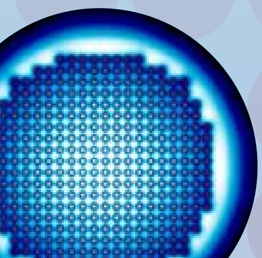
UNENE

UNIVERSITY NETWORK OF EXCELLENCE IN NUCLEAR ENGINEERING

ANNUAL REPORT 2015-2016








Acknowledgement

On behalf of the Members and Directors of UNENE, I express our appreciation to the UNENE Officers, Committee Chairs and 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. Andrew Hrymak
Chair
Board of Directors
University Network of Excellence in Nuclear Engineering (UNENE)

University Network of Excellence in Nuclear Engineering
Réseau D'Excellence Universitaire en Génie Nucléaire
Department of Engineering Physics
McMaster University
1280 Main Street West
Hamilton, ON, L8S 4L7
Canada

www.unene.ca

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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:

Bruce Power (BP)
Ontario Power Generation (OPG)
Canadian Nuclear Laboratories (CNL)
CANDU Owners Group (COG)
Canadian Nuclear Safety Commission (CNSC)
SNC-Lavalin
AMEC Foster Wheeler
Nuclear Waste Management Organization (NWMO)

McMaster University
Queen's University
University of Toronto
University of Ontario Institute of Technology (UOIT)
University of Waterloo
Western University
École Polytechnique Montreal (EPM)
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

Andrew Hrymak

It has been a productive year for the UNENE Board, which met regularly attending to business and program related matters. Growth continued in the research portfolio with two additional NSERC Industrial Research Chairs (IRC) to the current complement of six (6), increasing the number to eight (8) IRCs. This increased research capacity came with zero increase in current industry funding to UNENE through new funding partners for the additional IRCs. New industry funding from NWMO and COG made such composite funding possible with a cohesive and well aligned research program with that of industry.

Two key research facilities have been inaugurated in 2015; the Reactor Materials Testing Laboratory (RMTL) at Queen's University and the Centre for Advanced Nuclear Systems (CANS) at McMaster University.

Attention continued on succession planning for all aspects of UNENE; IRCs, NSERC Collaborative Research and Development (CRD) grants, Principal Investigators of research projects, and UNENE management.

A Search subcommittee was formed in mid-2016 to undertake the search for a new President amid Dr. B. Shalaby's intention to step down as President. This was coupled with similar plans from Dr. V. Snell, Program Director for Education. In October 2016, UNENE welcomed Mr. Jerry Hopwood as President and Dr. Nik Popov Program Director for Education. Mr. Gary Newman, VP Engineering Bruce Power, has been elected Vice-Chair of the Board.

Overall it has been a productive year for the Board, its subcommittees, the Research Advisory Committee (RAC) and the Education Advisory Committee (EAC).

The Board wishes to sincerely thank Dr. Paul Spekkens of OPG for serving as the Vice Chair of the Board, and his continual dedication and leadership in guiding the Board of Directors towards an industry focused program. Sincere thanks to Dr. Basma Shalaby for her contributions, dedication, and outstanding leadership over the last 7 years of her presidency to UNENE. The Board thanks Dr. Victor Snell for his thoughtful and strong leadership of the M.Eng program since 2009. Dr. Robert Speranzini (of CNL) provided many years of leadership and guidance as the Chair of the RAC, especially the very successful Annual Research Workshop. The Board thanks our colleagues for their contributions to UNENE and wish all a happy and healthy retirement.

Andrew Hrymak
Dean, Western Engineering
Western University
London, ON

REPORT OF THE VICE CHAIR ....

Paul Spekkens

This report marks the end of 14 years of my involvement in UNENE that started with its establishment in 2002. Looking back at those years, one can clearly see the industry's vision and leadership in embarking on a joint partnership with Canadian universities. The UNENE framework continues to prove its effectiveness in leveraging university knowledge vested in its academics and its research facilities. Today, industry invests just over $1.3M a year in Canadian universities. These funds are matched by NSERC, creating a strong research team of Industrial Research Chairs (IRCs) with programs that are aligned with mid- to-long term industry needs.

In 2015, the Board of Directors in conjunction with NSERC confirmed two additional IRCs, Clara Wren at the University of Western Ontario and Peter Tremaine at the University of Guelph. Both are closely aligned with industry requirements in the areas of High Temperature Heavy Water solutions and Radiation Induced Corrosion. Industry funding for these IRCs consists of collaboration between various industry stakeholders (NWMO, UNENE, EPRI and COG) in which all stakeholders objectives are addressed in two comprehensive University programs.

Three of the Board meetings were held at universities this year and included tours of the new Reactor Material Test Lab (RMTL) at Queen's and the Centre of Advanced Nuclear Systems (CANS) at McMaster University. These represent state-of-the art research facilities equipped to support life cycle research on CANDU plant components, along with increased knowledge of the microstructure behaviour of nuclear materials subjected to radiation and other reactor environments.

The Board also instituted a subcommittee to review UNENE's educational programs, the M.Eng and the Diploma in Nuclear Engineering. The intent of the subcommittee was to seek input from all industry members on the programs and on industry's long term needs for them. Outcomes included a confirmation to continuing the M.Eng & Diploma programs as a source of advanced graduate level courses for young industry professionals. They are valued as effective means of enhancing their knowledge in the design, engineering, physics and chemistry, and licensing of heavy water cooled reactor technology. Distance-learning tools and delivery on alternate weekends have been attractive features for young professionals who are already employed by industry. To date, over 120 industry staff have graduated with M. Eng. degrees.

In closing, I would like to thank all board members for their dedication and skill in making UNENE what it is today. I wish them continued success in the future.

Paul Spekkens
Vice President, Science and Technology Development
Ontario Power Generation

CORPORATE GOVERNANCE ....

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 representatives in the various 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 Canadian Nuclear Laboratories (CNL) (formerly AECL-CRL), Bruce Power, Ontario Power Generation, McMaster University, Queen's University, University of Toronto, University of Ontario Institute of Technology, Royal Military College, University of Waterloo and Western University.

Other industrial 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, SNC-Lavalin (formerly CANDU Energy Inc.), AMEC Foster Wheeler, École Polytechnique, University of New Brunswick, 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 renewable for additional terms. As of September 2014, Dr. Andrew Hrymak assumed the position of Chair and Dr. Paul Spekkens continued as Vice Chair through this reporting period (until his retirement in September 2016, succeeded by Gary Newman)
.

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 member organizations 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 renewable for additional terms. Current officers of UNENE for this reporting period of April 2015 to March 2016 are:

- Dr. Basma Shalaby, President and CEO, from September 2009
- Dr. Ben Rouben, Secretary / Treasurer, from July 1, 2008
- Dr. Victor Snell, Program Director, from June 23, 2008
- o Dr. Bill Garland (Ex. UNENE Executive Director) is currently working with COG as the Technical Director for the development of the Candu Textbook in collaboration with UNENE.

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

THE UNENE NETWORK

ONTARIO POWER GENERATION

Royal Military College

McMaster University

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Bruce Power

University of Toronto

University of Windsor thinking forward

Queen's University

University of New Brunswick UNB

UNENE University Network of Excellence in Nuclear Engineering

CANDU Owners Group Inc. COG "Strength Through Co-operation"

UOIT CHALLENGE INNOVATE CONNECT

University of Saskatchewan

Polytechnique Montréal Le génie en première classe

University of Waterloo

amec foster wheeler

CNSC CCSN

nwmo Nuclear Waste Management Organization Société de gestion des déchets nucléaires

Western Engineering

SNC·LAVALIN

Candu® An SNC-Lavalin Technology

University of Guelph

VISION AND STRATEGIC OBJECTIVES ....

"Vision and effective university-industry-government partnership promoting university-based education and research in nuclear science and 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.

General 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 industry.

Specific Objectives:

1. Enhance the supply of highly qualified graduates in nuclear science and technology
2. Sustain university-based research and development in nuclear science 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

Basma Shalaby

This year 2015/2016 was marked by many activities and achievements spanning over many facets of UNENE's operation. One notable achievement is the UNENE/NSERC endowment of two new IRCs, well recognized researchers with prior experience in industry. These scientists are in the field of High temperature chemistry and radiation induced corrosion respectively; Dr. Peter Tremaine (U of Guelph) and Dr. Clara Wren (Western University).

This year also marked the official inauguration of two new research facilities; at both McMaster and Queen's; the CANS at McMaster University and the RMTL at Queen's University. These will significantly enhance the capabilities of research in Canada in support of the nuclear industry at large.

Technology transfer between industry and research has also been given a boost through some funding from the OCE (Ontario Centre of Excellence) through its Talent Edge Program. This additional funding ($20K) was leverage to industry funding for an RMC researcher to intern at CNL for technology and knowledge transfer between both RMC and CNL on a UNENE funded program.

An update on UNENE Research and Education Programs was communicated to the Industry at large through a published paper and a presentation to the annual Canadian Nuclear Society (CNS) in June 2015. Many other presentations and outreach activities continued throughout the year; some invited and others on an opportunity basis, to various industry fora.

Two key CANDU related textbooks were published in the last 12 months; one documenting the scientific basis of the CANDU technology titled "The Essential CANDU" funded under a joint Project (COG/UNENE) and the Steam Generator Textbook (under COG).

Throughout the year many subcommittees were formed under the auspices of the Board of Directors. One of them was a due diligence review of the UNENE annual Budget, another on the M.Eng. program and the third was on "Structure and Governance".

Training modules were also delivered upon request to some industry members. The training was based on UNENE courses modified for in house training of industry employees.

In closing, since this is my last message as President, I would like to express my sincere appreciation for the support of UNENE Board of Directors, its subcommittees (RAC and EAC), the IRCs their teams and UNENE Administration during my tenure with UNENE.

Sincere wishes for a healthy and happy retirement to Dr. Paul Spekkens (BoD Vice Chair), Dr. Victor Snell (Program Director-Education) and Dr. Robert Speranzini (RAC Chair), and for their outstanding contribution and leadership in making UNENE what it is today

I wish Mr. Jerry Hopwood and Dr. Nik Popov every success in the future.

INCOMING PRESIDENT'S MESSAGE ....

Jerry Hopwood

It is a pleasure to have joined UNENE as the incoming President, and as I have read this Annual Report, I am highly impressed by the activities and achievements of UNENE. I have been a part of the Canadian nuclear industry for many decades; and much of that time has included research and development and training activities with UNENE members. I look forward with great enthusiasm to the work of the organization as it develops to meet the future. It is notable that, as Basma Shalaby and Paul Spekkens move on, they have been instrumental in leaving a thriving, vibrant organization. So, many thanks to Basma and Paul. Our nuclear industry is poised to play a crucial role in Canada's energy future. And UNENE is ready to continue playing a strong part.

EDUCATIONAL ACTIVITIES ....

Master's of Nuclear Engineering (M.Eng.) Degree Program Report from Education Advisory Committee and Program Director

Mahesh Pandey (Chair, EAC)
Emily Corcoran (Vice-Chair, EAC)
Victor Snell (UNENE Program Director)

Program Structure

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:
traditional research-oriented graduate degrees, or research assistantships, in nuclear-related disciplines; and the Master's of Engineering (M. Eng.) Degree program in Nuclear Engineering, jointly offered by member universities, with strong UNENE support and overall coordination. The M.Eng. program is accredited by the Ontario Universities Council on Quality Assurance and is aimed largely at people already working within the industry who wish to upgrade their education within the discipline of an academic environment. An approved UNENE Graduate Diploma program now offers a more focused option to students who want to specialize in certain areas, and/or do not want to commit to a full M.Eng.

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

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

Program Management

The education side of UNENE is managed as follows: The Education Advisory Committee (EAC) of UNENE advises the UNENE Board of Directors on education-related issues, including (for the M.Eng. Degree in Nuclear Engineering and the Graduate Diploma) the curriculum, admission standards, accreditation, course selection and delivery effectiveness, and soliciting students for the programs. The EAC also reviews and dispositions proposals from the Program Director on courses and course delivery. The Program Director, appointed by UNENE, is responsible for enrolment, logistics, educational quality and effectiveness, instructor selection, course delivery, and liaison work with universities. The UNENE Administrator executes the UNENE- and university-administrative aspects of the program.

Diploma

The Graduate Diploma Program was approved by the Ontario Universities Council on Quality Assurance on March 11 2015. It is a four-course alternative for working students who may not have the time nor the resources to pursue the M.Eng. but who nevertheless desire to broaden their skills and knowledge in the context of a rigorous academic program. Since approval, there has been a small but growing enrolment in the diploma. Since the list of courses offered by the two graduate programs is identical, it is possible in principle to transfer credits from one program to the other, provided a degree or diploma has not been formally awarded.

Enrolment

The past academic year saw a decrease in net enrolment in the UNENE M.Eng. As of the end of calendar 2015, there was an “active” enrolment (existing + accepted – inactive – graduated) of 17, with the determining factor being employer funding. The UNENE Board has set up a subcommittee to look at more effective ways by which UNENE can deliver nuclear graduate education to industry employees.

Figure 1 shows three of the students who graduated in 2015/16

Figure 1 – Some UNENE M.Eng. Graduates

Figure 2 summarizes the *cumulative* throughput of students as of end calendar 2015, for the life of the UNENE M.Eng.

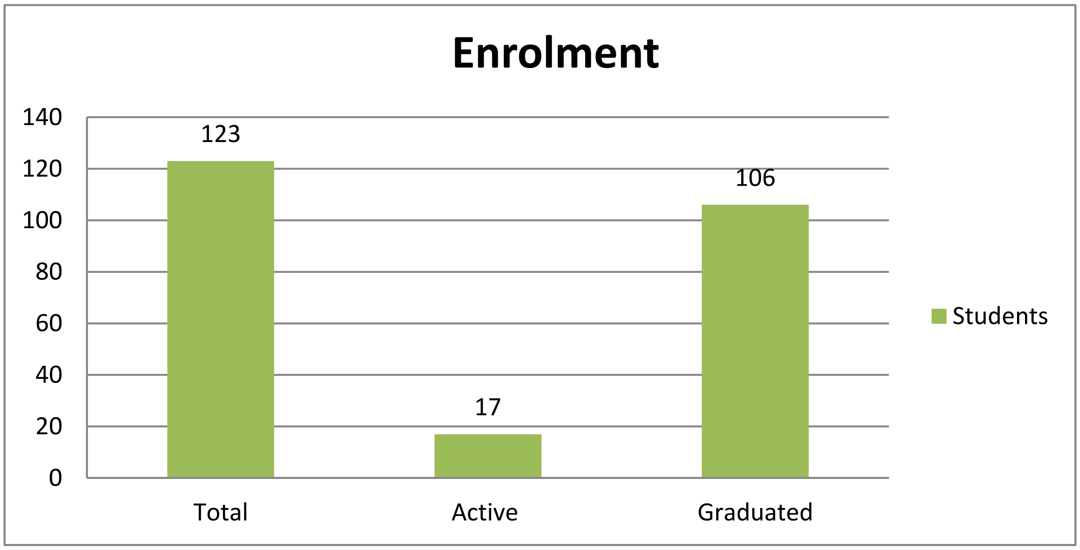


Figure 2 - Cumulative Lifetime UNENE Enrolment

Course Offerings

Course offerings remained unchanged from 2014 as they span the essential technical aspects of nuclear power. A new course entitled "Nuclear Energy in Society: Regulation and our Energy Future" has been approved but not implemented due to the drop in program enrolment. For the same reason the number of courses offered per year has been reduced – for the coming academic year, three courses are offered.

EAC Membership

The Committee met approximately quarterly throughout the calendar year. The EAC consists of one representative from each UNENE member. Mahesh Pandey was the Chairman, and Emily Corcoran was the Vice-Chairwoman, for the reporting period. EAC meetings are generally combined with RAC meetings. At the end of the reporting period, the EAC Committee Membership was as follows:

CNL	Bob Speranzini (RAC Chair) / Ramesh Sadhankar
Bruce Power	Peter Purdy
Guelph	Peter Tremaine
McMaster	John Luxat / Dave Novog
NWMO	Paul Gierszewski
OPG	Saad Dahdouh / Robert Veldhuis
Queen's	Mark Daymond
RMC	Emily Corcoran (EAC Vice-Chair)
Saskatchewan	Chary Rangacharyulu
Toronto	Roger Newman
UOIT	George Bereznai / Tony Waker

Waterloo	Mahesh Pandey (EAC Chair)
Western	Jin Jiang
Windsor	Ram Balachandar
CNSC	Dan Tello / David Newland
COG	Frank Doyle
AMEC Foster Wheeler	John MacKinnon
École Polytechnique	Jean Koclas
UNB	Derek Lister
NRCan	Dan Brady
Candu Energy	Sermet Kuran
COG	Frank Doyle / Gabe Balog

Ex-officio UNENE Officers:

President	Basma Shalaby
Program Director	Victor Snell
Secretary/Treasurer	Ben Rouben

RESEARCH ACTIVITIES

Report of the Research Advisory Committee (RAC)

Robert Speranzini, 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. Seven IRCs (including 1 new IRC approved this year), some with associate IRCs, are currently in place, with an eighth IRC now set up at the University of Guelph. 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 significant industry issues, resulting in researchers being trained in specialized fields of CANDU technology to help replenish expertise in the Canadian nuclear industry.

The Research Advisory Committee of UNENE meets two times a year. Robert Speranzini chaired the committee in this reporting period. The Committee membership for this reporting period comprised:

CNL	(Chair)	Robert Speranzini
Bruce Power		Peter Purdy
OPG		Saad Dahdouh
COG		Gabe Balog / Frank Doyle (replaced by Michael Brett in 2016 May)
CNSC		Daniel Tello / Keith Dewar
AMEC Foster Wheeler		John Mackinnon
McMaster University	(Past-Chair)	John Luxat / David Novog
Queen's University		Mark Daymond
Toronto		Roger Newman
UOIT		Anthony Waker / Ed Waller
University of Waterloo		Mahesh Pandey
Western Ontario	(Vice-Chair)	Jin Jiang
Ecolé Polytechnique		Jean Koclas
Royal Military College		Emily Corcoran
Guelph University		Peter Tremaine
UNENE		Ben Rouben

The main work of the committee has been:

1. Reviewing the progress of IRC research programs
2. Supporting grant applications for research funding that provide effective leveraging of UNENE funding.
3. Sponsoring an R&D Workshop and Student Presentations and Poster Session
4. Implementing new Collaborative Research and Development (CRD) projects
5. Monitoring progress of existing CRD research proposals
6. Supporting the establishment and renewal of IRCs and succession planning for IRCs

7. Improved progress reporting to better communicate the benefits of UNENE R&D
8. Improved understanding of university capabilities by facilitating industry member tours of university facilities
9. Strengthening interactions with and visibility of students (e.g. through student poster and student presentation sessions).

CHAIR PROGRAMS: The currently established UNENE/NSERC IRCs cover seven critical areas of CANDU technology as described below. During the period, existing chairs were renewed, as described below.

1) **Nuclear Materials** - Mark Daymond (Senior 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 was successfully renewed in 2012 (to 2017). Attention was paid to commissioning and operation of the Reactor Materials Testing Laboratory including the proton/He accelerator.

2) **Nuclear Safety** - John Luxat (Senior Chair)/ David Novog (Senior 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 modelling severe accident phenomena. The other focus of the program is theoretical modelling and experimental studies in Thermalhydraulics. The objective in this area is to improve understanding of heat transfer behaviour that influences both operational safety margins and the integrity of components during accidents. The IRC was successfully renewed in 2015 December (to 2020) with this second renewal including the Associate Chair being converted to a Senior Chair.

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 2014 (to 2019).

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 2014 (to 2019).

5) **Risk-Based Life Cycle Management** - Mahesh Pandey (Senior Chair), University of Waterloo. The primary objective of this chair is to advance the risk assessment and life-cycle management of critical components of CANDU reactors, namely, FCs, SGs and feeders. In the FC area, the program will develop methods for risk informed methods inspection optimization, and probabilistic modeling of spacer degradation. In the area of SGs, the program is developing a probabilistic model of SCC for predicting the life expectancy of steam generators. In the area of feeders, software to visualize the feeder wall thickness scan data is under development. In addition, models for predicting corrosion rate in buried piping, common cause failures in safety systems and life expectancy of dissimilar welds are in progress. To help nuclear industry demonstrate the compliance with environmental standards, the program is also developing statistical sampling plans and prediction methods. The Chair was successfully renewed in 2015 (to 2020).

6) **Health Physics and Environmental Safety** - Tony Waker (Senior Chair)/ Ed Waller (Associate 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; gas electron multipliers (GEMs) for tritium in air monitoring; microdosimetry and radiation quality of low energy photons and beta rays; radiation effects on non-human biota; and, simulation of CANDU radiation fields, robotic radiation mapping and dose visualization. This Chair was successfully renewed in 2014 (to 2019).

7) **Radiolysis Assisted Corrosion** - Clara Wren (Senior Chair), University of Western Ontario - UWO. This Chair was successfully renewed in 2015 April (for the third term) in collaboration with new industrial partners, the Nuclear Waste Management Organization (NWMO), and now including UNENE. The overall objective of the proposed IRC research program is to develop fundamental chemical knowledge while addressing corrosion research needs for two sectors of the nuclear industry. The first is the corrosion of metal containers that are designed to hold used nuclear fuel and the second is the corrosion of dissimilar metal weld regions of power reactor structural materials in the presence of ionizing radiation. The effects of liquid water and humid air radiolysis on localized corrosion in confined volumes, such as those encountered in weld cracks or

crevices, or in water droplets, will be investigated. The aim of the research in the current term is to provide the experimental data necessary to (1) assess the long-term integrity of the proposed NWMO waste container weld design and to determine whether any measures are required to meet design targets for container longevity and integrity, and (2) assess the integrity and longevity of the OPG reactor shield tank assembly, in particular, the potential for accelerated (galvanic) corrosion attack on carbon steel adjacent to the dissimilar metal weld at the periphery of the annular gap.

NON-CHAIR RESEARCH PROJECTS: A number of CRD projects (3 year term) have been awarded to university researchers in previous years with new rounds of CRD's initiated on an annual basis given the strong support for the program from the UNENE funding partners. During this period the following CRDs were approved by UNENE and applications have been submitted for NSERC matching funding.

- Clara Wren, Western, Radiolysis-Induced Corrosion of Dissimilar Metal Welds (supports Western IRC)
- Atef Mohany, UOIT, Modeling of Dynamic Response of CANDU fuel Bundle Due to Acoustic Pressure Pulsations in HTS Piping System

UNENE R&D WORKSHOP: A workshop was held in December as part of the UNENE R&D review and planning and in concert with a call for new Collaborative R&D (CRD) proposals. A student poster session was coordinated with the workshop and included prizes for the top 3 posters, kindly sponsored by the CNSC. A session for student presentations was also held following last year's successful session. About 95 attended the workshop (compared with 110 in 2014, 95 in 2013, 105 in 2012, and 85 in 2011) from industry (OPG, BP, COG, Candu Energy), member universities and other universities, and other stakeholders (NRCan, CNSC, CNL, NWMO, Fedoruk Centre) with a full agenda for the day:

- industry representatives and stakeholders articulated needs and R&D requirements;
- existing Industrial Research Chair (IRC) holders gave updates on progress and expected benefits of their work; and,
- a new session with a focus on new priorities, capabilities and facilities (Strathclyde University, Glasgow; nuclear security, UOIT; CANS, McMaster).

Examples of priorities and/or R&D needs presented includes:

- Decommissioning and waste management (OPG focus on Pickering site)
- Support for existing CANDU's
    1. safety and licensing; e.g. operational support, severe accident management
    2. material degradation assessment and mitigation strategies;
    3. components (fuel channels, feeders, SGs, fuel); probabilistic assessment of failures
    4. aging and life extension including margin/power recovery
- Next generation CANDU and SMRs (Community Energy Units)
- Security and safeguards

It was clear from university presentations that building of HQP and facilities is ongoing and has reached a sustainable and functional level. Programs focus on key R&D areas of interest to industry and stakeholders.

The call for new CRD proposals was issued based on priorities presented at the workshop.

UNENE STUDENT POSTER SESSION: A very successful student poster session was coordinated with the workshop. The poster session included 48 posters with about 85 participants (compared with 40 to 55 posters and 85-95 participants in previous years). Prizes were awarded for the top 3 posters as assessed by a team of industry and university representatives according to:

- Relevance to a current or emerging nuclear industry R&D issue (40%);
- Quality and originality of the work (30%); and,
- Effectiveness - poster appearance, and presentation & level of student interaction (30%).

Prizes were awarded to:

- First prize: Shannon Hill, Western, "The Corrosion Evolution on Carbon Steel under Deep Geological Disposal Conditions for Spent Nuclear Fuel Waste – A 12-Month Surface Analysis Study"
- Second prize: Thalia Standish, Western, "Galvanic Corrosion of Copper-Coated Carbon Steel for Used Nuclear Fuel Containers"
- Third prize: Moji Momeni, Western, ""Effects of pH and Radiation on Galvanic Corrosion of Stainless-Steel-Carbon Steel Welds"

In addition, an opportunity was given to industry and stakeholders to communicate career opportunities for students.

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 benefited from this network of expertise through numerous advisory and consultative exchanges. Examples of these consultations are presented in the reports of the IRCs.

Industrial Research Chairs (IRC)

Queen's University – Mark Daymond IRC

UNENE/NSERC IRC Program: Nuclear Materials

Overview

The IRC was renewed in April 2012 so is progressing through its present 5 year term, with a renewal application expected towards the end of 2016.

The specific goals of the program are to understand the materials of the fuel channel, and in particular impacts of processing choices and their aging mechanisms. The fuel channel includes the pressure tube, the calandria tube and the spacers which keep them separate over the lifetime of the channel. For example, one effort has been into understanding 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; work on Excel is funded from outside the IRC), 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. Work on spacers in 2015 was primarily funded by Prof Yao's CRD (see elsewhere in this report), with support from the IRC program. During the reporting period, the focus on irradiation damage and its effects of properties of Zr alloys has continued. This latter area will be a significant part of the Chair program in the future.

Program Highlights & Advances in Knowledge

One of the key events of 2015 was the completion of commissioning of the new TEM, SEM and most significantly the accelerator at the new CFI funded Reactor Materials Testing Laboratory (RMTL). We are moving on to radiological commissioning in 2016, as well as testing of the sample stations that will allow us to control temperature, stress etc. during irradiation.

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

Detailed research highlight

Effect of hydrides on irradiation of pressure tube material.
The pressure tube is the primary pressure boundary for coolant in the CANDU design and is susceptible to delayed hydride cracking, reduction in fracture toughness upon hydride precipitation and potentially hydride blister formation. The morphology and nature of hydrides in Zr-2.5%Nb with 100 wppm hydrogen was investigated using transmission electron microscopy;

due to the high quality images available in modern TEMs this has given greater understanding than was available using older tools. It was also found that the presence of hydrides changed the irradiation induced decomposition of the β phase; this is the first time that this has been observed, and is believed to be due to the interaction between H and vacancies. A particularly interesting effect is that of hydrogen on the irradiation induced redistribution of Fe; Fe is widely redistributed from the β phase into the α phase in the un-hydrided material, however, the loss of Fe from the β phase and subsequent precipitation is retarded in the hydrided material. These effects appear to be due to the interaction between alloying elements and vacancies produced during irradiation. This work will suggests that there are differences in the irradiation induced microstructural evolution of Zr based alloys when hydrogen is present.

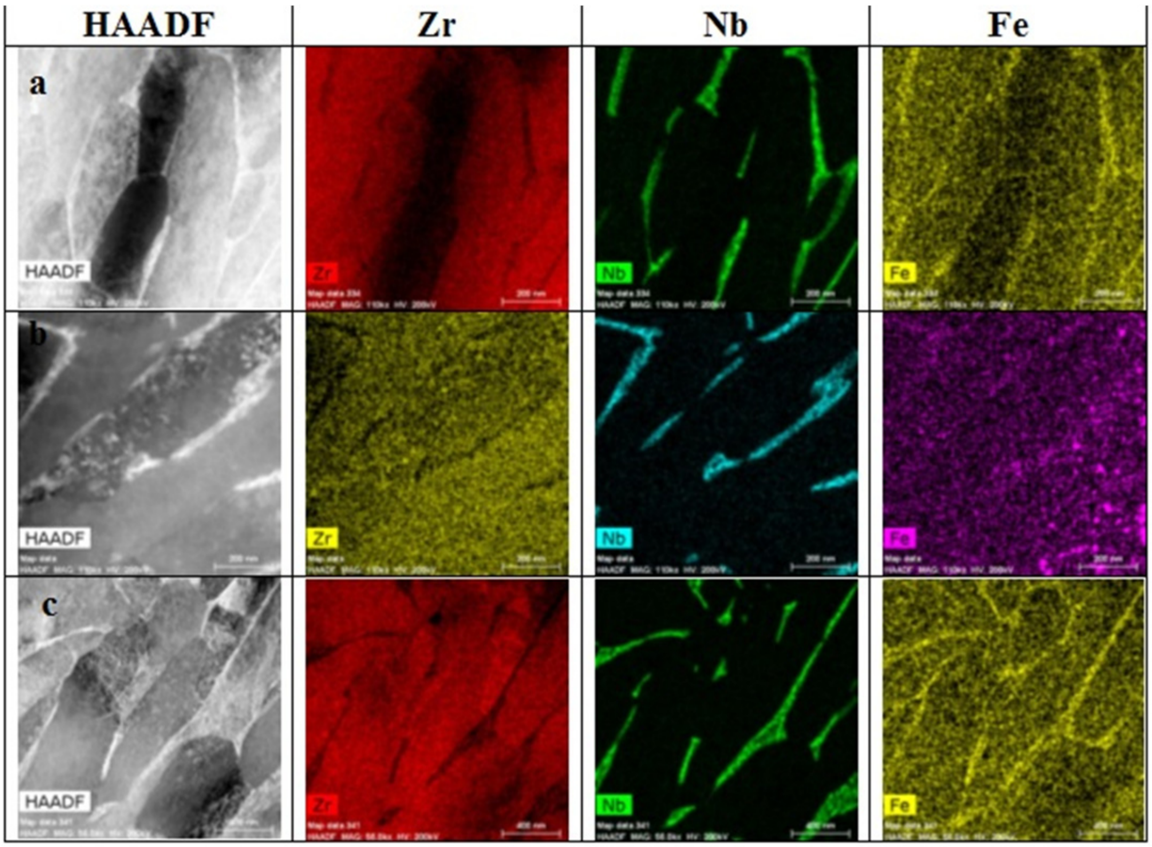


Figure. Grain boundary structure and chemistry of (a) unhydrided unirradiated Zr-2.5Nb, (b) unhydrided Zr-2.5%Nb irradiated to 10 dpa (by heavy ion irradiation), (c) Zr-2.5%Nb-100ppmH irradiated to 10 dpa. Of particular note, the Fe in b) is redistributed by the irradiation, while it remains in the beta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

More details of this work are described in Y. Idrees, Z. Yao, J. Cui, G.K. Shek, M.R. Daymond, "Zirconium Hydrides and Fe redistribution in Zr-2.5%Nb alloy under ion irradiation", in press J. Nucl. Mater., doi: 10.1016/j.jnucmat.2016.08.031.

Realized Outcomes to Industry

Queen's is working with Kinectrics on studying DHC in high (>100wppm) hydrogen content pressure tube material, as well as alternative approaches to hydrogen solubility measurement.

This has impact on end-of-life pressure tube conditions, and in our ability to predict how long the pressure tubes can continue to operate. In addition, we are working with Kinectrics to provide mechanical test data on proton irradiated Ni X750 spacer material. This has significant impact in understanding potential for spacer embrittlement, and hence in predicting maximum life for fuel channels.

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

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

Research Facilities and Equipment

The RMTL accelerator project funded by CFI/MEDT continues, with equipment purchase, installation and commissioning competed. A full suite is now operational and dedicated to nuclear materials testing, including:

- Accelerator (8MeV protons, 12 MeV alpha particles) for irradiation at a range of conditions;
- FEG TEM (with full suite of holders including tomography, heating, straining, EDX mapping)
- FEG SEM (with EBSD, EDX);
- Micromaterials Nanotester, capable of micro and nano testing up to 700degC.
- Sample preparation suite
- Nested Neutron Spectrometer for energy specific neutron detection (with Tony Waker, UOIT).

An NSERC proposal led by Prof Yao with Prof Daymond as co-investigator was successful in obtaining an upgrade for the TEM, significantly improving the accuracy of local strain measurements. This will be used for study of local strain fields in spacers, and around hydrides.

HQP Enrolled in the Program During 2015

The group is led by Prof. Mark Daymond with support from Assoc. Prof. Zhongwen Yao. Prof Yao leads the work on TEM characterisation, and many students / postdocs are co-supervised.

Postdoctoral fellows (5): Fei Long, Levente Balogh, David Kerr, He (Ken) Zhang, Yasir Idrees (supported by Kinectrics/Mitacs)

PhD students (10): Kazi Ahmmed, Qiang Fang, Hongbing Yu (also supported by NRCan), Qingshan Dong (also supported by Yao CRD), Travis Skippon, Chris Cochrane, Qiang Wang, Zhouyao Wang, Cong Dai, Oksana Simane.
New PhD students in 2015 (2): Alice Mao, Nima Nikpoor.
MSc students (2): Mitch Mattucci (joined 2015), Megan Swain (part time)

HQP that Graduated in 2015; number, type

- He (Ken) Zhang, PDF, went on to Stress Engineering Services Canada
- Yasir Idrees, PDF, went on to Cameco
- Qiang Fang, PhD, returned to China (his PhD was funded via a CSC Scholarship)
- Kazi Ahmmed, PhD, stayed at Queen's as PDF
- Fei Long, PhD, stayed at Queen's as PDF

Publications

Journal papers:

1. S. Di, Z. Yao, M.R. Daymond, X. Zu, S. Peng, F. Gao, "Dislocation accelerated void formation under irradiation in zirconium", v82(1), p94-99, Acta Mater. (2015).
2. C. Cochrane, M.R. Daymond, "Effect of interstitial O and Fe on the deformation of Zr2.5Nb studied by in situ neutron diffraction", Mat. Sci. Eng. A, v636, p10-23, (2015)
3. F. Long, Z. Yao, M.R. Daymond, "Deformation mechanism study of a hot rolled Zr-2.5Nb alloy by Transmission Electron Microscopy, part I: dislocation microstructures in as-received state and at different plastic strains", J. App. Physics, v117, 094307 (2015)
4. F. Long, M.R. Daymond, Z. Yao, M.A. Kirk, "Deformation mechanism study of a hot rolled Zr-2.5Nb alloy by Transmission Electron Microscopy, part II: in situ Transmission Electron Microscopy study of deformation mechanism change of a Zr-2.5Nb alloy upon heavy ion irradiation", J. App. Physics, v117, 104302 (2015)
5. H. Abdolvand, M. Majkut, J. Oddershede, J. Wright, M. R. Daymond, "Study of 3-D stress development in parent and twin pairs of a hexagonal close-packed polycrystal: Part I- in-situ three-dimensional synchrotron X-ray diffraction measurement", Acta Mater. v93, p246-255 (2015)
6. H. Abdolvand, M. Majkut, J. Oddershede, J. Wright, M. R. Daymond, "Study of 3-D stress development in parent and twin pairs of a hexagonal close-packed polycrystal: Part II-crystal plasticity finite element modeling", Acta Mater., v93, p235-245 (2015)
7. T. Skippon, M.R. Daymond, "On the predictions of self-consistent plasticity models: The effect of loading path mode during in situ diffraction tests", Mat. Sci. Eng. A, v634, p77-85, (2015)
8. H. Qiao, P.D. Wu, H. Wang, M.A. Gharghouri, M.R. Daymond, "Evaluation of elastic-viscoplastic self-consistent polycrystal plasticity models for zirconium alloys", Int. J. Solids and Structures, v71, p308-322, (2015)
9. P. Srirangam, Y. Idrees, J. Ilavsky and M. R. Daymond, "Ultra-small-angle X-ray scattering study of second-phase particles in heat-treated Zircaloy-4", J. Appl. Cryst. v48, p52-60, (2015).
10. Y. Idrees, E. Francis, Z. Yao, M. Preuss, M.R. Daymond, "Effects of Alloying Elements on the Formation of <c>-Component Loops in Zr alloy Excel under Heavy Ion Irradiation", J. Mat. Res.., v30(9), p1310-1334 (2015).

