of the time of refurbishment that would minimize the generation risk. The unit cost in this Figure refers to the unit cost of feeder replacement.

Figure 9: HTS system generation risk versus refurbishment considering feeder degradation

The developed GRA model to more accurately assess the risk and likelihood of failure over time will not only support the assessment of the timing and scope of refurbishment and replacement decisions, but also increase the flexibility, stability, and reliability of a plant’s capital investment planning and decision-making processes.

Risk-Informed Asset Management of Generators and Transformers

The operation of conventional systems, such as the turbine/generator and large transformers is often second in criticality only to the operation of the reactor itself. Because these components require long repair times, their failures can be significant contributors to lost power generation and plant trips. The developed life cycle cost analysis model incorporates time-dependent failure rates and uncertainty in costs and unavailability parameters. This model has been used to support the life cycle management of large transformers at a CANDU station.

Seismic Risk Analysis

Seismic design loads for systems, structures and components (SSCs) in old nuclear stations were evaluated using the Design Basis Earthquake (DBE) response spectrum defined by prevailing practices and standards of the nuclear industry in the 1970s, which
did not have consistent probabilistic basis. As old CANDU stations are planning for refurbishment, a seismic gap analysis between an existing structural design and new Code requirements based on probabilistic methods is necessary. To support a case for refurbishment of a plant, we have investigated the differences between the original DBE and response spectra calculated on the basis of modern standards and regulations.

**Practical Significance of Research**

- Effective fitness-for-service assessment of the reactor PHTS
- Improved communication with the regulator about managing the risk associated with degradation
- Minimize cost penalties associated with increased inspection and outage duration
- Overall improvement in operational efficiency

**Research Team**

**Current HQP**

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**Completion of HQP**

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- In the last 5 years, 17 personnel have completed training
- Employment: 3 NSS, 2 AECL, 1 Kinectrics, 1 Scandpower, 1 Apotex, 3 other Eng. firms, 3 Universities
- Two students have received offers from the nuclear industry

**Interaction with Industry**

A key objective of the IRC program is to facilitate the transfer of knowledge to industry through applications of the results of the fundamental research to practical industry
problems. Active collaboration and consultation with UNENE’s member industries has continued within conferences, workshops, and industry working groups, as well as through the publication of numerous technical papers and memoranda.

The Chair has maintained an active role in knowledge transfer by acting as a member of the organizing committee for the CNS 8th International Conf. on CANDU Maintenance, held in November 2008, in Toronto, Ontario. The Chair also offered well attended workshops in “Engineering Reliability and Life Cycle Management” as part of the International Conference on Nuclear Engineering organized by the American Society for Mechanical Engineers (ASME) in May 2008 (ICONE-16), in Orlando, Florida and June 2009 (ICONE-17) in Brussels, Belgium.

**Teaching**

- The Chair has continued to teach annually the Civ E 601 graduate course in “Engineering Risk and Reliability” at the University of Waterloo.
- In 2007 and 2009, UN 701 “Engineering Risk Analysis” was delivered to graduate students enrolled in the UNENE M.Eng. program.
- As anticipated, the “Fundamentals of Risk and Reliability” workshop developed by the Chair in the previous year has been fully embraced by the industry. The intensive training workshop has been delivered to OPG and CNSC staff multiple times. The interest in this training program continues to be high, with many more deliveries expected in the coming years to the members of the nuclear industry.

**Publications**

Selected publications in 2007-2009 are listed in the following sections.

**Journal papers**


Buildings. Accepted for publication (11 Sept 2009). Earthquake Engineering and Structural Dynamics.


Conference Papers


COG Reports


Overview

The period 2008/2009 has been one of dynamic growth and academic accomplishment at UOIT. During this period the Faculty of Energy Systems and Nuclear Science has seen its undergraduate programs in nuclear engineering and health physics firmly established with a total of 120 students successfully graduating from these programs and the percentage employment rate in the Canadian nuclear industry of these graduates an encouraging 80%. In September of 2008, OCGS approved UOIT's Masters program in nuclear engineering in the two fields of nuclear engineering and health physics and at the end of the current reporting period UOIT received approval for its Ph.D. program, again in the two fields of nuclear engineering and health physics. Thus, with a complete graduate program in place, UOIT can fully participate in the training of Highly Qualified Persons for the nuclear industry in Canada.

The UNENE/NSERC IRC for Health Physics and Environmental Safety was approved in July, 2008 and research funding started to flow to the Chair holders in September 2008. The core of the IRC research program is intended to enhance radiation protection for nuclear energy workers and the environment through studies in radiation measurement, radiation effects and radiation field modelling and visualization and can be more colloquially described as one of better measurements, better understanding and better communication. The research program focuses on improving real-time detection methods for mixed radiation fields and tritium and using signals from these devices to assist in radiation field mapping and visualization as well as developing a greater understanding of the comparative risks of different radiation exposures at low dose. Current research activities within the IRC framework are described in the following sections of this report along with other details related to IRC research at UOIT.

Research Program

Real-Time Measurements

Currently no personal alarming dosimeter for tritium-in-air is available for nuclear energy workers (NEW) and this gap is being addressed by two investigations. One study is of an ultra-thin plastic scintillator detection system to see if it can be used as the basis of a personal tritium monitor for operation in environments with substantial gamma fields. The second project is an investigation to better understand the effects of air and water vapour on the operation of proportional counters to assess if this technology can be optimized to form the basis of a compact tritium-in-air detection system. Another
radiation measurement ‘gap’ in nuclear power plant (NPP) operational health physics is that no instrument currently exists with an adequate energy response to accurately monitor neutrons or to provide the detection basis for a personal neutron dosimeter. Previous research of the IRC senior Chair has shown that tissue equivalent proportional counters (TEPC) are a good candidate instrument for mixed-field neutron-gamma dosimetry in CANDU power plants and a study is being carried out on a new development in TEPC technology to optimize the sensitivity, response and operation of a TEPC under NPP conditions.

**Radiation Quality**
Regulator 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. To address this issue a study is under way to describe the dosimetry of tritium irradiation at low doses in terms of the specific energy probability distributions for single and multiple events in mammalian cells and sub-cellular structures (microdosimetry). This study is being carried out combining methods of experimental microdosimetry and stochastic analysis, which have general applicability in low-dose radiation research.

**Radiation Field Modelling and Visualization**
Dose reduction for NEWs is a continual task of NPP health physics staff and an important objective of the IRC research program is to couple advanced computational methods to real-time measurement technology to greatly enhance training, ALARA and work optimization in NPPs. Consequently, a study is underway to investigate the use of Monte-Carlo methods to map and visualize radiation fields for complex geometries and work environments.

**Research Facilities**
UOIT was established in 2003 and as such is still in the process of facility building. A significant step forward will be made in 2011 when the construction of an Energy Research Centre will be completed on the UOIT campus. This centre will house laboratories specifically designed to support IRC research including purpose built neutron and gamma irradiation facilities. In the mean time The IRC program will continue to use facilities at other UNENE universities such as the McMaster Accelerator Facility. Presently at UOIT we have established laboratories for detector development, aerosol research and environmental radiation measurements.

**The Research Team**
Dr. Anthony (Tony) Waker holds the UNENE/NSERC Senior Industrial Research Chair. Prior to joining UOIT in 2005 Dr. Waker was senior researcher and manager of radiation biology and health physics at the Chalk River Laboratories of Atomic Energy of Canada Ltd. Dr. Waker’s career in radiation research started as a graduate student at the Joint European Research Centre in Ispra, Italy and continued with a post-doctoral period at the German Cancer Research Centre in Heidelberg, Germany. This was followed by a lectureship in the department of medical physics at the University of Leeds in the UK, which continued until 1991 when Dr. Waker joined AECL at Chalk River. Throughout his career Dr. Waker has been engaged in radiation detector development research for radiation protection dosimetry; experimental microdosimetry and its application to
neutron therapy, neutron activation analysis and neutron monitoring. His work also includes the measurement and quantification of radiation quality for cellular, sub-cellular and molecular systems for high LET radiation and low energy X-rays and beta particles.

Dr. Ed Waller holds the Associate UNENE/NSERC Chair. Dr. Waller earned his BSc in Physics and MScE in Chemical Engineering at the University of New Brunswick (UNB) and his PhD in Nuclear Engineering at Rensselaer Polytechnic Institute, New York (RPI). He worked for 15 years in industry (SAIC Canada), primarily in radiation safety and applications of radiation. In 2003 he joined the University of Ontario Institute of Technology. Dr. Waller is a Professional Engineer (PEng), Certified Associate Industrial Hygienist (CAIH) and Certified Health Physicist (CHP). He teaches radiation protection, health physics, environmental effects of radiation, Monte Carlo methods and a number of other courses at UOIT, and performs research in areas of dosimetry, applied health physics, radiation safety, counterterrorism and industrial hygiene.

Other IRC research team members are:
- Aslam Ibrahim – Post-doctoral Fellow specializing in neutron dosimetry, mixed-field microdosimetry and neutron beam design
- Abdukadir Al-Aydarous – visiting professor (University of Taif, Saudi Arabia) specializing in skin dosimetry and radiation measurements with scintillation detection systems
- Mohamad Awal – Research Associate (Electronics Technician) assisting experimental work and detector development
- Fawaz Ali – Ph.D student, about to embark on a PhD in detector design and modelling (graduated MSc Modeling and Computational Science under Dr. Waller, Dec 2009)
- Joseph Chaput – M.A.Sc student working on radiation field modelling and visualization
- Kirk Megna – M.A.Sc student working on tritium monitoring and scintillation detectors
- Christopher Woo – M.A.Sc student working on low energy X-ray and beta particle microdosimetry
- Nael Qashua – M.A.Sc student working on mixed field neutron-gamma monitoring
- Manirul Islam – M.Eng student working on gas-gain in proportional counters with electronegative counting gases
- Ada Ho – M.Eng (graduated) project subject – The modelling of radiation damage to the gastrointestinal tract.

Publications

Neutron Microdosimetric Response of a Gas Electron Multiplier
J. Dubeau and A.J. Waker

Opportunities to Improve the In-Vivo Measurement of Manganese in Human Hands
Aslam, D.R. Chettle, A. Pejovic-Milic and A.J. Waker
Orofacial Radiation Detection Device For Detection Of Radionuclide Contamination From Inhalation
Waller, E.

Book Review - Radiation Mechanics
Waller, E.J.

In Vitro Dissolution Study of Uranium Dioxide and Uranium Ore with Different Particle Sizes in Simulated Lung Fluid
Li, W., Skinner, R. Megna, K., Chen, J., Perera, S., Murimboh, J., Waller, E., Erhardt, L. and Cornett, J.

Use of Stable isotopes as Surrogates for Radionuclides for Security Studies
Andrews, W., Waller, E., Brousseau, P., Roy, G., Cao, X., Creber, K., and Erhardt, L.