11. J.L. Liang, M. Zhang, Y. Ouyang; G. Yuan; J. Zhu; J. Shen; M.R Daymond, “Contribution on the Phase Equilibria in Zr-Nb-Fe System” J. Nuc. Mater., v466, p627-633, (2015)

Conference presentations:

Oral presentations were made at the TMS Annual Meeting, February 2015;

- M.R. Daymond [invited], “Measurements of H solubility in Zirconium”
- M.R. Daymond [invited], “Energy Selective Neutron Transmission for determination of H concentration and diffusion rates in Zirconium”
- L. Balogh [invited], In-Situ Studies of Dislocation Structure Evolution during Annealing of Neutron Irradiated Zr-2.5Nb Alloy
- C. Cochane, Strain Induced Phase Transformation in a Zirconium Alloy Investigated Using Synchrotron and Neutron Radiation
- T. Skippon, Characterisation of internal strain during incremental loading of Zircaloy-2

Most of the group (Daymond, Yao, 3 postdocs, 14 students) attended the bi-annual COG FC Seminar in May 2015, and many presentations were made (1 oral presentation, 14 posters)

In addition group members made:

Two presentations at the “Canadian Nuclear Society Annual Conference”, held in Saint John, May 2015.

One oral presentation at the “9th International Conference on Advanced Computational Engineering and Experimenting”, held in Munich, Germany, June 2015

Two oral presentations at “Environmental Degradation of Materials in Nuclear Power Systems”, an international conference held in Ottawa, August 2015.

One poster presentation at Women in Nuclear Industry conference.

Much of the group (Daymond, Holt, 3 postdocs, 11 students) attended the UNENE R&D Workshop in December 2015, and presented their work (1 oral presentation, 10 posters)

Interactions /Consultations to Industry or Others

Prof. Daymond is a member of the COG Fuel Channels Technical Committee, the COG Fuel Channel Working Group on Crack Initiation and Fracture, the COG Fuel Channel Deformation Working Group and the COG High Stress Creep Task Group. Prof. Holt continues a strong interaction with the industry sponsors as an external consultant for CNL, Bruce Power and OPG (through Kinectrics Inc.), as a reviewer and a member of the COG Fuel Channels Technical Committee. Prof. Yao is a member of the COG Fuel Channel Working Group on Crack Initiation and Fracture. Profs. Holt, Daymond & Yao collaborate with CNL, Kinectrics and Nu-Tech precision metals on a number of research topics.

Daymond continues his collaboration with the Commissariat a l`ÉnergiesAtomique (CEA) in Paris. The group there is developing an ion irradiation facility with some overlap in capability compared to the RMTL, as well as developing models describing polycrystalline plasticity in irradiated material. He has also initiated a collaboration with Comisión Nacional de Energía Atómica of Argentina, working on aspects of hydrides and DHC. Other nuclear-related collaborations with Queen’s include Penn. State University (USA), University of Manchester (UK), Australian Nuclear Science and Technology Organization (ANSTO), APS & IVEM-Argonne National Lab (USA), Oxford Culham Science Centre (UK), Wuhan University (China), China Institute of Modern Physics (China) and UBST (China).

Western University – Jin Jiang IRC

UNENE/NSERC IRC Program: Controls, Instrumentation and Electrical Systems

<u>Overview</u>

This is the thirteenth successful year of operation of the Control, Instrumentation & Electrical System (CIES) Laboratory at The University of Western Ontario. With support from UNENE industrial partners and NSERC, the research lab has become an internationally recognized centre of excellence in Control, Instrumentation and Electrical Systems for nuclear power plants. In total, over 48 Highly Qualified Personnel (HQP) have been successfully trained in this lab, many of them are now playing important roles in the nuclear industry in Canada, as well as internationally throughout the world.

The overall program for the current program cycle is summarized in Fig. 1. A significant amount of research work has been carried out in the period from 2015 to 2016. In addition to the originally planned activities, there are several major events that are worth noting:

(1) The physical nuclear power control test facility (NPCTF) for I&C research has been successfully used by more than seven researchers on their research projects. The NPCTF has been used by researchers for fault-tree analysis, design for cyber security and insider-attack, validation of smart sensors, validation of a safety shutdown system based on HFC-6000 series instruments, development of mathematical models as well as process fault diagnosis using wireless sensor networks.

(2) A project has been awarded by Canadian Microelectronics Corporation (CMC) to explore the advantages and special consideration for deploying industrial wireless systems in nuclear power plant environments. As part of this project, WirelessHART standard based wireless sensor nodes have been installed on the NPCTF to acquire real-time data for system performance monitoring purposes (see Fig. 2). Work is currently in progress for installing ISA 100.11a standard based nodes. The data can also be accessed remotely via web portals. This hardware/software system will become a part of 'Canada's National Design Network'.

(3) A research plan has been established to work on the development of a wireless based system for monitoring severe accident conditions in a nuclear power plant. An application has been made to Ontario Research Fund for support.

(4) Together with McMaster, we have secured an NSERC CREATE grant to support reliability and safety analysis for nuclear power plants in the presence of earthquake.

The Chair and the research team have organized and/or participated in many activities. Within Canada, the 11th Annual UNENE I&C Workshop was successfully held on October 2nd, 2015 at the newly constructed Darlington Energy Complex (DEC) of Ontario Power Generation (OPG) in Courtice, Ontario.

The theme of this year's workshop was 'severe accident monitoring in NPPs'. Several representatives from UNENE industrial partners attended the workshop. A group picture is shown in Fig. 3.

Internationally, the Chair has attended the first IAEA CRP meeting on wireless technologies for NPP applications, held at the IAEA head quarter in Vienna on March 30th to April 2nd, 2015. A new research initiative on instrumentations for post-accident condition monitoring has started. The project involves CNL and other partners. The chair is also participating a working group on "Individuals, Technology and Organizational Factors under Severe Conditions". He has also attended the first workshop at COG on May 11th, 2015.

The Chair has offered a UNENE M.Eng. course UN0601 in January 2015. A class picture is shown in Fig. 5.

The Chair (IRC) has been presented with the 2015 Canadian Nuclear Achievement Award – 'Harold A. Smith Outstanding Contribution Award' – for his contributions in instrumentation and control for nuclear power plants both in Canada and internationally. The 'Harold A. Smith Outstanding Contribution Award' represents the top award by Canadian Nuclear Association (CNA) and Canadian Nuclear Society (CNS). The award certificate was presented at the CNS conference on June, 2nd (See Fig. 6.)

<u>Research Program</u>

The research program for the next five years can be illustrated in the diagram below:

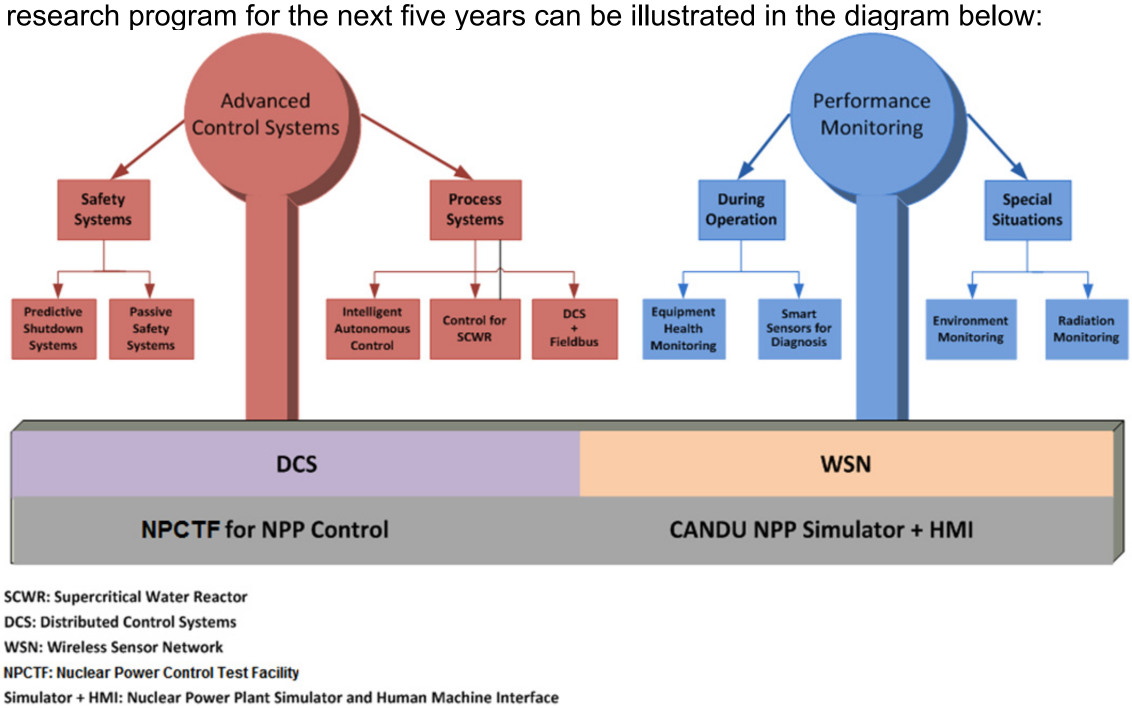


Fig. 1: Research activities under the IRC program

The research activities have been divided into two themes: (1) Advanced Control Systems; and (2) Performance Monitoring, for nuclear power plants. The research under the first theme is further divided into safety systems and process control systems. Topics investigated include 1) predictive safety systems, 2) passive safety systems, 3) intelligent autonomous control, 4) control for SCWR, and 5) adoption of advanced technologies (fieldbus, wireless). Under the second theme, techniques for both pre-accident and post-accident condition monitoring systems are examined. Topics in this theme include: 1) wireless technologies for equipment health monitoring within a nuclear power plant, 2) smart devices for plant condition monitoring, 3) environment monitoring, and 4) radiation monitoring in a post-accident condition where radiation hardened wireless sensor technologies are parts of the investigation.

The scope of the research program has also been extended with supplementary financial supports from CMC, CNL sponsored projects, an NSERC CRD grant, and the University Innovation Fund. It is expected that 19 highly qualified personnel will be trained through this program over the 5-year period of this term of the IRC program.

Research Facilities

Over the last thirteen years, we have established a suite of state-of-the-art research facilities to support research activities in the IRC program and to create a hands-on training environment for highly qualified personnel (HQP). The facilities have been upgraded to support the on-going research needs. The NPCTF has been instrumented with WirelessHART, ZigBee and ISA 100.11a based sensor nodes. DeltaV DCS system has been implemented to operate the NPCTF. A summary of the major facilities is listed below:

- Darlington NPP simulator
- Tricon v9 safety system
- HFC 6000 safety system
- HFC non-safety DCS
- FPGA development systems
- Siemens PCS 7 redundant DCS control system
- Honeywell C-300 DCS
- Emerson DeltaV DCS with full fieldbus connectivity
- Hardware experimental test bench
- Wireless monitoring nodes based on WirelessHART, ZigBee, and ISA100.11a standards
- Smart sensor development systems, and
- Nuclear Power Control Test Facility (NPCTF)

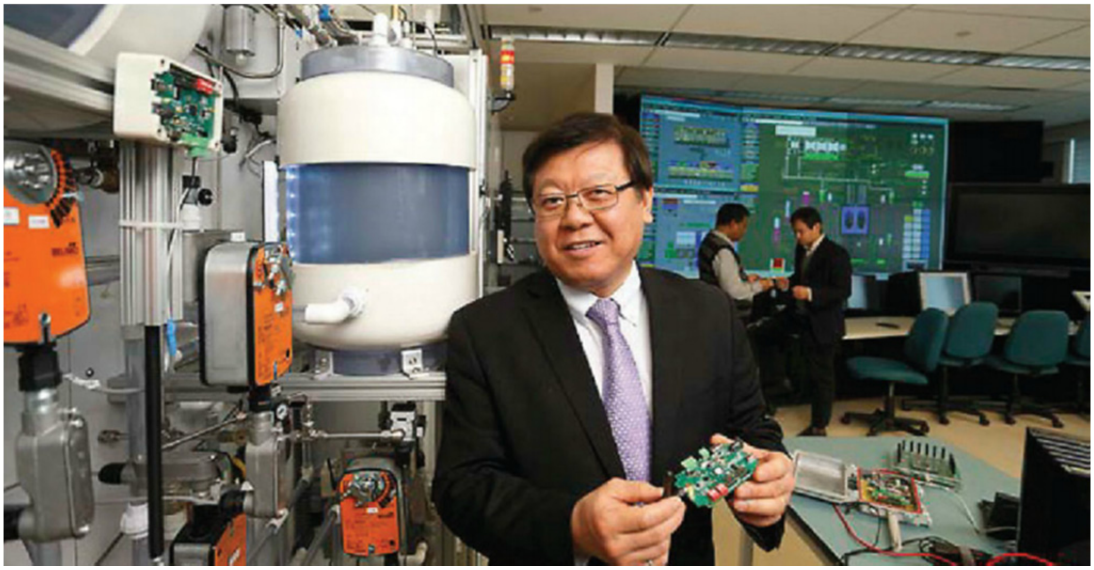


Fig. 2 Integration of wireless sensor networks in NPCTF

IAEA Coordinated Research Project (CRP) on wireless system in NPP

The Chair has recently been awarded an IAEA Coordinated Research Project (CRP). The CRP will provide some design recommendations for wireless technologies, along with necessary tools, that can be deployed in a NPP. A WSN system can offer unique benefits to I&C systems, as well as to process, equipment and environment monitoring applications in newly-constructed and/or refurbished nuclear power plants (NPPs). However, several challenges remain to be addressed before a WSN system can widely be accepted by NPPs. The challenges include, among others, i) integration of new wireless systems into the existing wired I&C systems must be such that the minimum required performance can be maintained, and that the integrated I&C system performs its functions adequately, ii) a WSN must perform reliably in the presence of high levels of EM interference from devices such as relays and motor driven pumps, and ionizing radiation sources, and 3) dependable WSN performance in harsh industrial environments that are cluttered with cable trays, piping, valves, pumps, motors, and concrete and steel structures. This CPR will investigate these issues by first evaluating i) requirements of existing I&C systems for nuclear power plant applications, and ii) the EM and radiation environments, and structural layout of typical NPPs with respect to signal paths for wireless sensor nodes. The work will involve information collection, analysis, simulation, and experiments.

The 11th NSERC/UNENE I&C Workshop

Nearly 30 academic researchers, graduate students and representatives from the Canadian nuclear industry met on Friday, Oct. 2 at the newly constructed Darlington Energy Complex (DEC) of Ontario Power Generation (OPG) in Courtice for the 11th University Network of Excellence in Nuclear Engineering (UNENE) Nuclear Instrumentation and Control (I&C) Workshop (see Fig. 3).

Fig. 3 11th Annual UNENE I&C Workshop at Darlington Energy Complex (DEC)

The theme of this year's workshop was regulatory requirements and measures that Canadian nuclear industries have taken for severe accident management. Rick Hohendorf, Director of Components Engineering at OPG opened the Workshop. Participants included distinguished guests, such as Basma Shalaby, President of UNENE; Fred Dermarkar, President of COG (CANDU Owners Group); Frank Saunders, Vice President of Bruce Power; and technical officers Quanmin Lei and Charles Zeng from CNSC (Canadian Nuclear Safety Commission).

All participants also had an opportunity to tour the newly constructed CANDU reactor mock-up training facility at the DEC (see Fig. 4). The tour was an exciting event for many participants as this was the first time they saw CANDU Calandria, reactor faces, and pressure tubes up close. The facility is constructed for training staffs for the upcoming Darlington Refurbishment projects that will launch in October 2016. The refurbishment of Darlington units will provide Ontarians with another 30 years of service.

Fig. 4 Visiting Darlington Energy Complex (DEC) during 11th Annual UNENE I&C Workshop

The workshop accommodated 14 presentations from Western researchers and industry partners, and a 20-minute movie on the demonstration of readiness by Bruce Power to nuclear emergencies.

Current Members of Research Team (as of December 31st, 2015)

- Dr. Jin Jiang (IRC Senior Chair)
- Dr. Xinhong Huang (Research Engineer)
- Dr. Ataul Bari (Research Engineer)
- Dr. Sungwhan Cho (Postdoctoral Fellow)
- Dr. Quan Wang (Postdoctoral Fellow)
- Mr. Binggang Cui (Research Assistant)
- Mr. Drew Rankin (PhD Candidate)
- Mr. Ahmad Osgouee (PhD Candidate)
- Ms. Xirong Ning (PhD Candidate)
- Mr. Qiang Huang (PhD Candidate)
- Mr. Ning Peng (PhD Candidate)
- Mr. An He (MESc Candidate)
- Mr. Long Ding (Visiting Student)

Publications (selected)

Book chapter:

[1] J. Jiang, "Electrical Systems", - in The Essential CANDU (Edited by Bill Garland), UNENE, 2014.

Journal Papers:

[1] D. J. Rankin and J. Jiang "Predictive Trip Detection for Nuclear Power Plants," IEEE Transactions on Nuclear Science (TNS) (Accepted on June 15th, 2016).
[2] D. Q. Wang and J. Jiang, "An Efficiency Booster for Energy Conversion in Natural Circulation Loops," Nuclear Engineering and Design, (Accepted for publication on April 27, 2016).
[3] S. Cho and J. Jiang, "Change Detection in the Mean of a White Gaussian Process by the Backward Standardized Sum," Journal of Communications in Statistics – Theory and Methods, (accepted on April 14, 2016)
[4] Q. Wang and J. Jiang, "Examination on Architecture and Protocol of Industrial Wireless Sensor Network Standards," IEEE Communications Surveys and Tutorials, (Accepted on March, 28, 2016)
[5] A. Bari and J. Jiang, "A review of wireless sensor networks for nuclear power plant applications," International Journal of Nuclear Safety and Simulation (IJNS), Vol. 6, No. 1, 2015.
[6] G. Dutta, R. V. Maitri, C. Zhang, and J. Jiang, "Numerical Models to Predict Steady and Unsteady Thermal-hydraulic Behaviour of Supercritical Water Flow in Circular Tubes," Nuclear Engineering and Design, (Accepted for publication), April, 26, 2015.
[7] G. Dutta, C. Zhang, and J. Jiang, "Numerical Analysis to Investigate the Effects of Thermal-hydraulic Instabilities on Deterioration Heat Transfer and Wall Temperature in the CANDU Supercritical Water Reactor," ASME, Nuclear Engineering and Radiation Science, (Accepted for publication), Feb. 27, 2015.
[8] G. Dutta, C. Zhang, and J. Jiang, "Analysis of Parallel Channel Instabilities in the CANDU Supercritical Water Reactor," Annals of Nuclear Energy, Vol. 83, pp. 264-273, 2015.
[9] B. S. Wang, D. Q. Wang, J. Jiang, J. M. Zhang, and P. W. Sun, "Efficient functional reliability estimation for a passive residual heat removal system with subset simulation based on importance sampling," Progress in Nuclear Energy, Vol. 78, pp. 36-46, Jan. 2015.

[10] G. Dutta, C. Zhang, J. Jiang, "Analysis of Flow Induced Density Wave Oscillations in the CANDU Supercritical Water Reactor," Nuclear Engineering and Design, Vol. 286, pp. 150–162, 2015.

Refereed Conference Papers:

[1] D. Q. Wang and J. Jiang, "A review of study and design improvement of natural circulation based heat removal systems," Proceeding of The 20th Pacific Basin Nuclear Conference, April 5 to April 9, 2016, Beijing, China.
[2] J. Jiang, J. P. Ma, D. J. Rankin, A. Bari, "A Physical Simulator in supporting of Research & Development for Instrumentation and Control Systems in Nuclear Power Plants," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[3] S. W. Cho, and J. Jiang, "Tree Analysis of the Shutdown System in a Physical Nuclear Power Plant Simulator," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[4] S. W. Cho, and J. Jiang, "A Study of Analytical Redundancy of the Heater Control Process of a Physical Nuclear Power Plant Simulator," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[5] X. R. Ning and J. Jiang, "Identification and Analysis of Safe Operating Boundary of Dynamic Systems," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[6] M. Gverzdys, J. Jiang, T. Schaefer and S. Yang, "Implementation and Experimentation of a Reactor Shutdown System using HFC6000," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[7] B.G. Cui and J. Jiang, "Development of Dynamic Models for Thermal-hydraulic Processes based on Simscape Toolbox," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[8] A.Bari, J.P. Ma, and J. Jiang, "Demonstration of Wireless Sensor Networks based Fault Diagnosis," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[9] Q. Huang, and J. Jiang, "Literature Review on Radiation Effects on Wireless Post-Accident Monitoring Systems and Rad-Hardened Design Techniques," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).
[10] D. J. Rankin and J. Jiang, "Analytically Compensated SGLC Test Facility," 9th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies (NPIC&HMIT 2015).


Fig. 5 UNENE M. Eng. course UN0601 class photo (2015)

Fig. 6 Harold A. Smith Outstanding Contribution Award from the CNA

Western University – Clara Wren IRC

UNENE/NSERC IRC Program: Radiation-Induced Chemistry and Corrosion

Overview

This is the first progress report for the 3rd term of the NSERC IRC in Radiation-Induced Chemistry and Corrosion, which was renewed in April 2016 by NWMO and UNENE. The aim of the research projects conducted in the 3rd term of the IRC is to provide the scientific and technical basis for: (1) assessment of the integrity and longevity of the weld design of the proposed NWMO Mark II container for long-term disposal of used nuclear fuel, and (2) assessment of the corrosion performance of CANDU nuclear reactor structural components, in particular, End Shield Cooling (ECS) systems. This report summarizes the progress against the IRC milestones for work addressing the concerns of UNENE.

As the nuclear power reactors are aging and their life-times are extended, accurate assessment of the integrity and longevity of the reactor structural materials is increasingly important. For example, current investigation into a leak in the End Shield Cooling (ESC) System in the Pickering Unit 6 nuclear reactor has raised a potential issue. Moisture from the ESC system leak could possibly reach a location in the annular air gap which exists around the periphery of the Calandria tank assembly and its supporting structures where corrosion would be problematic and needs careful evaluation. In particular, the potential for accelerated (galvanic) corrosion attack on carbon steel (CS) adjacent to the dissimilar metal weld between CS (SA36) and stainless steel (SS) (SA240, Type 304L) at the periphery of the annular gap (**Fig. 1**) must be addressed.

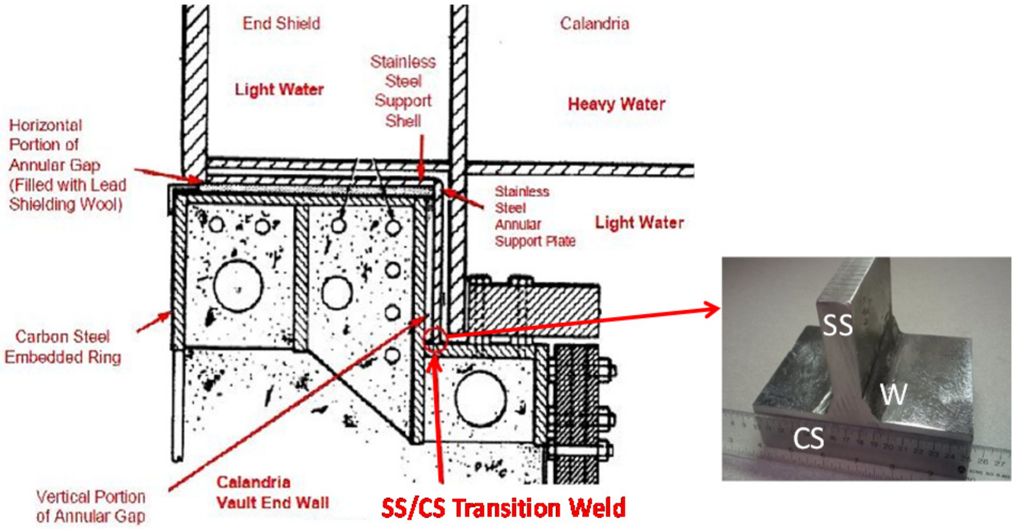


Fig. 1: Schematic of the periphery of the calandria tank assembly and its supporting structures. The red circle indicates the location of the carbon steel (CS) and stainless steel (SS) weld joint.

The corrosion kinetics of an alloy depend not only on its metallurgical properties, but also on the redox and electrolyte properties of water in contact with the alloy. Those properties can change considerably depending on the concentration of redox active species present, pH and temperature. The annular gap environments include the added challenge of ionizing radiation that will drive radiolysis of liquid water. Radiolysis affects the redox conditions by decomposing water to create redox active species such as H_2O_2. The concentrations of the redox active species can effectively control the corrosion rates of metal alloys. Radiolysis of humid air produces nitric oxides and nitric acid that are easily absorbed and lower the pH of any water in contact with the humid air. Since these radiolysis products can affect corrosion kinetics considerably, evaluating corrosion performance and the designs of chemistry control systems to limit corrosion in nuclear environments must consider the effect of radiation fields that are present, particularly γ-radiation, on water chemistry.

Assessing the effects of water radiolysis on corrosion kinetics is difficult, primarily because aqueous corrosion, even in the absence of radiation, is already a complicated function of solution conditions. As well, the chemical system that exists in irradiated water in contact with air can run to several hundred coupled reactions. When the reactions with metal surfaces and dissolved transition metal ions are included, careful and detail experiments and analyses are required to extract information on the reaction mechanisms, key reaction processes and their rates. The aim of the IRC research is to identify those key controlling reactions and to understand their dependences on environmental conditions.

The IRC program in the 3rd term was designed to develop fundamental chemical knowledge while addressing corrosion research needs for two sectors of the nuclear industry. The scientific objective of the UNENE sponsored research is to determine the combined effects of γ-radiation and exposure environments (such as pH and temperature) on corrosion of individual alloys (CS, SS and weld material (W = SS309) and galvanic corrosion at weld joints. Towards meeting this objective, the following tasks are being performed:

1. Radiolysis modeling of the anticipated annular gap environments,
2. Aqueous corrosion of individual steels (CS, SS and W) as a function of exposure environmental parameters with or without radiation, and
3. Galvanic corrosion of CS-W and W-SS as a function of exposure environmental parameters with or without radiation.

<u>Progress Report on the UNENE Sponsored Projects of the IRC Program</u>

Radiolysis Modeling of the Anticipated Annular Gap Environments

To determine radiolytic oxidant concentrations that may be present and important to the steel (CS, SS and W) corrosion under the anticipated annular gap environments. two different radiolysis kinetic models are being developed: (1) water radiolysis and (2) humid air radiolysis. The progress to date in this project includes construction and verification of these models. The models are now undergoing testing and refinement as more relevant experimental data are available.

Radiolysis-Induced General Corrosion of Individual Steels

To develop a mechanistic understanding of aqueous corrosion of different steels used in the shield tank assembly and supporting structures in the presence of continuous flux of γ-radiation, detailed corrosion kinetic studies are being conducted as a function of solution redox and solvation parameters. These studies form the basis line for water droplet (or thin water film) corrosion and galvanic corrosion studies. The corrosion kinetics are studied by performing a combination of corrosion tests using alloy coupons and electrochemical experiments using alloy working electrodes. The steel coupons and electrodes used in this study are cut from the weld samples supplied by Ontario Power Generation (OPG) (**Fig. 1**). The changes in surface composition and morphology are investigated using various surface imaging and spectroscopic analyses and the change in dissolved metal concentrations. The exposure environmental parameters investigated in the corrosion studies include pH, temperature, ionic strength, dissolved O_2, [H_2O_2] and [HNO_3].

Radiolysis-induced water droplet and galvanic corrosion of dissimilar metal welds

The effects of radiolysis on galvanic corrosion of a dissimilar metal weld in confined volumes such as those encountered in the annular gaps of the shield tank assembly, or in water droplets, are being investigated in the absence and presence of γ-radiation. These corrosion studies are being conducted using off-cut samples from the weld block supplied by Ontario Power Generation (OPG)

(**Fig. 1**). A combination of experiments with computational model analyses are being performed. The experimental approach is similar to that described above and includes both electrochemical analyses and coupon corrosion tests, followed by a suite of surface, gas and solution analyses. For the coupon corrosion tests, the surfaces are either fully submerged or partially covered with water droplets in humid air or in an inert cover gas. The coupon corrosion tests are being extended to general corrosion tests of individual steels exposed to vapour and water droplets to assist in the interpretation of the galvanic corrosion results. Examples of the experimental results are presented in **Fig. 2**. The studies will be expanded to investigate the effects of ionic strength, [H_2O_2] and [HNO_3].

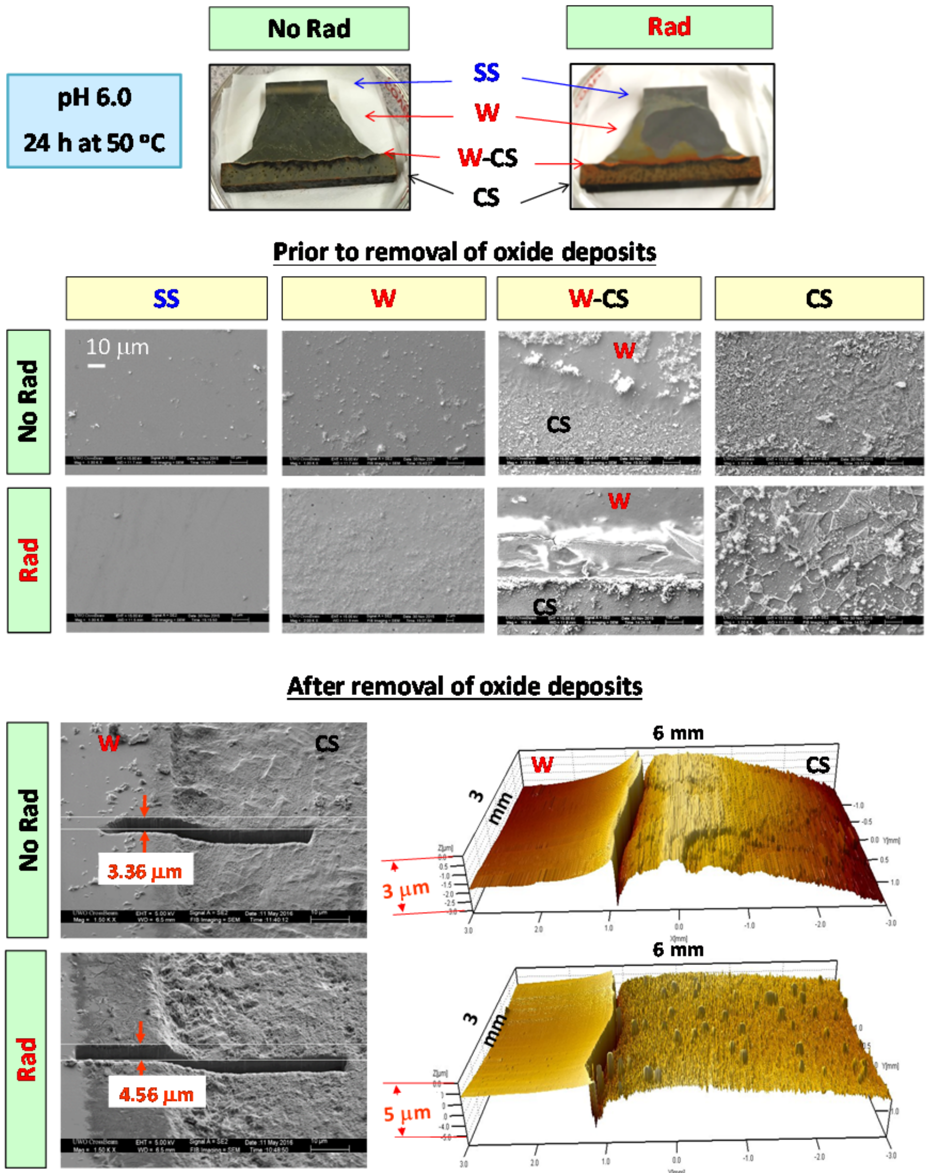


Fig. 2: Surfaces and depth profiles of the CS, SS and W areas of the off-cut coupons from the OPG weld block (Fig. 1) after 24 h of corrosion in aerated 0.01 M borate solutions at pH 6.0 at 50 °C.

Research Facilities And Equipment

The radiation assisted materials performance Science (RAMPS) laboratory led by the Chair is equipped with a suite of equipment for performing leading research in the field of radiation-induced chemistry and corrosion. The major facilities and instruments include (**Fig. 3**):

- a Co-60 gamma radiation chamber that provides a high dose rate (3 kGy/h (May 2016)),
- a suite of electrochemical equipment including potentiostats and frequency response analyzers, ultra-low current and voltage measuring systems,
- several pressure vessels for high temperature/pressure and supercritical water corrosion studies,

- a gas chromatograph with three detectors (mass selective, thermal conductivity, electron capture detectors)
- a UV-Vis absorbance and fluorescence spectrometer, a photoemission spectrometer,
- an attenuated reflectance FTIR (Fourier transfer infrared), and
- a scanning optical microscope with a very high resolution.

In addition, the Chair's research team members have access to and receive training on a suite of sophisticated surface analysis instruments through Surface Science Western for SEM/EDX (scanning electron microscope/energy disperse x-ray), Auger, XPS (X-ray photoelectron spectrometer), profilometry, etc., Biotron for TEM (transmission electron microscope) and ICP-MS (inductively coupled plasma – mass spectrometer), the Nanofabrication Facility (Nanofab) for Focus Ion Beam (FIB) and SEM/EDX, and the Zircon and Accessory Phase Laboratory (ZAPLab) for EBSD (electron backscatter diffraction), and to the Tandetron Accelerator Facility for heavy ion-beam irradiation.