Overview of Hazard Assessment and Emergency Planning Software of Use to RN First Responders
Waller, E.J., Millage, Blakely, Ross, Mercier, Sandgren, Levine, Dickerson, Nemhauser, Nasstrom, Sugiyama, Homann, Buddemeier, Curling and Disraelly

Radiological Hazard Estimates from Contaminated Mask Filters
Waller, E. and Erhardt, L.

Comparison of Experimental and Computational Neutron Spectroscopy at a 14 MeV Neutron Generator Facility
Waller, E., Cousins, T., Desrosiers, M., Jones, T., Buhr, R. and Rambousky, R.

Radiation Protection Issues Related to Canadian Museum Operations
Waller, E., Cole, D. and Jamieson, T.

In press/conferences
Performance of a High Sensitivity Multi-Element Tissue Equivalent Proportional Counter for Radiation Protection Neutron Monitoring Measurements
Aslam and A. J. Waker – Journal of Health physics

A Preliminary Study of the Performance of a Novel Design of a Multi-Element Tissue equivalent proportional Counter for Neutron Monitoring
A.J. Waker and Aslam – presented at the 11th Symposium on Neutron and Ion Dosimetry, Cape Town, October, 2009

Design of a Multielement TEPC for Neutron Monitoring

Spectroscopic Equivalent Proportional Counter for An In Vivo Neutron Activation Facility
A.J. Waker and Aslam – presented at the 14th Symposium on microdosimetry, Verona, October, 2009

Radiological Science Education in the Context of the Nuclear Industry in Ontario

Anthony Waker – 1st International Conference on Advances in Nuclear Instruments, Methods, Measurements and Analysis (ANIMMA), Marseille, France, June, 2009

MEDECOR - A MEdical DECORporation tool to assist first responders, receivers and medical reach-back personnel in triage, treatment and risk assessment after internalization of radionuclides
Waller, E. and Wilkinson, D.
Health Phys, accepted, 2009.

CT Diagnostic Reference Levels (DRL) in Ontario (Invited)
Waller, E.
Ontario Association of Radiologists Annual General Meeting, Toronto, Ontario, 24 May 2009

Quantitative Triage Assessment Indicators and Risk Aversion Models for Radionuclide Intake and Incorporation
Waller, E.

A Coupled Computational Fluid Dynamics – Monte Carlo Radiation Transport Approach to Radioactive Particle Transport Problems
Ali, F. And Waller, E.

Triage and Treatment Strategies for Radionuclide Inhalation Scenarios
Waller, E.
American Industrial Hygiene Conference & Expo (AIHce), Toronto, ON, 1-4 June 2009

Optimization of MEDical DECORpotation (MEDCOR) tool for time and use for improved bio-effects
CRTI Summer Symposium, Ottawa, June 2009.

MEDECOR2 – MEdical DECORpotation Tool Version 2 – To assist first responders, receivers and medical reach-back personnel in triage, treatment and risk assessment from internalized radionuclides
10th International Conference on Health effects of Incorporated Radionuclides (HEIR), Santa Fe, NM, 10-14 May 2009.
Use of Stable Isotopes as Surrogates for Radionuclides for Security Studies
Andrews, W., Waller, E., and Erhardt, L.
8th International Conference on Methods and Applications of Radioanalytical Chemistry (MARC VIII), American Nuclear Society Biology and Medicine Division, Kailua-Kona, Hawaii, April 2009

Radiation Triage Mask
Waller, E.

A Combined Hardware-Software Strategy for Triage of Internally Contaminated Persons
Waller, E. and Wilkinson, D.

Parallelization of Neutron Transport Approximation via Monte Carlo
Ali, F. and Waller, E.

Training the Next Generation of Radiation Protection Professionals in Canada
Waller, E.

Teaching Effective Problem Solving Skills to Radiation Protection Students
Waller, E.

Assessing Risk from Low Energy Radionuclide Aerosol Dispersal
Waller, E., and Perera, S.

Canadian Space Agency Discipline Working Group for Space Dosimetry and Radiation Science
Waller, E., Waker, A., Wilkinson, D. and Lewis, B.

MEDECOR - Software to Assist Medical Personnel and First Responders in Determining Appropriate Triage and Treatment for MEduced DECORporation of Internalized Radionuclides
Waller, E., and Wilkinson, D.

Miscellaneous Software Applications of Interest to RN Emergency Responders and Planners
Waller, E.

An Orofacial Radiation Detection Device for Rapid Triage of Personnel at Risk of Internal Radionuclide Contamination from Inhalation
Waller, E.

The Long Path of Tc-99m in North America
Cevera, M., Johnson, T., and Waller, E.

An Orofacial Radiation Detection Device For Detection Of Radionuclide Contamination From Inhalation
Waller, E.
NATO Human Factor and Medicine (HFM) Panel 099, Research Task Group (RTG) 033 – Radiation Bioeffects and Countermeasures Meeting, La Tronche, France, June 2008

The Role of the Industrial Hygienist in Assessing Aerosol Threat from a Radiological Dispersal Device
Waller, E.
2008 American Industrial Hygiene Conference & Expo (AIHce), Minneapolis, Mn, 4-7 June 2008.

Collaborations and Interactions

Both senior and associate Chairs are engaged in collaborative research across Canada and internationally. Regular contact is maintained with the IRC industrial partners and advantage is taken of the close proximity of UOIT with OPG Health Physics at Whitby through joint seminars and discussions. UOIT also maintains an MOU with OPG to act as a back-up emergency response site for environmental radiation measurements. Research collaborations include McMaster University, RMC, INFN – Legnaro, Italy, Fukui University of Technology, Japan. Other interactions that are relevant to the work and development of the IRC are:

- Senior Chair serves on the Health, Safety and Environment Technical Committee of the Candu Owners Group Inc (COG)
- UOIT is a member of the Durham Nuclear Health Committee and is represented by Dr. Waker
- Associate Chair is a Canadian delegate to the NATO Human Factors in Medicine Research Task Group (HFM-099 RTG-033) in Radiation Bioeffects and Countermeasures.
- Associate Chair invited to Nuclear Energy Institute Nuclear Industry Expert list, http://resources.nei.org/ExpertsList/Home.aspx
Queen’s University – Lynann Clapham  CRD

NSERC/UNENE Collaborative Research and Development Grant on Measurement of near-surface residual stress in CANDU feeder pipes using magnetic non-destructive evaluation techniques

1.1 Objective and Introduction
The objective of the proposed work is to develop a magnetic non-destructive evaluation (NDE) probe for measuring residual stresses in CANDU feeder pipes. These feeder pipes, which are typically mild steel with a 60mm diameter OD with a 7mm wall thickness, transport heavy water coolant into and out of fuel channels in CANDU nuclear reactors. Residual stresses (strain) in these feeders has become a concern after cracks were discovered in some bend regions. A tool for non-destructively evaluating residual stresses in these feeders is needed, and is the focus of this project. The work is co-funded by NSERC and UNENE, the University Network of Excellence in Nuclear Engineering, with in-kind support from AECL.

Common NDE methods based on ultrasonics or eddy currents are relatively insensitive to strain. Magnetic NDE techniques are strain sensitive, but a number of practical difficulties limit their widespread use for this purpose. The two magnetic NDE techniques that are being investigated in this project are based on Magnetic Barkhausen Noise (MBN) and Magnetic Flux Leakage (MFL) principles. Application of either MFL or MBN to feeder pipe strain measurement requires consideration of the following:

1. Residual stresses are notoriously difficult to non-destructively measure and quantify, particularly in in-service engineering components.
2. Consistent strain detection using either MBN or MFL is highly dependent on experimental conditions such as probe lift-off and sample surface preparation.
3. Feeder pipes have over 18 different bend configurations, so the probe will have to be able to adapt to changing surface curvatures.
4. Feeder pipes are very closely packed at the CANDU reactor face, so access to the entire pipe surface will be limited and clearance will be a significant problem.
5. The working environment of the probe at the CANDU reactor face is radioactive, so human manipulation of the measurement probe is necessarily limited.
The work for this project began in July, 2005. The work plan for the first year was to investigate both MFL and MBN techniques to determine which would prove to be the best candidate technique for further development. This work was mainly the task of Steven White, a PhD student on this project, with additional assistance provided by a summer student (Ben Lucht) and a 4th year Engineering Physics undergraduate thesis student (Paul Webster). After a year of investigating MBN and MFL, it was clear that BOTH have strong potential for this application. As a result, from year 2 onwards the project was split into two complementary projects:

1) **To develop an MBN probe for residual strain measurement in CANDU feeder tubes.** This aspect of the project formed the basis for the PhD thesis work of Steven White. Steven completed this work in the summer of 2009 and is now in the process of writing 3 papers about his thesis work (earlier he published one paper and has presented in one conference). In addition to Steven, undergraduate research assistants (Kris Marble, Tom Mak and Davin Young) were involved in this aspect of the project as part of their summer projects.

2) **To develop an MFL probe for residual strain measurement in CANDU feeder tubes**

   During the summer of 2006 an undergraduate summer RA (Tom Mak) laid much of the groundwork for the experimental aspects of this project. An MSc student (Ryan Yee) was to begin working on the project Sept 2006, however in late August this student informed me that he had a job and wasn’t going to pursue the project. As a result work on this aspect of the project was delayed for one year. However Tom Mak returned in September 2007 as an MSc student to work on this project. He has now completed the bulk of the experimental work on his thesis project and is writing his thesis. He is expected to be finished by December 2009.

By the end of the project had made considerable progress towards developing a working probe for the residual stress evaluation in CANDU feeders. As important, however, is the fact that we also considerably advanced the scientific knowledge and technological applications of both techniques. A summary of both aspects of the project (1 and 2 above) are summarized below.

### 1.2 Development of an MBN technique for the measurement of stress in CANDU feeders

MBN has been recognized for many years as having the potential for non-destructive stress measurement, but two main practical limitations have prevented its development beyond the lab:

1. The technique is highly sensitive to the lift-off of the probe from the surface, with slight variations causing significant signal variations. This project has overcome this problem by introducing a feedback mechanism for controlling the flux into the sample, regardless of the liftoff. This is discussed in section 1.2.1 below.

2. While our group has pioneered an angular MBN strain scanning method, our traditional technique involves physically rotating the MBN probe.
While this is adequate for flat plate samples, it is not suitable for curved feeder pipe surfaces. In this project, a new 4-pole (tetrapole) probe which does not need to be mechanically rotated, rather a variation in the flux introduced through the 4 poles effectively “rotates” the field. This is introduced in section 1.2.2 below. Furthermore, considerable modelling work has been conducted in order to optimise the tetrapole magnet design (section 1.2.3) and also the pickup coil design (section 1.2.4), and signal processing (section 1.2.5).

1.2.1 Addressing lift-off issues: As mentioned above, lift-off/surface contact problems represent a significant obstacle to the application of this technique. Magnetic modelling was conducted at Queen’s and AECL to study exciter coil placement and the effect of feedback on the excitation field. This suggested that a pole-piece mounted feedback coil would help to decrease lift-off sensitivity. Using the modelling result as a guide, PhD student Steve White designed and built a number of probes having different feedback coil parameters, in addition to modifying and re-designing the instrumentation needed to drive and interpret signals from the probes. Figure 1 shows the MBN probe coil geometry including the flux sensing (feedback) coil.