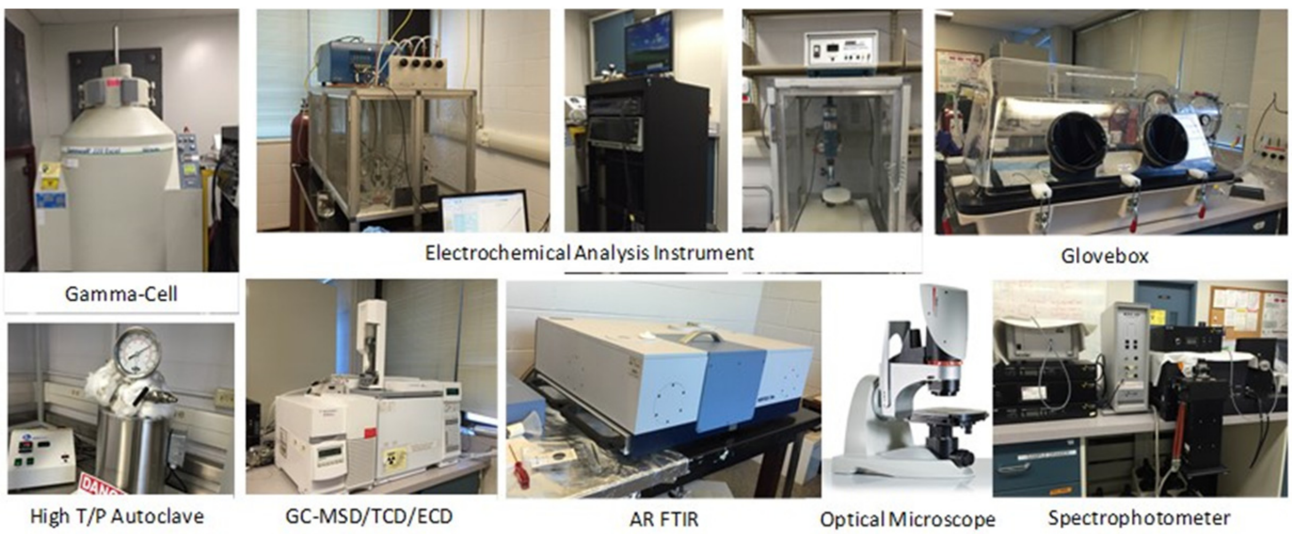


Fig. 3: Major facilities and instruments in the RAMPS laboratory

<u>HQP</u>

Current (As of May 2016):

- 2.5 Research Associates: Dr. J.J. Noel (50%), Dr. J. Joseph, Dr. G. Whitaker
- 9 PhD Candidates: T. Sutherland, M. Momeni, D. Guo, R. Morco, J. Turnbull, Y.G. Shin, C. Spark, M. Zakeri, M. Naghizadeh
- 3 MSc Candidates: A. Jean, M. Li, R. KarimHaghighi

Completed Training in 2015 – May 2016:

- Dr. Linda (Michael) Wu (Postdoctoral Fellow, 14/05 – 15/08) – Currently at CNL, ON
- Ms. Balsam Ibrahim (MSc, Aug 2015) – Currently at 3M London, ON

Publications (2015 – May 2016)

Summary: 18 papers in peer reviewed journals and proceedings
5 invited talks and 34 presentations – not listed

Peer-Review Journal Publications (Selected):

1. A.Y. Musa, J.C. Wren*. Combined Effect of Gamma-Radiation and pH on Corrosion of Ni-Cr-Fe Alloy Inconel 600. *Corros. Sci.* 109 (2016) 1-12.
2. M. Momeni, M. Behazin, J.C. Wren*. Mass and Charge Balance (MCB) Model Simulations of Current, Oxide Growth and Dissolution in Corrosion of Co-Cr Alloy Stellite-6, *Journal of The Electrochemical Society*, 163 (3) C1-C12 (2016).
3. R.P. Morco, A.Y. Musa, M. Momeni, J.C. Wren*. Corrosion of Carbon Steel in the [P_{14666}][Br] Ionic Liquid: The Effects of γ-Radiation and Cover Gas. *Corros. Sci.* 102 (2016) 1-15.
4. V. Subramanian, J.M. Joseph, H. Subramanian, J.J. Noel, D.A. Guzonas, J.C. Wren*. Steady-State Radiolysis of Supercritical Water: Model Predictions and Validation. *ASME J. Nuclear Rad. Sci.,* 2016 (2016), 021021-1-021021-6.
5. L.M. Alrehaily, J.M. Joseph, J.C. Wren*. Radiation-Induced Formation of Co_3O_4 Nanoparticles from Dissolved Co^{2+}(aq) in Aqueous Solution: Probing the Kinetics Using Radical Scavengers. *Phys. Chem. Chem. Phys*, **17 (**2015) 24138 – 24150.
6. L.M. Alrehaily, J.M. Joseph, J.C. Wren*. Radiation-Induced Formation of Chromium-Oxide Nanoparticles: Role of Radical Scavengers on the Redox Kinetics and Particle Size. *J. Phys. Chem. C*, *119* **(**2015) 16321–16330.
7. R.P. Morco, J.M. Joseph, J.C. Wren*. The Chemical Stability of Phosphonium-Based Ionic Liquids under Gamma Irradiation. *RSC Adv.*, 5 **(**2015) 28570-28581.
8. M. Momeni, J.C. Wren*. A Mechanistic Model for Oxide Growth and Dissolution Kinetics during Corrosion of Co-Cr and Ni-Fe-Cr Alloys. *Faraday Discuss.* 180 **(**2015) 113 - 135.
9. A.Y. Musa, M. Behazin, J.C. Wren*. Oxide Film Growth Kinetics on Ni-Cr-Fe Alloy 600 as a Function of Potential at 25 and 80 °C. *Electrochim. Acta.* 162 (2015) *185-197*.

Refereed Conference Papers (Selected):

10. B. Ibrahim, D. Zagidulin, S. Ramamurthy, J.C. Wren, D.W. Shoesmith*. Radiolytic Corrosion of Cu Nuclear Waste Containers. *Proc. The 17th International Conference on Environmental Degradation of Materials in Nuclear Power Systems (ENVDEG)* – Water Reactors, Ottawa, Ontario, Aug. 9-12, 2015.
11. L. Wu, D. Guo, *A. Van Belois*, J.J. Noël, P.G. Keech, J.C. Wren*. Radiation-Assisted Corrosion of Carbon Steel Nuclear Waste Container. *Proc. The 17th ENVDEG*, Ottawa, Ontario, Aug. 9-12, 2015.

McMaster University – John Luxat IRC

UNENE/NSERC IRC Program: Nuclear Safety Analysis

Overview, Scope and Main Objectives

The research focuses of the NSERC/UNENE Industrial Research Chair and Associate Chair in Nuclear Safety Analysis at McMaster University is nuclear safety analysis methods, nuclear safety thermalhydraulics and severe accident prevention/mitigation. The objectives for this research program are to perform industry relevant research, generate top quality graduates for the nuclear industry, and provide an expert resource for industry, government, public and media consultations. The success of this program is illustrated through: a) the extent and frequency of industry consultations by the chairs, b) the number and quality of the HQP produced, c) the research output and additional leveraging of resources, and d) the number of media and public requests for IRC input.

The scope of the research covers the multi-disciplinary nature of nuclear safety analysis and severe accident analysis. This requires knowledge and skills that can be found in the Faculty of Engineering at McMaster University. The Chair program enhances and extends this nuclear safety knowledge and skills base while actively supporting the Canadian nuclear industry. The Chair program has enabled McMaster University to establish a robust, innovative and sustainable faculty research network and has been recognized internationally for its research and quality of graduates. A major success indicator has been the very high degree of leveraging and the number of lead roles assumed by the chairs.

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. 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 2015 a successful application was prepared to renew Dr. Luxat's Senior Chair for a third term and to promote Dr. Novog's Associate Chair to a Senior Chair. The terms of the two Senior Chairs start on January 1, 2016.

Since the initial award, the IRC program has catalyzed nuclear research and HQP training at McMaster as evidenced by new faculty hires in nuclear engineering and materials, expansion of HQP from 3 to over 30 enrolled graduate students. The success of the Chairs has also led to expansion in the number of faculty in nuclear engineering at McMaster with a new reactor physics professor who joined in 2009. An additional senior professor was hired in 2012 specializing in nuclear waste management and was awarded a Tier I Canada Research Chair. Over the course of the chair program 3 distinguished visiting scholars in the safety analysis area have resided at McMaster.

The resulting knowledge, skills and innovation are applied to improving safe operation and competitiveness of nuclear power generation, and to examine severe accident behaviour and accident management for beyond design basis events. 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 toolsets used 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, expansion of the tools and experiments supporting the safety cases, and helping meet the HQP training requirements for the nuclear energy sector.

The program has advanced beyond Canada to include international cooperation and exchanges. Examples of these activities include participation in OECD-NEA and IAEA activities and working groups, student exchanges and visiting research positions, and recognition at international meetings and conferences.

The research objectives of the IRC program are related to:

- *Nuclear safety, plant modeling and uncertainty estimation – the focus here is on improved modeling and uncertainty approaches so as to better demonstrate available margins and event progressions.*

- *Severe accident phenomena and mitigation means - given the wide ranging implications of Fukushima on the nuclear industry, McMaster is working in collaboration with many international researchers. This includes examining international methods and tools for severe accident predictions and new experiments to support in-vessel retention.*

- *Development of risk analysis methodologies for extreme events which are complementary to probabilistic risk assessment – this includes collaboration with industry stake holders on multi-unit accident effects and overall plant robustness.*

- *Thermalhydraulic performance and improved reactor output - research here focuses on the improvement of methodologies and their experimental bases such as to support the fuel and fuel channel integrity metrics.*

These activities make use of existing facilities at McMaster (such as the McMaster Nuclear Reactor), newly built facilities (such as the Critical Heat Flux Test Loop) and the CFI-MRI funded Center for Advanced Nuclear Systems(CANS) which in the final stage of completion.

<u>Research Facilities and Equipment</u>

Over the first two terms of the IRC there has been exceptional success in leveraging industry investments and expansion of university facilities related to nuclear engineering:

ORF-Research Excellence: 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 and Dr. Novog as a co-principal investigator. This program is complementary to UNENE and provided an addition $5M of provincial funding to support nuclear research at six universities in Ontario. The ORF project was wrapped up over the last several years and was judged to be extremely successful based on the research output, infrastructure improvements and HQP generated.

CFI-MRI research Infrastructure: In 2008 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). In early 2016 the Center for Advanced Nuclear Systems (CANS) project, led by Dr. Luxat was completed. This Centre was funded by a $24.5M grant from Canadian Foundation for Innovation (CFI), the Ontario Ministry for Research and Innovation (MRI) and McMaster University. This regional research infrastructure provides a Post Irradiation Examination (PIE) facility consisting of a suite of hot cells to handle irradiated reactor material, prepare samples, and perform mechanical testing and scattering Electron Microscope (SEM) examination, including Focused Ion Beam (FIB) milling of small samples of material equipment; advanced material characterization tools, such as a 3-D Atom Probe and an additional SEM/FIB device for examination of non-irradiated material; a thermal testing laboratory (at McMaster); and a radiation dose laboratory (at UOIT). The PIE facility is the only one of its kind at a university world-wide (see Fig. 1). This infrastructure, together with the McMaster Nuclear Reactor and the Canadian Center for Electron Microscopy, provides a world class materials and thermal testing center unique in North America. The project was supported by a majority of Canadian nuclear energy related companies (OPG, Bruce Power, AECL, Kinectrics) as well as a number of leading international organizations (EPRI, EdF, Bechtel). In addition Dr. Novog received a $275k CFI - Leaders Opportunity Fund grant for a Phase Doppler Anemometer System for thermalhydraulic experiments.

Fig. 1 The CANS PIE Hot Cell Facility

The computational facilities at McMaster have undergone significant upgrades as a result of the IRC program in safety analysis and successful leveraging opportunities. The computational facilities include a central computational cluster and several high performance workstations. A Linux-based high performance computer cluster with a total of 88 processors, 144 GB of memory and 6 TB of disk storage. This cluster is to be upgraded in early 2017 to provide a total of 152 processors. In addition students utilize 8 high-performance workstations for various CFD, physics and thermalhydraulic analyses.

Through the agreements between COG and RSICC code databank access was obtained to the SCALE reactor physics package, used by 3 students for propagating nuclear data uncertainties to the few group collapsed cross sections. This included work using TSUNAMI, TRITON and KENO packages within SCALE. Also access to MCNP and SERPENT is provided where one student is engaged in an experimental and computational study of gamma flux distribution in the McMaster Nuclear Reactor core and another student is examining the application of SCALE to CANDU technologies. Through the US NRC CAMP agreement McMaster is also piloting the application of the RELAP/TRACE and PARCS toolset for CANDU. Access to the USNRC sponsored and Sandia Laboratories developed MELCOR severe accident software was obtained through the CNSC.

Experimental Thermalhydraulics and Severe Accident Phenomena

In support of high temperature heat transfer behaviour relevant to design and beyond design basis accidents several experiments were performed on CHF and quench behaviour. A PhD was also completed on high temperature quench behaviour in cylindrical geometries and several publications generated in collaboration with the Department of Mechanical Engineering. Another CHF facility was built to obtain low pressure CHF data on downward facing surfaces to study the behaviour under these configurations, relevant to severe accidents in CANDU reactors, in particular In-Vessel Retention of molten corium. As a result of the quench (see Figure 2) and CHF tests new experiments are being performed to support CHF on external surfaces (calandria vessel and calandria tubes) as well as examining heat transfer under severely degraded situations.

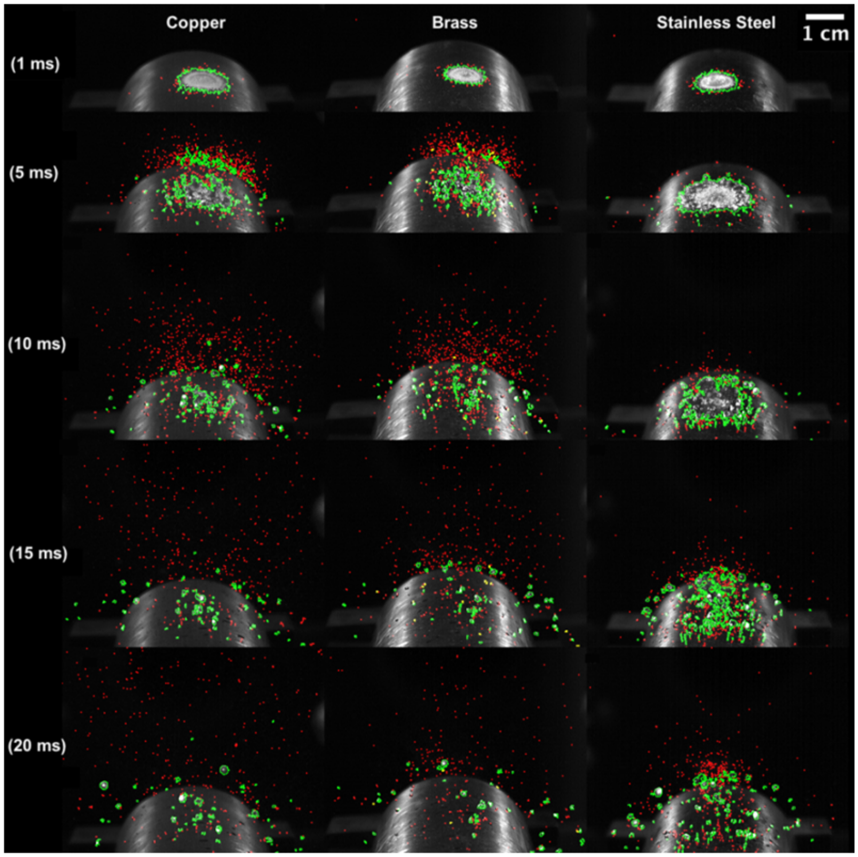


Figure 2: Image processed sequences of droplet explosion on various heated surfaces at Ts = 300°C

Research Program

The research program at McMaster continues to be very strong and covers a large number a projects. In 2015 the Chair programs will apply for a third-term renewal with NSERC. The high level objectives of the NSERC-UNENE Senior Industrial Research Chairs in nuclear safety and thermalhydraulics are to:

1. *Develop and enhance analysis methodologies in the area of nuclear safety analysis with a focus on improving nuclear safety, accident analyses and uncertainty estimation.*
2. *Support the development of severe accident analysis methodologies and mitigation strategies.*
3. *Perform fundamental and applied research and development in the areas of thermalhydraulics under normal and accident conditions and assess the potential for improved reactor output.*
4. *Support assessment of Fuel and Fuel Channel Integrity under accident conditions.*
5. *Train the next generation of Highly Qualified Personnel for the nuclear industry.*
6. *Provide expertise to the university, government and the public in the area of nuclear safety.*

Consistent with these high level objectives, the proposed research program of the Dr. Luxat's IRC for the next term will focus on the following areas:

- Severe Accident Modeling and Analysis
- Severe Accident Mitigation and Nuclear Safety Risk Assessment
- The Safety of Advanced Fuel Cycles in CANDU reactors
- Development of advanced methodologies for nuclear safety analysis and supporting experimental studies.
- Consolidation of analysis methodology for evaluating Fuel Channel Integrity (consolidation of work completed in previous terms)
- Advancement of the understanding of the inter-relationships between uncertainties in safety calculations.
- Extensive collaborations have been established with faculty members in the Civil engineering Department at McMaster on risk analysis and seismic risk assessment. Dr. Luxat is a co-applicant on three NSERC Research Tools & Instruments (RTI) Grants to upgrade the seismic test capability in the Applied Dynamics laboratory and is a Co-PI and Nuclear Safety Program Leader on the successful CREATE grant *"Canadian Nuclear Energy Infrastructure Resilience under Seismic Systemic Risk (CaNRisk)"*, [Wael El-Dakhakhni, PI] https://canriskcreate.ca/. This CREATE Grant award was $1,650,000.

These focus areas are all of high importance to the Canadian nuclear industry due to: unresolved issues with severe accidents, their mitigation and methods to accommodate uncertainties associated with common cause external hazards in multi-unit site nuclear safety assessments (issues that have developed from the Fukushima events); efforts underway by CANDU reactor designers to develop and market reactors that are optimized to handle multiple advanced fuel cycle options.

Training and Enrolment

The IRCs (Dr. Novog and Luxat) at McMaster have been extremely successful. A total of 20 Masters students have graduated from the program over Terms 1 and 2 with three more thesis defences pending. Seven PhD student have graduated including 2 who completed in 2014. Currently there are 13 Masters and 6 PhD students enrolled in the nuclear program supervised by Dr. Luxat and Dr. Novog. Approximately 13 past students are employed at AMEC-NSS, 3 at CANDU Energy, 4 at CRL, 9 at Bruce Power and 8 at OPG and 2 at CNSC.

There have been 28 summer student projects in the nuclear area supervised by the IRC professors. Approximately half have gone on to graduate studies and many of the others are employed at Bruce Power, OPG, NSS and AECL. In addition 8 graduate students have had internships in the Canadian nuclear industry (AECL and NSS) during the program.

Research exchanges and agreements have been, or are being pursued with, Penn State, University of Manchester, University of Pisa, INPG-Grenoble, CEA-Cadarache and Idaho National Laboratories. A total of 6 McMaster students have gained international experience (4 more planned) with a comparable number of foreign students performing research at McMaster.

Publications: 2013-2015

Submitted, Accepted or Published in Journals

1. K. Takhrouri, J. Luxat, M, Hamed, "Measurement and Analysis of the Re-wetting Front Velocity during Quench Cooling of Hot Horizontal Tubes, (Submitted to Nuclear Engineering and Design)
2. K. Takhrouri, J. Luxat, M, Hamed, "Experimental Investigation of Quench and Re-wetting Temperatures of Hot Horizontal Tubes Well above the Limiting Temperature for Solid–Liquid Contact , (Submitted to Nuclear Engineering and Design)
3. K. Takhrouri, M, Hamed, J. Luxat, "Re-Wetting Delay Time during Cooling of Hot Horizontal Tubes Well above the Limiting Temperature for Solid–Liquid Contact", (Submitted to International Journal of Heat and Mass Transfer)
4. A. Behdadi and J.C. Luxat, "Critical heat flux for downward-facing pool boiling on CANDU calandria tube surface", Nuclear Engineering and Design, (Submitted to Nuclear Engineering and Design)
5. Schneider and J.Luxat, "Natural Convection and Core Uncovery Analysis for the McMaster Nuclear Reactor", (Submitted to Annals of Nuclear Energy)
6. M. Ball, C. McEwan, J.C. Luxat, D.R. Novog, "The Dilution Dependency Of Multi-Group Uncertainties", Science and Technology of Nuclear Installations, Dec. 2014.
7. L. Xia, J. Jiang, and J.C. Luxat, "Power distribution control of CANDU reactors based on modal representation of reactor kinetics", Nuclear Engineering and Design, (278) May 2014.
8. A. Behdadi And J.C.Luxat, "Developments towards Mechanistic Modeling of Critical Heat Flux on a Candu Calandria Tube Following Pressure Tube Contact", Nuclear Technology, Vol 181, No. 1, pp 157-169, Jan 2013.
9. M. Gocmanac and J. C. Luxat, "Critical Heat Flux on a Downward Facing Surface with Obstructions", ANS Trans., Vol. 109, Washington DC, USA, November, 2013.
10. A. Morreale And J.C.Luxat, "Controllability and Relative Safety Evaluation Metrics for Advanced Fuel Cycles in Candu", Submitted To Annals Of Nuclear Energy, 2013
11. M. Ball, D.R.Novog and J.C. Luxat, "Analysis of Implicit and Explicit Lattice Sensitivities using DRAGON", Nuclear Engineering and Design, 2013.
12. A. Morreale, M. R. Ball, D. R. Novog And J. C. Luxat," The Behaviour of Transuranic Mixed Oxide Fuel In A Candu-900 Reactor", Nuclear Technology, July 2013
13. J.C. Luxat, "Accidents, Black Swans and Risk", Can. Nuclear Soc. Bulletin, July 2013

Referred Conference Proceedings

1. A, Schneider and J.Luxat, "Single-Phase and Two-Phase Natural Convection in the McMaster Nuclear Reactor", Proc. 16th International Conference on Nuclear Reactor Thermalhydraulics (NURETH16), Chicago, Illinois, June 2015.
2. A.C. Morreale and J.C. Luxat, "A Study on Optimal Age of Actinide Feedstock for use in Transuranic Mixed Oxide Fuels in CANDU Reactors", 35th Annual Conference of the Canadian Nuclear Society, St. John, NB, May, 2015.
3. J. Vecchiarelli, J. Luxat, D. Mullin, and E. Chan, "On the Concept of a Hierarchal Safety Goals Framework", Proc. International Workshop on Multi-Unit PSA, Ottawa, November 17-20, 2014.
4. J. Luxat, "The Challenges Of "Black Swan" Events: Risk Analysis and Nuclear Safety", Proc. IAEA Technical Meeting on Developing Methodologies for Complementary Assessment of Nuclear Power Plants' Robustness against the Impact of Extreme Events, Vienna, Austria, July 7th -11th, 2014.

5. J. Luxat, “Complementary Approaches for Risk Assessment and Management”, Proc. Int. Workshop on Whole-Site Risk Characterization of Nuclear Power Plants: Site Safety Goals and Holistic Approaches to Risk Assessment, Toronto, ON, January 14-15, 2014.
6. A.C. Morreale and J.C. Luxat, “The Effect of Actinide Composition on Transuranic Mixed Oxide Fuel Lattice Physics Parameters In CANDU”, Proc. 19th Pacific Basin Nuclear Conference (PBNC 2014), Vancouver, British Columbia, Canada, August 24-28, 2014.
7. Behdadi, F. Talebi and J.C. Luxat, "Critical heat Flux modeling on downward facing surfaces", Proc. 19th Pacific Basin Nuclear Conference (PBNC 2014), Vancouver, British Columbia, Canada, August 24-28.
8. A. Morreale, Y. Friedlander, J. C. Luxat, “Assessment of Advanced Fuel Cycle Options in CANDU Reactors”, Proc. GLOBAL 2013, Salt Lake City, Utah, USA, September 29 - October 5 2013.
9. J.C. Luxat, “Accidents, Black Swans and Risk”, 34th Annual CNS Conference, Toronto, June 2013 .
10. A.Morreale, D. Novog,and J.C. Luxat, “Assessment of a Transuranic Mixed Oxide Fuelled CANDU Reactor”, 34th Annual CNS Conference, Toronto, June 2013.

Technical Reports

1. J. Vecchiarelli, K. Dinnie and J. Luxat, “Development of a CANDU Whole-Site PSA Methodology”, CANDU Owners Group Report, COG-13-9034, December 2013.

Other Presentations

1. J. Luxat, et al, ““The CANS Post-Irradiation Examination Facility at McMaster University”, Proc. HOTLAB 2015, Leuven, Belgium, Sep. 27- Oct 1, 2015.
2. John C. Luxat, “The Case for New Nuclear”, Canadian Nuclear Society Bulletin, Vol 34, No. 4, pp. 5-10, Dec. 2013.
3. J.C. Luxat, “High Consequence/Low Frequency Events and the Limits to PRA”, COG External Hazards Workshop, Toronto, September 9 -10, 2013 (invited).
4. J.C. Luxat, “High Consequence/Low Frequency Events and the Limits to PRA”, COG Risk & Reliability Task Team, Toronto, October 2, 2013 (invited).
5. J.C. Luxat, “Energy Resilience, Global Challenges, and the Future of Nuclear Power”, Luncheon Keynote, Future of Nuclear Conference, Toronto, October 9, 2013 (invited)
6. J.C. Luxat, “Expert Review of Severe Accident Analysis Consequence Assessment” supporting Level 2 PRA’s for Darlington, Bruce B and Pickering A.

Interactions and Consultations

A large number or private and public consultations were performed ranging from technical consulting advisory work. A summary of these interactions are:

- Member, international Steering Committee, NURETH 17 Conference, to be held Sep. 3-8, 2017, X’ian, China.
- Member, McMaster Institute for Multi-Hazard Systemic Risk Studies, 2015.
- Chair, Independent Review Panel assessing performance of the Center for Nuclear Energy Facilities and Structures (CNEFS), NC State University, November 2 -4, 2015.
- Appointed Member & Vice-Chair, CSA N290B Technical Committee: Reactor Safety and Risk Management (May 2014). Developing nuclear standards CSA N290.16 – BDBA; CSA N290.17 – PSA; CSA N290.18 – PSR.

- Chair, CSA N290B Technical Sub-Committee developing nuclear standard CSA N290.18 – Periodic Safety Review.

- Member of Project Advisory Committee, the Sylvia Fedoruk Canadian Centre for Nuclear Innovation, Saskatchewan, June 2012.
- Independent Expert Review Panel Member, Darlington GAR/IIP Reports, OPG July/August 2013.
- Appointed Member of Project Advisory Committee, the Sylvia Fedoruk Canadian Centre for Nuclear Innovation, Saskatchewan, (2012-present).
- Independent Expert Reviewer:
    - AFCR Design Review, Candu Energy
    - Loss of Shutdown Analysis for EC-6, Candu Energy
    - Candu NUE Design Review, Candu Energy

- Member, Executive Committee, American Nuclear Society Thermal Hydraulics Division, 2009-2012.
- Member, Program Committee (2012- present) and Honours & Awards Committee (2012-.2017), American Nuclear Society Thermal Hydraulics Division,
- Board of Directors, American Association for Structural Mechanics in Reactor Technology (AASMiRT) , 2012 – present.
- Member Advisory Board, International Association for Structural Mechanics in Reactor Technology (IASMiRT) , renewed 2012
- Member, AECL Board of Directors, 2008 – October 2013
- Member, Human Resources and Governance Committee of the Board of Directors, Atomic Energy of Canada, Ltd., 2011 - 2013
- Chair, Ad-hoc Science, Technology and Nuclear Oversight Committee of the Board of Directors, Atomic Energy of Canada, Ltd., 2012
- Member (Advisory), COG Safety & Licensing Technical Committee

<u>Other</u>

- Elected Fellow, The Canadian Academy of Engineering (CAE), June 2012
- Elected Member, The International Nuclear Energy Academy (INEA), September 2012
- Awarded American Nuclear Society Thermal Hydraulics Division Technical Achievement Award, November 2012

McMaster University – David Novog IRC

UNENE/NSERC IRC Program: Nuclear Reactor Safety and Thermalhydraulics

Overview

The NSERC Industrial Research Chair renewal is intended to expand on existing strengths and talents to undertake a major research endeavour in science and engineering of interest to industry. The program is supported by the federal government through the Natural Sciences and Engineering Research Council (NSERC) of Canada and by a consortium of industrial partners with an interest in nuclear energy. McMaster was fortunate to recruit two high profile industry leaders as a direct result of the NSERC-UNENE program and over the first and second terms, the program has been extremely successful. This success and the subsequent growth of R&D have solidified McMaster as a Canadian leader in this field. The success has given rise to two IRCs at McMaster, the original Chair Prof. J.C. Luxat, and the newly appointed senior Chair D.R. Novog.

Dr. Novog has emerged as one of the top R&D faculty in Canada within Nuclear Engineering in terms of Highly Qualified Personnel (HQP) training and research output. He is frequently called on by the public, media and industry to provide expert opinions on nuclear safety, including international collaborations with the International Atomic Energy Agency (IAEA) and activities within the Organisation for Economic Co-Operation and Development(OECD). His HQP have received several prestigious awards, and his students have won best paper and scholarship competitions at both the national and international level.

The high level objectives of the NSERC-UNENE Senior Industrial Research Chairs in nuclear safety and thermalhydraulics are to:

1. Develop and enhance analysis methodologies in the area of nuclear safety analysis with a focus on improving nuclear safety, accident analyses and uncertainty estimation.
2. Support the development of severe accident analysis methodologies and mitigation strategies.
3. Perform fundamental and applied research and development in the areas of thermalhydraulics under normal and accident conditions and assess the potential for improved reactor output.
4. Support assessment of fuel and fuel channel integrity under accident conditions.
5. Train the next generation of Highly Qualified Personnel for the nuclear industry.
6. Provide expertise to the university, government and the public in the area of nuclear safety.

Program Results /Highlights

Funding for the Associate Chair Term II was completed in April 2015 and the application process for promotion of Dr. Novog to Senior IRC and the renewal of Dr. Luxat's Senior IRC was successful with a start date of January 1, 2016. The successful application was possible only with the strong support of UNENE and the nuclear industry in Canada. A major activity in 2015 in addition to the Chair renewal was related to moderator subcooling in Bruce A and Pickering A (funded separately by COG). This work provided funding and support during the period off 2015 while the NSERC approval of the Chair renewal was being processed.
A total of 9 HQP graduated from my group in 2014/2015 with a majority working in nuclear or nuclear related sectors. There are 14 HQP currently in my group (8 MASc, 5PhD and 2 PDF). Research leveraging has been very successful in 2014/2015 including the recently completed NSERC-COG CRD ($500000), NRCAN-NSERC-AECL GEN IV award ($320000), MITACS ($90000), and CNSC ($50000).

Cases with Realized outcomes to Industry

- Enhanced operating flexibility and reactor output by exploring alternative methodologies to enhance safety margins. Prof. Novog is an external expert on trip setpoint calculations and statistical methodologies and has in the past supported the original implementation of EVS (2004) for Bruce Power and OPG Neutron Overpower Protection. In 2015, the CNSC issued a letter providing positive indication of acceptance for EVS2010. Through AMEC-FW, Prof. Novog is consulting in 2016 to ensure the remaining issues from the CNSC expert consultant's report issued in 2013 have been successfully dispositioned.

- Early stage severe accident modelling, core disassembly, operator intervention, and mitigation. Figure 1 shows the results of RELAP5 simulations of the unmitigated response to a complete station blackout (SBO). This work couples RELAP with pressure-tube, Calandria-tube and core disassembly models to predict the relevant phenomena over a range of initial reactor conditions. The work was initiated in 2015 and will continue in 2016 and provides alternative methodologies to codes like MAAP4-CANDU.

- Safety of advanced fuel cycles in CANDU reactors. In 2015/2016 Dr. Novog initiated work on Accident Tolerant Fuels in CANDU along with N. Onder of CNL. This includes examining both GENIV ATF and GEN III ATF designs for use in existing GEN II reactors. This work requires advanced codes like SERPENT and our experience with the code in the NRCAN-NSERC-AECL program (see Figure 4 for example) has provided us a platform for the ATF work. Continuing in 2016 are full core simulations and subchannel (COBRA-TF) simulations to determine the potential benefits of the ATF fuel designs.

- Experiments, model development and analysis to support improved accuracy and uncertainty quantification for fuel and channel integrity. A major activity in 2015 was related to moderator subcooling in Bruce A and Pickering A and funded separately by COG. A new facility was designed constructed and commissioned which can perform both the required COG tests as well as NSERC-UNENE tests of calandria tube-moderator heat transfer. A large number of scaled and separate effect tests were completed in 2015 including Pickering A inlet diffuser characterization (Figure 2), mixed convective flow around a Calandria tube (Figure 3) and Bruce A inlet port cauterization. The tests will continue in 2016.

• Application of new toolsets and methodologies to CANDU in support of refurbishment and long term code replacement. Prof. Novog plays a key role in computational tool assessment, in particular for assessment of codes such as RELAP5, TRACE and R7 in thermalhydraulics, DONJON, SERPENT in reactor physics as contenders for the next generation IST toolset. In 2016 Dr. Novog provided expert review of COG's vision and strategy for IST toolset replacement.

• Uncertainty analysis methods and covariance, participation in the OECD-NEA international benchmarks. Out involvement has focused on lattice physics uncertainty propagation (which initiated with a previous PhD student Dr. M. Ball). This work aligns with interest and proposed COG funding in this area as well as with tool development of the SCALE/TSUNAMI code system.

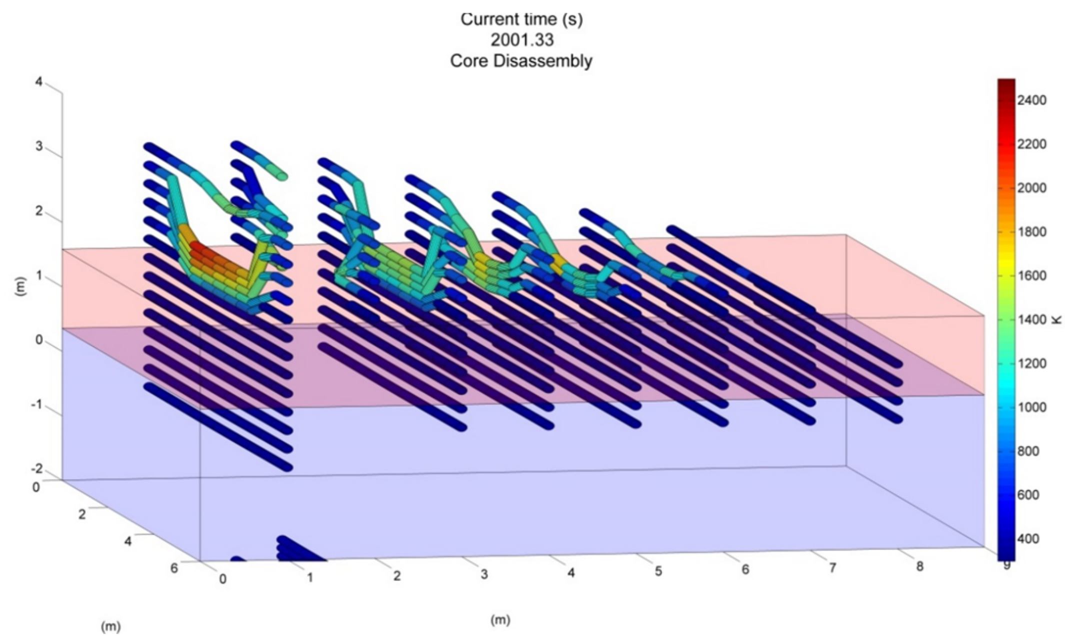


Figure 1: RELAP5/SCDAP Prediction of Fuel Channel Deformation During a Postulated Station Blackout without Emergency Mitigating Equipment (30000s from start of event).

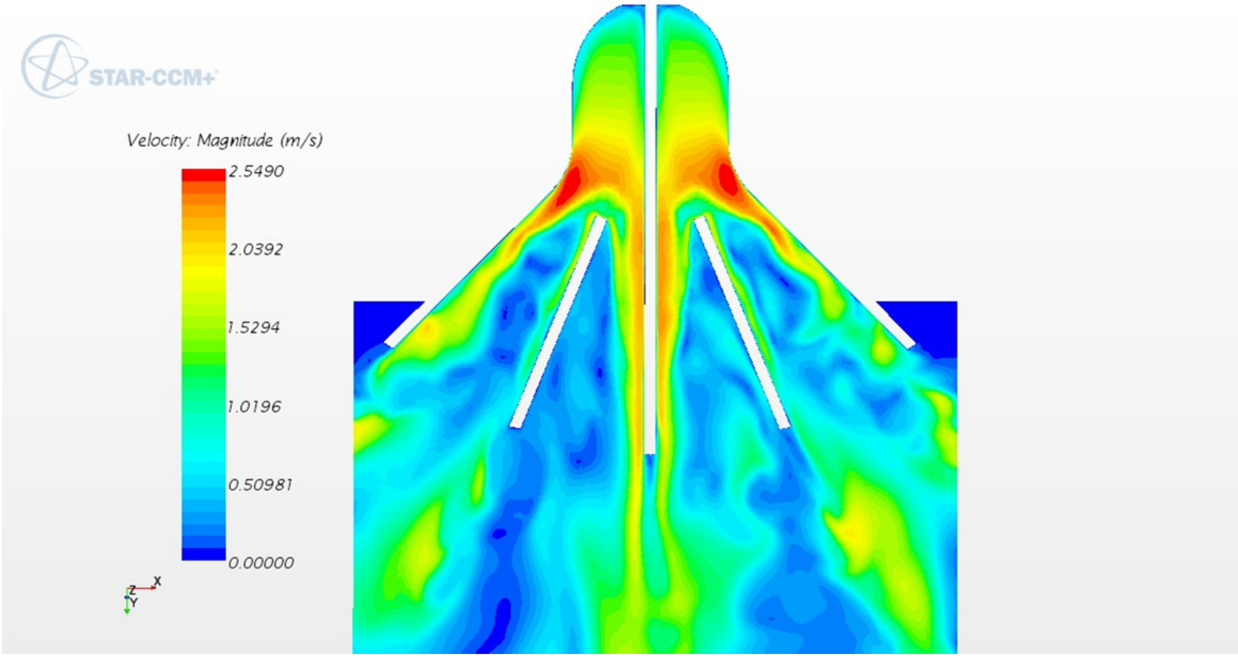
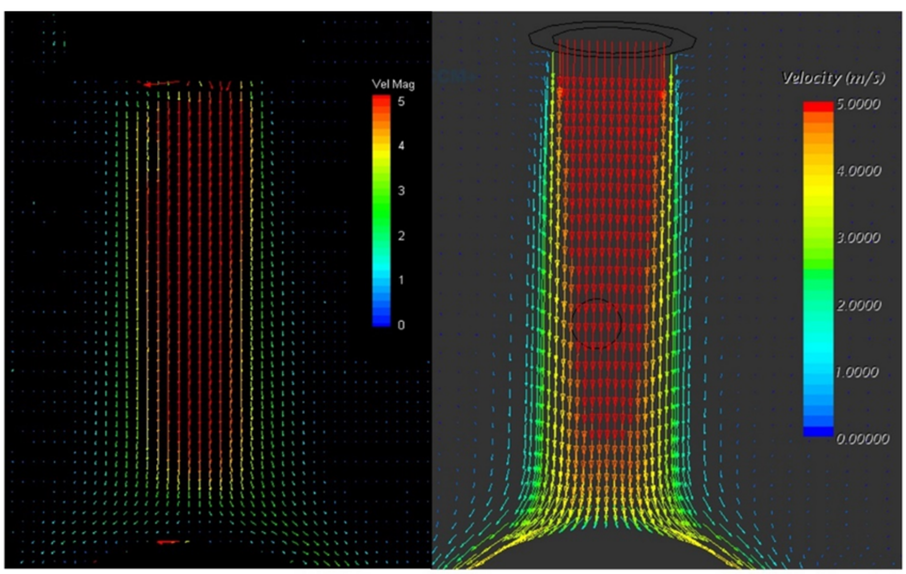


Figure 2: CFD Prediction of the Experimental Pickering A Inlet Diffusers for the COG Sponsored Moderator Flow Tests.



Isothermal Jet Impingement onto Cylinder a) Experimental PIV Results, b) Standard k-ε model CFD

Figure 3: PIV Measurements of Round Jet Impingement on an Unheated Calandria Tube (left) vs. CFD (right) in support of separate-effect testing in the COG sponsored Moderator Flow Tests.

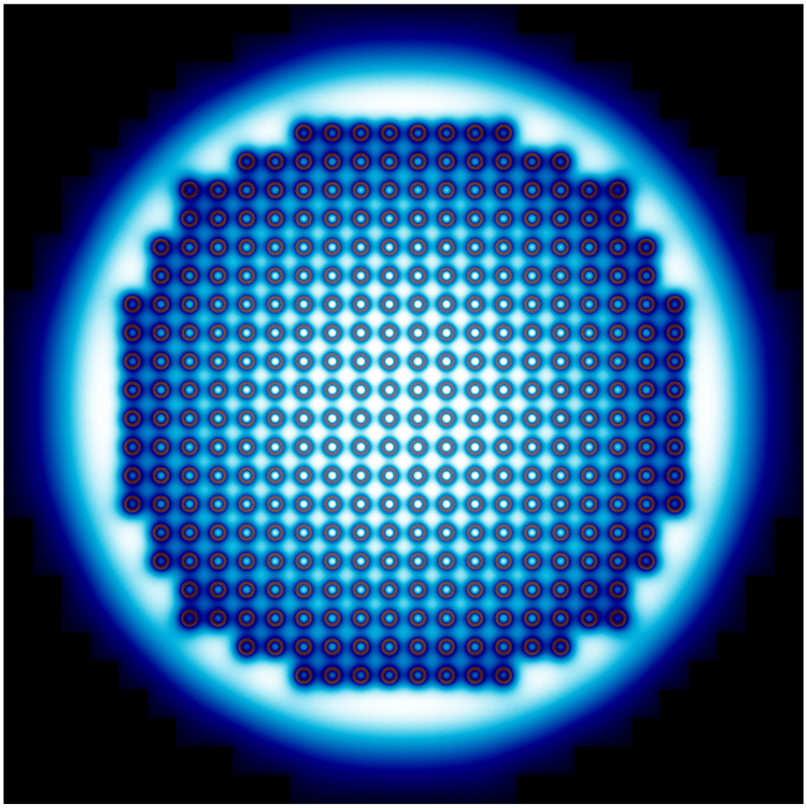


Figure 4 SERPENT Full Core Simulations of the Canadian SCWR Reactor Sponsored by NRCAN-NSERC-AECL.

<u>Research Facilities and Equipment</u>

Flexible transient CHF and PDO test facility (up to 16MPa and fast blowdown, power or flow transients).
Moderator test facility – 1/16 scale facility for moderator temperature and flow measurement.
Separate effect test facility – tube bank, single tube, interfacial measurements under isothermal conditions.
High velocity isothermal test loop (funded my McMaster Nuclear Reactor) – flow up to 25 kg/s.
Time Resolved Practical Image Velocimetry – 2D planner imaging of flow and turbulence
Laser Doppler Anemometer – 2 and 3 dimensional point velocity and turbulence measurements
Laser Induced Fluorescence – 2d non-intrusive temperature mapping

<u>Current HQP</u>

- Justin Spencer (PhD part-time) – Critical Heat Flux in End-Shields to support severe accident phenomena
- James Strack (PhD) – Measurement of moderator temperature and flow for Bruce A and Pickering A (COG funded).
- Ahmad Mogharabi (PhD) – Advanced lattice physics modelling
- Frederic Salaun (PhD) – Reactivity control and flux shaping in advanced reactors.

- Feng Zhou (PhD) – Severe accident analysis
- Kendal Boniface (MASc) – Simulation of intermittent flow in RELAP5
- Chris Hollingshead (MASc) – Flow distribution measurement and simulation in Bruce A moderator inlets.
- Travis Sheashgreen (MASc) – Flow distribution measurement and simulation in Pickering A inlet diffusers.
- David Joyal (MASc) – Measurement and simulation of mixed buoyant and inertial flows in geometries relevant to a CANDU calandria.
- Graik Patterson (MASc) – Transient CHF testing
- Simon Younan (MASc) – CANDU accident tolerant fuels
- Liz MacConnachie (MASc) – Calandria tube bank boiling heat transfer
- Pan Wu (Post Doc) – transient CHF measurement
- Erwin Elhassan (Post Doc) – McMaster Reactor Physics Core Follow

HQP that Graduated in 2014/2015

- Ken Leung – RELAP5 and interfacial area measurements (employed at Bruce Power).
- David Hummel – SCWR reactor physics (employed at CNL).
- Brad Statham – Scimetric (test and development group)
- D. McClure – Kinectrics
- Mengmeng Lou – Financial services
- Paul Szymanski – CNSC
- Curtis McCewan – Bruce Power
- Fabricia Pinero – Candu Energy Inc.
- Yang Wu – PhD at University of Tokyo

Publications /Journal Papers

1. M. Rohde, J. W. R. Peeters, A. Pucciarelli, A. Kiss, Y. F. Rao, E. N. Onder, P. Mühlbauer, A. Batta, M. Hartig, V. Chatoorgoon, R. Thiele, D. Chang, S. Tavoularis, D. Novog, D. McClure, M. Gradecka and K. Takase, A Blind, Numerical Benchmark Study on Supercritical Water Heat Transfer Experiments in a 7-Rod Bundle", Journal of Nuclear Engineering and Radiation Science, Vol. 2, Iss. 2, 2016.
2. A.Moghrabi, D.R. Novog, "Lattice Physics Characteristics of the Canadian SCWR", Nuclear Review, 2016.
3. F. Salaun and D.R. Novog "Optimization of the Control Blade Sequence for the Canadian SCWR Using PARCS/RELAP5 and DAKOTA", accepted for publication in Nuclear Review, 2016.
4. D. Hummel and D.R. Novog, "Analysis of Shutoff Rod Effectiveness During A Loss of Coolant Accident Using Coupled Thermalhydraulics and 3-Dimensional Neutron Kinetics", accepted to Nuclear Review, 2016.
5. B. Statham and D.R Novog, "Effect of Pressure Transients on the Critical Heat Flux in Water", submitted to Nuclear Engineering and Design, 2016.
6. F. Zhou, D.R. Novog, C. Allison, "Validation of a Coupled RELAP5-Thermomechanical Deformation Model for Prediction of Early Phase Severe Accidents in CANDU Reactors" (submitted to Science and Technology of Nuclear Installations, 2016).
7. M. Tucker, R. Laurent, D.R. Novog, " Use of SERPENT generated cross sections for CANDU Ful Core Reactor Physics Simulations", (submitted to Nuclear Technology 2016).
8. M. Ball and D.R. Novog, "Propagation of Nuclear Data Uncertainties Through Lattice and

Core Physics Calculations for a CANDU Reactor" (in preparation for Nuclear Engineering and Design 2016).
9. D. Hummel and D.R. Novog, "Coupled 3D Neutron Kinetics and Thermalhydraulic Characteristics of the Canadian Supercritical Water Reactor", Nuclear Engineering and Design, 2015.
10. F. Zhou and D.R. Novog, "RELAP5 Simulation of CANDU station blackout Accidents with/without external water make-up", Pacific Basin Nuclear Conference, China, 2016.
11. B.Statham, D. R. Novog, "Transient Critical Heat Flux Measurements during Blowdown", Proc. 36th Annual Conference of the Canadian Nuclear Society, Toronto, ON, Canada, June 19-22, 2016.
12. F. Zhou, D.R. Novog, C. Allison, "Coupling RELAP5 to Fuel Channel Mechanistic Modelling for Severe Accident Analysis", Proc. 36th Annual Conference of the Canadian Nuclear Society, Toronto, ON, Canada, June 19-22, 2016.
13. M. Lou, D.R. Novog, C. Allison, "RELAP5 MOD4 Analysis of the Canadian SCWR to Loss of Coolant Accidents", Proc. 36th Annual Conference of the Canadian Nuclear Society, Toronto, ON, Canada, June 19-22, 2016.
14. J. Sharpe, F. Salaun, D. Hummel, A. Moghrabi, W. Ford, M. Nowak, J. Pencer, D.R. Novog and A. Buijs, "A Benchmark Comparison of the Canadian Supercritical Water-cooled Reactor (SCWR) 64-element Fuel Lattice Cell Parameters using Various Computer Codes", Canadian Nuclear Society Annual Conference 2015.
15. M. Rohde, J. W. R. Peeters, A. Pucciarelli, A. Kiss, Y. F. Rao, E. N. Onder, P. Mühlbauer, A. Batta, M. Hartig, V. Chatoorgoon, R. Thiele, D. Chang, S. Tavoularis, D. Novog, D. McClure, M. Gradecka and K. Takase, A Blind, Numerical Benchmark Study on Supercritical Water Heat Transfer Experiments in a 7-Rod Bundle", 5th International Symposium on Supercritical Water-cooled Reactors, Helsinki, 2015.
16. D.R. Novog, Y. Wu, "Response of the Canadian SCWR to Loss of Offsite Power and Station Blackout", the 5th International Symposium on Supercritical Water-cooled Reactors, Helsinki, 2015.
17. D. Hummel, D.R. Novog, "Coupled 3D Neutron Kinetics and Thermalhydraulic Characteristics of the Canadian SCWR", the 5th International Symposium on Supercritical Water-cooled Reactors, Helsinki, 2015.
18. F. Salaun, J. R. Sharpe, D. W. Hummel, A. Buijs, D. R. Novog, "Optimization of the PT-SCWR Control Blade Sequence using PARCS and DAKOTA", the 5th International Symposium on Supercritical Water-cooled Reactors, Helsinki, 2015.

Interactions /Consultations to Industry

- Independent expert review of COG Integrate IST vision and strategy (2016).
- Review of dispositions to CNSC consultants report on EVS 2010/EVS2011 (2016)
- Member (Advisory), COG Safety & Licensing Technical Committee
- IAEA Collaborative Research Project Expert (2012-2015).
- Technical Committee member for the American Nuclear Society Physics (PHYSOR) and Thermalhydraulics (NURETH) Conferences
- CNS Conference technical committee, CNS student conference technical committee (2009-2016).

University of Toronto – Roger C. Newman IRC

UNENE/NSERC IRC Program: Corrosion Control and Materials Performance in Nuclear Power Systems

Overview

This IRC program is in its third 5 year term, which began in September 2014. The research focuses on mechanisms, prediction and control of metallic corrosion, with ancillary activities such as electrodeposition, studies of hydrogen in pressure tube material, and electrochemical condition monitoring generally. The materials studied range from industrial alloys through pure laboratory melts to simulated alloy lattices.

The IRC research takes place alongside a number of other corrosion activities (e.g. corrosion aspects of nuclear waste management; corrosion in supercritical water under the NSERC-NRCan-AECL Generation IV nuclear program). Roger Newman also holds NSERC Discovery and Discovery Accelerator grants for research in nanoporous metals. Collaborations are under way with most local universities that have UNENE programs (McMaster, Western, Queens, Waterloo), as well as internationally (Johns Hopkins, Manchester, Arizona State, etc.).

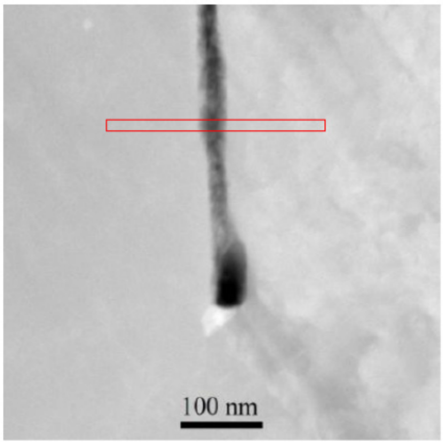
2015 Highlights

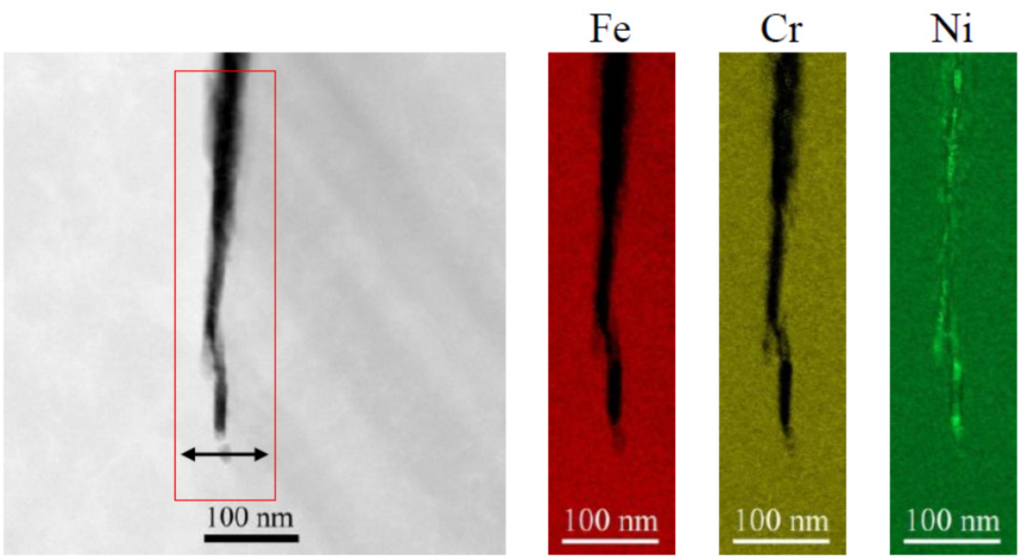
Continuing PhD students produced high-quality output in the high-resolution characterization of cracks and surface corrosion, often in collaboration with the CCEM, McMaster University, using analytical electron microscopy and atom-probe tomography (APT). The unpublished results of Suraj Persaud on APT of alloy oxidation, shown in last year's annual report, have been accepted for publication in *Acta Materialia*. Alongside the continuing students, a group of new MASc students joined in September 2015, working on a diverse range of topics, including lead effects on corrosion, internal oxidation, and the stability of sulfate in steam generator crevice environments (and the effects of the resulting reduced sulfur species).

The high-resolution characterization of cracks is of keen interest to industry, especially the achievement of relatively routine cross-sections of crack tips and subsequent TEM study. In the coming years, such studies will become routine for the analysis of plant artefacts, a huge leap forward compared with the conventional SEM era.

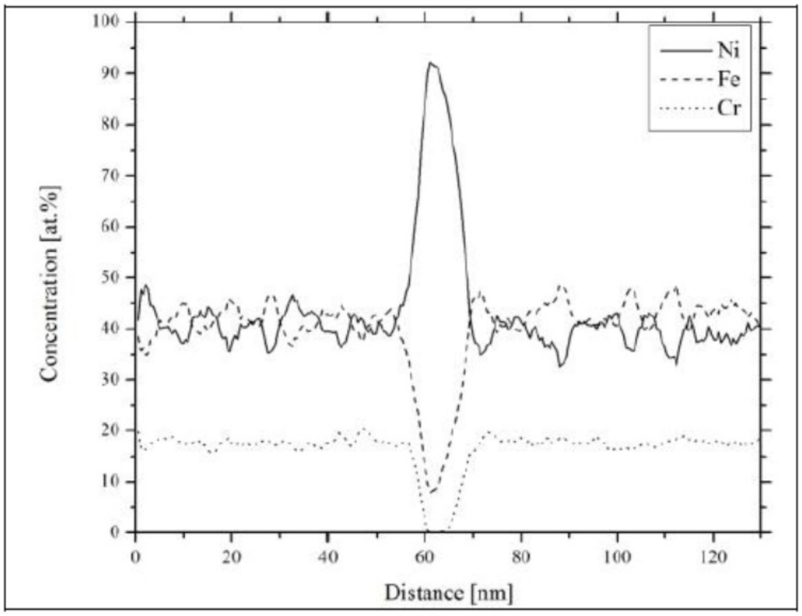
There are strong synergies between the IRC research and the group's research on nanoporous metals. MASc student Ayman El-Zoka is plating foreign metals into nanoporous metallic corrosion products, so that they can be interrogated by APT without fracturing under the stresses inherent in this technique. Again, in future this will lead to advances in the nanoscale study of important plant-related phenomena.

A new example of a stress corrosion crack section is shown in the figures below (PhD student Mariusz Bryk, and CCEM). The material was Alloy 800, exposed to a caustic solution at 280°C. The crack growth proceeds by dealloying of Fe and Cr, leaving a Ni-rich nanoporous layer (light contrast in the first image) that triggers the next crack advance.





The next figure shows the composition profile along the arrowed line in the second image -



The Research Group and its Facilities

As of December 2015, the group consisted of 4 PhD students, 6 MASc students, 1 postdoctoral fellow, and 2 Senior Research Associates. Several undergraduates and MEng students also contributed. About 2/3 of this effort was supported by the IRC program.

The group is well equipped for electrochemistry and microscopy, including atomic force microscopy, and has a growing facility for high-temperature, high-pressure testing in water, steam or aqueous solutions. An Arcast cold-crucible induction melter was ordered in 2015 and will be delivered and commissioned in mid-2016. A new feature this year is the plan for a rapid increase in the exploitation of the recently acquired OCCAM facility for electron microscopy and surface science. Particular students are being trained to use some of the advanced methods personally.

Three recent graduates (Adrian Vega, Jagan Ulaganathan, Suraj Persaud) are now working at Canadian Nuclear Laboratories.

Examples of Specific Industry Interactions

There has been continuing consulting assistance to OPG in the area of electrochemical monitoring in reinforced concrete for life prediction of dry storage containers for used nuclear fuel. The contractor started site work in 2012, and data are being analyzed as they are produced.

Roger Newman was closely involved in national and international collaborative meetings organized by COG and CNL personnel, on stress corrosion cracking in particular, and gave ad hoc advice to OPG and others on plant issues.

Public Output

Roger Newman gave invited presentations at the following events –

S.Y. Persaud and R.C. Newman, Advanced Characterization of Stress Corrosion Cracking Precursors in Nickel Base Alloys, *EDSA 2015*, Chennai, India, February 2015.

W. Zhang, A.G. Carcea and R.C. Newman, Pitting of steam-generator tubing alloys in solutions containing thiosulfate, and sulfate or chloride, *Faraday Discussion: Corrosion Chemistry*, London, UK, April 2015.

S.Y. Persaud and R.C. Newman, Advanced Characterization of Stress Corrosion Cracking Precursors in Nickel Base Alloys, *Nuclear Stress Corrosion Cracking Workshop (One-day International Meeting)*, Manchester, UK, April 2015.

Numerous contributed talks and posters were given by members of the group at academic and industrial events, notably the following talk given by Suraj Persaud –

S.Y. Persaud, B. Langelier, R.C. Newman, G.A. Botton, A Study on the Oxidation Behaviour of Nickel Alloys and the Likely Effect on PWSCC Susceptibility, Proc. 17th Int. Int. Conf. on Environmental Degradation of Materials in Nuclear Power Systems–Water Reactors, Ottawa, August 2015.

The following journal articles were published or accepted, in addition to various conference and workshop papers, and major contract reports for NWMO and Nagra (Switzerland) –

S.Y. Persaud, S. Ramamurthy, and R.C. Newman, Internal oxidation of alloy 690 in hydrogenated steam, *Corros. Sci*., 90, 606-613 (2015).

N.S. McIntyre, J. Ulaganathan, T. Simpson, J. Qin, N. Sherry, A.G. Carcea, R.C. Newman, M. Kunz, and N. Tamura, Microscopic Cracking on Flat Alloy 600 Surfaces Following Accelerated Caustic Corrosion: Mapping of Strains and Microstructure During the Corrosion Process, *Corrosion*, 71, 65-70 (2015).

S.Y. Persaud, A.G. Carcea, and R.C. Newman, An electrochemical study assisting the interpretation of acid sulfate stress corrosion cracking of NiCrFe alloys, *Corros. Sci*., 90, 383-391 (2015).

S.Y. Persaud, S. Ramamurthy and R.C. Newman, The Effect of Weld Chemistry on the Oxidation of Alloy 82 Dissimilar Metal Welds, *Corros. Sci*., 91, 58-67 (2015).

W. Zhang, A.G. Carcea and R.C. Newman, Pitting of steam-generator tubing alloys in solutions containing thiosulfate and sulfate or chloride, *Faraday Discussion 180*, “Corrosion Chemistry”, 233-249 (2015).

S.Y. Persaud, R.C. Newman, A. Korinek, G.A. Botton, The influence of the high Fe and Cr contents of Alloy 800 on its inter- and intragranular oxidation tendency in 480°C hydrogenated steam, *Corros. Sci.,* accepted.

S.Y. Persaud, R.C. Newman, J. Smith, A. Korinek, G.A. Botton, High resolution analysis of oxidation in Ni-Fe-Cr alloys after exposure to 315°C deaerated water with added hydrogen, *Corros. Sci*., accepted.

B. Langelier, S.Y. Persaud, R.C. Newman, G.A. Botton, An Atom Probe Tomography Study of Internal Oxidation Processes in Alloy 600, *Acta Materialia*, accepted.

University of Waterloo – Mahesh D. Pandey IRC

UNENE/NSERC IRC Program: Risk-Based Life Cycle Management of Engineering Systems

Overview

The main research objective of the Waterloo Chair program is to improve the life cycle management of nuclear plant systems through the development and application of advanced risk and reliability models. Another important objective is the training of HQP for the industry. The key research areas include reliability analysis, statistical estimation, aging management, site-wide hazard aggregation, common cause failures in PSA and generation risk assessment. Practical applications of the basic research include fuel channels, feeders, steam generators and other important systems, structures, and components. The Waterloo Chair program was successfully renewed for the third five year phase in March 2015. Key industry-related projects undertaken in 2015 are summarized in the next Section.

Research Program and Outcomes

Optimizing Feeder Weld Inspections

Wall Thickness Prediction at the Grayloc Weld
The 6-probe ultrasonic tool is used for feeder wall thickness inspections near the Grayloc weld. However, due to design and operational limitations, the tool can, at best, measure the wall thickness at ≥ 1.75 mm axial distance away from the weld. Because the wall thickness is trending negatively toward the Grayloc weld for many feeders, it is important to estimate the minimum thickness (T_0) immediately adjacent to the weld.

In this project, the wall thickness at the weld was estimated using spatial statistical analysis methods applied to the sparse data in the 6-probe trending file. Figure 1illustrates the analysis results for a sample feeder. The main benefit of the developed methodology, besides accounting for both local and global changes in wall thickness across the original trending file, is that it allows the reliable prediction of T_0 at the Grayloc weld using the vast amount of existing 6-probe inspection data, and therefore reduces the need for extensive inspections using other more costly methods, such as the MIT weld inspection tool.

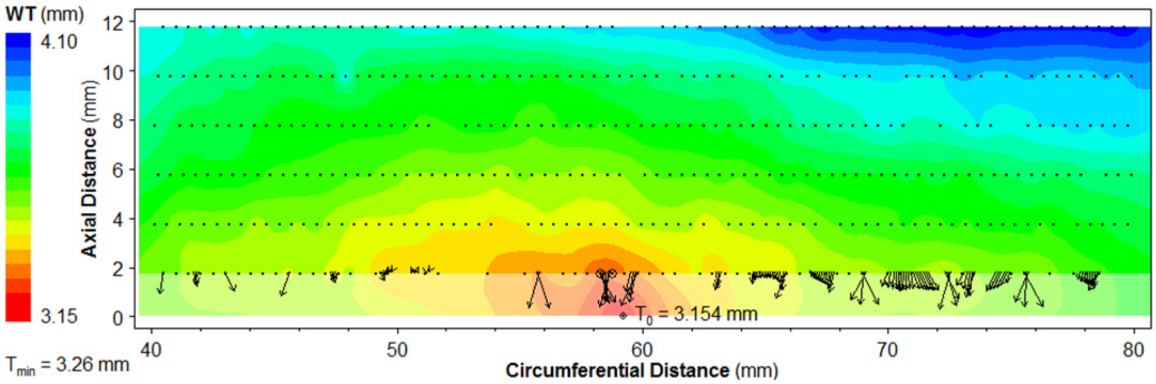


Figure 1: Prediction of minimum wall thickness (T_0) at the edge of the Grayloc weld for a sample outlet feeder.

Probabilistic Fitness-for-Service Assessment

The MIT feeder weld inspection tool is planned to be deployed in upcoming outages at Darlington station. Due to its improved capability, there is a concern that it may find a lower wall thickness as compared to current predictions based on the 6-probe. To support the risk assessment, we analyzed previous inspection data from Pickering reactors to characterize the probability associated with the difference between the two inspection techniques. The developed distribution was then used to predict the risk associated with the upcoming inspections, both in terms of the risk of discovering a non-compliant feeder, as well as the probability of fitness-for-service of the uninspected feeder population.

Figure 2 shows the impact of the inspection sample size on the overall plant risk prior to refurbishment. It is evident that a very high level of risk reduction can be achieved by the inspection of only a small portion of the overall feeder population (each Darlington unit has a total of 480 outlet feeders).

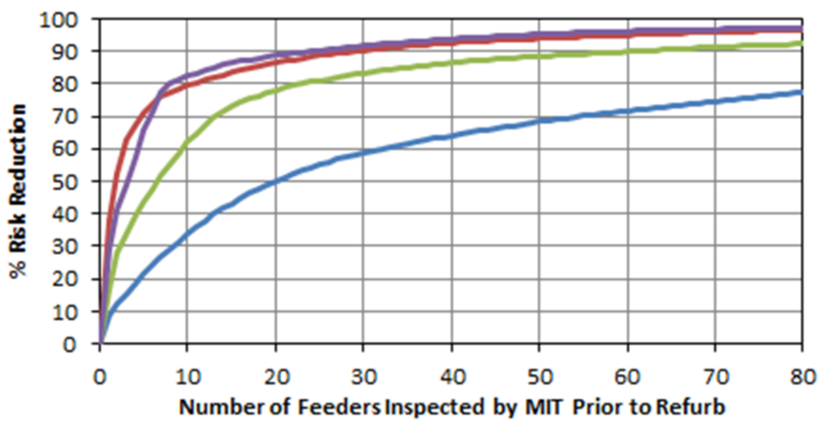


Figure 2: Impact of inspection sample size on overall plant risk. Each line represents a different reactor unit.

Life Cycle Management of PHT Pump Motors

The primary heat transport (PHT) pumps circulate the pressurized heavy water coolant through the reactor fuel channels. Each pump is driven by a large motor, whose failure results in an immediate forced outage. The main concern is the aging degradation of the motor winding insulation over time, which results in an increased chance of failure in the future.

The main objective of this on-going project is to estimate appropriate failure rates (i.e., probabilistic models) for the PHT pump motors at Darlington station using both station specific and industry generic data, and to predict the long-term operating risk and optimal timing and strategy for motor replacement. The replacement of each motor is impacted significantly by high cost (several $ millions) and long procurement/refurbishment times (up to a year or more).

Figure 3 shows the preliminary results for the overall breakdown in risk associated with the Base Case planning scenario. As shown in Figure 3, the highest risk is associated with winding and bearing failures, with the other failure modes having a significantly smaller impact. The planned motor replacements (i.e., during Darlington refurbishment) also add considerably to the overall risk, mainly due to the high replacement cost of each motor.

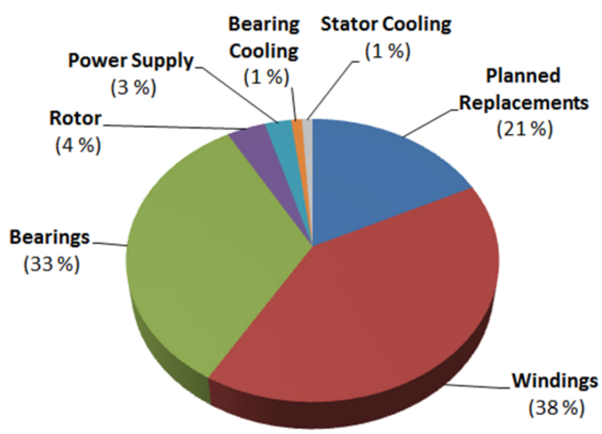


Figure 3: Preliminary risk breakdown for the Base Case planning scenario.

<u>Other Projects</u>

- Probabilistic modelling of optimized Inconel spacer degradation
- Review of probabilistic PT-CT contact assessment methodology
- Prediction of creep deformation in CANDU 6 fuel channels
- Administration and updating of an interactive website for IAEA-CRP for the analysis of pressure tube diametral creep
- Review of plant aging management risk ranking methodology for Darlington station
- Uncertainty analysis of thinning rates for Darlington feeders
- Data visualization software for degradation assessment transferred to OPG
- Drafting of CSA standard for PSA in nuclear power plants

- Compliance with environmental standards: Impact of Darlington and Pickering discharge on aquatic life

Benefits to the Industry

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

Research Team

Current Team
PhD – 7, MASc – 3, PDF – 2, Research Associates – 1, Research Engineer – 1

Employment of students after completing the training:
- Pacific Northwest National Laboratory, Canadian Nuclear Safety Commission (CNSC), Ontario Power Generation (OPG)

Publications

Selected Journal Papers

(1) Jyrkama, M.I., Bickel, G.A. and Pandey, M.D. (2016). Statistical analysis and modelling of in-reactor diametral creep ofZr-2.5Nb pressure tubes. Nuclear Engineering and Design, 300, 241-248.
(2) Jyrkama, M.I. and Pandey, M.D. (2016). On the separation of aleatory and epistemic uncertainties in probabilistic assessments. Nuclear Engineering and Design, 303, Pages 68-74.
(3) Jyrkama, M.I, Pandey M.D., Angell P., and Munson, D. (2016). Estimating External Corrosion Rates for Buried Carbon Steel Piping in Different Soil Conditions. Accepted for publication in *AECL Nuclear Review*, April 1, 2016.
(4) Pandey, M.D. Cheng, T.J. and van der Weide, J.A.M. (2016). Higher Moments and Probability Distribution of Maintenance Cost in the Delay Time Model. Journal of Risk and Reliability Analysis, 1748006X16641767, first published on April 25, 2016
(5) van der Weide, J.A.M. and Pandey, M.D. (2015). A stochastic alternating renewal process model for unavailability analysis of standby safety equipment. *Reliability Engineering and System Safety*, 139, 97-104.
(6) Balomenos, G.P. and Pandey, M.D. (2015). Finite element reliability and sensitivity analysis of structures using the multiplicative dimensional reduction method. Accepted for publication in J. Structure and Infrastructure Engineering.
(7) Higo, E. and Pandey, M.D. (2015). A Required Level of Enhancing Life Safety Derived from the Cost for Substituting Nuclear Energy in Japan. Journal of Integrated Disaster Risk Management, 5(2), 153-165.
(8) Jiang, W., Li, B., Xie, W.C. and Pandey, M.D. (2015). Generate floor response spectra: Part 1. Direct spectra-to-spectra method. Nuclear Engineering and Design, 293, 525-546.

(9) Li, B., Jiang, W., Xie, W.C. and Pandey, M.D. (2015). Generate floor response spectra: Part 2. Response spectra for equipment-structure resonance. Nuclear Engineering and Design, 293, 547-560.