Steve also investigated different possible methods for driving and feedback, evaluating the relative merits of controlling the probe using magnetic field (H) control, and magnetic flux (B) control. He has shown that feedback flux control is a superior method for attaining MBN signal consistency despite liftoff. Figure 2 illustrates this – Fig 2(a) shows that the MBN result with field control varies considerably with liftoff, while Figure 2(b) indicates that the result for all liftoff conditions is similar if one uses flux feedback control.
Figure 2: $\text{MBN}_{\text{energy}}$ lift-off response (for liftoff values of 0, 0.6, 1.2 and 1.8mm) as a function of a) applied field and b) sample flux density for the Si-Fe steel sample.

1.2.2 The new tetrapole design  Since physical rotation of the coil is problematic on a non-planar surface, Steve developed a probe that will perform an angular MBN measurement without the need for physical rotation – rather the field rotation will be done electronically. His design involves two perpendicular dipole probes – to create a “tetrapole” probe, as shown in Figure 3. Varying the amplitude/phase of the exciter signal in each probe is expected to produce an angular vector superposition of the magnetic field in the sample, thus accomplishing a rotation of the MBN exciter field without the physical probe movement of the probe, as illustrated in Figure 4.

Figure 3: “Tetrapole” probe (left) and also schematic in side view (middle) and bottom-up view (right).
1.2.3 Tetrapole modelling

Once the basic tetrapole magnet was designed and working, a considerable amount of modelling work was conducted to examine how best to modify and optimise the design. Figure 5 shows models of two different tetrapole designs considered in this phase of the project. An example modelling result is seen in Figure 6, which shows the effect of tetrapole coil driving frequency on the flux pattern in the sample flux distribution.

Figure 4: “Tetrapole” probe operation – rotating the field at the centre of the probe by varying the field in the set of blue dipoles and the set of green dipoles. The red arrow on the tetrapole schematic indicates the sum field direction.

Figure 5: Two different tetrapole designs evaluated during the modelling phase.
1.2.4 Pickup coil modelling
The pickup coil sits at the centre of the tetrapole magnet arrangement and detects the MBN signals. In addition to tetrapole exciter coil modelling, a considerable amount of modelling was done to determine the optimum configuration and composition for the pickup coil design. A number of different configurations were considered – a bare coil, a coil with a ferrite core, a coil with an external brass shield, and a coil with an external ferrite sheath. All combinations of the above were also considered. Figure 7 shows the cross section through the centre of the sample region – indicating the area sensitivity of the composite pickup coil.

Figure 7: showing that composite pickup coil has greater, more localized sensitivity than coil only

1.2.5 Signal processing
Work on signal analysis and processing also formed a significant part of the final stages of the thesis work. Figure 8 shows results of signal processing before and after filtering.
Figure 8: shows the averaged Power Spectral density of Barkhausen noise as a function of the excitation coil phase for 128 BN cycles at 58Hz. The streaks in the raw data are resonances in the background noise spectrum and are not associated with BN. b) A soft digital peak filter decreases the power of these artefacts. c) A 3rd order Bessel band pass filter is applied between 3 and 350 kHz. This creates a very clean BN spectrum.

1.3 Progress towards objectives: MFL technique

A magnetic flux control system was designed that implements integral (Hall sensor) and proportional (coil) feedback. This system, shown in figure 10, allows specification of the magnetic flux density through the feedback coil and Hall sensor, which is then converted in LabView to a reference voltage $V_{ref}$. The output voltages of the feedback coil ($V_{fc}$) and Hall sensor ($V_{h+}$ and $V_{h-}$) are compared to the reference voltage. The amplifier adjusts its output such that $V_{ref} = V_{fc} + V_{h+} - V_{h}$ when $R_{vh} = R_g = R_{fc}$.

Figure 10: A simplified schematic of the proportional-integral flux control system. Excitation and feedback coils are wound onto a U-core magnetic. Between the
magnet and sample is a Hall sensor, which provides integral feedback to the control system.

This control system was tested on mild steel plate samples in a single axis stress rig (SASR) with three flux leakage sensors (shown in figure 11): a coil with its axis parallel to the sample surface normal, a Hall sensor oriented parallel to the surface normal, and a sensing coil set perpendicular to the applied magnetic field and the surface normal (referred to as the anisotropy sensor). The first two measurements were preformed twice: once with the magnetic field parallel to stress, then with the field perpendicular to stress. Neither of these measurements indicated significant MFL stress sensitivity.

![Figure 11: three different MFL probe designs tested](image)

The anisotropy sensor was rotated about 360°; measurement data was acquired in increments of 15°. Anisotropy signal amplitude varied sinusoidally with a period of 180°, shown in figure 2. Increased stress levels produced a noticeable effect on the anisotropy signal. To quantify this effect, anisotropy signals were calibrated to a background measurement at zero stress. These calibrated signals were fit in MATLAB as 180° periodic sine waves, and the amplitudes were extracted.
Figure 12: A modified anisotropy sensor designed to mount on curved pipe surfaces. The mounting bracket is omitted from this figure for clarity. The sensing coil is located between the poles of the U-core and is spring mounted.

Finally, a new sensor was built to test the anisotropy system for use on CANDU feeder pipes. This is shown in Figure 12. The system was miniaturized and modified to function on curved surfaces, and is still undergoing testing.
Table Submission
from
Dr. Lynann Clapham, Professor
Department of Physics, Engineering Physics & Astronomy
at Queen’s University

<table>
<thead>
<tr>
<th>Name</th>
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</table>
University of Western Ontario – Robert Klassen  CRD

NSERC/UNENE Collaborative Research and Development Grant on Microindentation studies of the local ductility of Zr-2.5Nb CANDU pressure tubes

Principal Investigator:  Robert J. Klassen  
University of Western Ontario

Co-Investigator:  Brad J. Diak  
Queen’s University

Overview

The objective of this research project is to use microindentation testing techniques; namely spherical- and pyramidal-microindentation, to assess the local mechanical properties of the Zr-2.5Nb alloy used in CANDU pressure tubes. Spherical micro-indentation is used to deduce the flow stress versus plastic strain relationships in the radial-, axial-, and transverse-directions of a pressure tube at temperatures from 25°C to 400°C and, thus, provide data on the directional anisotropy of the plastic flow properties. Pyramidal micro-indentation creep tests and indentation strain rate-change tests are used to assess the effect of indentation direction, temperature and irradiation damage (as simulated with Zr⁺ ion irradiation) on the parameters that define the kinetics of the plastic deformation of the Zr-2.5Nb alloy.

The data from this investigation will allow more accurate predictions to be made of the extent of local stress relaxation occurring as a result of creep deformation around surface flaws, such as scratches and fretting flaws, in CANDU pressure tubes during service and will provide a testing methodology that can potentially be used for in-cell assessment of local variations in the mechanical properties of irradiated fuel channel materials.

Outcomes from this research

1)  Spherical micro-indentation testing of Zr-2.5Nb material
Spherical micro-indentation tests were performed at 25°C in the radial-, axial-, and transverse-directions of a non-irradiated Zr-2.5Nb pressure tube off-cut. The average indentation stress \( \sigma \) and plastic strain \( \varepsilon \) are determined from the measured indentation force \( F \), indentation depth \( h \), and the indenter contact radius \( a \) using the following expressions:

\[
\sigma = \frac{F}{\psi h^2} \quad \text{and} \quad \varepsilon = \alpha \left( \frac{a}{R} \right)
\]  

(1)
The parameters $\psi$ and $\alpha$ were determined by fitting the calculated $\sigma$, $\varepsilon$ values to $\sigma$ - $\varepsilon$ curves obtained from uniaxial compression tests performed on the same Zr-2.5Nb material. It was found that the values of $\psi$ and $\alpha$ are different by about 15% for the axial-, radial-, and hoop-directions. This reflects the mechanical anisotropy of the highly textured Zr-2.5Nb pressure tube material when deformed at room temperature. Spherical indentation and uniaxial compression tests are now being done at elevated temperatures (100, 200, 300, and 400°C) and the methodology developed from the room temperature tests will be applied to analyse the data. This research will result in empirical expressions for $\psi$ and $\alpha$ as a function of indentation direction and temperature which will allow the use of spherical micro-indentation testing to obtain $\sigma$ versus $\varepsilon$ curves for localized regions of pressure tube material without the need to make large uniaxial tension or compression specimens. This has an obvious application for obtaining $\sigma$ - $\varepsilon$ flow curves from radioactive material removed from nuclear reactors.

Pyramidal micro-indentation hardness tests were performed on sectioned spherical indentations to map the variation in hardness, and hence the variation in the equivalent plastic strain, around the indentation. Similar tests will be performed on spherical indentations made at 100, 200, 300, and 400°C. Knowing the distribution of plastic strain around spherical indentations made in pressure tube material in the three orthogonal directions at various temperatures will provide benchmark data against which researchers can assess the accuracy of their finite element models.

2) Microindentation creep testing of non-irradiated Zr-2.5Nb
Constant-force indentation creep tests, of one hour duration, were performed at indentation depths of $h_0 = 0.1, 0.5, 1.0, 5.0, 8.0, \text{ and } 10.0 \mu m$ in the radial-, axial-, and transverse-directions of non-irradiated Zr-2.5Nb pressure tube material at temperatures of 25, 100, 200, 300, and 400°C.

The indentation strain rate $\dot{\varepsilon}_{\text{ind}}$ was calculated from the constant-force indentation creep test data and was expressed as a function of temperature $T$ and indentation stress $\sigma_{\text{ind}}$ by the following equation which expresses the strain rate resulting from a creep deformation process occurring by a mechanism of dislocation glide limited by interaction with discrete obstacles distributed in the microstructure.

$$\dot{\varepsilon}_{\text{ind}} = \dot{\varepsilon}_0 e^{\frac{\Delta G_0}{kT}} \left( \frac{\sigma_{\text{ind}}}{\sigma_0} \right)^m$$

In this equation $\Delta G_0$ is the activation energy of the obstacles that are limiting the dislocation glide through the indented material. By fitting Eq. (2) to the measured $\dot{\varepsilon}_{\text{ind}}$ and $\sigma_{\text{ind}}$ data $\Delta G_0$ was found to increase with increasing temperature for the Zr-2.5Nb samples tested.

The magnitude of the measured $\dot{\varepsilon}_0$ and $\Delta G_0$ suggests that the obstacles controlling the creep rate of Zr-2.5Nb at 25°C are dislocation / dislocation or dislocation/grain boundary interactions. This was confirmed by TEM micrographs of foils that were extracted from directly below crept microindentations using focused ion beam milling.
3) Microindentation creep testing of ion-irradiated Zr-2.5Nb Constant-force indentation creep tests (of one hour duration) were also performed on Zr-2.5Nb pressure tube material that was irradiated with 8.5 MeV Zr$^+$ ions to levels corresponding to 5 and 30 displacements per atom (dpa) at a depth of about 3 $\mu$m. These levels of ion irradiation were chosen to simulate the microstructural damage imparted to Zr-2.5Nb from neutron irradiation over the lifetime of a CANDU pressure tube.