Selected Conference Papers/Presentations/Industry Reports

(10) Daigle, O.D. and Pandey, M.D. (2016). Corrosion of coated pipe samples: an overview and statistical analysis of NBS-API data. PVP2016-63981, pp.1-8: ASME-PVP Conference, July 17–21, 2016, Vancouver BC.
(11) Munson, D., Pandey, M.D., Jyrkama, M.I., Angell, P. (2016). Historical Rates of Soil Side Corrosion for Use in FFS Evaluations of Buried Metallic Pipe. PVP2016-63923. ASME-PVP Conference, July 17–21, 2016, Vancouver BC.
(12) Tsembelis, K., Eom, S., Jin, J., Pandey, M.D. and Christodoulou, N. (2016). A case study on the normality of the Monte-Carlo simulation results. PVP2016-63622: ASME-PVP Conference, July 17–21, 2016, Vancouver BC.
(13) Pandey, M.D. Wang, Z. and Cheng, T.J. (2015). Stochastic Process Models for Life Cycle Cost and Utility Analysis, pp.1-8. 12th Int. Conf. Applications of Statistics and Probability in Civil Engineering, ICASP12. Vancouver, Canada, July 12-15, 2015.
(14) Raimbault, J.R., Walbrudge, S. And Pandey, M.D. (2015). Application of the Multiplicative Dimensional Reduction Method (M-DRM) to a Probabilistic Fracture Mechanics Problem. Page 1-8, 12th Int. Conf. Applications of Statistics and Probability in Civil Engineering, ICASP12. Vancouver, Canada, July 12-15, 2015.
(15) Ni, S., Cai, Z., Xie, W.C., Pandey, M.D., Liu, W. and Han, M. (2015). Seismic fragility analysis for structures, systems, and components of nuclear power plants: part 1 —issues identified in engineering practice. Proc. SmiRT- 23, pp.1-9. Manchester, United Kingdom, August 10-14, 2015.
(16) Cai, Z., Ni, S., Xie, W.C., Pandey, M.D., Liu, W. and Han, M. (2015). Seismic fragility analysis for structures, systems, and components of nuclear power plants: part ii —use of multiple ground-mottion parameters. Proc. SmiRT- 23, pp.1-10. Manchester, United Kingdom, August 10-14, 2015.

<u>Interaction with Industry</u>

- Participation in COG projects with industry partners
- Member of CSA technical subcommittee for the development of the new standard N290.17 “Probabilistic safety assessment for nuclear power plants”
- Organization of Workshops and Conferences
    - Workshop in ”Probabilistic Methods for Nuclear Research” with CNL staff in January 2015
    - Risk and reliability workshop with CNSC staff in May 2015
    - Development of training courses in collaboration with OPG and COG on the ”Modelling of Common Cause Failures in PSA” and ”Fundamentals of Seismic PSA” to be delivered in 2016

UOIT – Anthony Waker IRC
– Edward Waller (Associate IRC)

UNENE/NSERC IRC Program: Health Physics and Environmental Safety

Overview

Research directed towards the enhancement of radiation protection through studies in radiation measurement, radiation effects and radiation field modelling and visualization remains at the core of the 2015 IRC in Health Physics and Environmental Safety at UOIT. April 2015 marked the beginning of the 2nd year of the renewed IRC and, added to the scope of research already established, work has been initiated on establishing methods and facilities for the study of environmental dosimetry for non-human biota. Attention has also been directed to the recently emerging issue of eye dosimetry resulting from the expected lowering by the Canadian Nuclear Safety Commission of the annual eye-dose limit from 150 mSv to 20 mSv.

During the period January 2015 to December 2015 we graduated 5 HQPs at the MASc. level; and at year's end 16 HQPs were still in training: Senior Chair – 1PDF; 2 PhD; 1 MASc. Associate Chair – 4 PhD; 10 MASc; 2 MEng.

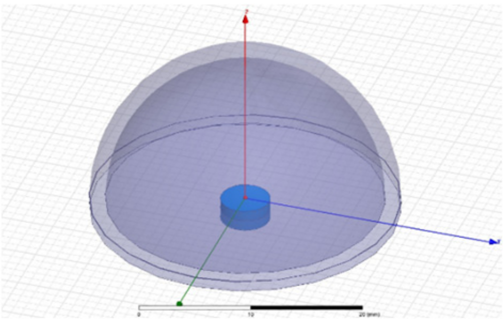
A total of five presentations by IRC HPQs in training (2 Senior Chair; 3 Associate Chair) were made during the year at national and international conferences including the Canadian Radiation Protection Association annual meeting and the Health Physics Society annual meeting.

UOIT continues to develop its radiation research infrastructure and during 2015 an EPR spectrometer for environmental non-human biota dosimetry was purchased and commissioned.

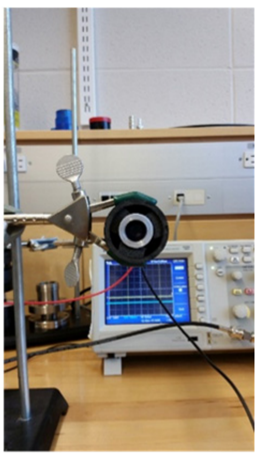
Program Results /Highlights (*Senior Chair*)

At the center of the senior Chair research program are the dual tasks of developing advanced methods of real-time monitoring in mixed radiation fields typically encountered in nuclear power plants and other nuclear workplaces, and the investigation of the impact of radiation quality in radiation risk from occupational or environmental exposures. Real-time measurement work has principally been concerned with improving mixed-field neutron-gamma monitoring using low pressure proportional counters and fundamental studies of new detection systems such as Gas Electron Multipliers. Real-time instrumentation work was expanded in 2015 to address the issue of eye-dosimetry that arose due to the expected lowering of the annual limit for eye exposure from 150 mSv to 20 mSv. Progress in these activities is detailed below and also in the section dealing with industry and international collaborations.

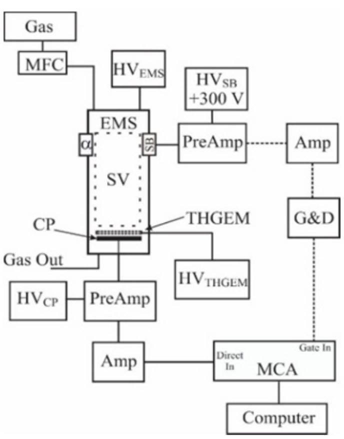
Real-Time Measurement



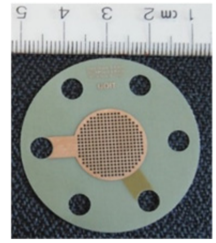
During the first IRC term and into the renewal period we have experimentally verified the advantages of using multi-element tissue equivalent proportional counters in radiation protection monitoring through their increased sensitivity without any increase in the physical size of the detector itself. During 2015 we have extended this study by considering manufacturing simplicity as a critical element of the technology-transfer process for any multi-element device with potential for commercialization. To address this issue an MASc student (David Broughton) completed an electrostatic and dosimetric modelling study of a completely novel TEPC design based on hemispherical geometry and gas multiplication using a spherical anode rather than the usual thin anode-wire. These modelling results were sufficiently encouraging that construction of a prototype counter for experimental concept-testing will be carried out in 2016 by a new graduate student. If the results of modelling are confirmed experimentally this device will form the basis of a new range of more easily manufactured TEPCs for individual detector and multi-element use.



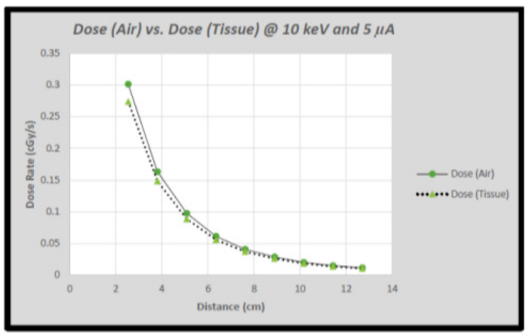
Addressing an emerging industry radiation protection issue due to the proposed dramatic change in Canadian regulations concerning occupational dose limits for the lens of the eye an investigation was initiated looking at the use of plastic scintillators, dimensionally modelling the human eye, for monitoring eye-lens dose in work-place fields. Initial results for ^{137}Cs and X-rays, where the response of the eye-dose monitor was compared to the response of an ion chamber measuring air-kerma, have proved sufficiently encouraging that the study will be continued and computer modelling will be used to improve and refine the design of the monitor for real-time work-place field use.



The measurement of tritium in air in CANDU power plants is an operational health physics issue that continues to hold interest. We have been studying various detection methods within the IRC program including thin plastic scintillators (described in earlier reports) and gas-ionization counters. A fundamental problem with gas-ionization devices is the rapid deterioration of gas-gain due to the presence of oxygen in air and electron-attachment. To study charge transport in gases at a fundamental level an Electron Mobility Spectrometer (EMS) has been designed and constructed to measure the transit time and electron attachment effects in proportional counter fill- gases. We have used the EMS to study the multiplication properties of a thick-Gas Electron Multiplier detector as a function applied electric field in different counting gases. The relative gas-gain and resolution of the THGEM within the EMS were measured at various applied voltage settings. It was observed a potential difference across the THGEM of +420 V and potential difference across the induction region of +150 V for this EMS setup resulted in the minimum voltage requirements to operate with a stable gain and best resolution. Furthermore, it was observed the gain is strongly affected not only by the potential difference across the THGEM, but also by the applied voltage to the anode and resulting potential difference between the THGEM and anode. These results indicate that the overall transit time of electrons and pulse formation time is very similar between anode-wire and Thick-GEM devices and a thick-GEM is a suitable multiplication device to use in charge transport studies and radiation detection devices based on gas ionization.



Radiation Quality



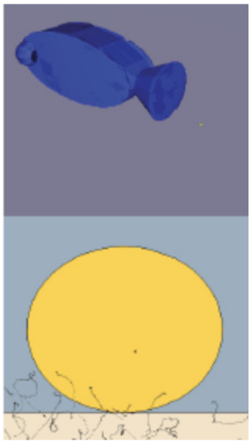
Ongoing discussion about the appropriateness of the radiation weighting factor that is applied to derive the equivalent dose from an absorbed dose measurement is most acute within the context of the operation of Candu power plants for tritium exposures. Working directly with tritium gas and low-energy beta emitters in general is difficult and in order to test new measuring devices and concepts we have installed an x-ray generator capable of producing low-energy electrons to mimic low energy betas. This is an extension of on-going work to build a low energy X-ray beam to mimic low energy betas from tritium decay. This irradiation apparatus was constructed and dosimetrically characterized in 2015 ready for biophysical experiments to examine radiation quality effects for non-human biota.

Program Results /Highlights (*Associate Chair*)

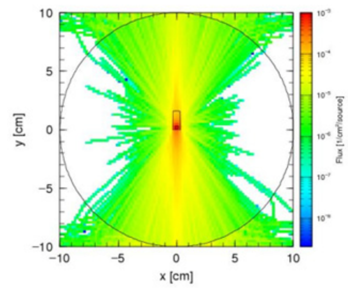
The overall objectives of the Associate Chair program are to extend computer modeling capability in the fields of novel detectors and computer simulation of radiation fields encountered in the nuclear workplace and its environment; to include realistic and scenario based source terms, to perform experimental measurements of secondary electron fields from shielded gamma sources; to advance the mobile robotic platform (RadBot); and to enhance research in the general area of environmental safety. The intent being to specifically target areas of research of interest to industry and regulators, such as improved environmental transfer factors, modeling of radionuclide transport, dose and risk for abnormal releases, tritium physicochemistry in the environment (OBT; HTO), exposure effects on valued ecosystem components/reference animals and plants (specifically aquatic organisms that may be affected by routine and non-routine nuclear plant discharges) and low dose measurement and assessment on reference animals and plants

Radiation Field Modeling, Prediction and Dosimetry of Various Radiation Fields in a CANDU Environment

Modeling efforts during 2015 have been in Monte Carlo simulation of non-human biota for dosimetry estimates. Conference presentations have reported on results obtained by 3D simulating the radiation environment for a Pumpkinseed fish and eggs (see figure), and compared to other environmental dose estimation tools (RESRAD and ERICA). A second PhD study was also initiated in 2015 focussing on environmental dose to frogs.



Another significant area of modeling has been in establishing contact dose conversion factors for encapsulated radioisotope sources. The result will be a revision of these factors (a first since the miod-1970s) to update those found in NCRP Report No. 40. The simulations, conducted using the Monte Carlo transport code PHITS, allow for E-M field effects, and can estimate the behaviour of electrons in an E-M field, such that it is possible to design an experiment to measure pure gamma fields without the interference of Compton scatter electrons. A simulated electron flux map is depicted for a 75mT magnetic field. Experiments to confirm the predictions of theoretical modelling are planned for early 2016



Another student in the area of mathematical modeling and computational science has been exploring molecular dynamic simulations to determine the potential effect of low energy beta emission (such as might be found from tritium near DNA strands). This work is carried out in collaboration with the Faculty of Science at UOIT.

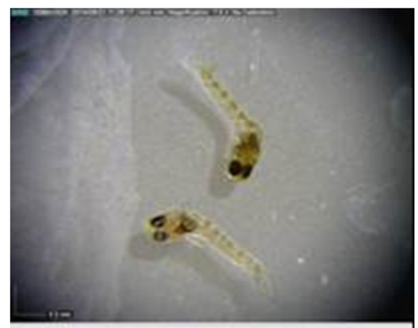
Real-Time Mapping and Visualization of Radiation Fields

During 2015 one PhD student graduated with a thesis on robotic mapping and special localization of radiation sources. This work on improved mapping and localization will continue with a Masters student project into 2016. The system under development has been termed RadBot and is being investigated for use with contaminated environments, asymmetric radiation fields in nuclear plant environments and mining applications.

Also in 2015 research involving the development of an environmental scanner (depth sensor) and radiation detector (for monitoring gamma-ray photons) was carried out by a PhD student to advance research in dose visualization. The data from the depth sensor and radiation detector will be jointly monitored when navigated throughout an environment building real-time datasets of depth information and radiation measurements. A Monte Carlo simulation environment will also be automatically constructed and run backwards (also called an adjoint calculation) simulating photons leaving the detector locations and going into the environment with the relative response in each point of the measurement in the array being used to define the associated frequency of photons originating from each detector. The most frequently traversed surfaces will be identified as regions of interest and displayed to the user via a virtual/augmented reality interface for the purposes of guiding the user to these locations to ensure they are monitored. The transparent radiation field voxelization model will be displayed in the same interface to communicate the calculated and monitored three dimensional distribution of radiation within the local environment.

Environmental Radionuclide Transport, Dose and Risk Assessment

During 2015 two PhD students were assigned projects on non-human biota radiation effects. These PhD students have been investigating low-dose effects to non-human biota, and commenced experiments using electron paramagnetic resonance spectroscopy on calcified tissue samples. In order to add to the knowledge base of radiation effects to non-human biota, it is important to define benchmark values for a variety of species. One of the challenges this approach is facing is the identification of biological endpoints. Endpoints for non-human biota can range from mortality of the individual to fertility and thus impairment of the population fitness. American Flagfish have proven to be an excellent test species for laboratory studies. An experimental set-up was designed to investigate effects from irradiation with Cs-137 to American Flagfish. Preliminary experiments to assess the suitability of the methodology were conducted by exposing Flagfish eggs to 44 h of ionizing radiation of five different dose rates. The subsequent observation of the developing fry showed no effect on hatching. However, the mortality and observed vertebral malformations were increased with increasing absorbed dose. One reoccurring malformation that became apparent at high dose rates after hatching but before absorption of the yolk sack is a bending of the spine. This is suspected to be a result of developmental defects in the embryonic stage.



Research Facilities and Equipment

Research facilities built up at UOIT consist of a mixed radiation field dosimetry laboratory; nuclear instrumentation laboratory; environmental radiation laboratory; aerosol laboratory; *REB, AUP and OMAFRA* approved animal care facility. Added to research infrastructure in 2015 was an electron paramagnetic resonance (EPR) dosimetry laboratory.

Collaborations and Interactions /Consultations with Industry

In 2015 Dr. Waller participated in numerous IAEA and UN activities in the areas of direct value to the nuclear power industry, these contributions to the world-wide nuclear engineering community included:

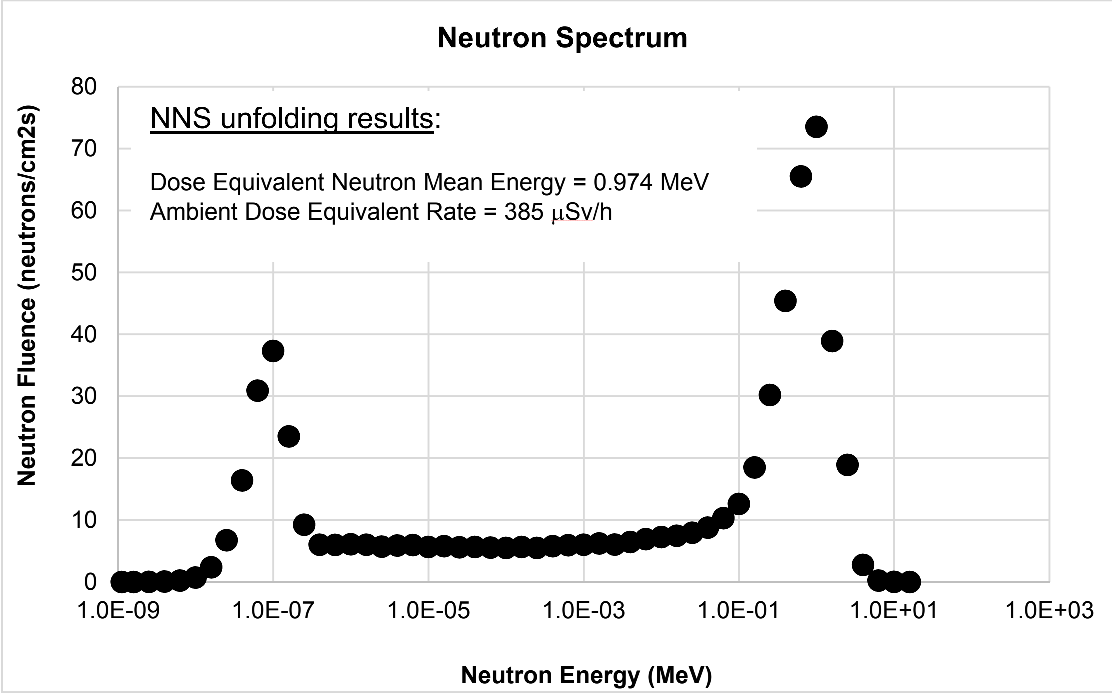
United Nations Scientific Committee on the Effects of Atomic Radiations (UNSCEAR)
Dose from radioactive discharges
Dose from electricity generation
Chair of expert group on discharge methodology and doses from electricity generation

International Atomic Energy Agency (IAEA)
Interface between safety and security functions
Contingency planning
Nuclear security exercises
Emergency Preparedness and Response Training performance indicators

Through Dr. Waker, UOIT is an associated partner in a 'Marie Curie Initial Training Network' for advanced radiation dosimetry (ARDENT) coordinated by the radiation protection service at CERN http://ardent.web.cern.ch/ardent/ardent.php

In October 2015, Drs. Orchard and Waker obtained 16 hours of beam time at the CERN high altitude radiation field simulation target station CERF in order to carryout measurements with low pressure proportional counters for comparison with other instruments and methods developed in European laboratories.

In 2015 Drs. Orchard and Waker began an ongoing collaboration with Queen's University Research Materials Testing Laboratory (RMTL) to conduct neutron spectrometry and dosimetry at this new research facility. The neutron fluence spectrum shown below was measured in the accelerator hall at a reference position close to a Faraday cup 'beam stop'. The Nested Neutron Spectrometer (NNS) used for these experiments was purchased by Queen's as part of the overall CFI grant and our collaboration includes the training of RMTL staff in the use of the NNS.



Publications /Journal Papers

REFERRED JOURNAL ARTICLES

"Measurement of neutron energy spectra and neutron dose rates from $^{7}Li(p,n)^{7}Be$ reaction induced on thin targets.", J. Atanackovic, W. Matysiak, J. Dubeau, S.Witharana, and A. J.Waker, Nucl. Inst. Method. A, 774, 6-16, 2015

"Environmental microdosimetry: microdosimetric characterisation of low-dose exposures", A. J. Waker, T. Mahilrajan and H. Sandhu
Radiat. Prot. Dosim., 166(1-4), 204-209, 2015

"Investigation of a thick gas electron multiplier for use in an electron mobility spectrometer." G.M. Orchard, S. Puddu, and A.J. Waker, Nuclear Instruments and Methods Physics Research A: - *submitted 2015*

"The Role of the Health Physicist in Nuclear Security", Waller, E. and van Maanen, J., Health Phys. 108(4):468-476. 2015

"Experimental Modeling of Wind Driven Bin-by-Bin Resuspension Factors of Freshly Fallen Radionuclides after an Energetic Release from a Radiological Dispersal Device", Perera, S., Akhtar, A., and Waller, E. J. Nuc. Eng. Rad. Sci. 1:1-10. 2015

"Physical Design of a Nuclear Facility Security Training Environment and Interfacing with Adversary Probability of Interruption Software", Waller, E., Adderly, M., Hayward, M., Reid, S., Ruttan-Morillo, J., J. Physical. Security. 8(1):1-18. 2015

"Using Perturbation Theory to Derive a Rigorous Upper Bound for the Biological Damage

Caused by Recoiling Nuclei during Beta Decay", Magill, M., de Haan, H. and Waller, E., Rad. Env. Bio. *submitted*. 2015

CONFERENCE PRESENTATION/ POSTERS

"Comparative Performance Analysis of a New Tissue Equivalent Proportional Counter for Neutron Monitoring and Dosimetry.", Broughton, D.P., Orchard, G., and Waker A.J. Health Physics Society 60th Annual Meeting, Indianapolis, Indiana, July 2015.

"Measurement of the spatial and energy neutron fluence distribution of a P 385 D-D Neutron Generator and an isotopic neutron source at the UOIT irradiation facility using a Nested Neutron Spectrometer." Orchard, G.M., Hatakeyama, T. and Waker, A.J. Canadian Radiation Protection Association, Winnipeg, Manitoba, Canada, May 2015.

"Modeling the Effectiveness of Nuclear Security through Computer Simulation", Chornoboy, N. and Waller, E., Institute of Nuclear Materials Management (INMM) 56th Annual Meeting, Indian Wells, California, 12-16 July 2015.

"Off-line Core Modeling in a CANDU Reactor", Gilbert, J. and Waller, E., Health Physics Society 60th Annual Meeting, Indianapolis, Indiana, 12-16 July 2015.

"Monte Carlo Modeling of the Fastscan Whole Body Counter Response", Graham, H. and Waller, E., Health Physics Society 60th Annual Meeting, Indianapolis, Indiana, 12-16 July 2015.

"An Assessment of Radiation Effects to American Flagfish", Tzivaki, M. and Waller, E., Health Physics Society 60th Annual Meeting, Indianapolis, Indiana, 12-16 July 2015.

"Modelling the Defence of Nuclear Sites for the Prevention of the Loss of Special Nuclear Material", Waller, E. Chornoboy, N., Health Physics Society 60th Annual Meeting, Indianapolis, Indiana, 12-16 July 2015.

"The Interface of Safety and Security in the Response to a Malicious Act", Waller, E., 9th International Experts' Meeting on Assessment and Prognosis in Response to a Nuclear or Radiological Emergency (IEM-9), International Atomic Energy Agency, Vienna, Austria, 20-24 April 2015.

"Examination of Secondary Electrons generated by Encapsulated Gamma Sources to Improve Contact Dosimetry Estimates", Heritage, E. and Waller, E. Canadian Nuclear Society CNS 35th Annual Conference, Saint John, NB, 31 May – 3 June 2015.

"A Preliminary Assessment of Radiation Effects on American Flagfish", Tzivaki, M. and Waller, E. Canadian Nuclear Society CNS 35th Annual Conference, Saint John, NB, 31 May – 3 June 2015.

"Modelling the Defence of Nuclear Sites for the Prevention of the Loss of Special Nuclear Material", Chornoboy, N. and Waller, E. Canadian Nuclear Society CNS 35th Annual

Conference, Saint John, NB, 31 May – 3 June 2015.

“CFD Modelling of the Wind Chamber used for Radioactive Particle Resuspension Experiment”, Perera, S., Waller, E., Walsh, P., Doxatar, A. and Akhtar, A. 25th Canadian Congress of Applied Mechanics. CANCAM 2015, Western University. London, ON. 31 May – 4 June 2015.

“Examination of Secondary Electrons generated by Encapsulated Gamma Sources to Improve Contact Dosimetry Estimates”, Heritage, E. and Waller, E. Canadian Radiation Protection Association CRPA 2015 Annual Meeting, Winnipeg, MB, 12-15 May 2015.

“Using Perturbation Theory to Derive a Rigorous Upper Bound for the Biological Damage caused by Recoiling Nuclei During Beta Decay”, Magill, M., Waller, E. and de Haan, H. 14th Annual Chemical Biophysics Symposium. Toronto, Ontario. 10-12 April 2015

Collaborative Research and Development (CRD)

University of Guelph – Peter Tremaine CRD

CRD Title: Predictive Models for D2O Isotope Effects On Ionization And Metal Hydrolysis under CANDU Reactor Coolant Conditions

Overview

Since Dr. Tremaine's appointment in 2001, the University of Guelph has sought to create a state-of-the-art research center for the development of high-precision instruments and theoretical tools to determine the thermochemical properties of aqueous systems under nuclear reactor operating conditions. Areas of particular importance to the 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 reactors; and (iii) the need for basic research to model reactor coolant and boiler chemistry under extreme conditions.

The grant to Guelph in 2006 was the first CRD grant awarded to a university by UNENE. The grant, and UNENE's network of contacts, have proved to be a key element in establishing the university's expertise in this field. 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 of creating 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^{o}C and 30 MPa. The \$36,000/yr grant from UNENE has been leveraged with NSERC partnership program grants to provide operating funds of approximately \$350,000/yr for nuclear-related R&D. During the past year, these funds have supported 1 undergraduate, 3 graduate students, 3 postdoctoral fellows, and 2 research associates.

Program Results/Highlights

New NSERC/UNENE Senior Industrial Research Chair

Professor Tremaine has been named the NSERC/UNENE (University Network of Excellence in Nuclear Engineering) Senior Industrial Research Chair in High Temperature Aqueous Chemistry. Industrial partners involved in the NSERC chair are UNENE, the CANDU Owner's Group, the Nuclear Waste Management Organization and the Electric Power Research Institute. The proposal was submitted in July, 2015. The site visit was held in October. NSERC's positive decision was announced in January for a start date of April 1, 2016. The chair is funded by \$890,000 from NSERC and \$990,000 from industry. Combined with additional support from industrial and university partners, the Chair will receive \$1,325,000 in research funding over the next five years.

Current Projects

In addition to Dr. Tremaine's current UNENE CRD grant, the nuclear-related research at Guelph has been supported by four other grants.

(i) "D_2O Isotope Effects on Hydrolysis and Ionization Equilibria in High-Temperature Water", NSERC/UNENE CRD Grant: (2005-2009; 2009-2012; renewed 2013) ($91,200/yr x 3).
(ii) "Aqueous Chemistry of Metals under Supercritical Water Reactor Coolant Conditions", NSERC/NRCan/AECL Collaborative Research Grant: (2012-2016) ($80,000/yr x 4).
(iii) "Aqueous Chemistry of Fission Products and Actinides under Supercritical Water Reactor Coolant Conditions", NSERC/NRCan/AECL Collaborative Research Grant: (2012-2016) ($50,000/yr x 4).
(iv) "Aqueous Electrolytes and Non-Electrolytes Under Hydrothermal Conditions" NSERC Discovery Grant: (2005-2011; renewed 2011-2016) ($45,000/yr x 5).
(v) "Aqueous Speciation and Liquid-Liquid Phase Separation of Boric Acid at Temperatures up to 350 °C" Electric Power Research Institute (EPRI) Contract: (2012-2016) (~$150,000/yr x 3).

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 ^{o}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 H_2O and D_2O, for simple acids and bases at the extreme temperatures and pressures encountered in nuclear reactors (250 to 300 EC 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, are used to measure *differences* in the chemical equilibrium constants in H_2O and D_2O under identical conditions. The second and third phases are using these instruments, and a new custom-made Raman spectrometry system, to calibrate a number of D_2O buffer systems and pD indicators for laboratory use at temperatures up to 300 EC, and to develop an improved, practical model for estimating the magnitude of D_2O isotope effects on metal hydrolysis and metal oxide solubility under CANDU operating conditions. Recent results have included the conductivity measurements to quantify the difference in ionization constants and transport properties of acids and fission products between light and heavy water at temperatures up to 325 ^{o}C. These are among the first such results ever reported under such extreme conditions. Initiatives to develop a chemical equilibrium model for heavy-water primary coolant chemistry are underway. The project will contribute to research aimed at extending the lifetime of existing reactors by providing criteria for optimizing primary circuit pD 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 D_2O 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 and Equipment

The current suite of high-precision instruments includes 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≅10^{-5} g/cm^3) needed to measure standard partial molar properties of aqueous electrolytes up to 350 ^{o}C. The UV-visible flow system constructed in 1999, has the stability needed for quantitative spectroscopic studies up to 275 EC, and is being upgraded for operation up to 400 ^{o}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 CFI and NSERC Strategic Grants, supported by AECL and UNENE, have added a new high temperature (50 – 300 ^{o}C) solution calorimeter and state-of-the-art Raman spectrometer capable of making in situ measurements of aqueous solutions at supercritical conditions. Cells suitable for use under CANDU-PHW and CANDU SCWR reactor coolant conditions have been developed.

Current HQP

In 2013/14, the Hydrothermal Chemistry Group graduated one PhD student and four MSc students. The group now consists of two postdoctoral fellows, three research associates, three PhD students, two MSc students and two summer/co-op students. Research Associate Dr. Jenny Cox (BSc U. Toronto, PhD, ETH, Zurich) manages the laboratory. Dr. Hugues Arcis and MSc student Kwame Agbovi (MSc, Queens) worked on our UNENE D_2O project conductivity measurements. Dr. Lucas Applegarth, Dr. Swaroop Sasidharanpillai and honours chemistry student John Noel carried out Raman studies on the UNENE project. Dr. Olivia Fandino Torres; PhD students Jane Ferguson, Chris Alcorn and Daniel Nieto Roca; and MSc student Christine McGregor worked on projects related to the supercritical water reactor, PWR boric acid chemistry, or basic research. Co-op PhD student, Jacy Conrad joined the group in September, 2015. The projects include collaboration with computational chemists, Prof. Cory Pye (St. Mary’s University), and Scott Hopkins (University of Waterloo).

HQP that Graduated

Jane Ferguson transferred from her MSc to a nuclear-related PhD program within our group.

Publications/Journal Papers

Published Research Papers

1. Limiting Conductivities of Univalent Cations and the Chloride Ion in H_2O and D_2O under Hydrothermal Conditions, J. Plumridge, H. Arcis and P. R. Tremaine, *J. Solution Chem.* (Special issue honouring Prof. R.H. Wood). 44,1062–1089 (2015).
2. Non-complexing Anions for Quantitative Speciation Studies by Raman Spectroscopy in Fused-silica High Pressure Optical Cells under Hydrothermal Conditions. L. M. S. G. A Applegarth, C. Alcorn, K. Bissonette, J. Nöel, P. Tremaine. *Appl. Spectroscopy* **8**, 972-983 (2015).
3. Theoretical Study of Deuterium Isotope Effects on Acid-Base Equilibria under Ambient and Hydrothermal Conditions, N. Mora-Diez, Y Egorova, H. Plommer, P. R. Tremaine, *JCS Advances* **5**, 9097-9108 (2015).
4. Thermodynamics of the Sodium–Iron–Phosphate–Water System Under Hydrothermal Conditions: The Gibbs Energy of Formation of Sodium Iron(III) Hydroxy Phosphate, $Na_3Fe(PO_4)_2$•$(Na_{4/3}H_{2/3}O)$, from Solubility Measurements in Equilibrium with Hematite at 498–598 K, S. Quinlan, D. Chvedov, L.N. Trevani and P. R. Tremaine, *J. Solution Chem*. (Special issue honouring Prof. R.H. Wood) 44, 1121–1140 (2015).
5. Absorption of CO_2 in aqueous solutions of 2-methylpiperidine: Heats of solution and Modeling. Coulier, Y.; Lowe, A.; Tremaine, P. R.; Coxam, J. Y.; Ballerat-Busserolles, K., Int. J. Greenhouse Gas Control 47, 322-329 (2016).
6. Ionization constants of DL-2-Aminobutyric Acid and DL-Norvaline under Hydrothermal Conditions by UV-Visible Spectroscopy, D.E. Nieto Roca, C.M. Romero and P.R. Tremaine, J. Solution Chem. (Submitted)
7. The Limiting Conductivity of the Borate Ion and its Ion-Pair Formation Constants with Sodium and Potassium Ions in Aqueous Solutions up to Near-Critical Conditions by AC Conductivity H. Arcis, J.P. Ferguson,G. H. Zimmerman, and P. R. Tremaine, Phys. Chem. Chem. Phys. (Submitted)
8. Ionization of Boric Acid in Water from 298 K to 623 K by AC Conductivity and Raman Spectroscopy, H. Arcis, J. P. Ferguson, L. M. S. G. A. Applegarth, G. H. Zimmerman, and P. R. Tremaine, J. Chem. Thermodynamics. (Submitted)

Published Proceedings from Conferences and Workshops

None in 2015.

Conference Presentations

1. Limiting Conductivity of Borate and Ion-pair Formation Constants of Alkali Borates under Nuclear Reactor Coolant Conditions by AC Conductivity Methods. Jane Ferguson, Hugues Arcis, Greg Zimmerman and Peter Tremaine. 98th Canadian Chemistry Conference and Exhibition (Ottawa June 17th, 2015).
2. D_2O Isotope Effects on Proton Hopping in High Temperature Aqueous Solutions by AC Conductivity. Hugues Arcis, Jeff Plumridge and Peter Tremaine. 19th Symposium on Thermophysical Properties, Boulder, CO, USA, June 21 - 26, 2015.
3. Boric Acid Ionization Constants and Ion-Pair Formation Constants of Sodium and Potassium Borate under Nuclear Reactor Coolant Conditions by AC Conductivity Methods. Hugues Arcis*, Jane Ferguson, Gregory Zimmerman and Peter Tremaine. 19th Symposium on Thermophysical Properties, Boulder, CO, USA, June 21 - 26, 2015

4. Boric Acid Ionization Constants and Ion-Pair Formation Constants of Sodium and Potassium Borate up to 623 K by AC Conductivity Methods. Gregory H. Zimmerman, Hugues Arcis, Jane Ferguson, and Peter Tremaine. CALCON 2015, Baltimore, MD, USA, July 12 - 16, 2015.
5. Boric Acid Water Chemistry under Hydrothermal Conditions by AC Conductivity Methods. J. P. Ferguson*, H. Arcis, G. H. Zimmerman, P. R. Tremaine. University Network of Excellence in Nuclear Engineering (UNENE) Student Poster Session, Toronto, ON, December 15, 2015.
6. Raman Investigation on the Complexation and Speciation of Aqueous Uranyl Sulfate under Gen IV Supercritical Water - Cooled Reactor Coolant Conditions, C. Alcorn*, L.M.S.G.A Applegarth, J.S. Cox and P.R. Tremaine, University Network of Excellence in Nuclear Engineering (UNENE) Student Poster Session, Toronto, ON, December 15, 2015.