The initial indentation stress $\sigma_{\text{ind}}(t=0)$ was found to increase with increasing ion irradiation. $\sigma_{\text{ind}}(t=0)$ show a similar dependence upon indentation depth and indentation direction as the non-irradiated Zr-2.5Nb however $\Delta G_0$ (Eq. 2) increases with increasing ion irradiation. This indicates that the ion damage induces a population of crystal defects into the Zr-2.5Nb that directly affect the activation energy associated with creep deformation.

4) Microindentation strain rate change tests of non-irradiated Zr-2.5Nb
Pyramidal microindentation tests were performed, at room temperature, to indentation depths of 2 $\mu$m and 10 $\mu$m on the non-irradiated and ion-irradiated Zr-2.5Nb samples. Periodically during the tests the indentation strain rate was changed suddenly by a factor of ten to assess the effect of irradiation hardening on the strain rate sensitivity of the hardness of Zr-2.5Nb. The first stage of these tests were performed at Queen's university and the data are presently being analysed.

Research Facilities

This research project has made use of facilities located in three Canadian universities (the University of Western Ontario, Queen's University, and McMaster University). The majority of the microindentation tests were performed with the high-temperature microindentation and nanoindentation testing facilities located in the Faculty of Engineering at the UWO. The Zr$^+$ ion irradiations were performed with the Tandetron ion accelerator and the fabrication of TEM samples using focused ion milling was performed at the nanofabrication laboratory both of which are located in the Faculty of Science at the UWO. The TEM investigations were performed at the Brockhouse Institute for Materials Research at McMaster University. The microindentation strain rate change tests were performed in the Faculty of Engineering and Applied Science at Queen's University.

Research Team

Principal Investigator (R.J. Klassen)
- Primary organizer of the project. Recruited the four graduate students (2 PhDs and 3 MEngs) and one summer student.
- Set up the test matrix.
- Scheduled all testing.
- Liased with the supporting company (AECL (UNENE member)).
Co-investigator (B. Diak)
- Prof. Brad Diak is supervising the microindentation strain rate change tests at Queen’s University. Prof. Diak’s expertise in the kinetics of plastic deformation is essential in correctly interpreting the results of the pyramidal indentation creep and strain-rate change tests performed on the non-irradiated and the ion-irradiated Zr-2.5Nb samples.

PhD Grad. Student (B. Bose)
- Completed the bulk of the micro-/nano-scale indentation creep tests at temperatures of 25, 100, 200, 300, and 400°C.
- Completed all the indentation creep testing of the Zr+ ion irradiated (5 and 30 dpa) samples.
- Performed TEM analyses of the indentation plastic zone of non-irradiated and ion-irradiated Zr-2.5Nb samples.
- Performed indentation strain rate change tests at Queens University.

PhD Grad. Student (R. Oviasuyi)
- Finished the room temperature spherical micro-indentation testing and the uniaxial compression tests on the Zr-2.5Nb samples.
- Assessed the anisotropic plastic strain around spherical indentations.
- Performed uniaxial compression tests at 100, 200, 300, and 400°C.

MEng Grad. Students (N. Dorairaj, N. Islam, M.A. Bashar)
- Worked on characterising the plastic zone beneath spherical indentations.
- Worked on assessing the effect of internal oxidation on the indentation creep of zirconium alloys.

Publications

The findings from this research have resulted in two conference presentations [1,2] and one submitted journal paper [3].


**Interactions with Industrial Sponsors**

The results that were achieved to date were presented at the Chalk River Laboratories (CRL) on May 12, 2009 to an audience of about 30 Researchers/engineers who were involved in pressure tube flaw assessments.

Considerable interest arose from this presentation particularly in the use of spherical micro-indentation testing for performing in-cell measurements of the mechanical properties of highly radioactive material.

Based upon the findings presented there was agreement in principle to:

1) Use spherical microindentation to test the flow stress of Zircaloy circular disks that were previously irradiated to high neutron fluence at the ATR reactor in Idaho Falls and which are now in storage at CRL.

2) Use the pyramidal nano-indentation techniques to assess the effects of Oxygen ingress and internal oxidation on the hardness of Zr-4 fuel sheathing exposed to high temperature similar to that during a LOCA event.

This demonstrates the usefulness of the findings of this study to players in the Canadian nuclear industry.
Overview

This research is concerned with modelling fluid flow and heat transfer in subchannel geometries. Computational fluid dynamics (CFD) is being used to model the flow pulsations that occur in the gap region of nuclear fuel bundles. Simulations are validated against experiments to assess the validity of the models used, in particular the turbulence models. The long term of the research is to develop an improved understanding of the underlying physics of the flow pulsations. This will then allow for development of simple models which capture the important physical phenomena and can be incorporated into industrial safety analysis codes such as ASSERT-PV. The benefit to industry will be more accurate predictions of fuel sheath temperatures as well as development of highly qualified personnel for potential employment in the nuclear industry.

For the period April 2007 to September 2009, two graduate students (George Arvanitis and Deep Home) worked on this UNENE supported research. Their work was computational in nature and the research facilities required were high speed computers as well as the commercial CFD code ANSYS-CFX. The simulations were performed using the quad computers in the Mechanical Engineering CFD Lab as well as the high performance cluster in Dr. John Luxat’s laboratory. George and Deep’s activities over the period April 2007 to September 2009 are summarised below.

Research Program

George Arvanitis started his Masters degree in September 2006 on numerical modelling of subchannel flow pulsations using unsteady Reynolds Averaged Navier-Stokes (RANS). George was very productive over the period covered by this progress report. He completed the research for the thesis, the thesis writing, and he successfully defended his thesis in the fall of 2008. His work in unsteady RANS was successful in capturing the experimental results for pulsation frequency with an error of about 15%. He has a number of conference papers (listed below) as well as a recently published journal paper in Nuclear Engineering and Design. Although George Arvanitis has Canadian citizenship, he is from Greece and returned to Greece after defending his thesis to complete a mandatory term in the Greek army. He has now completed that term and returned to Canada in November 2009. He is currently in talks with Nuclear Safety Solutions regarding potential employment with them.

Deep Home began his Ph.D. in September 2004. During the period April 2007 to September 2009, Deep focused his research on the simulation of the flow pulsations
using Detached Eddy Simulation (DES) and on writing up the work prior to 2007. DES is a hybrid RANS modelling approach that uses Large Eddy Simulation in the flow regions away from walls, while unsteady RANS is used in the near wall region. Careful modelling is required at the interface between the two regions. He had previously used DES to predict a channel flow problem to allow him to become familiar with DES as well as to validate the method against published Direct Numerical Simulation results. The channel simulations have now been published in the journal *Numerical Heat Transfer*. He has completed the simulation of gap pulsations in subchannel geometries and has validated against experimental data. He has completed a first draft of his thesis and I expect him to defend his Ph.D. in early 2010. Deep has numerous conference papers (including papers at NURETH and the American Nuclear Society meeting in 2009) as well as two journal papers. He will write at least one more journal paper detailing the results of the DES simulations for subchannel flows.

Deep has recently started working at Nuclear Safety Solutions. In many ways, Deep Home is an example of a UNENE success story! He has done great research (with excellent publications) and is now working in the nuclear industry. I expect the same of George.

Meetings were held with the UNENE research advisory committee as the work progressed. These meetings were held at the Bruce Power offices in Toronto in October 2007 and July 2008. We received positive feedback and constructive comments from the RAC.

**Journal Publications**


**Conference Publications**


1. Overview

The safe operation of nuclear reactors requires complete understanding of the thermal-hydraulic phenomena taking place in the nuclear reactor core, especially those occurring under postulated accident conditions. However, the complexity of the CANDU nuclear reactor core geometry and two-phase flow behaviour create challenges for theoretical and experimental studies. In the case of a loss of coolant circulation, an accurate prediction of two phase flow behaviour in pressure tubes, where steam continues to be generated due to decay heat, is highly important in CANDU reactor safety analyses.

1.1 Objectives

The objectives of the research project are to obtain fundamental information on (1) vapour bubble buildup and venting in a horizontal CANDU fuel channel (IBIF phenomenon) following a loss of forced circulation during reactor outages, and (2) the effect of pressure tube sagging on the venting of steam during IBIF incidents, and (3) the liquid film dryout phenomenon leading to Critical Heat Flux (CHF) under steady state operation and certain accident conditions such as a loss of reactor regulation accident. The information collected will be useful for devising viable technologies to enable the CANDU reactor designers and operators to extend the applicability of the existing experimental data on the IBIF phenomena and liquid film dryout, and gain additional safety margins (or return to full-power) and operational flexibility (i.e., shorter reactor outages).

1.2 Scope of Investigation

The scope of the IBIF study can be summarized as follows:

- Constructing an experimental facility nearly exactly duplicating the geometry of a CANDU reactor pressure tube together with 13 replicas of 37-element fuel bundles.
- Study of bubble formation and migration throughout the system by injecting air bubbles into the rod bundles.
- Study of the effect of pressure tube sagging on the IBIF phenomena.
- Study the existence of buoyancy-induced two-phase flow circulation.

In the liquid film dryout study, the objectives were:

- to study the behaviour of a thin film of water flowing on metal rods simulating the uranium fuel rods used in CANDU reactors.
- to measure the liquid film’s thickness profile near a discontinuity on the rod surface using a Laser Confocal Displacement Meter (LCDM) as a function of liquid and gas flow rates and gap distance, including the possibility of liquid
film dry-out near the discontinuity.
- to suggest possible improvements on the CANDU fuel bundle design based on the understanding of the liquid film behaviour gained through this study.

To achieve the above objectives, an IBIF experimental facility was designed, constructed simulating a CANDU reactor pressure tube, and used to obtain data on the vapour venting time. The boiling phenomenon in fuel bundles was simulated by injecting air bubbles into the stagnant water inside the pressure tube. The liquid film study was conducted by constructing an air-water flow loop and measuring liquid film distributions using a novel liquid film thickness sensor.

2. Research Program/Outcomes

2.1 Intermittent Buoyancy Induced Flow (IBIF) Study

Experiments have been conducted using a IBIF flow loop described in the next section. The main parameters varied in the experiments included the simulated power level, i.e. the air-injection rate, the water level inside the feeder pipes and sagging of the pressure tube from a horizontal position.

A system of pressure transducers and video cameras were used to collect the data. This information was subsequently processed and analyzed to present the results. Experiments showed that the air bubbles injected into the pressure tube rapidly rose towards the top, merged together and formed a continuous layer rather than remaining as discrete bubbles. The observed behaviour is illustrated in Fig. 1.

![Fig. 1 Two-phase flow behaviour during IBIF](image)

Air then flowed along the pressure tube towards the end section and vented into the feeder pipes forming a slug flow in the feeder pipes.

2.1.1 Effect of Air Injection Location on Venting Time

The goal of this study was to investigate the effect of air injection location on the gas venting time. Air was injected at different locations throughout the length of the pressure tube and the time interval between the start of the air injection and air venting was measured. In order for the results to be consistent the air injection rate and the water levels inside the water tanks were kept constant for each run. The only parameter varied in different runs was the location of the air injection. The experiments were performed at three different simulated power levels. The results summarized in Table 1 show that the venting time decreases with the venting distance and the bubble expansion velocity is relatively constant.
Table 1 Effect of the air injection location on the venting time

<table>
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<tr>
<th>Simulated Power Level(SPL), kW</th>
<th>Average Venting Time, s</th>
<th>Venting Distance, cm</th>
<th>Bubble Expansion Velocity, cm/s</th>
<th>Average Bubble Expansion Velocity, cm/s</th>
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<td>1.1</td>
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</table>

The observed system behaviour also showed that the air bubbles introduced into the pressure tube rapidly rose towards the top and formed a continuous layer rather than remaining as discrete bubbles. Air then flowed along the pressure tube towards the end section and vented into the feeder pipes forming a slug flow in the vertical feeder pipes.

2.1.2 Parametric Effects

Additionally, the following effects have been investigated.

- Combined Effect of Feeder Water Level and Air-Injection Rate on the Venting Time
  As expected, the experimental results showed an increase in the venting time with an increase in the water levels inside the feeder pipes and with the decreasing simulated power level, i.e. the air injection rate.

- Effect of Multiple Air Injections on the Venting Time
  The results for two and three simultaneous air injections indicated that the simultaneous air injections lead to a decrease in the venting time. Thus, the pressure tube venting in the CANDU reactor core is expected to be accelerated due to the large number of nucleation sites on the fuel rods inside the pressure tube during the loss of coolant circulation event.

- Effect of Pressure Tube Sagging on the Venting Time
  In order to study how the pressure tube sagging affects the venting time, the supports of the pressure tube at the centre were lowered as shown in Fig. 2. The average venting time data showed that even small sagging of the pressure tube in the middle by 12.5 mm (0.5 inch) could cause a significant decrease in the venting time by 8% compared to the horizontal pressure tube as shown in Table 2. Upon further increases in the depth of sagging down to 50.8 mm (2-inches), the venting time was further reduced by 14%.
Fig. 2 Sagging of the pressure tube

Table 2 Effect of pressure tube sagging on venting time

<table>
<thead>
<tr>
<th>Sagging Distance, Inch</th>
<th>Inclination Angle, deg</th>
<th>Venting Time (sagged tube), s</th>
<th>Decrease in the Venting Time, %</th>
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<tr>
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<td>0</td>
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- Oscillatory behaviour
Once the air injection is initiated the venting of air would occur through either the left or right feeder pipe on a random basis, as the water level in one of the header tanks would increase and the level in the opposite tank would decrease. This process continues until a critical water level is reached in the header tank and the venting process switches directions. Afterwards the process repeats itself. This oscillatory behaviour can be characterized by a certain frequency of oscillations. The oscillation frequency increased almost linearly with a decrease in the initial water level in the feeder lines, but decreased with an increase in the air injection rate.

2.2 Liquid Film Dryout Study
2.2.1 Experimental Observations and Challenges
The formation of a liquid film on the metal rod was visible from outside the glass tube as shown in Fig. 3. The thin liquid film formed a ridge near the discontinuity. The displacement of the liquid film surface could be determined by detecting the displacement of an objective lens in the Laser Confocal Displacement Meter (LCDM) that was moved frequently by a tuning fork, as the laser beam passing through the objective lens was focused on the target. However, errors were induced in the measurements by the refraction of the laser beam passing through the curved glass tube wall, and scattering and reflection of the laser beam from the target back into the LCDM. Thus, for the LCDM it was difficult to measure the thickness of a thin liquid film formed on a metal rod from outside the cylindrical glass tube.
An alternative measuring method that would solve the difficulties described above was then developed by constructing two test pieces as shown in Fig. 4 and conducting tests. A metal rod was inserted inside an outer jacket made of a transparent circular and rectangular channel (Fig. 4). The cylindrical glass tube was found to affect the measurements due to the lens effect of the curved wall, but the rectangular channel allowed unbiased liquid film thickness measurements.

2.2.2 Initial measurements
Measurements of the liquid film thickness on a cylindrical rod inside a rectangular glass channel were then performed with the LCDM. A thin water film was formed and left to evaporate naturally. As shown in Fig. 5, the time evolution of the evaporating liquid film thickness was successfully measured.
2.2.3 Redesign of the experimental apparatus
Based on the initial tests we redesigned the apparatus to measure the thickness of the thin liquid film formed on a cylindrical rod by air shear inside a rectangular channel. In the modified design the inner metal rod can be separated by a variable gap similar to the earlier design (Fig.3).

2.3 Future Work
For the IBIF study, a two-phase flow model will be developed to predict the air bubble expansion velocity through a pressure tube containing a fuel bundle for different inclinations. After validation, calculations will be conducted for a steam-water two-phase flow in a CANDU reactor at different saturation pressures and temperatures. Suggestions will also be made to devise viable technologies for the CANDU reactor designers and operators to extend the applicability of the existing experimental data on the CHF and IBIF phenomena, and gain additional safety margins.

3. Research Facilities

3.1 An IBIF Experiment Facility
An IBIF experiment facility was designed and constructed by an MASc student (Zheko Karchev). With assistance from the industry sponsors on the design, and an in-kind contribution of 26 zircalloy endplates, thirteen rod bundles were constructed and placed in a horizontal acrylic tube simulating a pressure tube in a CANDU reactor as schematically shown in Fig. 6. A 9.0-m long, 4-inch ID horizontal tube made of acrylic resin was used as the simulated pressure tube. It consisted of four sections connected by flanges. The horizontal pressure tube contained 13 rod bundles simulating 37-rod fuel assemblies.

![Experimental Set-Up for an IBIF Study – Overall View](image)

The end section of the pressure tube was connected to a vertical feeder tube as shown in Fig. 7.
The boiling phenomenon inside the pressure tube was simulated by injecting air through four small nozzles attached to the pressure tube as shown in Figs. 8 and 9.

Fig. 7 End section of the pressure tube and connection to a feeder pipe

Fig. 8 Air injection to simulate steam generation due to decay heat

Fig. 9 Photograph of the pressure tube, rod bundles and air injection tubes
3.1.1 Simulated Fuel Bundles
The 37-fuel rod assembly was simulated by an acrylic model that utilized Zircalloy endplates actually used in CANDU reactors and provided by Bruce Power. The endplates were used to hold the acrylic rods in place as shown in Figs. 10 and 11.

![Acrylic Rods](image1)

Fig. 10 Fuel rod bundle made of acrylic rods and Zircaloy endplates

![Zircaloy End Plates](image2)

Fig. 11 Photographs of acrylic rod bundle and Zircaloy endplates

Thirteen bundles were fabricated using acrylic rods of 12.7 mm OD, which closely match the nuclear fuel rods used in CANDU reactors.

3.1.2 Instrumentation and Data Acquisition System
Four video cameras are used to continuously record the two-phase flow in the pressure tube. The images from the four video cameras are combined into a single image and recorded simultaneously as shown in Figs. 12 and 13.

![CCTV Camera](image3)

Fig. 12 A CCTV camera used to monitor the two-phase flow in the pressure tube

![Quad Video Splitter](image4)

Fig. 13 A quad video splitter and simultaneous display of flow
3.1.3 Void Fraction Measurement
The void fraction throughout the system is monitored by measuring the differential pressure at different locations on the pressure tube. A differential pressure transducer with a range of 1 psid is attached to the vertical feeder tube as shown in Fig. 14 and the pressure tap locations are 40 and 110 cm above the pressure tube. The differential pressure transducer measures the “collapsed water level” between the pressure taps assuming the friction pressure drop to be negligibly small compared to the gravitational component. The void fraction can be readily calculated using the water and air densities, gravitational acceleration and the distance between the pressure taps.

![Differential Pressure Transducer](image1)

**Fig. 14** Differential pressure transducer installed on a vertical feeder pipe

A differential pressure (DP) transducer with a small measurement range of 10 inch water column is used to measure the void fraction distribution along the pressure tube as shown in Fig. 15. For each DP transducer, pressure taps are located at the top and bottom of the pressure tube at eight different locations. Eight pairs of valves are used to connect the DP transducer to one pressure tap location. Under quasi-steady state conditions, switching the valves allows the void fraction distribution throughout the tube to be monitored.

![Differential Pressure Transducer](image2)

**Fig. 15** Differential pressure transducer for measuring the void fraction distribution along the pressure tube
Another end section design shown in Fig. 16 was fabricated to simulate the actual end section of a pressure tube of a Darlington reactor.

Fig. 16 A pressure tube end section design simulating that of a Darlington reactor

3.2 Liquid Film Experiment Apparatus
An experimental apparatus was designed and constructed as shown in Fig. 17. A steel rod of 13 mm diameter was inserted inside a concentric transparent glass tube with an inner diameter of 20.0 mm (Fig. 17a). The steel rod had two parts connected by a screw and the distance between the rods could be adjusted by an outside knob. The steel rods were aligned to stay concentric inside the glass tube by placing some spacers in the gap between the steel rod and the inner surface of the glass tube. From one end of the tube high speed air was pumped through an air inlet. Water came to the top surface of the inner metal rod through the perforations (see Fig. 17b) and formed a thin layer on the steel rod by air shear.

Fig. 17 A schematic showing a) the experimental apparatus and b) the water inlet and perforations on the inner metal cylinder.

Water and air flow rates were controlled to form a long thin film of water that reached the discontinuity between the steel rods. The whole test section was 3.0 m long and the thickness of the thin film over the rod and near the discontinuity between the rods was measured by a Keyence laser confocal displacement meter (LCDM, model LT-9030(M). In comparison to the conventional electrical or conductivity probe, the LCDM has many inherent advantages: (1) Instantaneous changes in the film thickness can be measured by the LCDM without disturbing the film flow and with a high resolution down to 0.01µm.

A second test section was also built with a circular metal rod in a rectangular channel instead of a circular channel as shown in Fig. 18.
Fig. 18 Redesigned test section: a circular rod inside a rectangular glass channel

Research Team

Principal Investigator: M. Kawaji supervised the work on both liquid film thickness measurement and IBIF experiments.

Industry scientists and engineers: Dr. Laurence Leung of AECL, Mr. Marc Kwee of Bruce Power, and Mr. Muhammad I. Ali of Ontario Power Generation actively participated in the design of experimental facilities, discussion of the experimental results and direction of this research project.

A postdoctoral researcher (Dr. Kausik Das) designed and constructed the liquid film thickness measurement apparatus, and has been conducting the measurements.

An MASc student (Zheko Karchev) constructed the IBIF experimental apparatus, conducted the experiments and analyzed the results. He completed his M.A.Sc. degree in September, 2009, and continues to work on this project as a research assistant.