Interactions with Industry

Committees and Board:

Dr. Tremaine serves on four industrial advisory committees for the nuclear industry:

(i) Member, MULTEQ Database Advisory Committee, Electric Power Research Institute (EPRI).
(ii) Member, Advisory Committee NSERC/AECL Chair in Radiation Chemistry held by Prof. Clara Wren, Univ. Western Ont. (2005 to 2015)
(iii) Member of the Canadian National Committee of the International Association for the Properties of Water and Steam (Prof. W. Cook, UNB, Chair).
(iv) Associate Member of the COG Chemistry Working Group (C. Stuart, CNL, Chair).

Project-related Interactions with Industry

The UNENE Project Advisory Committee has visited Guelph on an annual basis, from 2006 to 2013. The Committee also provides technical advice for the Strategic and CRD grant funded projects for this group. The UNENE Project Advisory Committee did not meet in 2014 because our proposal to incorporate Dr. Tremaine's program into an Industrial Research Chair with support from UNENE and COG was in progress. Dr. Tremaine is providing input on Canadian nuclear industry R&D needs as a member of the EPRI MULTEQ Database Committee (Monthly conference calls + annual 3-day meeting in Reston, Va.), which recently published and updated databases for the solubility of magnetite, transition-metal ferrites and chromites. He is also an associate member of the COG Chemistry Working Group, and has made an annual presentation at the April meeting in 2015. Dr. Tremaine also meets biannually with the EPRI Pressurized Water Reactor Technical Committee (P-TAC) to report on a contract-funded research project on fuel deposit chemistry.

External Employment of Students, PDFs and Research Associates

Past students postdoctoral fellows and research associates have been recruited into career positions at AECL (Chalk River Laboratories), engineering consulting companies, and university teaching positions at UOIT. One of our 2013 MSc graduates has gone on to further energy-related graduate work (PhD) in France; one is teaching at Laurentian University; one is employed at the CNSC; and one has moved to the United States.

University of Ottawa – Stavros Tavoularis CRD

CRD Title: Experimental and Computational Studies of Two-Phase Flows in Nuclear Reactor Systems

<u>Overview</u>

The objective of this project is to apply, and further develop, available experimental and computational fluid dynamics (CFD) methods to the study of two-phase flow characteristics in tubes and in header-feeder systems of the type used in CANDU nuclear power plants. The main experimental tasks are: i) constructing a versatile header/feeder model, in which different combinations of active inlet turrets and active feeders can be selected; ii) assembling a database of measurements of gas and liquid flow rates in the feeder tubes of this model, while also documenting the turret inlet conditions and the flow patterns inside the header; and iii) assessing the effect of flow obstructions inside feeder tubes on the gas and liquid flow rates. The main task of the computational analysis is to perform CFD simulations of air-water flows at the same inlet flow conditions and in the same geometries as those of the experiments and to compare the simulation results to the measurements to verify the applicability of CFD as a tool for two-phase flow simulation at conditions and geometries of interest to nuclear safety analysis. The proposed experimental and numerical investigations will be conducted using state-of-the-art tools and will advance the technical capabilities of nuclear reactor designers and safety analysts. They are in direct support of the CNL air-water header facility tests.

The project has been very successful and has its results have been published in 7 journal papers (5 published, 1 submitted, 1 in preparation, as of May 2016), two graduate theses and several conference presentations and technical reports. There is accumulating evidence demonstrating that this work has so far been disseminated extensively, and that it is on its way to make an impact in the field. The following sections outline progress achieved during 2015.

<u>Anticipated Benefits to Industry</u>

The research program aims at producing original measurements and numerical simulations that will enhance the information and tools available to nuclear engineers for analyzing the operation and safety of CANDU header systems. In the short term, the results of the project will be used to support the two-phase flow measurements in the header test facility at CNL with wire-mesh sensors. In the longer term, the results will be used to assist CNL staff in performing CFD simulations of the header system and in developing constitutive relations for the two-fluid model to be included in CATHENA 4, the next generation system thermalhydraulics code being developed by CNL. This grant is enabling uOttawa to educate several students in nuclear reactor thermalhydraulics, thus providing the nuclear industry with a pool of prospective highly skilled research engineers to replace the currently retiring generation of such personnel, which were mostly hired approximately three decades ago. As most universities in Canada, USA and elsewhere eliminated or drastically reduced their educational and research programs in Nuclear Engineering, graduates with this type of expertise are needed urgently. The students to receive doctorates through this program will also be eligible to pursue academic careers, thus strengthening the few existing Canadian academic programs in Nuclear Engineering and helping establish new ones.

Interactions /Consultations to Industry

The University of Ottawa team is in close contact with CNL staff, particularly the Thermalhydraulics Development Branch, having frequent discussions concerning research plans and priorities.

Research Facilities and Equipment

Experimental facility: A Modular Header Facility was commissioned in Summer 2014 at the University of Ottawa Fluid Mechanics Laboratory (Figure 1). The main component of the facility is a 203 mm I.D. horizontal cylindrical header made of black-anodized aluminium. The header has two inlet turrets, with inner diameters of 32.5 mm and 154 mm, respectively. The larger turret may be capped with a clear acrylic cover, thus permitting visual observation of the header interior. Two additional observation ports made of clear acrylic were installed at either end of the header. Twenty feeder ports with end flanges were arranged in axially equidistant groups of four *banks*. Each bank consists of five feeder ports, which are connected to the header at three angles of inclination; two ports are horizontal and across from each other, two ports are inclined at 45° below horizontal and one port is vertical, pointing downwards. The header is described as *modular*, as it permits any combination of feeder ports to be connected to *active feeders* during an experiment, while the remaining ports are blocked by solid plugs made of polyvinyl chloride (PVC), up to the inside diameter of the header body. The feeders are tubes made of clear PVC with an inside diameter of 32.5 mm. The active feeders are attached to the feeder ports using standard flanges. Beside the header and feeders, the facility comprises a stainless steel water tank, a centrifugal pump and a 32.5 mm I.D. clear PVC inlet line. This facility complements the existing air-water flow loop at the University of Ottawa, which was designed and constructed as part of a previous UNENE CRD grant. These two facilities are being used for the collection of measurements in air-water flows in numerous experimental configurations that contribute to our understanding and predictive capabilities of gas-liquid flows and are of interest in nuclear safety analysis. Past and ongoing experiments have been conducted in different header-feeder combinations, as well as in horizontal, vertical upward and vertical downward air-water pipe flows in all two-phase flow regimes of interest.

CFD Laboratory: The principal investigator's CFD laboratory currently comprises four multi-processor servers and two workstation clusters having a total of approximately 300 threads for parallel processing with 600 GB RAM and 6 high-end multiprocessor personal computers for data pre- and post-processing. In addition, the team makes use of the large-scale, shared computing facilities of HPCVL (High Performance Computing Virtual Laboratory) and RQCHP (Réseau québécois de calcul de haute performance). The applicant has access to commercial and open-source CFD packages with multi-phase simulation capabilities (Star-CCM+ and OpenFOAM).

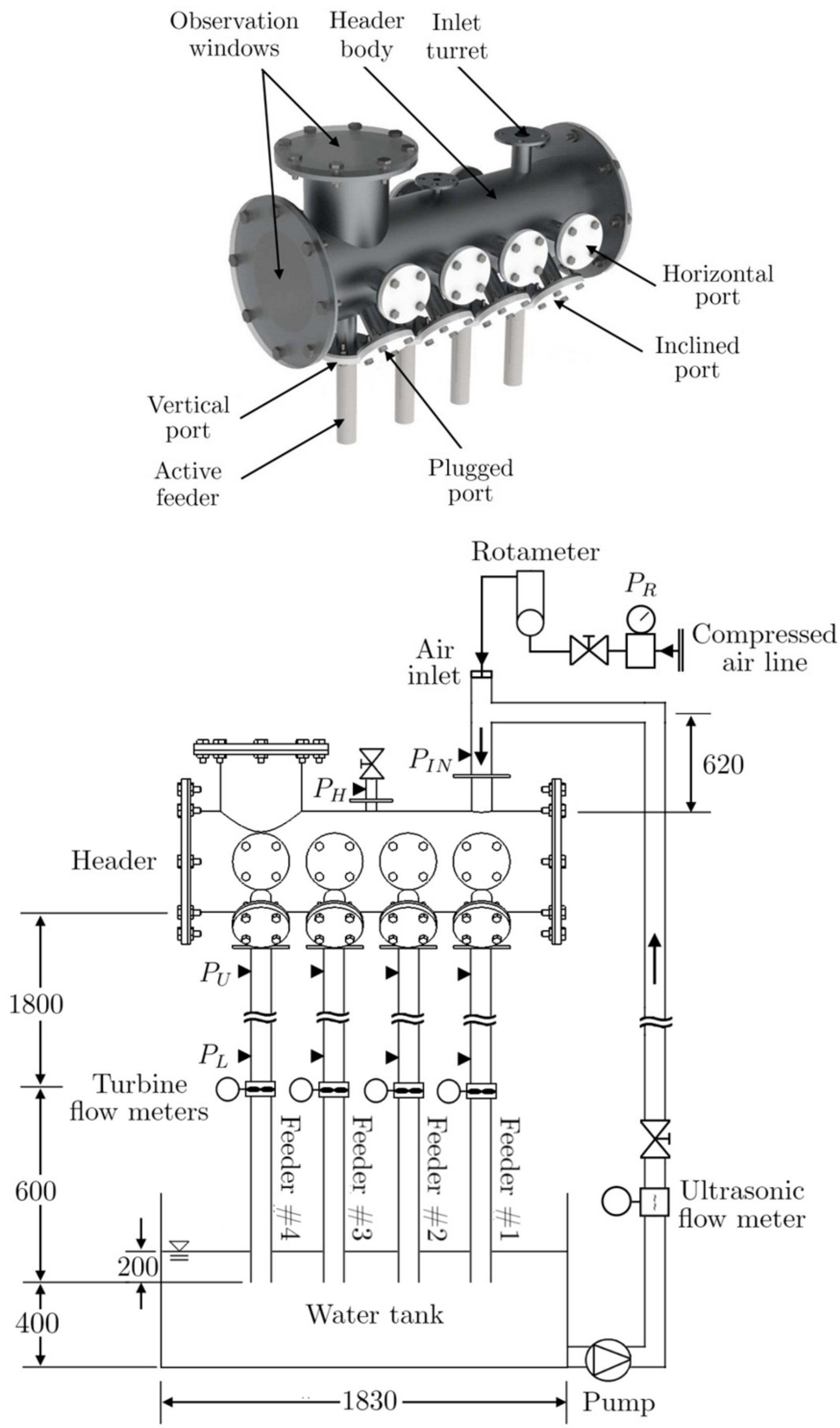


Figure 1. Three-dimensional view of the modular header (top) and schematic diagram of modular header facility (bottom). All dimensions are in mm.

<u>Program Results /Highlights</u>

Experimental results: The study of two-phase flow in header-feeder systems requires the simultaneous collection of measurements in a large number of feeder pipes. In past years, we have used the uOttawa air-water flow loop to develop novel experimental techniques for the identification of the flow pattern and measurement of the flow rates of both phases in gas-liquid pipe flows [Shaban and Tavoularis, 2014 a,b,d, 2015 a,e]. These methods were automated, non-intrusive and economical, so that their use would be feasible in industrial as well as laboratory settings. To meet these conditions, we followed an inter-disciplinary approach that combined the use of classical single-phase flow instrumentation, signal analysis and machine learning.

The most important advantage of the experimental methods using machine learning is their scalability, which means that they can be deployed effectively and at a relatively low cost in complicated industrial or laboratory installations. We further developed and used similar techniques to measure the two-phase flow distribution in the downward feeders of the University of Ottawa modular header facility [Shaban and Tavoularis, 2015b]. The purpose of this study was to investigate the flow distribution among the feeders of a header-feeder system; an uneven distribution of liquid flow during postulated accident scenarios may introduce safety concerns. The flow patterns in the header and near the feeder inlets were observed visually and were found to depend on the overall gas and liquid flow rates as well as the number and locations of active feeders. The two-phase flow distributions in the feeders were also found to be correlated with the flow patterns in the header (Figure 2). This work is the subject of a manuscript which has been recently published in *Nuclear Engineering and Design*.
Future experiments planned in the Modular Header facility will be aimed at studying the effect of different feeder orientations on the two-phase flow distribution, as well as assessing the effect of flow obstructions inside the feeder tubes on the gas and liquid flow distribution. A new multi-probe conductivity measurement system is being designed and constructed. This system will be integrated in the modular header facility, in order to fully investigate the phase distribution in the header and to provide high quality measurements for validation of CFD simulations.

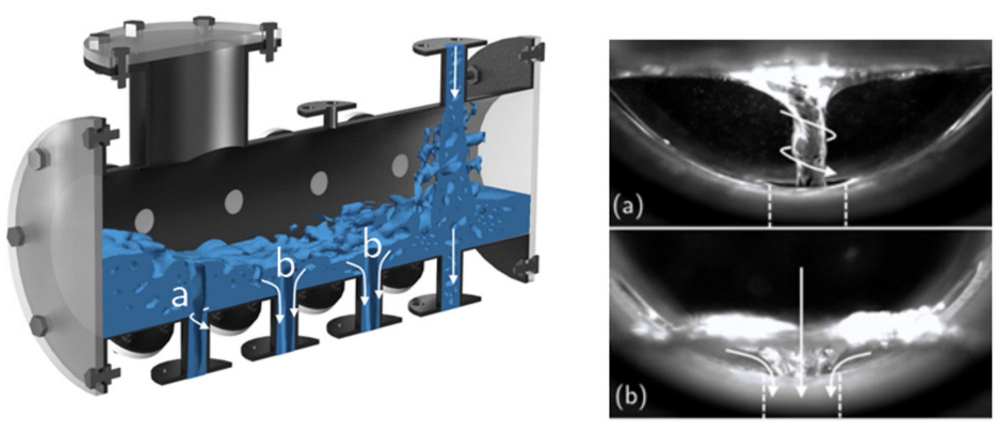


Figure 2. Left: Cross-section view of a header showing the instantaneous flow pattern obtained from a numerical simulation using the Volume of Fluid method. Right: Flow mechanisms into feeders from the modular header: (a) vortex-induced flow and (b) vortex-free flow.

Computational work: An emerging need in industry is the development of best practice guidelines for two-phase flow simulations, similar to those that already exist for single phase flow simulations. In past years, we have evaluated a variety of CFD models implemented in commercial and open source CFD codes for several flow configurations. Most recently, we carried out detailed numerical simulations of fundamental two-phase flows, particularly, the flow of Taylor bubbles rising in stagnant liquid columns. The objective of this study was to shed light on the turbulence and heat transfer characteristics of two-phase slug flow. The flow structures that influence the coalescence of consecutive Taylor bubbles are also being investigated. This work is the subject of a manuscript that is currently in preparation.

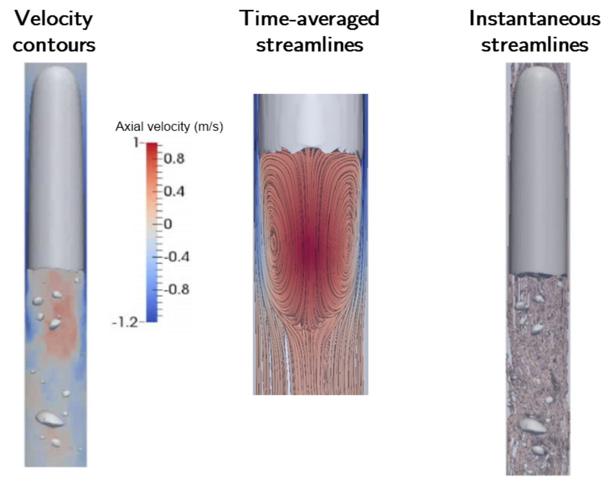


Figure 3. Main features of the velocity field around a rising Taylor bubble.

Current personnel will also be assessing the possibility of developing closure models for the two-phase flow equations that are insensitive to flow condition, such that they can be applied to a wide variety of problems. Other future numerical work includes simulations of the two-phase flow in a header-feeder configuration, for which experimental data will be collected in the Modular Header Facility.

Training of Highly Qualified Personnel (HQP)

The following persons have been engaged in this project.

- Azim Bin Mohd Arshad, Ph.D. candidate (full-time, started January 2016): Experiments and numerical simulations of two-phase flows.
- Armel Don, Research Assistant (part-time, January - May 2016): Design and construction of multi-probe void fraction measurement system. *Current Employer:* Linamar Corporation.
- Harun Oria, Ph.D. candidate (full-time, January 2015 - April 2016): Experiments and numerical simulations of two-phase flows. *Current Employer:* Unknown.
- Dr. Hassan Shaban, Ph.D. (completed 2015): Experiments and numerical simulations of two-phase flows in pipes and in header-feeder systems, application of machine learning methods in the study of two-phase flows. *Current Employer:* ICF International.
- Dr. Dongil Chang, Research Associate (part-time, completed 2015): Numerical simulations of two-phase flows. *Current Employer:* Altair Engineering Inc.
- Etienne Lessard, M.A.Sc. (completed 2013): Measurement of two-phase flow in horizontal pipes with wire-mesh sensors. *Current employer:* Canadian Nuclear Laboratories (CNL).
- Dr. Yuan Liu, Research Assistant (completed 2011): Evaluation of CFD methods for two-phase flows. *Current employer:* Life Prediction Technologies Inc.

Publications /Journal Papers

1. Shaban, H. and Tavoularis, S., 2016a. “On the accuracy of gas flow rate measurements in gas–liquid pipe flows by cross-correlating dual wire-mesh sensor signals.” *International Journal of Multiphase Flow* 78, pp. 70-74.
2. Shaban, H. and Tavoularis, S., 2016b. “Wire-mesh tomography: areas of application, performance evaluation and measurement uncertainty.” Flow Measurement and Instrumentation (submitted).
3. Shaban, H. and Tavoularis, S., 2016c. “Detached Eddy Simulations of Taylor bubble flows.” International Journal of Multiphase Flow (in preparation).
4. Shaban, H. and Tavoularis, S., 2015a. “The wire-mesh sensor as a two-phase flow meter.” Measurement Science and Technology 26, 015306 (16 pp).
5. Shaban, H. and Tavoularis, S., 2015b. “Distribution of downward air-water flow in vertical tubes connected to a horizontal cylindrical header.” Nuclear Engineering and Design 291, pp. 90-100.
6. Shaban, H. and Tavoularis, S., 2015c. “Detached eddy simulations of Taylor bubbles rising in stagnant liquid columns.” Bulletin of the American Physical Society 60 (21): 68th Annual Meeting of the APS Division of Fluid Dynamics, D9.00003 (1 pp.).
7. Shaban, H. and Tavoularis, S., 2015d. “Zorbubbles: Producing flow regimes in air-water flow.” Video entry, APS Gallery of Fluid Motion, http://gfm.aps.org/meetings/dfd-2015/55e1b23a69702d060d0e0000.
8. Shaban, H., 2015e. “Experimental investigations of internal air-water flows.” Ph.D. thesis, University of Ottawa, Ottawa, Canada.
9. Oria, H., H. Shaban and S. Tavoularis, 2015. Air-water flow distribution in multiple vertical tubes branching from a horizontal header. Thousand Islands Fluid Dynamics Meeting, T.I.M. 2015, Gananoque, Canada.
10. Shaban, H. and Tavoularis, S., 2014a. “Measurement of gas and liquid flow rates in two-phase pipe flows by the application of machine learning techniques to differential pressure signals.” International Journal of Multiphase Flow 67, pp. 106-117.
11. Shaban, H. and Tavoularis, S., 2014b. “Identification of flow regime in vertical upward air-water pipe flow using differential pressure signals and elastic maps.” International Journal of Multiphase Flow 61, pp. 62-72.
12. Lessard, E., Shaban, H. and Tavoularis, S., 2014c. “Measurements in horizontal air-water pipe flows using wire-mesh sensors.” 2014 Canada-China Conference on Advanced Reactor Development (CCCARD-2014), Niagara Falls, Canada, 27 - 30 April, 2014.
13. Shaban, H. and Tavoularis, S., 2014d. “Identification of flow regime in air-water pipe flow using differential pressure fluctuations and elastic maps.” Thousand Islands Fluid Mechanics Meeting, Gananoque, Canada, 30 May - 1 June, 2014.
14. Lessard, E., 2014e. “Measurements in horizontal air-water pipe flows using wire-mesh sensors.” M.A.Sc. Thesis, University of Ottawa, Ottawa, Canada.
15. Shaban, H, and Tavoularis, S., 2014f. “Development of drift-flux models for evaluating two-phase mass flow rates in a header facility.” Technical Report UO-MCG-DFM-2014-01 (110 pp.), University of Ottawa, Ottawa, Canada.

Royal Military College of Canada – Thomas Krause CRD

CRD Title: Advanced Inspection of Candu Steam Generator Tubing Structures Using Transient Eddy Current

Overview

This project focuses on challenges in CANDU(R) steam generator (SG) inspection and maintenance that are not presently addressed by conventional inspection technologies. Development of transient eddy current (TEC) technology is targeting inspection issues associated with support plate degradation and fouling, which lead to tube corrosion and loss of SG efficiency. Inspection and monitoring of these conditions can be integrated with preventive maintenance programs, thereby advancing station-life management processes. Extension of the transient eddy current technique to other in-reactor tubular structures is also a goal of this project.

The objectives of this project are:

1. Develop transient eddy current technology, including probe design, optimized for inspection conditions associated with SG tube geometry (completed).
2. Advance the analysis of transient eddy current data for rapid signal feature recognition and extraction of key inspection parameters (completed).
3. Identify processes associated with generation of transient eddy current signals in tube geometry in the presence of common tube flaws, support plates, degradation modes, and various fouling conditions (completed).
4. Model and develop theory that describes transient eddy current for various steam generator tube structural geometries in order to advance analytical and predictive capabilities for assessment of steam generator degradation and fouling conditions (completed).
5. Validate theoretical models with data obtained under simulated and real steam generator inspection conditions (completed).
6. Extend developed TEC models to more general in-reactor tubular structures such as fuel channel pressure tube to calandria tube gap and liquid injection shutdown system (LISS) nozzle proximity to calandria tube (progressing).

Program Results /Highlights

In the past year, 5 of the 6 objectives have been completed. Under the 6th objective, work has continued in the area of steel pipe thickness measurement. Completed tasks include **1** a modified TEC probe that can be used to characterize magnetite at trefoil broach supports and measure remaining thickness of broach support ligaments from within SG tubes [4], **2** demonstration of artificial neural networks for simultaneous measurement of four parameters at baffle supports including support structure hole size, tube off-centering in two dimensions and fret depth [2] and **3** development of TEC analytical models for the separate measurement of permeability and conductivity [1].

Steam generators are subject to a number of degradation modes at support structures, which if serious enough can require plugging or removal of tubes. Flow assisted corrosion or tube vibrations, may cause wall loss in support structure ligaments. Fouling, the accumulation of corrosion deposits on support structures, which includes magnetite, may obstruct flow holes, as simulated in Figure 1, and limit inspection by conventional eddy current methods. Figure 2 shows a photograph of a probe developed in this project for inspection of trefoil broach supports.

Figure 3 shows the pick-up coil responses for coils aligned with an unobstructed flow region (solid black curve) and flow regions completely obstructed by magnetite for three cases of increasing relative permeability. The inset shows a close up of the pick-up coil peak where the greatest effect due to changes in permeability was observed.

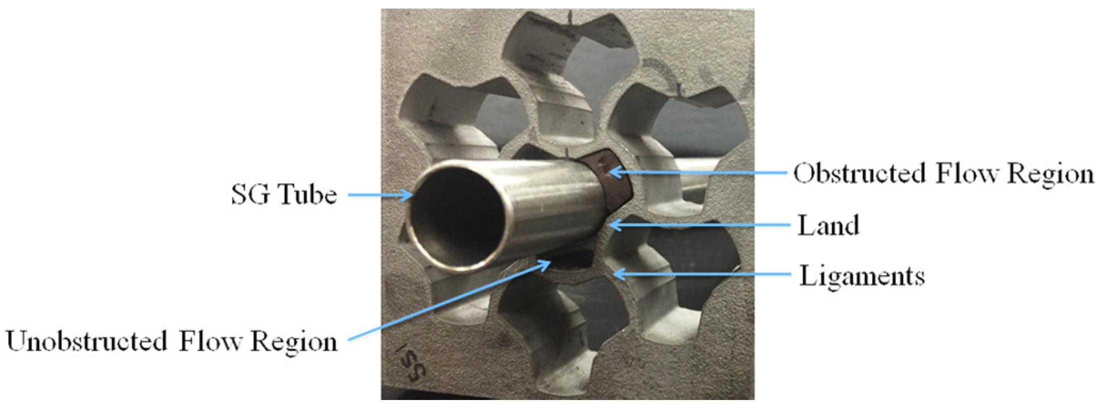


Fig. 1. Trefoil broach support sample with a SG tube and simulated magnetite obstructing flow region [4].

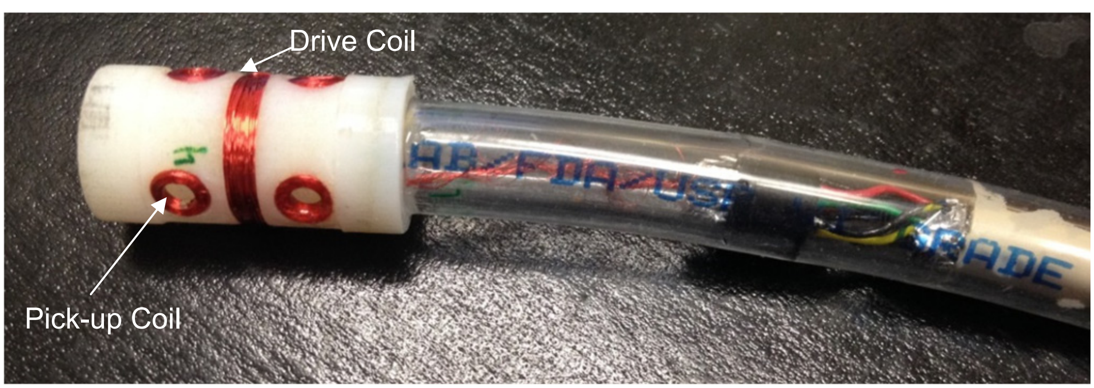


Fig 2. PEC probe developed for inspection of broach support structures [4].

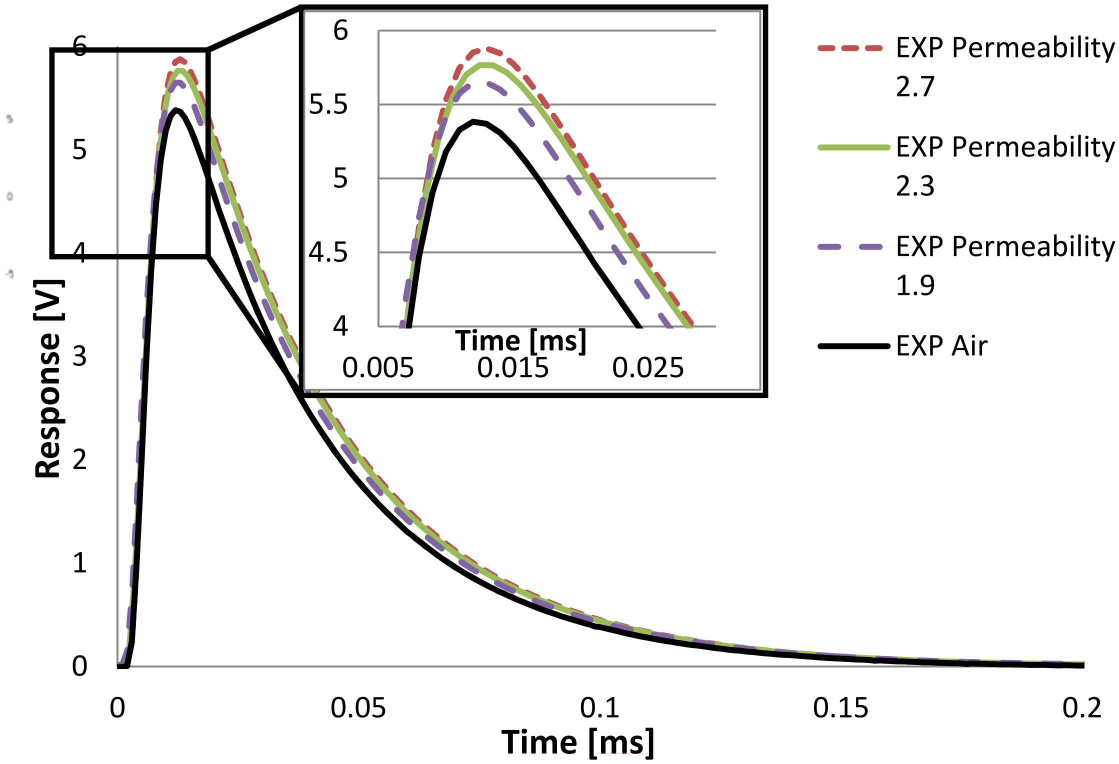


Fig. 3. Experimental results showing effect of relative permeability, μ_r, on pick-up coil response [4].

Figure 4 shows peak height of pick-up coil response varies linearly with relative permeability, μ_r, of magnetite [4]. A small increase in relative permeability is seen to have a large effect on the peak height. For the strong magnetite sample (μ_r=2.7) the peak height increases by approximately 9%, relative to the no magnetite case. This effect can be explained by considering the probe, magnetite and broach support as forming a magnetic circuit. As μr of the magnetite increases, the reluctance of flux passing to the pick-up coil decreases and resulting pick-up coil response increases. Extracting peak height could provide a means of characterizing the relative permeability of magnetite obstructing flow regions in trefoil broach supports.

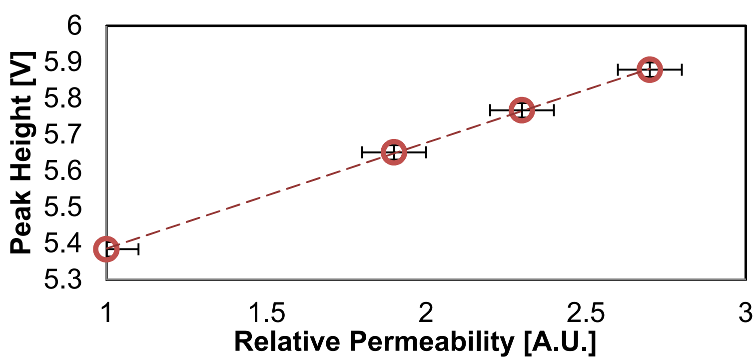


Fig. 4. Signal peak height versus μ_r (to one standard deviation) of magnetite obstructed hole [4].

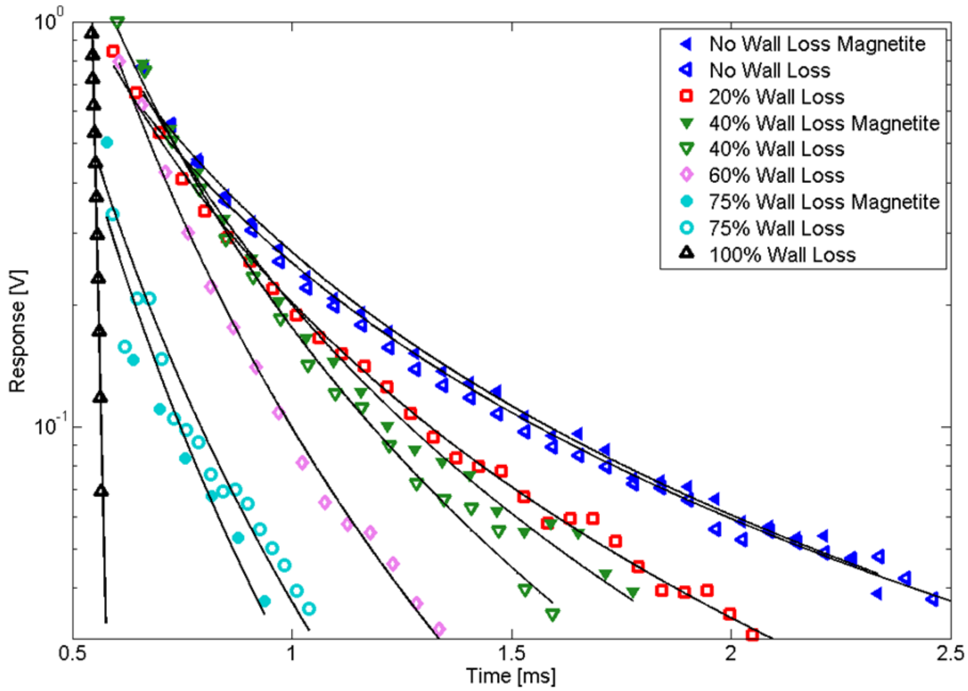


Fig. 5. Pick-up coil responses when flow regions are unobstructed and completely obstructed (0%, 40% and 75% wall loss only) by magnetite with μ_r=1.9 [4].

Wall loss on the far side of broach support lands may be detected by observing the long transient decay times of pick-up coil responses [4]. Figure 5 shows a semi-log plot of voltage response as a function of the experimental results for pick-up coils located at lands, for no wall loss (0%), and wall losses of 20% to 100% of one ligament. Also shown are wall loss measurements in the presence of holes completely obstructed by magnetite with μ_r=1.9 for wall loss cases of 0%, 40% and 75%. Little difference in response between open and magnetite obstructed flow-hole cases is observed. The experimental results show progressively decreasing relaxation time with increasing wall loss. Solid curves in Figure 5 are a best fit of the signal voltage response to a power law expression, that is robust under variable lift-off and angle conditions, and in the presence of magnetite as given by:

$$V = At^{-b},$$

where A is the power law coefficient and b is the power law exponent. Independence of wall loss response to the presence of magnetite is attributed to clear separation of electromagnetic diffusion times associated with magnetite, which occurs at early times at the peak, from that of the surrounding ferromagnetic support structure that occurs at later times.

The second main result of this past year was demonstration of artificial neural networks (ANN) for simultaneous measurement of four parameters at baffle supports, including support structure hole size, tube off-centering in two dimensions and fret depth [2]. Degradation of nuclear SG tubes and support structures can result in a loss of reactor efficiency. Regular in-service inspection, by conventional eddy current testing (ECT), permits detection of cracks, measurement of wall loss, and identification of other SG tube degradation modes. However, ECT is challenged by overlapping degradation modes such as might occur for SG tube fretting accompanied by tube off-set within a corroding ferromagnetic support structure. TEC was examined for inspection of Alloy-800 SG tubes and associated carbon steel drilled baffle support structures. Support structure hole size was varied to simulate uniform corrosion, while SG tube was off-set relative to hole axis. TEC measurements were performed in this case using an 8 pick-up coil configuration, rather than the 6 coil configuration shown in Figure 1, in the presence of flat-bottom rectangular frets as an overlapping degradation mode. Time-voltage data was processed by a modified principal component analysis (MPCA) to reduce data dimensionality, and MPCA scores were input into an artificial neural network that simultaneously targeted four independent parameters associated with; support structure hole size, tube off-centering in two dimensions and fret depth. The neural network was trained, tested, and validated on experimental data and provided estimates to within 2% of hole inner diameter (ID) and 3% of fret depth targets [2]. Estimates of hole ID and tube position were further improved when fret depth was used as an input, as might occur if fret depth inspection results from conventional eddy current or ultrasonics are available.