Publications


Interactions With Industrial Sponsors Or Collaboration

A series of meetings have been held with the representatives of the industry sponsors to discuss the design of the experimental facilities, experimental parameters, data interpretation and future directions.

The industrial partners provided detailed information on the CANDU fuel bundle and end shield designs for the IBIF experiments and simulation of liquid film dryout simulation. They also provided 26 endplates for fabrication of 13 simulated rod bundles which have been used in the IBIF experiments.

The industrial sponsors also suggested the direction of the project changed to focus more on the measurement of a liquid film thickness profile over a gap in the fuel rod rather than conducting numerical simulation analyses of the liquid film behaviour as proposed originally.
UNENE BI-ANNUAL REPORT 2007-2009

University of Guelph – Peter Tremaine CRD

NSERC/UNENE Collaborative Research and Development Grant on D2O Isotope Effects on Hydrolysis and Ionization Equilibria in High Temperature Water

Overview

Since its establishment with Dr. Tremaine’s appointment in 2001, the University of Guelph has sought to develop a state-of-the-art research program to develop high-precision instruments and theoretical tools for determining the thermochemical properties of aqueous systems at extremes of temperature and pressure. Areas of particular importance to the nuclear industry are (i) the development of the Generation IV Supercritical Water CANDU reactor concept and hydrogen co-generation technology; (ii) lifetime extension of the current CANDU 6 and Advanced CANDU reactors; and (iv) the need for basic research under extreme conditions.

The UNENE CRD grant to Guelph was the first funding to the center from the nuclear industry. The grant, and UNENE’s network of contacts, have proved to be a key element establishing the center. In addition to the targeted research projects funded by UNENE and other government/industry partnerships, the university has made significant progress towards its long-term goal to create a state-of-the-art research center for high-temperature water chemistry in Ontario, with quantitative measurement capabilities for dealing with reactor chemistry problems at temperatures and pressures in excess of 450 °C and 30 MPa.

Research Program/Outcomes

Current Projects:

In addition to Dr. Tremaine’s UNENE CRD grant, the nuclear-related research at Guelph is supported by four other grants.

(i) "D2O Isotope Effects on Hydrolysis and Ionization Equilibria in High-Temperature Water" NSERC/UNENE CRD Grant: (2005-2009; renewed 2009-2012) ($87 k/yr x 3).
(iii) "Aqueous Electrolytes and Non-Electrolytes Under Hydrothermal Conditions" NSERC/NRCan/AECL CRD Grant (2009-2011) ($100 k/yr x 3).
(v) "Aqueous Electrolytes and Non-Electrolytes Under Hydrothermal Conditions" NSERC Discovery Grant: (2006-2011) ($60 k/yr x 5).
Research Results

CANDU nuclear reactors are a uniquely Canadian technology in that their design is based on the use of heavy water in a closed loop to transfer heat from the reactor core to the steam generator. Optimizing primary coolant chemistry requires detailed models for the chemical behaviour of metal oxides, dissolved gases and pH-control additives at temperatures as high as 300 °C, using data determined in light water systems. The methods now used to correct these models for the differences between light-water and heavy-water systems are based entirely on room temperature studies. Tremaine’s UNENE CRD grant is for a definitive laboratory study to provide fundamental data and understanding for the difference in ionization constants between H₂O and D₂O, for simple acids and bases at the extreme temperatures and pressures encountered in nuclear reactors (250 to 300 °C and 10 MPa). The first phase developed high precision AC conductance, densimetry, and UV-visible methods to measure the deuterium isotope effect on acid-base ionization. These state-of-the-art instruments, constructed of inert materials to withstand the corrosive conditions that exist in high temperature water, allow us to measure differences in the chemical equilibrium constants in H₂O and D₂O under identical conditions, directly. The second phase will use these instruments, and a new custom-made Raman spectrometry system, to measure data for a number of model systems and to develop an improved, practical model for estimating the magnitude of D₂O isotope effects on metal hydrolysis and metal oxide solubility, under CANDU operating conditions. The project will contribute to research aimed at extending the lifetime of existing reactors by providing criteria for optimizing primary circuit pH to reduce feeder tube thinning. It will make a long term contribution to Canada’s leadership role in heavy water technology by providing a fundamental understanding of D₂O isotope effects on chemical equilibria under extreme conditions of temperature and pressure.

Tremaine’s other research uses state-of-the-art instruments to determine ionization and association constants for simple acids, bases, dissolved metals, and organic complexes under near-critical and super-critical conditions that will be encountered in the Generation IV CANDU Supercritical Water-cooled Reactor (“SCWR”). The projects include the construction of high-pressure cells and calibration of the equipment for operation in the supercritical region, measurements on several acids, bases and salts relevant to Gen IV steam generator chemistry, and the development of equations to predict the behaviour of aqueous species under these extreme conditions. The experimental equipment, models, and new research capabilities will all be directly applicable to the current CANDU reactor fleet.

Research Facilities

The current suite of high-precision instruments include several with unique capabilities. The high-temperature platinum vibrating tube densimeter, constructed in 1997, is one of fewer than six worldwide that provide the precision (1 x 10⁻⁵ g cm⁻³) needed to measure standard partial molar properties up to 350 °C. The UV-visible flow system constructed in 1999, has the stability needed for quantitative spectroscopic studies up to 275 °C, and is being upgraded for operation up to 400 °C. The AC flow conductance instrument, constructed at the University of Delaware, is one of only two such instruments in North America, with the capability to operate under supercritical conditions. These instruments all make use of inert cells fabricated from platinum,
zirconium, titanium or Hastelloy C, and high-pressure liquid chromatography pumps with precise external pressure-control and sample injection systems. Recent Canadian Fund for Innovation (CFI) and NSERC Strategic Grants, supported by AECL and UNENE, have added new 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.

Research Team

In 2006/07, the hydrothermal chemistry group consisted of four PhD students, two MSc students, one postdoctoral fellow and our Research Associate, Dr. Liliana Trevani. Postdoctoral fellow Dr. Diego Raffa (PhD Univ. Buenos Aires), PhD student Kristy Erikson (MSc Lethbridge) and summer student Sarah Moore joined the group this year, specifically to work on our UNENE D₂O project. PhD students Ephraim Bulemela and Melerin Madekufamba, will work on projects related to the supercritical water reactor. A new MSc student Vanessa Mann will work on underlying research, as will MSc student Erik Balodis and visiting PhD student Jana Ehlerova (Univ. Liberec, Czech Republic).

Publications

Published Research Papers


*Published Proceedings from Conferences and Workshops*


*Interactions With Industry*

*Committees and Boards:*

Dr. Tremaine 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.

(i) Vice-Chair, R&D Advisory Panel Atomic Energy of Canada Ltd. The Panel reports to the Board of Directors through its Science & Technology Sub-Committee.

(ii) Member, MULTEQ Database Advisory Committee, Electric Power Research Institute (EPRI).

(iii) Chair of the Canadian National Committee, International Association for the Properties of Water and Steam (IAPWS). The CANDU Owners Group and the National Research Council provide funding and liaison, the University of Guelph provides the secretariat.

(iv) Chair, (with Ian Hey, COG), IAPWS Workshop on Water and Steam Chemistry, Toronto, May 11-12, 2009.

(v) Member, Proposal Committee for a CFI Regional Platform for Sustainable H$_2$ Production (2008 -2009) (Chaired by Greg Naterer, UOIT): $19 M request, LOI approved, application unsuccessful

(vi) Member representing UNENE (J. Luxat, Chair) NCE “Nucleus” Proposal Committee, (2009); The LOI approved, application unsuccessful.
(vii) Member, Advisory Committee NSERC/AECL Chair in Radiation Chemistry held by Prof. Clara Wren, Univ. Western Ont. (2005 to present).

Project-related Interactions with Industry:

The UNENE Project Advisory Committee visited Guelph on an annual basis, in December 2006 and January 2008 and 2009. The UNENE Committee also provides technical advice for the Strategic and CRD grant funded projects. One of his students Francis Brosseau, has been awarded an NSERC AECL Industrial Postgraduate Scholarship, and spent two 10 week terms at Chalk River Labs, (June-Aug, 2008 and 2009). He will graduate in 2010.

External Employment of Students, PDFs and Research Associates

Senior research associate, Dr. Liliana Trevani, started a tenure-track faculty position as Assistant Professor at the University of Ontario Institute of Technology January, 2009. Postdoctoral Fellow Dr. Diego Raffa (2005-2007) is now employed by Quest Oil Ltd. (Calgary). Postdoctoral Fellow Dr. Ephraim Bulemela, started work as a Research Officer in the Analytical Chemistry Department at AECL (Chalk River Labs) in June 2008. MSc student Erik Balodis (2007) accepted a position as Staff Scientist, R&D Division, Bank of Canada. PhD student Jana Ehlerova (University of Liberec, Czech Republic) spent two 1 year exchange visits to Guelph (2006/07 and 2008/09), and graduated in 2009.
Auditors’ report

To the Directors of the
University Network of Excellence in Nuclear Engineering

We have audited the balance sheet of the University Network of Excellence in Nuclear Engineering as at March 31, 2008 and the statements of operations and cash flows for the year then ended. These financial statements are the responsibility of the corporation’s management. Our responsibility is to express an opinion on these financial statements based on our audit.

We conducted our audit in accordance with Canadian generally accepted auditing standards. Those standards require that we plan and perform an audit to obtain reasonable assurance whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation.

In our opinion, these financial statements present fairly, in all material respects, the financial position of the corporation as at March 31, 2008 and the results of its operations and the changes in its financial position for the year then ended in accordance with Canadian generally accepted accounting principles.

<original signed by>

Hamilton, Ontario
August 20, 2008

Grant Thornton LLP
Chartered Accountants
Licensed Public Accountants
University Network of Excellence in Nuclear Engineering

Statement of Operations

Year ended March 31

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Revenue</strong></td>
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<tr>
<td>Grants</td>
<td>$1,653,561</td>
<td>$1,396,236</td>
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<td>Education revenue</td>
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<td>$36,093</td>
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<td>Interest income</td>
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<td>$47,495</td>
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<td><strong>Total revenue</strong></td>
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<td>$1,489,764</td>
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<td><strong>Expenditures</strong></td>
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<td>Administration fees</td>
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<td>Bank charges</td>
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<td>Depreciation</td>
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<td>$3,237</td>
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<td>Insurance</td>
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<td>$4,944</td>
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<td>Office</td>
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<td>Professional fees</td>
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<td>Program preparation</td>
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<td>Research expense</td>
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<td><strong>Total expenditures</strong></td>
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<td>$1,066,565</td>
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<td>Unrealized gain on investments (Note 3)</td>
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<td>-</td>
</tr>
<tr>
<td><strong>Excess of revenue over expenditures</strong></td>
<td>$316,928</td>
<td>$401,199</td>
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Operating surplus

<table>
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<tr>
<th></th>
<th>2006</th>
<th>2007</th>
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<tbody>
<tr>
<td>Beginning of year</td>
<td>$1,200,735</td>
<td>$799,536</td>
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<td>Excess of revenue over expenditures</td>
<td>$316,928</td>
<td>$401,199</td>
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<tr>
<td><strong>End of year</strong></td>
<td>$1,517,663</td>
<td>$1,200,735</td>
</tr>
</tbody>
</table>

See accompanying notes to the financial statements.
# University Network of Excellence in Nuclear Engineering

## Balance Sheet

**March 31, 2006 and 2007**

### Assets

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cash</td>
<td>$ 180,084</td>
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<td>Temporary investments (Note 3)</td>
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<td>1,316,819</td>
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<td>Receivables</td>
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<td></td>
<td>1,795,362</td>
<td>1,990,324</td>
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<td>Trust funds</td>
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<td></td>
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<td>Cash – World Nuclear Conference (Note 5)</td>
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<tr>
<td>Property and equipment (Note 4)</td>
<td>4,705</td>
<td>6,140</td>
</tr>
<tr>
<td></td>
<td><strong>$ 2,133,796</strong></td>
<td><strong>$ 1,388,464</strong></td>
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### Liabilities

<table>
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<tr>
<th></th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accruals</td>
<td>$ 111,354</td>
<td>$ 11,453</td>
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<td>Deferred grants (Note 5)</td>
<td>171,050</td>
<td>176,276</td>
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<td></td>
<td>282,404</td>
<td>187,729</td>
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<tr>
<td>Trust funds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payables - World Nuclear Conference (Note 6)</td>
<td>333,729</td>
<td></td>
</tr>
<tr>
<td>Equity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surplus</td>
<td>1,517,663</td>
<td>1,260,726</td>
</tr>
<tr>
<td></td>
<td><strong>$ 2,133,796</strong></td>
<td><strong>$ 1,388,464</strong></td>
</tr>
</tbody>
</table>

**Commitments (Note 7)**

[Signature] [Signature]

See accompanying notes to the financial statements.
### University Network of Excellence in Nuclear Engineering

**Statement of Cash Flows**

*Year ended March 31*

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Increase (decrease) in cash and cash equivalents</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excess of revenue over expenditures                  $ 316,828</td>
<td>$ 401,199</td>
<td></td>
</tr>
<tr>
<td>Unrealized gain on investments                         (12,721)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Depreciation                                                 3,435</td>
<td>3,237</td>
<td></td>
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<tr>
<td></td>
<td>307,642</td>
<td>404,436</td>
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<td>Change in non-cash operating</td>
<td></td>
<td></td>
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<tr>
<td>Receivables                                               (23,874)</td>
<td>381</td>
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<tr>
<td>Prepaid expenses                                          -</td>
<td>749</td>
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<tr>
<td>Accruals                                                  99,901</td>
<td>(32,610)</td>
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<td></td>
<td>383,669</td>
<td>372,956</td>
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<tr>
<td>Financing activities</td>
<td></td>
<td></td>
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<tr>
<td>Decrease in deferred grants</td>
<td>(5,226)</td>
<td>(22,903)</td>
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<tr>
<td>Investing activities</td>
<td></td>
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<tr>
<td>Purchase of temporary investments                       (3,268,549)</td>
<td>(1,416,819)</td>
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<tr>
<td>Redemption of temporary investments                      3,016,820</td>
<td>100,000</td>
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<tr>
<td>Purchase of capital assets                               -</td>
<td>(2,252)</td>
<td></td>
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<tr>
<td></td>
<td>(251,728)</td>
<td>(1,319,071)</td>
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<tr>
<td><strong>Net increase in cash and cash equivalents</strong></td>
<td>126,715</td>
<td>(989,018)</td>
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<td><strong>Cash and cash equivalents</strong></td>
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<tr>
<td>Beginning of year                                        $ 53,379</td>
<td>1,092,397</td>
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<tr>
<td>End of year                                               $ 160,064</td>
<td>53,379</td>
<td></td>
</tr>
</tbody>
</table>

See accompanying notes to the financial statements.
University Network of Excellence in Nuclear Engineering
Notes to the Financial Statements
March 31, 2008

1. Nature of operations

The organization is an alliance of universities, nuclear industry corporations, research and regulatory agencies for the support and development of nuclear education, research and development capability in Canadian universities.

2. Summary of significant accounting policies

The organization follows generally accepted accounting principles accepted in Canada in preparing its financial statements. The preparation of financial statements necessarily involves the use of estimates and approximations. Should the underlying assumptions change, the actual amounts could differ from those estimates. The significant accounting policies used in the preparation of the financial statements are as follows:

Grants

Grant revenue is recognized in accordance with the periodic amounts invoiced to the grantees. Any excess funds that are received are deferred and will be recognized in accordance with the organization’s invoicing to the grantees.

Educational revenues

Educational revenues are recorded using the net method of revenue recognition.

Depreciation

Rates of depreciation applied to write-off the cost of equipment over their estimated lives on a straight line basis are as follows:

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer equipment</td>
<td>3 years</td>
</tr>
<tr>
<td>Furniture and equipment</td>
<td>5 years</td>
</tr>
<tr>
<td>Website</td>
<td>3 years</td>
</tr>
</tbody>
</table>

The depreciation is pro-rated in the year of acquisition.

Cash and cash equivalents

Cash and cash equivalents consists of balances with chartered banks and funds held by a Canadian University on behalf of the organization. Short-term investments which have a term to maturity of three months or less from the acquisition date are considered cash equivalents and are recorded at cost, which approximates market value.
University Network of Excellence in Nuclear Engineering  
Notes to the Financial Statements  
March 31, 2009

2. Summary of significant accounting policies (continued)

Temporary investments

Temporary investments consist of cashable guaranteed investment certificates with banks, and are carried at the lower of cost and market value. The weighted average interest rate of the guaranteed investment certificates is 4.32%.

Financial instruments

As of April 1, 2007, the organization adopted CICA Handbook Section 3855, Financial Instruments—Recognition and Measurement; CICA Handbook Section 3856, Hedges; and CICA Handbook Section 1530, Comprehensive Income; and the amendments to CICA Handbook Sections and Accounting Guidelines resulting from the issuance of these Sections. Under the new standards, all financial assets must be classified as held-to-maturity, loans and receivables, held-for-trading or available-for-sale and all financial liabilities must be classified as held-for-trading or other. Financial instruments classified as held-for-trading will be measured at fair value with changes in fair value recognized in the statement of operations. Financial assets classified as held-to-maturity or as loans and receivables and financial liabilities not classified as held-for-trading will be measured at amortized cost. Available-for-sale financial assets will be measured at fair value.

The organization has classified its financial instruments as follows:

<table>
<thead>
<tr>
<th>Financial Asset</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cash</td>
<td>Held-for-trading</td>
</tr>
<tr>
<td>Temporary investments</td>
<td>Held-for-trading</td>
</tr>
<tr>
<td>Receivables</td>
<td>Loans and receivables</td>
</tr>
<tr>
<td>Accruals</td>
<td>Other liabilities</td>
</tr>
</tbody>
</table>

3. Temporary investments

The investments have been classified as held-for-trading and are reported at fair value effective April 1, 2008 fiscal year in accordance with the adoption of CICA Handbook, section 3855, Financial Instruments. The new standards require prospective application. The adjustment to record investments at fair value for the current year has been recorded on the statement of operations. The 2007 comparative amounts are reported at cost plus accrued interest and no transitional adjustment was required.
University Network of Excellence in Nuclear Engineering
Notes to the Financial Statements
March 31, 2008

4. Property and equipment

<table>
<thead>
<tr>
<th></th>
<th>2008 Net</th>
<th>2007 Net</th>
<th>Accumulated</th>
<th>Book Value</th>
<th>Book Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Net</td>
<td>Net</td>
<td>Cost</td>
<td>Depreciation</td>
<td></td>
</tr>
<tr>
<td>Computer equipment</td>
<td>$ 4,932</td>
<td>$ 4,932</td>
<td>$ -</td>
<td>$ 1,593</td>
<td>$ 1,593</td>
</tr>
<tr>
<td>Furniture and equipment</td>
<td>9,359</td>
<td>4,654</td>
<td>4,705</td>
<td>6,577</td>
<td></td>
</tr>
<tr>
<td>Website</td>
<td>16,079</td>
<td>16,079</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$ 30,370</td>
<td>$ 25,665</td>
<td>$ 4,705</td>
<td>$ 8,140</td>
<td></td>
</tr>
</tbody>
</table>

5. Deferred grants

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruce Power</td>
<td>$155,550</td>
<td>$155,550</td>
</tr>
<tr>
<td>McMaster University</td>
<td>15,600</td>
<td>20,726</td>
</tr>
<tr>
<td></td>
<td>$171,150</td>
<td>$176,276</td>
</tr>
</tbody>
</table>

6. Trust funds

The organization is maintaining a bank account and paying expenses on behalf of the World Nuclear Conference. Any remaining funds at the conclusion of the conference are repayable to the World Nuclear University.
Auditors’ report

To the Directors of the
University Network of Excellence in Nuclear Engineering

We have audited the statement of financial position of the University Network of Excellence in Nuclear Engineering as at March 31, 2009 and the statements of operations and cash flows for the year then ended. These financial statements are the responsibility of the corporation’s management. Our responsibility is to express an opinion on these financial statements based on our audit.

We conducted our audit in accordance with Canadian generally accepted auditing standards. Those standards require that we plan and perform an audit to obtain reasonable assurance whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation.

In our opinion, these financial statements present fairly, in all material respects, the financial position of the corporation as at March 31, 2009 and the results of its operations and the changes in its financial position for the year then ended in accordance with Canadian generally accepted accounting principles.