Cases with Realized outcomes to Industry

N/A

Research Facilities and Equipment

Royal Military College has several in-house built pulsed eddy current systems and 3 COMSOL licences operated on dual-quad workstations with average 100 GBytes RAM.

Current HQP

One Doctoral and three Masters Level students.

HQP that Graduated

2 Masters Students graduated – Jeremy Buck and Sarah Mokros have both found employment in the Inspection, Monitoring and Dynamics Branch, Chalk River Laboratories, Canadian Nuclear Laboratories.

1 Ph.D. graduated – Daniel Desjardins is a Captain in the RCAF and will be starting a lecture position in the Physics Department, Royal Military College of Canada, Kingston August 2016.

Publications /Journal Papers

Peer Reviewed Publications:

[1] D.P.R. Desjardins, T.W. Krause, and L. Clapham, 'Transient eddy current method for the characterization of magnetic permeability and conductivity', Nondestructive Testing and Evaluation International, 80, June 2016, Pgs. 65-70.

[2] J.A. Buck, P.R. Underhill, J. Morelli and T.W. Krause, "Simultaneous Multi-Parameter Measurement in Pulsed Eddy Current Steam Generator Data using Artificial Neural Networks", IEEE Transactions on Instrumentation & Measurement, 65, No. 3, March 2016, Pgs. 672-679.
[3] J.A. Buck, P.R. Underhill, S.G. Mokros, J. Morelli, V.K. Babbar, B. Lepine, J. Renaud and T.W. Krause, "Pulsed eddy current inspection of support structures in steam generators", IEEE Sensors Journal, 15, No. 8, August 2015, Pgs. 4305-4312.

Conference Proceedings:

[4] S. Mokros, J. Buck, P. R. Underhill, J. Morelli and T.W. Krause, 'Pulsed Eddy Current Technology for Steam Generator Tube Support Structure Inspection,'19th World Conference on Non-Destructive Testing 2016, June13-17, Munich, Germany.
[5] S.G. Mokros, J. Buck, P.R. Underhill, J. Morelli, and T.W. Krause, 'Pulsed Eddy Current Response to Magnetite at Broach Supports in Steam Generators', 39th Annual Canadian Nuclear Society Student Conference, Saint John, May 31-June 3, 2015.
[6] J. Buck, P.R. Underhill, S.G. Mokros, J. Morelli, V.K. Babbar, B. Lepine and T.W. Krause, 'Regression Analysis of Pulsed Eddy Current Signals for Inspection of Steam Generator Tube Support Structures', 39th Annual Canadian Nuclear Society Student Conference, Saint John, May 31-June 3, 2015.
[7] J.A. Buck, P.R. Underhill, J. Morelli and T.W. Krause, 'Analysis of Pulsed Eddy Current Data using Regression Models for Steam Generator Tube Support Structure Inspection', Vol. 35, edited by: D.E. Chimenti, Melville, New York (© 2016 American Institute of Physics), AIP Conf. Proc. 1706, Pgs. 090005-1 to 090005-10.
[8] V. K. Babbar, B. Lepine, J. Buck, P. R. Underhill, J. Morelli and T. W. Krause, 'Finite Element Modeling of Wall-Loss Sizing in a Steam Generator Tube Using a Pulsed Eddy Current Probe', AIP Conf. Proc. 1650, 1453-1459 (2015).
[9] S.G. Mokros, J. Buck, P.R. Underhill, J. Morelli, and T.W. Krause, 'Pulsed Eddy Current Response to Magnetite at Broach Supports in Steam Generators', 39th Annual Canadian Nuclear Society Student Conference, Saint John, May 31-June 3, 2015.
[10] J. Buck, P.R. Underhill, S.G. Mokros, J. Morelli, V.K. Babbar, B. Lepine and T.W. Krause, 'Regression Analysis of Pulsed Eddy Current Signals for Inspection of Steam Generator Tube Support Structures', 39th Annual Canadian Nuclear Society Student Conference, Saint John, May 31-June 3, 2015.

Conference Presentations/Poster (not repeated from above):

[11] K. Faurschou, J. Morelli, P. R. Underhill, C. Kramer, J. Buck, B. Lepine and T.W. Krause, 'Pulsed Eddy Current Measurements of Bulk Steel Pipe Wall Thickness', Marriott Hotel – Toronto Airport, Dec 15-16, 2015. Poster.
[12] D. Johnston, J. Buck, P.R. Underhill, J. Morelli and T. W. Krause, 'Pulsed eddy current detection of loose parts in steam generators', Marriott Hotel – Toronto Airport, Dec 15-16, 2015. Poster and Oral Presentation.
[13] D. Johnston, J. Morelli and T.W. Krause, 'Pulsed Eddy current detection of loose parts in CANDU® nuclear reactor Steam Generators', 51st Annual Canadian Undergraduate Physics Conference (CUPC), Trent University, Peterborough, ON, Oct. 22-25, 2015.
[10] T.W. Krause, J. Buck, J. Morelli, S. Mokros, and P.R. Underhill, 'Developments in Pulsed Eddy Current Technology for Inspection of Steam Generator Tube Support Structures', NDT in Canada Conference, June 15-17, 2015, Edmonton, AB.
[11] J. Buck, P. R. Underhill, S. Mokros, J. Morelli and T. W. Krause, V. Babbar and B. Lepine, 'Regression Analysis of Pulsed Eddy Current Signals for Inspection of Steam Generator Tube

Support Structures,' Inspection Monitoring and Dynamics Branch, Canadian Nuclear Laboratories, Feb. 18, 2015. Invited
[12] S. Mokros, J. Buck, P. R. Underhill, J. Morelli and T. W. Krause, 'Pulsed Eddy Current Inspection of Broach Support Structures', presentation to Inspection Monitoring and Dynamics Branch, Canadian Nuclear Laboratories, Feb. 4, 2015. Invited.

Interactions /Consultations to Industry

In March 2015, S. Mokros and J. Buck, and in May 2016 K. Faurschou, gave paper presentations for Electromagnetic NDE WG meetings at OPG.

[13] K. Faurschou, J. Morelli, T.W. Krause and P.R. Underhill, 'Analytic Modelling of Tile Holes for Pulsed Eddy Current using Flat Plate Approximation', Electromagnetics NDE Working Group Meeting, 1910 Clements Rd., Ajax, ON, May May 12, 2016.
[14] S. Mokros, J. Buck, P.R. Underhill, J. Morelli, and T.W. Krause, 'Pulsed Eddy Current Response to Flaws at Broach Support Structures in Steam Generators', 230 Westney Road, Ajax, ON, March 11, 2015.
[15] J. Buck, S. Mokros, P.R. Underhill, J. Morelli, and T.W. Krause, 'Multiple Linear Regression Applied to Multi-Variable Pulsed Eddy Current Analysis', 230 Westney Road, Ajax, ON, March 11, 2015.

Royal Military College of Canada – Thomas Krause CRD

CRD Title: Comprehensive Model of Eddy Current Based Pressure Tube to Calandria Tube Gap Measurement

Overview

This project focuses on generating a comprehensive three dimensional (3D) finite element method (FEM) model of eddy current (EC) probe response to changes in gap between the pressure tube (PT) and calandria tube (CT) in a CANDU nuclear reactor fuel channel. EC based gap measurement is used in predictions of time-to-contact between PT and CT and is, therefore, important for safety and licensing of CANDU® reactors. Although gap measurement systems are presently being qualified by fuel channel inspection service providers, no comprehensive three dimensional (3D) model of transmit-receive EC response to changes in PT to CT gap is presently available. EC gap response has been analytically modeled in two dimensions (2D) using flat plate geometries, but these models do not accurately reproduce many of the factors that affect gap measurement accuracy. In particular, a 3D model is required to incorporate effects of curved PT and CT geometry, local variations in PT diameter, ovality, PT wall thickness and resistivity, and probe lift-off and tilt. A validated 3D eddy current model could be used as part of an inspection qualification program by inexpensively supplementing laboratory and field measurements and assisting in quantification of the effect of essential parameters on gap measurement accuracy.
The objectives of this project are:

1. Generate a comprehensive model of eddy current measurement of pressure tube to calandria tube gap beginning with a 2D analytical model followed by 3D FEM (COMSOL) modelling in order to quantify the effects of essential parameters on gap measurement accuracy (initiated).
2. Assemble an experimental set-up for laboratory PT to CT gap measurement using actual transmit-receive eddy current probe technology (completed).
3. Acquire EC signals under variable PT and CT gap, PT resistivity variation, local pressure tube diameter and wall thickness variations, PT and CT ovality, and proximity of external structures such as LISS nozzles (progressing).
4. Validate theoretical models with data obtained, first under laboratory conditions, simulating actual fuel channel geometries, and second, if available by examination of real in-channel inspection data (progressing).
5. Use models to explore effects of variable in-reactor measurement conditions.
6. Make recommendations for achieving improvements in accuracy within existing gap measurement systems and identify key parameters affecting PT to CT gap measurement accuracy with the goal of providing support for inspection qualification programs.

Program Results /Highlights

This project was funded as of August 1, 2014. In the past 1.5 years progress was made towards objectives 1 to 6 above. Masters students starts have been September 2014 and May 2016. Students have develped 3D FEM and analytic models of pressure tube-to calandria tube gap propbe response. Basic comparisons of FEM model results with available 2D anlaytical model solutions and acquired experimental data have been made. Two 3rd year summer students started in May, 2016.

CANDU® reactor fuel bundles are immersed in a heat transport coolant (~300 °C) within a 6 m long pressure tube (PT). A gas-filled calandria tube (CT) surrounds the PT and thermally isolates it from the heavy water moderator (~50°C) surrounding the fuel channels. Four annulus spacers separate the hot PT from the cool CT, with the goal of preventing contact and consequent potential formation of hydride blistering on the PT, which can lead to cracking. As a consequence, ensuring that contact will not occur is a key nuclear regulator requirement.

In-reactor gap monitoring is performed by inspection systems that deliver an eddy current (EC) probe, which is sensitive to the proximity of the CT from within the PT [1]. Figure 1 shows a 2D representation of the EC probe configuration. The parameter of interest is the separation between the PT and CT, which in 2D can be approximated as the distance between two infinite planes. The EC probe is of a transmit-recieve type, with one drive coil and two pick up coils. One pick-up is located close to the drive coil and the other further away. As a 1st approximation, a 2D model may be considered for the close pick up coil, since its centre-to-centre spacing, S, is ~11 mm, while nominal PT inner diameter (ID) is 104 mm [1]. Parameters that affect measurement of PT to CT gap include variations from the nominal PT wall thickness of 4.2 mm and resistivity (~52 $\mu\Omega\cdot$cm), and distance of the EC probe from the PT ID surface, known as lift-off (LO) [1]. These parameters can vary under in-reactor conditions due to irradiation and pressure induced creep, which will increase PT diameter, decrease wall thickness and may alter PT resistivity [1]. These variables complicate the accurate determination of EC measured gap under typical in-reactor inspection conditions.

Planar Analytical Models

2D analytical solutions for the response of EC amplitude to changes in gap have been validated by experiments [2]. The analytic solutions based on Dodd and Deeds solutions [4] make the approximations that PTs and CTs are infinite parallel plates [2].

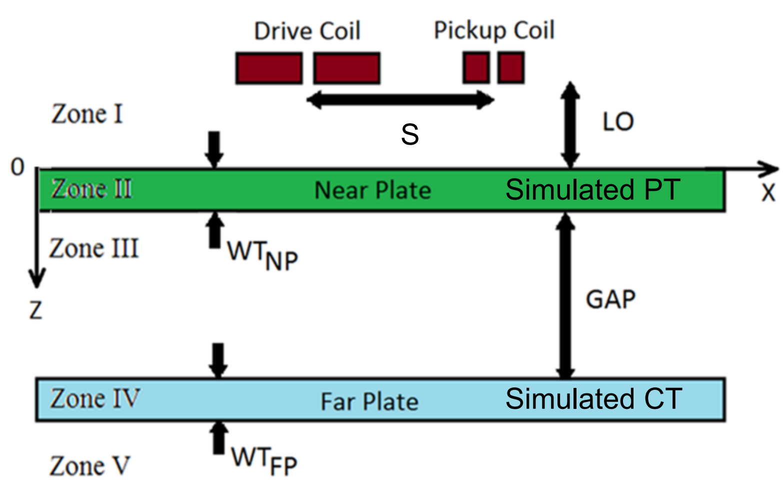


Figure 1: Cross-sectional view of eddy current probe above a conducting layered structure used for the 2D analytical model. Zone I is air, Zone II is the near plate, simulating the PT, Zone III is the air gap between near plate and far plate, which simulates the CT, Zone IV is the far plate and Zone V is air. S is the coil-to-coil spacing, while WTNP and WTFP are the near and far plate wall thickness, respectively.

Analytic models that account for the constant voltage excitation of the coil [5] rather than the constant amplitude current [4] have also been developed. The models have been used to generate impedance plane response to changes in PT-CT gap that shows excellent agreement with experimental results over a wide range of sample resistivity (1.72 $\mu\Omega$·cm to 174 $\mu\Omega$·cm) and wall thickness (1 mm to 5 mm). Figure 2 shows the most recent modeling results.

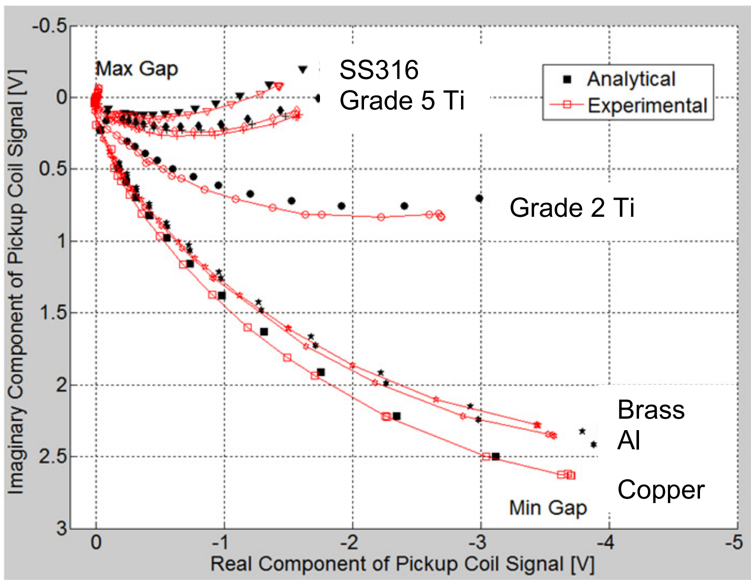


Figure 2: Measured and predicted 8 kHz gap profiles for varying far plate samples. Each gap profile consists of the real and imaginary voltage induced in the receive coil. Plate gap increases from right to left. Grade 5 Titanium was used as the near plate.

COMSOL Multi-Physics FEM Models

A 2D Finite Element Method (FEM) model, using COMSOL version 5.0 (AC/DC module with frequency domain analysis), was performed for the same geometry as for the analytical results as shown in Figure 2 [6]. However, 3D properties of the PT and CT geometry, such as tube curvature, varying wall thickness over the sensing area, and lift-off of the probe due to local changes in PT curvature [3], motivated the generation of 3D models for eddy current based measurement of PT to CT gap. A 3D FEM model was prepared as shown in Figure 3. The model used the actual curved tube geometry along with a multi-turn drive coil excited by a 1 V, 4 kHz time-harmonic voltage source. The drive coil was connected in series to a 100 Ω resistor and the receive coil was connected in series to a11 kΩ resistor to match the experimental configuration. PT-CT gap was varied from 0 to 16 mm for a 4 kHz excitation applied to the coils.

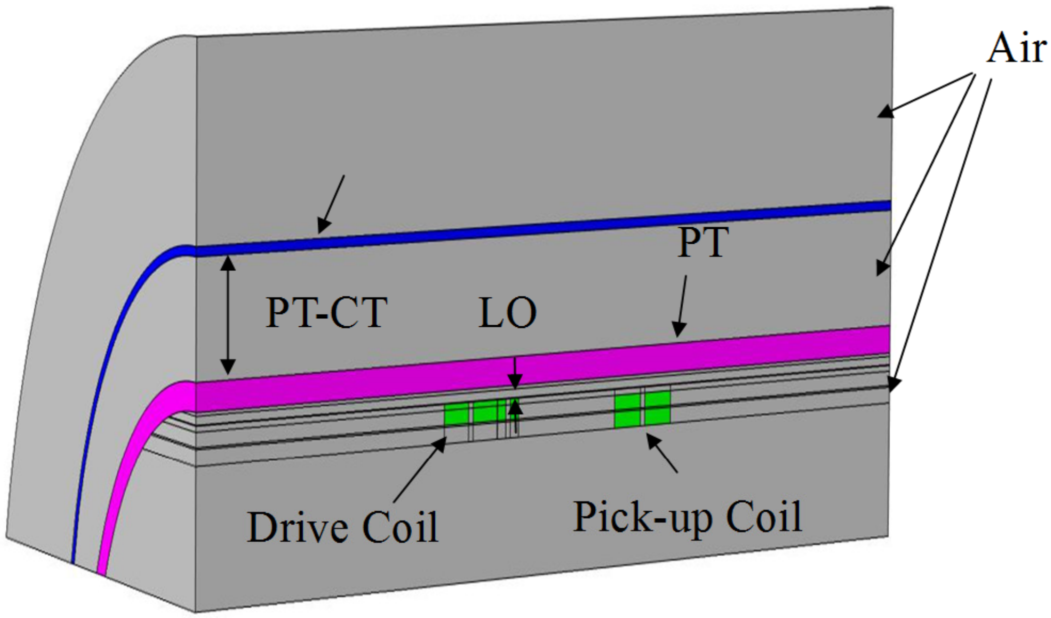


Figure 3: COMSOL model for 3D PT-CT curved geometry.

Experimental System for Model Validation

An experimental set-up for EC based PT to CT gap measurement has been developed. Figure 4 shows the in-house manufactured transmit-receive EC gap probe for variable gap measurements. Resistivity and wall thickness of PT samples have been characterized. Multi-frequency dependence of EC response (2, 4, 8 and 16 kHz) on PT to CT gap variation has been performed.

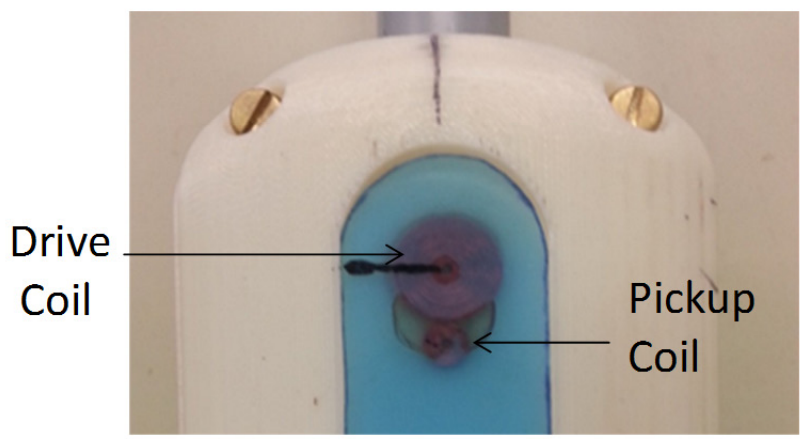


Figure 4. In-house built transmit-receive eddy current gap probe.

Results

Comparison of 3D FEM model with experimental impedance plane display of pickup coil response for gap changing from 0.5 to 16 mm is shown in Figure 5. The origin corresponds to infinite gap (no CT), while data furthest from the origin corresponds to 0.5 mm PT-CT gap. Good agreement between modelling and experimental results is observed.

Conclusions

Modeling of eddy current based pressure tube (PT) to calandria tube (CT) gap measurement is well under way. Two and three dimensional finite element method (FEM) models have been generated and have been compared with validated 2D analytic results [2,5]. In the case of a pickup coil, comparison with experimental measurements has also been performed. Excellent agreement between analytic solutions and experimental data has been observed. Good qualitative agreement between 2D and 3D FEM models and experimental data has been observed.

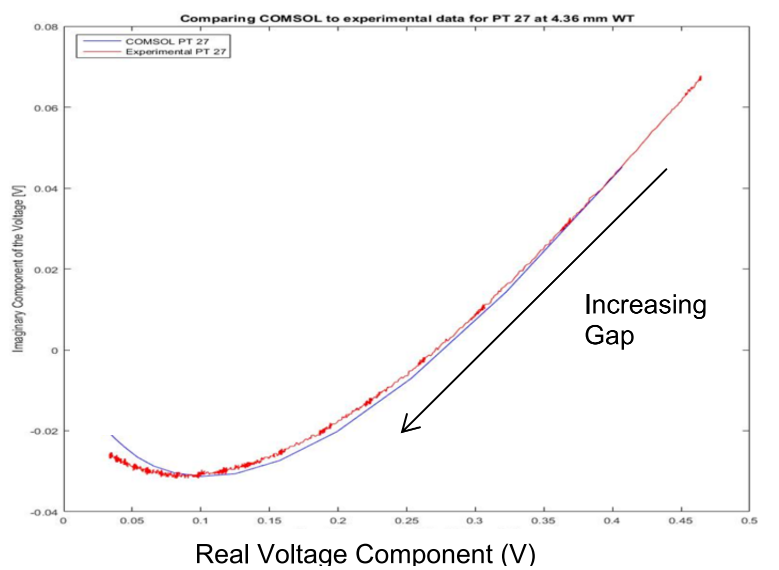


Figure 5: Comparison between 3D FEM model with experimental data for close pickup gap probe response increasing from 0.5 mm to 16 mm.

However, further validation and comparison with far pickup coil measurements, where PT and CT curvature and wall thickness variation may play a more important role, is required. In the coming year FEM modeling, with requisite experimental validation, will be performed for cases of varying PT-CT gap, probe lift-off, PT wall thickness and PT resistivity. The models will be used to explore effects of variable in-reactor measurement conditions. In addition, the effect of LISS nozzles on gap measurement will be investigated experimentally.

References

[1] S. Shokralla and T.W. Krause, ‘Methods for Evaluation of Accuracy with Multiple Essential Parameters for EC Measurement of PT-CT Gap in CANDU® Reactors’, CINDE Journal, 35, No. 1, Jan/Feb 2014, pgs. 5-8.
[2] S. Shokralla, S. Sullivan, J. Morelli, T. W. Krause, ‘Modelling and Validation of Eddy Current Response to Changes in Factors Affecting Pressure Tube to Calandria Tube Gap Measurement’, NDT&E International, 73, March 2015 Pgs. 15-21.
[3] S. Shokralla, T.W. Krause, J. Morelli, ‘Surface Profiling with High Density Eddy Current Non-Destructive Examination Data’, Nondestructive Testing and Evaluation International, 62, March 2014, pgs. 153-159.
[4] C. V. Dodd, W. E. Deeds, ‘Analytical solutions to eddy-current probe-coil problems’, Journal of Applied Physics, 39 (6) (1968) pgs. 2829–2839.
[5] D. Desjardins, T. W. Krause and L. Clapham, “Transient Response of a Driver-Pickup Coil Probe in Transient Eddy Current Testing”, NDT&E International, Vol 75, pp 8-14, 2015, vol. 75, p. 8–14.

Cases with Realized outcomes to Industry

N/A

Research Facilities and Equipment

Royal Military College possess an MS5800 eddy current system, same used for in-reactor inspections and 3 COMSOL licences operated on dual-quad workstations with average of 180 GBytes RAM, each. Coil winding equipment and 3D printing capability.

Current HQP

Two Masters Level and two 3rd year summer students.

HQP that Graduated

N/A

Publications /Journal Papers

Conference Proceedings:
[6] M.S. Luloff, J. Morelli and T. W. Krause, ‘Model of Eddy Current Based Pressure Tube to Calandria Tube Gap Measurement", 19th World Conference on Non-Destructive Testing 2016, June13-17, Munich, Germany.

[7] M.S. Luloff, J. Morelli and T. W. Krause. ‘Finite Element Modeling of Eddy Current Probes for CANDU® Fuel Channel Inspection’, COMSOL Conference 2015 Boston, Boston, Marriott Newton, MA. Oct. 7-9, 2015. http://www.comsol.com/paper/download/259281/luloff_paper.pdf

Conference Presentations/Poster (not repeated from above):

[8] T.W. Krause, M. Luloff , G. Klein, J. Morelli and P.R. Underhill, ‘Model of Eddy Current Based Pressure Tube to Calandria Tube Gap Measurement’, UNENE Research Advisory Committee Meeting, Hamilton, ON. May 4, 2016.
[9] M. Luloff, J. Morelli and T. W. Krause, ‘Finite Element Modelling of Eddy Current Probes for CANDU® Fuel Channel Inspection,’ UNENE Student Presentations, Marriott Hotel – Toronto Airport, Dec 15-16, 2015. Poster and Oral Presentation.

<u>Interactions /Consultations to Industry</u>

M. Luloff and G. Klein gave presentations for the Electromagnetic NDE working group meeting in May 12, 2016, held at 1910 Clements Rd. Ajax, OPG. OPG and Bruce Power representatives were present.

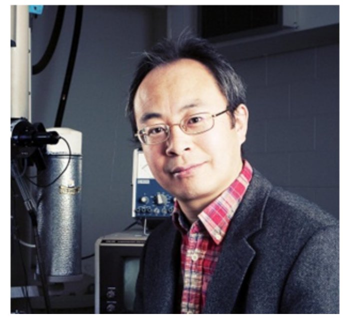
[10] M. Luloff, J. Morelli and T.W. Krause, ‘Solution for a Transmit-Receive Eddy Current Probe above a Layered Planar Conductive Structure’, Electromagnetics NDE Working Group Meeting, 1910 Clements Rd., Ajax, ON, May May 12, 2016.

[11] G. Klein, J. Morelli and T.W. Krause, ‘Modelling and validation of eddy current based pressure tube to calandria tube gap measurements’, Electromagnetics NDE Working Group Meeting, 1910 Clements Rd., Ajax, ON, May May 12, 2016.

Queen's University – Zhongwen Yao CRD

CRD Title: Aging of Inconel X-750 Spacer Material

Overview



Dr. Zhongwen Yao was awarded the NSERC/UNENE/ Collaborative Research and Development (CRD) Grant on June 1, 2013.

In modern CANDU® reactors, spacers are tight fitting springs that provide support to the pressure tube, separate it from the cold calandria tube (80°C) and prevent creep deformation of the pressure tube. It is essential that the spacers in fuel channels maintain their integrity throughout the fuel channel life, so the pressure tubes can be guaranteed not to come in contact with the calandria tubes, risking hydride blister formation and pressure tube rupture in which case the nuclear power plant would be accidentally shut down. The first generation of spacers were made of Zr-2.5Nb-0.5Cu and designed to fit loosely with pressure tube. However the relaxation of the spring due to irradiation led directly to the P2 G16 incident in 1983. As a result, the spacers in CANDU reactors were changed to a tight fitting design made of Inconel X-750. In principle, Inconel X-750 is a γ' Ni_3[Al, Ti] strengthened Ni based superalloy which possess excellent mechanical strength and good creep properties in addition to oxide and corrosion resistance at high temperatures. However, in recent years the effect of aging on the properties of Inconel X-750 spacers has been a growing concern for the CANDU industry. Often spacers from removed channels have been found to be broken. Mechanical tests on removed spacers have been conducted in CRL and results suggest that they may have become embrittled.

The main objective of this project is to develop an understanding of the embrittlement behaviour of the spacer, to address life management issues in existing operating reactors. The focus of this project is to examine the effects of displacement damage using energetic ions (as an analogue to fast neutron irradiation), combined with the effect of helium (via implantation carried out using tandem accelerators, to simulate the effect of helium produced by n-α reactions from Ni) on the properties of Inconel X-750: Ni (70%min), 13-17 Cr, 5-9 Fe, 2.25-2.75 Ti, 0.4-1.0 Al, 0.7-1.2 Nb+Ta. The short and long term results are directly applicable to understanding the effect of aging on the integrity of CANDU spacers. The techniques and analysis methods applied here to ion irradiated materials help characterize neutron irradiated materials being studied at the Chalk River Laboratory (CRL) in parallel where the work can be rather challenging in terms of the complexity in operation of radioactive materials. The following sections outline progress achieved during 2015.

Program Results /Highlights & Advances in Knowledge

In this study, TEM with **in-situ** ion irradiation instead of traditional ion irradiation is primarily employed in bulk materials. The investigation was mainly carried out at JANNuS facility of Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM), France. The figure 1 illustrates irradiation facilities JANNUS. The samples must be loaded with our own designed sandwich installation. Irradiation process was carried out at the JANNUS Orsay facility employing dual ion beams of 1 MeV Ni^+ and 15 keV He^+. Three samples were irradiated up to different doses of 1, 5, and 10 dpa at 400 °C with helium implantation rate of 200 appm/dpa.

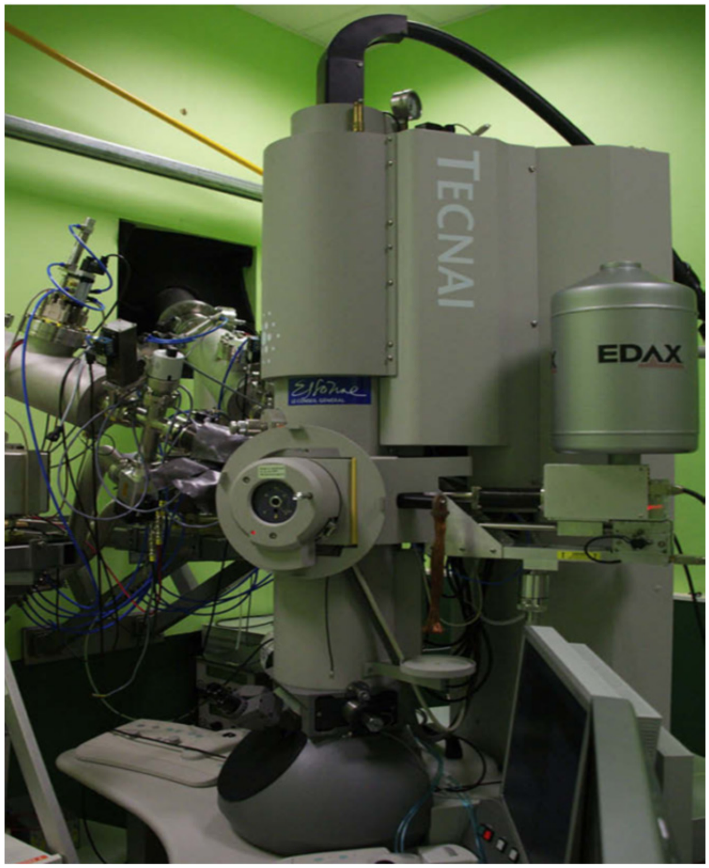


Fig. 1 TEM with in-situ ion beam facilities - Dual beam JANNUS facility at CSNSM in France.

The previous helium pre-implantation was summarized in the UNENE-2014 annual report. The results showed the relevance of cavity formation with magnitude of helium content, however the preimplantation is rather limited, and not real to reactor condition. Other than adding the helium ahead, here the helium is added gradually with the same pace of ion irradiation, which might be more realistic. The simultaneous dual beam irradiation is supposed to be closer simulation of neutron irradiation. The focus is given to the microstructure evolution of Inconel X-750 during dual beam (Ni^+/He^+) irradiation using TEM characterization.

The EDX analysis of X-750 before irradiation depicts distribution of main elements (Ti, Al, Cr and Fe) into and at the vicinity of γ′ precipitates, as shown in Figure 2. Ti and Al enrichment as well as Cr and Fe depletion within γ′ phases are clearly indicated.

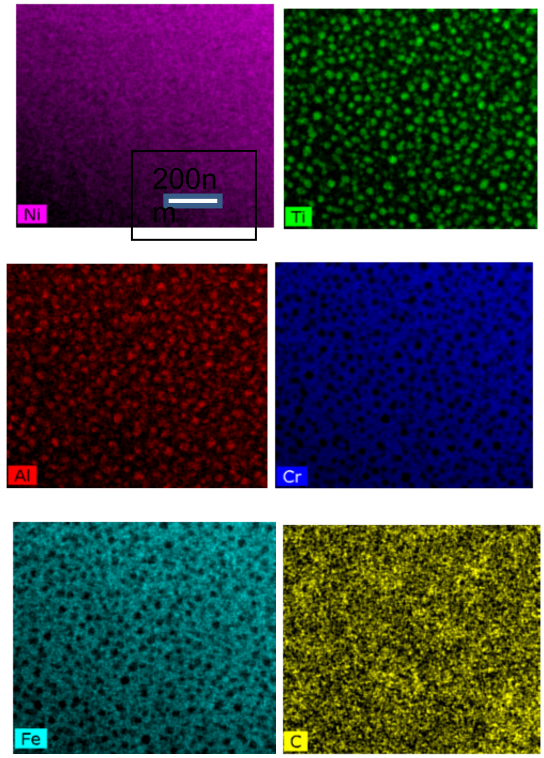


Fig. 2. ChemiSTEM mapping of X-750 prior to irradiation showing elements distribution within γ′ precipitates

Through the (110) pole diffraction pattern along with line plot of intensity at different dose levels of 1 to 10 dpa. For the sake of quantitative measurement of γ′ disordering, the intensity ratio (I matrix/I precipitates) was calculated by using the intensity plot related to each irradiation dose. The supperlattice reflections are still visible in samples irradiated up to 1 and 5 dpa. However, the intensity ratio decreases from 0.9 to 0.85 when the irradiation dose increases from 1 to 5 dpa. Therefore, the partial disordering of γ′-precipitates happened after irradiation to 5 dpa. The supperlattice reflections have completely disappeared at 10 dpa and the intensity profile depicts no peak at the supperlattice position. Hence, it implies that the γ′ precipitates have been disordered completely while the dose increased to 10 dpa.

In contrast to single ion irradiation in which the γ′ precipitates disordered at low dose (0.06) dpa, the disordering process of γ′ precipitates occurred at 100 time higher dose during dual beam irradiation, due to effect of helium on dynamic reordering of γ′ phase. The analysis depicted commence of γ′ precipitate dissolution after 5 dpa and significant progress of the dissolution after irradiation to 10 dpa.

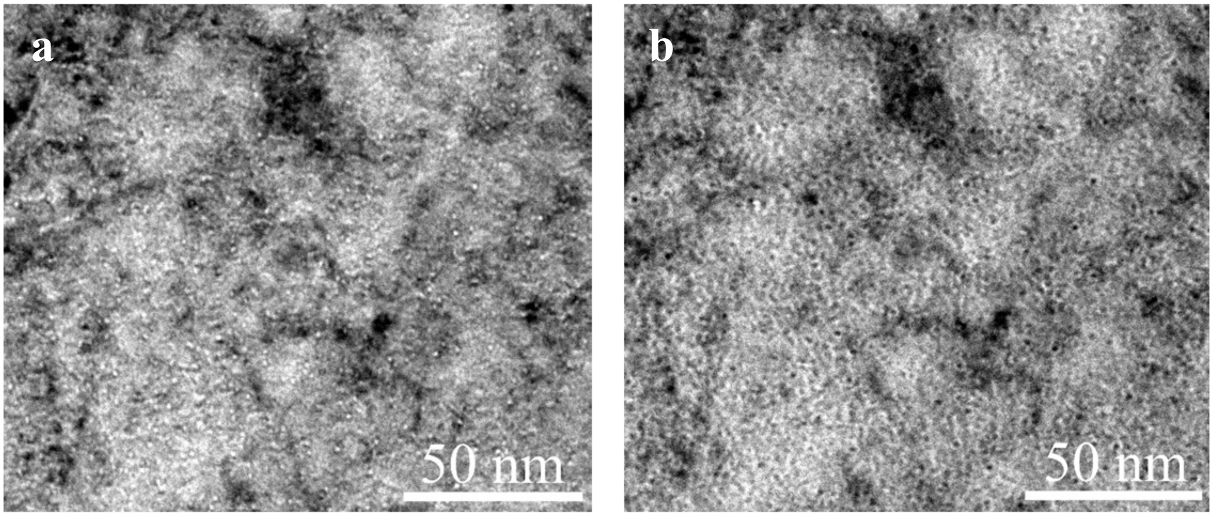


Fig. 3. a) under focus and b) over focus TEM bright field micrographs showing cavities after irradiation to 10 dpa.