<original signed by>

Hamilton, Ontario
September 8, 2009

Grant Thornton LLP
Chartered Accountants
Licensed Public Accountants
### University Network of Excellence in Nuclear Engineering

#### Statement of Operations

Year ended March 31

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Revenue</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grants</td>
<td>$1,738,320</td>
<td>$1,659,561</td>
</tr>
<tr>
<td>Education revenue</td>
<td>65,475</td>
<td>45,728</td>
</tr>
<tr>
<td>Interest income</td>
<td>55,215</td>
<td>82,552</td>
</tr>
<tr>
<td><strong>Total revenue</strong></td>
<td>1,860,010</td>
<td>1,781,841</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Expenditures</strong></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Administration fees</td>
<td>164,795</td>
<td>191,620</td>
</tr>
<tr>
<td>Bank charges</td>
<td>106</td>
<td>108</td>
</tr>
<tr>
<td>Depreciation</td>
<td>1,832</td>
<td>3,435</td>
</tr>
<tr>
<td>Donations</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Insurance</td>
<td>4,897</td>
<td>4,944</td>
</tr>
<tr>
<td>Office</td>
<td>33,051</td>
<td>27,567</td>
</tr>
<tr>
<td>Professional fees</td>
<td>11,445</td>
<td>8,272</td>
</tr>
<tr>
<td>Program preparation</td>
<td>-</td>
<td>4,898</td>
</tr>
<tr>
<td>Research expense</td>
<td>1,320,453</td>
<td>1,236,550</td>
</tr>
<tr>
<td><strong>Total expenditures</strong></td>
<td>1,557,579</td>
<td>1,477,634</td>
</tr>
</tbody>
</table>

| Unrealized gain on investments | 302,431 | 304,207 |

| **Excess of revenue over expenditures** | $312,935 | $316,928 |

<table>
<thead>
<tr>
<th><strong>Operating surplus</strong></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning of year</td>
<td>$1,517,663</td>
<td>$1,200,735</td>
</tr>
<tr>
<td>Excess of revenue over expenditures</td>
<td>$312,935</td>
<td>$316,928</td>
</tr>
<tr>
<td><strong>End of year</strong></td>
<td>$1,830,598</td>
<td>$1,517,663</td>
</tr>
</tbody>
</table>

---

See accompanying notes to the financial statements.
University Network of Excellence in Nuclear Engineering
Statement of Financial Position
March 31

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assets</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cash</td>
<td>$ 204,903</td>
<td>$ 180,094</td>
</tr>
<tr>
<td>Temporary investments</td>
<td>1,744,621</td>
<td>1,591,288</td>
</tr>
<tr>
<td>Receivables</td>
<td>73,250</td>
<td>34,000</td>
</tr>
<tr>
<td><strong>Total Assets</strong></td>
<td>$ 2,022,774</td>
<td>$ 1,758,382</td>
</tr>
<tr>
<td>Trust funds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cash – World Nuclear Conference (Note 5)</td>
<td>54,631</td>
<td>333,729</td>
</tr>
<tr>
<td>Property and equipment (Note 3)</td>
<td>3,375</td>
<td>4,705</td>
</tr>
<tr>
<td><strong>Total Liabilities</strong></td>
<td>$ 2,080,760</td>
<td>$ 2,183,796</td>
</tr>
<tr>
<td><strong>Equity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surplus</td>
<td>1,830,598</td>
<td>1,517,683</td>
</tr>
<tr>
<td><strong>Total Equity</strong></td>
<td>$ 2,080,760</td>
<td>$ 2,183,796</td>
</tr>
</tbody>
</table>

**Liabilities**
Current

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accruals</td>
<td>$ 40,156</td>
<td>$ 111,554</td>
</tr>
<tr>
<td>Deferred grants (Note 4)</td>
<td>155,985</td>
<td>171,050</td>
</tr>
<tr>
<td><strong>Total Liabilities</strong></td>
<td>$ 195,551</td>
<td>$ 282,404</td>
</tr>
</tbody>
</table>

Trust funds
Payables - World Nuclear Conference (Note 5) | 54,631 | 333,729 |

**Commitments (Note 7)**

_________________________ Director ___________________________ Director

See accompanying notes to the financial statements.
<table>
<thead>
<tr>
<th>Description</th>
<th>2009</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase (decrease) in cash and cash equivalents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excess of revenue over expenditures</td>
<td>$312,935</td>
<td>$316,928</td>
</tr>
<tr>
<td>Unrealized gain on investments</td>
<td>(10,504)</td>
<td>(12,721)</td>
</tr>
<tr>
<td>Depreciation</td>
<td>1,932</td>
<td>3,435</td>
</tr>
<tr>
<td>Change in non-cash operating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receivables</td>
<td>(39,250)</td>
<td>(23,874)</td>
</tr>
<tr>
<td>Accruals</td>
<td>(71,189)</td>
<td>58,930</td>
</tr>
<tr>
<td></td>
<td>183,915</td>
<td>363,669</td>
</tr>
<tr>
<td>Financing activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease in deferred grants</td>
<td>(15,665)</td>
<td>(5,226)</td>
</tr>
<tr>
<td>Investing activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase of temporary investments</td>
<td>(2,000,000)</td>
<td>(3,241,437)</td>
</tr>
<tr>
<td>Redemption of temporary investments</td>
<td>1,847,151</td>
<td>2,989,709</td>
</tr>
<tr>
<td>Purchase of capital assets</td>
<td>(602)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(153,451)</td>
<td>(251,728)</td>
</tr>
<tr>
<td>Net increase (decrease) in cash and cash equivalents</td>
<td>24,909</td>
<td>(126,715)</td>
</tr>
<tr>
<td>Cash and cash equivalents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beginning of year</td>
<td>180,094</td>
<td>52,979</td>
</tr>
<tr>
<td>End of year</td>
<td>$204,903</td>
<td>$180,094</td>
</tr>
</tbody>
</table>

See accompanying notes to the financial statements.
University Network of Excellence in Nuclear Engineering
Notes to the Financial Statements
March 31, 2009

1. Nature of operations

The organization is an alliance of universities, nuclear industry corporations, research and regulatory agencies for the support and development of nuclear education, research and development capability in Canadian universities.

2. Summary of significant accounting policies

The organization follows generally accepted accounting principles accepted in Canada in preparing its financial statements. The preparation of financial statements necessarily involves the use of estimates and approximations. Should the underlying assumptions change, the actual amounts could differ from those estimates. The significant accounting policies used in the preparation of the financial statements are as follows:

Grants

Grant revenue is recognized in accordance with the periodic amounts invoiced to the grantors. Any excess funds that are received are deferred and will be recognized in accordance with the organization’s invoicing to the grantors.

Educational revenues

Educational revenues are recorded using the net method of revenue recognition.

Depreciation

Rates of depreciation applied to write-off the cost of equipment over their estimated lives on a straight line basis are as follows:

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Life期 (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer equipment</td>
<td>3</td>
</tr>
<tr>
<td>Furniture and equipment</td>
<td>5</td>
</tr>
<tr>
<td>Website</td>
<td>3</td>
</tr>
</tbody>
</table>

The depreciation is calculated using the half year rule in the year of acquisition.

Cash and cash equivalents

Cash and cash equivalents consists of balances with chartered banks and funds held by a Canadian University on behalf of the organization. Short-term investments which have a term to maturity of three months or less from the acquisition date are considered cash equivalents and are recorded at cost, which approximates market value.
University Network of Excellence in Nuclear Engineering  
Notes to the Financial Statements  
March 31, 2009

2. Summary of significant accounting policies (continued)

Temporary investments

Temporary investments consist of cashable and non-cashable guaranteed investment certificates with banks, and are carried at the lower of cost and market value. The balance of the investments includes the accrued interest receivable on the investments at year end. The weighted average interest rate of the guaranteed investment certificates is 2.71%.

Financial instruments

Financial instruments classified as held-for-trading will be measured at fair value with changes in fair value recognized in net income. Financial assets classified as held-to-maturity or as loans and receivables and financial liabilities not classified as held-for-trading will be measured at amortized cost. Available-for-sale financial assets will be measured at fair value.

The organization has classified its financial instruments as follows:

<table>
<thead>
<tr>
<th>Cash</th>
<th>Held-for-trading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Temporary investments</td>
<td>Held-for-trading</td>
</tr>
<tr>
<td>Receivables</td>
<td>Loans and receivables</td>
</tr>
<tr>
<td>Accruals</td>
<td>Other liabilities</td>
</tr>
</tbody>
</table>

New accounting standards

Effective April 1, 2008, the organization adopted the accounting and disclosure requirements of the CICA’s two new accounting standards, Section 3662, Financial Instruments – Disclosures, and Section 3663, Financial Instruments – Presentation. The new standards did not have a material effect on the financial position of the organization.

Effective April 1, 2008, the organization also adopted the CICA’s new accounting standard, Section 1535, Capital Disclosures, which requires the disclosure of both quantitative and qualitative information that enables users of financial statements to evaluate the entity’s objectives, policies and processes for managing capital. The new standard did not have an effect on the financial position of the organization.

3. Property and equipment

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost</td>
<td>Accumulated Depreciation</td>
</tr>
<tr>
<td>Computer equipment</td>
<td>$4,932</td>
<td>$4,932</td>
</tr>
<tr>
<td>Furniture and equipment</td>
<td>$9,981</td>
<td>$8,586</td>
</tr>
<tr>
<td>Website</td>
<td>$18,072</td>
<td>$18,072</td>
</tr>
</tbody>
</table>

$30,972  $27,597  $3,375  $4,708
University Network of Excellence in Nuclear Engineering
Notes to the Financial Statements
March 31, 2009

4. Deferred grants

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruce Power</td>
<td>$142,215</td>
<td>$155,500</td>
</tr>
<tr>
<td>McMaster University</td>
<td>13,180</td>
<td>15,500</td>
</tr>
<tr>
<td></td>
<td>$155,395</td>
<td>$171,000</td>
</tr>
</tbody>
</table>

5. Trust funds

The organization is maintaining a bank account and paying expenses on behalf of the Local Committee for the World Nuclear University Summer Institute 2008. Any remaining funds at the conclusion of the Summer Institute 2008 are repayable to the Local Committee for the World Nuclear University Summer Institute 2008.

6. Financial instruments

Fair value of financial instruments

The carrying value of cash and cash equivalents, contributions receivable, investments and payables and accruals reflected in the balance sheet approximate their respective fair value due to the relatively short term maturities of these instruments, investments consist of guaranteed investment certificates.

Interest rate risk

The interest rate risk is the risk that arises from fluctuations in interest rates and the degree of volatility of these rates. The organization does not use derivative instruments to reduce its exposure to interest rate risk.

Liquidity risk

Liquidity risk is the risk that the organization cannot meet its demand for cash of fund obligations as they come due. Liquidity risk also includes the risk of not being able to liquidate assets in a timely manner at a reasonable price. Management manages liquidity risk and monitors the cash and funding needed on a regular basis.
BOARD OF DIRECTORS AND OFFICERS .................................

Voting Members and Directors

Peter Mascher, Chair, McMaster U
Dwight Willett, Vice Chair, Bruce Power
Paul Spekkens, OPG
Beth Medhurst, AECL
Elgin Ozberk, Cameco
Tom Harris, Queen’s U

Christina Amon, U of Toronto
Michael Worswick, U of Waterloo
Brent Lewis, RMC
George Bereznaï, UOIT
Tarlochan Sidhu, U of Western Ontario

Non-Voting Members

Jean Koclas, École Polytechnique
John Froats, COG
Peter Gilmour, CNSC
Derek Lister, UNB
John McKinnon, NSS
Peter Tremaine, U of Guelph
Committee Chairs and Vice-Chairs

Roger Newman
Chair, EAC
U of Toronto

Katherine McCulloch
Vice Chair, EAC
OGP
2007-2009

David Connal
Vice Chair, EAC
AECL
2009 -

John Luxat
Chair, RAC
McMaster U
2006-2009

Bob Speranzini
Chair, RAC
AECL
2009 -

Charles Kittmer
Vice Chair, RAC
AECL

Officers and Staff

Bill Garland
Executive Director.
2006-2008,
President 2008-
McMaster U

Basma Shalaby
President
2010 -

Ben Rouben
Secretary / Treasurer
2008-

Victor Snell
Program Director
2008-

Jim Findlater
Accountant