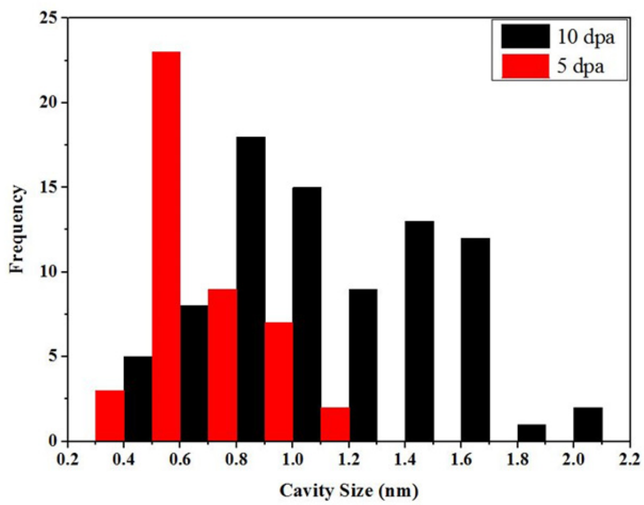


Fig. 4. Cavities size distribution in 5 and 10 dpa irradiated samples.

No visible cavity observed after 1 dpa irradiation and injection of 200 appm helium; on the other hand, cavity nucleation and growth were detected after irradiation to 5 and 10 dpa corresponding to 1000 and 2000 appm helium concentration, respectively. The figure 4 shows the size distribution of cavities. Clearly with increasing dose, the average size of cavities also increased.

Helium implantation also had considerable effect on dislocation loops formation. Large Frank loops developed after dual beam irradiation to all different doses level of 1, 5, and 10 dpa at 400 °C.

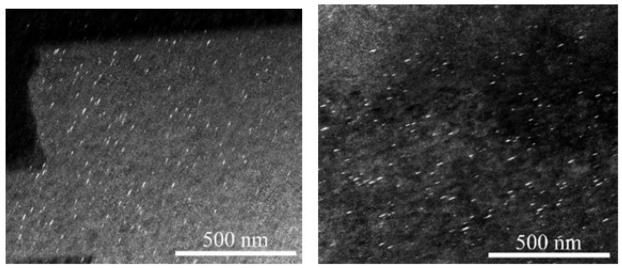


Fig. 5. Rel-rod images after irradiation to the different doses, a) to 5 dpa and b) to 10 dpa, showing the evolution of Frank loops

Weak beam dark field g (4g) condition with g = 002 close to the zone axis [110] was adopted to characterize the irradiation induced dislocation loops. Figure 5 presents the dark field 'Rel-rod' TEM micrographs, showing development of irradiation induced defects at different doses of 5 and 10 dpa. As is depicted, the density and size of 1/3 <111> Frank loops don't change significantly with dose increment of 10 dpa. It is found Thant the greater size of Frank loops was obtained at higher doses; moreover, the higher density of Frank loops was detected with increasing irradiation dose. The high density and large size of these loops are mainly attributed to additional helium interstitials.

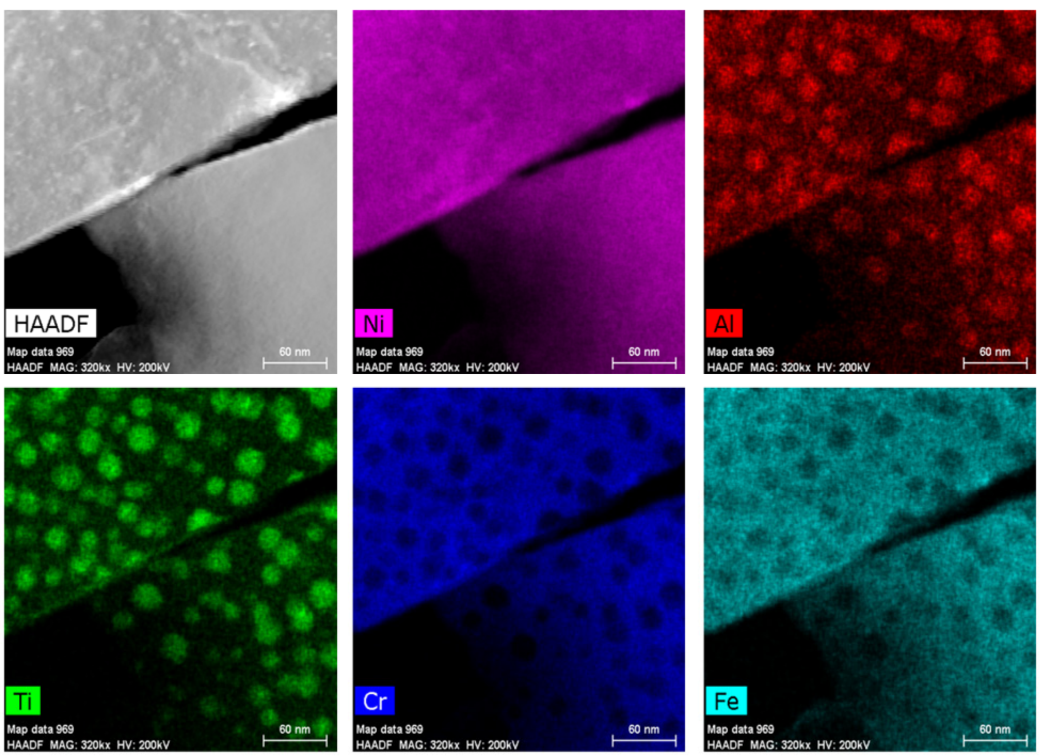


Fig. 6 The TEM in-situ straining was performed with the sample irradiated at 300°C to 0.06 dpa. The Chemi-STEM shows the element map of deformed area.

The primary tests of deformation were performed using in-situ TEM straining as figure 6 showed. It is evident those γ′ precipitates at the crack tip have been sheared which might lead to the irradiation caused softening. It is well proved from our very recent nano indentation tests.
Overall, our progress on the project well followed the steps of original proposal. In the near future we will carry out the following work listed, to meet the final objective of project, mechanical testing of irradiated X750 alloys.

- Micro-mechanical testing, in particular nano-indentation at RT / High temperatures.
- Macro-mechanical testing with standard tensile tests.
- To continue the in-situ TEM straining tests.

Cases with Realized outcomes to Industry; knowledge transfer, Technology Application to industry etc.

The CRD research is to assist the ongoing work in AECL, 'Fuel Channel Life Management / Microhardness of Inconel X-750'.

Research Facilities and Equipment Established Recently or in the Near Future also Existing Ones

1. A computer cluster was built for calculating the damage morphology in alloys.
2. A sophisticated TEM lab is being built with in-situ heating, straining, 3D construction and low background measurement capabilities, considered as unique equipment in Canada.

Current HQP enrolled in the programs; number and type

The NSERC/UNENE CRD involved close collaboration with Prof. Mark Daymond of Queen's University, Dr. Malcolm Griffiths of the AECL-CRL in the areas of microstructure characterization and rate theory calculation of Ni superalloy.

Seven HQP are being trained by this CRD project. Namely, Ken Zhang (PhD, Queen's), Sali Di (PhD, Queen's), Iris Wang (MSc, Queen's), Pooyan Changizian (PhD, Queen's), Qingshan Dong (PhD, Queen's), Adam Brooks (UG, Queen's), Fengfeng Luo (PhD, Wuhan U).

HQP that had Graduated; Number, Type and Specify where Employed

Dr. Sali Di been hired by an Alberta company. Ms. Iris Wang found a PhD position in Beijing University.

Publications/Journal Papers

Peer-reviewed Journal Papers

1. Changizian*, P., Zhang*, K. H., & Yao, Z. (n.d.). Effectof simultaneous helium implantation on the microstructure evolution of InconelX-750 superalloy during dual beam irradiation. Philosophical Magazine, 95(35), 3933–3949, (2016).

2. Di*, S., Yao, Z., Daymond, M. R., Zu, Xiaotao, Peng, Gao Fei. Dislocation-accelerated void formation under irradiation in zirconium. *Acta Materialia*, *82*, 94–99, (2015).

Conference Oral Presentations

1. Yao Z. (2015). The ion irradiation of X750 at Queen's University, Ottawa, One day Ni alloy meeting.
2. Dong, Q., & Yao, Z. (2015). Effect of annealing and irradiation on the microstructure and phase stability of a potential CANDU Zr spacer. UNENE Annual Meeting.
3. Changizian, P., & Yao, Z. (2015). Mechanical properties of irradiated X-750 spacer material evaluated with nano-indentation methods. UNENE Annual Meeting.
4. Yu, H., Yao, Z., & Daymond, M. (2015). Effect of heavy ion irradiation on the microstructure of Zr-Excel alloy pressure tube. Fuel Channel Seminar.
5. Idrees, Y., & Yao, Z. (2015). Irradiation Induced Beta Phase Decomposition in Dual Phase Zr Alloys. Fuel Channel Seminar.
6. Yao, Z., & Di, S. (2015). Component Dislocation Loop Nucleation in Zirconium under Irradiation: Atomic-level Simulations. Fuel Channel Seminar.
7. Changizian, P., & Yao, Z. (2015). Microstructure characterization of dual beam (Kr+2/He+) irradiated Inconel X-750 spacer material. Fuel Channel Seminar.
8. Yao, Z., & Zhang, K. (2015). Radiation Induced Degradation of CANDU Spacers. Fuel Channel Seminar.

Technical Reports

1. Fuel Channel Life Management: Micro-hardness of Inconel X-750 Spacers, internal confidential report of AECL.
2. The IVEM Research Highlight Report of Zircaloy and Ni-Alloys, Argonne National Lab - EMC Annual Review of DOE-USA in 2015.

Interactions/Consultations to Industry or Others

This CRD program directly benefits the parallel study of neutron irradiated spacer program in Chalk River Lab. The university research involved strong collaboration with AECL–CRL, Kinectrics and Argonne National Lab.

Dr. Yao has refereed the scientific proposals for EMIR JANNUS in France. He refereed one funding proposal for the Sylvia Fedoruk Canadian Centre for Nuclear Innovation.

Dr. Yao also reviewed a number of manuscripts for the Journal of Nuclear Materials and the Journal of Materials Science.

UOIT – Atef Mohany CRD

CRD Title: Investigation of the Dynamic Response of CANDU Fuel Bundle Due to Acoustic Pressure Pulsations in the HTS Piping System

Overview

The main objectives of this project are to experimentally investigate the effectiveness of passive acoustic damping devices on the attenuation of acoustic pressure pulsations in piping system and to numerically simulate the dynamic response of CANDU fuel bundle due to acoustic pressure pulsations.

Program Results /Highlights

The NSERC CRD grant has just been awarded with a starting date of July 1, 2016. So, there are no results to report at the moment.

Cases with Realized outcomes to Industry

N/A

Research Facilities and Equipment

A comprehensive design of the experimental setups is complete. The construction of the test loops will start soon. The 3D layouts of both the water loop and the air loop that will be built for this project are shown below.

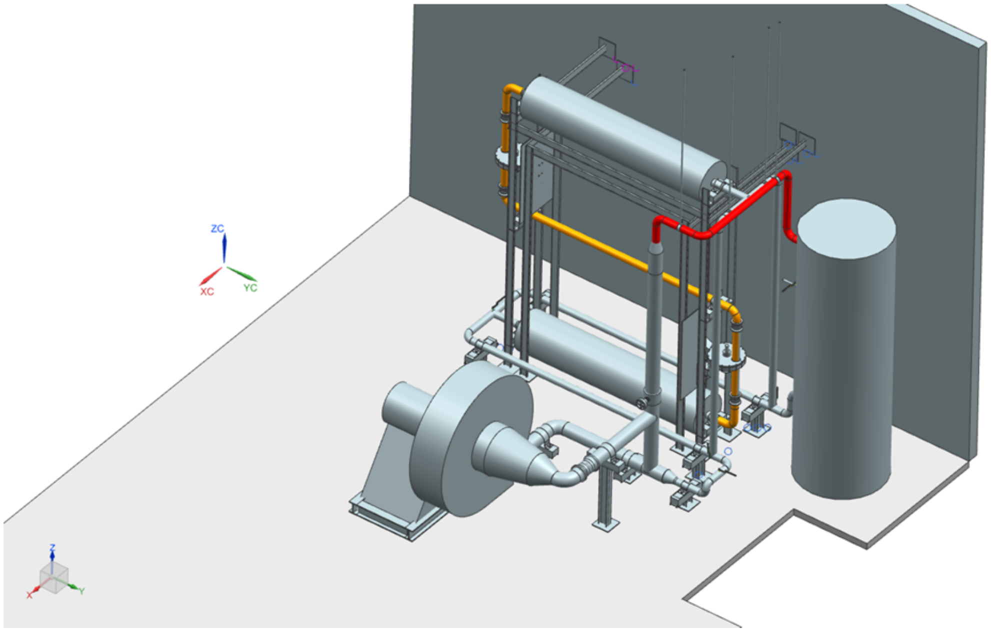


Fig. 1: Isometric view of the air loop. The test pipe is shown in orange.

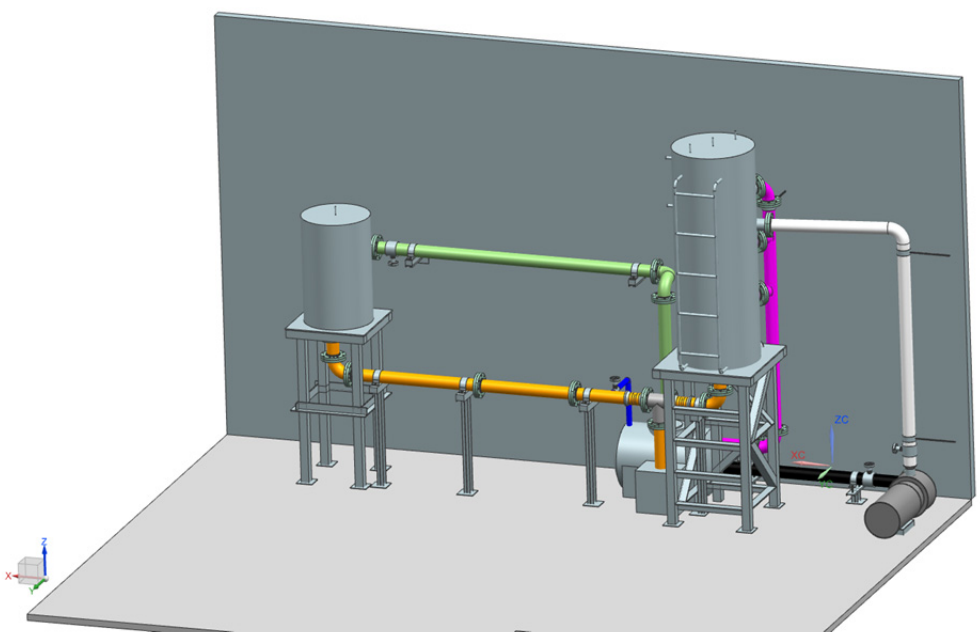


Fig. 2: Isometric view of the water loop. The test pipe is shown in orange

Current HQP

A PhD student has been recruited in September 2015. He completed the required graduate courses for his PhD degree and he is working now on the construction of the test loops. Another Masters student has been recruited and he will join the research group in September 2016.

HQP that Graduated

N/A since the project will start in July 2016.

Publications /Journal Papers

N/A since the project will start in July 2016.

Interactions /Consultations to Industry

N/A since the project will start in July 2016.

UOIT – Eleodor Nichita CRD

CRD Title: Improved CANDU Core Homogenization and Benchmark Models

Overview

With concerns about climate change ever present, nuclear energy continues to be an attractive source of electricity which has minute CO2 emissions and is stable, reliable, and almost inexhaustible. In Ontario, the CANDU-reactor fleet has been providing approximately 50% or more of the provincial electricity supply. For CANDU reactors to continue to be an important contributor to the provincial energy supply they have to satisfy ever increasing economic and safety demands. In particular, increasingly accurate and detailed simulation models are required for the safety analysis of existing, as well as future, CANDU reactors. The broad objective of this proposal is twofold: To develop a new, more accurate, method for calculating the neutron power distribution in a nuclear reactor by using advanced homogenization methods and to develop detailed CANDU-specific benchmark problems to test the newly-developed method, as well as other methods and codes in current use in the Canadian nuclear industry. As a result of the proposed research, the Canadian nuclear industry will enjoy improved capabilities of its computer simulation tools. For its part, the University will increase its expertise in the area of advanced nuclear reactor simulation tools and its graduate students trained as part of this project will enjoy sound knowledge of nuclear engineering and experience working on a challenging engineering problem. New knowledge will be generated and advancements will be made in the area of nuclear engineering related to CANDU reactors.

1. *Global-local iterations using discontinuity factors*

As part of this project, a new global-local iteration model will be developed for CANDU lattices, whereby cross sections and discontinuity factors will be generated using non-reflective node-boundary conditions. The node boundary conditions will be determined by performing iterations between the core calculations and the single-node (cell) calculations. At each iteration, node boundary conditions from the previous core calculation will be used in a single-node (cell) calculation to calculate updated cross sections and discontinuity factors which will be used in the subsequent core calculation. The iterative process will continue until convergence. The converged values of the node-boundary currents are expected to be very close to the exact values and hence the resulting homogenized cross sections and discontinuity factors are expected to yield more accurate full-core results than standard homogenization. Single-cell (lattice) calculations will be performed using the lattice code DRAGON and core calculations will be performed using the DISDIF3D diffusion code developed at UOIT, which is a finite-difference diffusion code which allows the use of discontinuity factors.

2. *Development of a partial-cell homogenization model*

One way to reduce homogenization-related errors is to use smaller homogenization regions. The possibility of using partial-cell homogenization will be investigated. A CANDU cell will therefore be divided into rectangular sub-regions and homogenized cross sections will be generated for such smaller regions. Different cell sub-divisions will be studied to determine the ones that yield the best results. Such a partial-cell homogenization method, which does not rely on discontinuity factors, has the advantage of not requiring any changes to be made to the existing full-core diffusion codes and only requires a change in the procedure for generating cell-averaged cross sections. DRAGON models for CANDU bundles will be developed and used to generate homogenized cross sections for parts of the cell. Diffusion calculations will be performed using DONJON. A partial-core benchmark model will be used to compare transport results with results obtained using full-cell homogenization and with results obtained using partial-cell homogenization, to assess the efficacy of the latter.

3. Development of detailed CANDU benchmarks and code-suite comparisons

Two full-core benchmark models will be developed: one for a 380-channel core and another one for a 480-channel core. The full-core models will include the full complement of channels, so as to preserve the bi-directional fuelling symmetry and will use 69-group energy detail and explicit fuel composition at each burnup. Partial core benchmark models will focus on two types of regions that customarily pose homogenization problems: regions including reactivity devices (in particular mechanical control rods and shutdown rods) and regions including reflector. The developed benchmarks will be used to compare results obtained using the WIMS-IST/RFSPIST suite of codes and the DRAGON/DONJON suite of codes. The DRAGON/DONJON calculations will be performed at UOIT and the WIMS-IST/RFSP-IST calculations will be performed at OPG and UOIT.

<u>Program Results /Highlights</u>

The project started in April 2014, with the first students enrolling in September 2014. Progress for each objective, for the period April 2015-March 2016 is shown below.

1. *Global-local iterations using discontinuity factors*

   The possibility of using global-local iterations and discontinuity factors to reconstruct pin-by-pin powers in CANDU cells has been investigated. A simple, 3x3-cell, two-dimensional model which does not include a reflector region has been developed to test the global-local iteration method and pin-power reconstruction for CANDU configurations. Results for the 3x3 model show pin power errors below 0.5% when diffusion calculations are compared with transport (DRAGON) calculations. Results will were presented at the CNS International Simulation Conference (November 2015) and were published the Transactions of the American Nuclear Society. A one-dimensional model which includes reflector is currently under development.

2. *Development of a partial-cell homogenization model*

   A simple DRAGON-based full-cell homogenization model has been developed as well as a DRAGON model for partial-cell homogenization. Results were published the Transactions of the American Nuclear Society. Model refinements have been discussed with the technical advisory committee and are now being implemented

3. *Development of detailed CANDU benchmarks and code-suite comparisons*

   Possible concepts, configurations and size for full-core and partial-core benchmarks have been discussed with the technical advisory committee and models are currently being developed.

HQP

- 2 Ph.D. Students
- 1 PDF
- 1 M.A.Sc. Student

HQP that Graduated

N/A

Publications /Journal Papers

E. Usalp and E. Nichita, “Leakage-Corrected Discontinuity Factors for PHWR Lattices – A simple Test”, Proc. 7th International Conference on Modelling and Simulation in Nuclear Science and Engineering, Ottawa, Ontario, Canada, October 18-21, (2015)

E. Nichita and E. Usalp, “Pin Power Reconstruction for PHWR Reactors Using Leakage-Corrected Discontinuity Factors”, Trans. Am. Nucl. Soc., **112**, (2015)

E. Nichita and S. Mohapatra “Application of SPH Factors to PHWR Lattice Homogenization”, Trans. Am. Nucl. Soc., 114, (2016)

Interactions /Consultations to Industry

The technical advisory committee has been established. Two meetings were held with the OPG collaborator and an additional meeting with the full advisory committee. Additionally, the research team participate in two two-day meetings of the UNENE RAC.

UOIT – Scott Nokleby CRD

CRD Title: Development of New Fuel Channel Inspection Tools for Increased Inspection Speed

Existing CANDU fuel channel inspection techniques are extremely time consuming. First, they require the reactor to be off-line. Second, they only enable one fuel channel to be inspected at a time. These shortcomings have been identified as priority concerns by Ontario Power Generation's (OPG's) Inspection, Maintenance, and Commercial Services (IM&CS) Non-Destructive Examination Department. This project proposed to address these shortcomings by developing two new inspection tools.

The first tool would be a self-contained system that can be inserted into a fuel channel as part of a fuel bundle string, while the reactor is on-line, and perform the necessary inspections of the fuel channel. This system, dubbed the capsule, must be able to provide required Non-Destructive Examination (NDE) tests in the extremely demanding, high temperature, high-flux core environment, and there-fore must be radiation hardened and total dose fault tolerant.

The second tool would be a fire-and-forget, self-propelled inspection tool that can be inserted into a fuel channel of a reactor that is off-line. Multiple copies of this tool, dubbed the crawler, will be capable of being inserted into multiple fuel channels and will perform inspections in parallel, despite being inserted sequentially by a delivery machine such as the Channel Inspection and Gauging Apparatus for Reactors (CIGAR) or the Universal Delivery Machine (UDM).

The project was approved for a February 2012 start, but due to the timing of the notification for the project and the ability to recruit HQP to work on the project; the project did not commence until May 2012. In addition, upon further discussion with OPG personnel, the initial focus of the project was shifted towards developing the prototype for the second tool discussed above, the fire-and-forget, self-propelled inspection tool, the crawler. It is anticipated that some of the developed technologies for this prototype can be extended to the capsule prototype discussed above.

In addition, to the Principal Investigator, Scott Nokleby, and the co-applicant, a number of HQP were involved in the project. One PhD (part-time) student (Mr. Cliff Chan) and four MASc students (Mr. Shivam Shukla, Mr. Jordan Gilbert, Mr. Mark Manning, and Mr. Abu Khan), along with one MEng student (Mr. Yuchen Yang) worked on different aspects. In addition, three undergraduate summer research students (Mr. Jordan Gilbert, Ms. Hannah Graham, and Mr. Cameron Verstegen) were involved with the project. From September 2012 until April 2013, two fourth year capstone design groups (one group of five students and one group of four students) also worked on the project.

A detailed literature review of existing CANDU fuel channel inspection systems along with other possible pipe inspection technologies was conducted. The development of the new inspection systems proceeded on three fronts.

First was the development of a method to allow wireless communication of data through the fuel channel closure plug. This piece is critical to allow the functioning of the overall system. Potential technologies were investigated and an initial concept has been proposed (see Figure 1). A simple proof-of-concept prototype was built to verify the design concept.

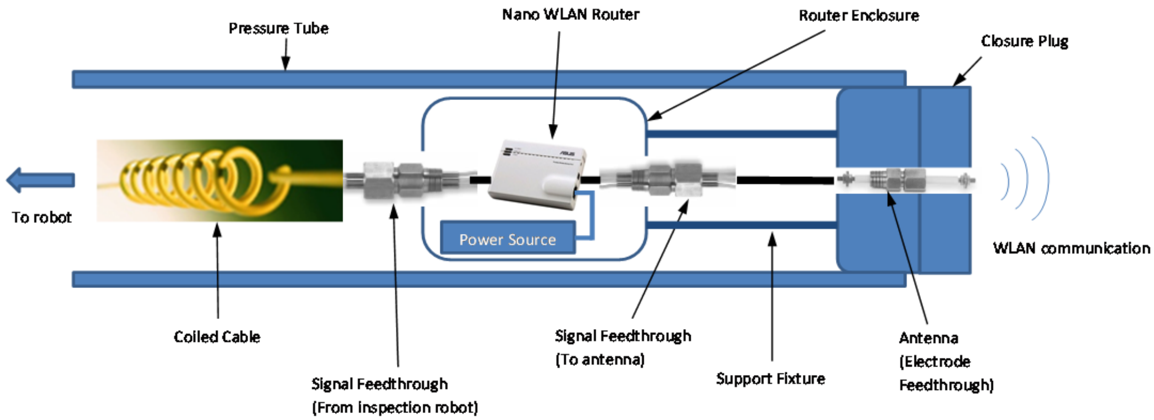


Figure 1: Concept Design for Modified Closure Plug

The second avenue of investigation was the development of a robotic crawler that would move the inspection head in the channel. Concept generation and selection were performed and a proposed design concept was selected. A simple proof-of-concept prototype was originally built followed by several iterations of prototypes built with rapid prototyped parts. These prototypes allowed various concepts to be tested. The final prototype design was completed and a proof-of-concept prototype has been built (see Figure 2).

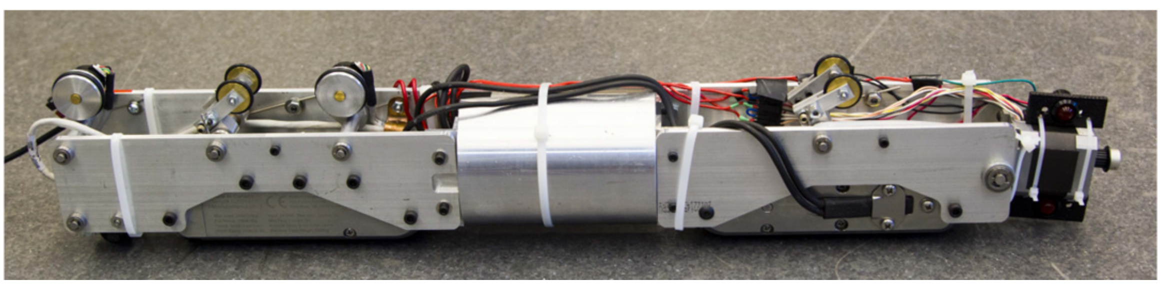


Figure 2: Proof-of-Concept Prototype of Crawler

The third avenue of research involved the development of a localization system in order to accurately determine the position of the crawler in the pipe. A test rig was built that allowed for testing the accuracy of different localization techniques (see Figure 3). In addition, a Kalman filter approach for fusing the data from the three encoders mounted on the system has been developed.

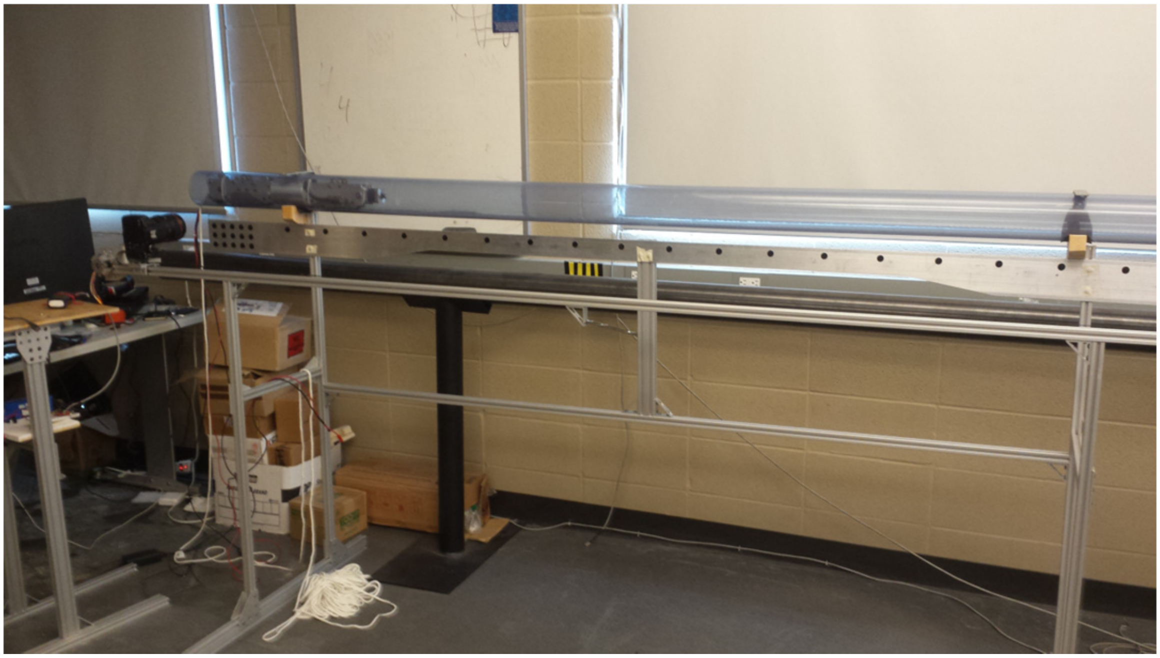


Figure 3: Localization System Test-Rig

Concurrently to the work above, A MCNP model of a CANDU reactor was developed in order to determine flux levels that the proposed crawler would experience (see Figure 4). The modeling data was used in the detailed design of the crawler and the developed model can be used in the future development of the online inspection system.

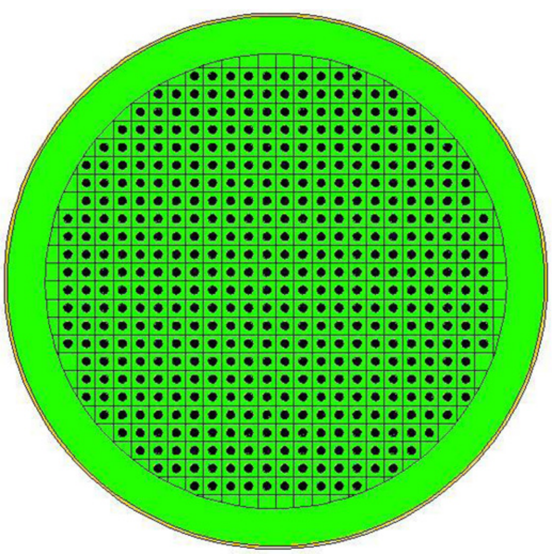


Figure 4: MCNP Model of a CANDU Reactor

Work was conducted on the development of a new flaw replication tool that can be used in-situ (see Figure 5). Two different concepts were developed, one involving a laser scanner and the other involving a stereo-vision-based system. A proof-of-concept prototype of the laser scanning system was built and tested. Work on the stereo-vision-based system is still ongoing.

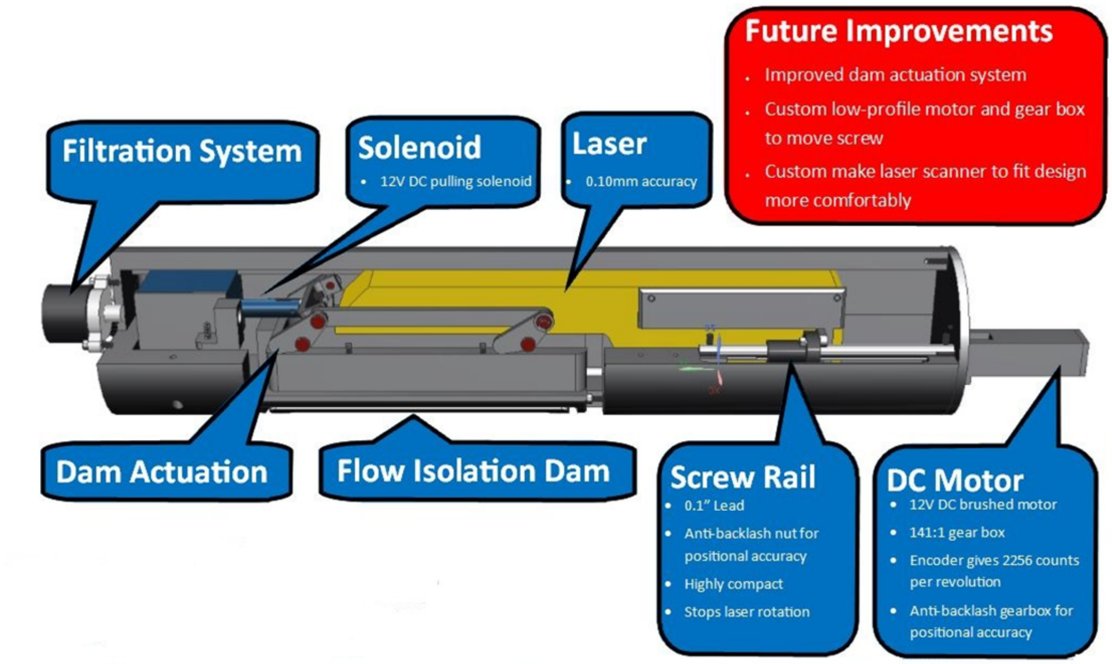


Figure 5: Conceptual Design for an In-Situ Flaw Replication Tool

Publications:

Gilbert, J., Manning, M., Nokleby, S. B., and Waller, E., 2015, “Preliminary Development and Modelling of a Next Generation Inspection System for CANDU Reactors,” in *Proceedings of the 35th Annual Conference of the Canadian Nuclear Society*, May 31 – June 3, Saint John, Canada, 12 pages.

Gilbert, J., Nokleby, S. B., and Waller, E., 2015, “MCNP Simulation of Offline Core Dose in CANDU Reactors,” Poster, UNENE Workshop, December, Toronto, Canada.

University of Waterloo – Wei-Chau Xie CRD

CRD Title: Seismic Risk Analysis of Nuclear Plants

Overview

The objective of this research project is to develop comprehensive methodologies for the accurate determination of floor response spectra (FRS). The method will provide a complete probabilistic characterization of FRS as an integral part of seismic risk analysis. The methods overcome the deficiencies of existing direct method and will reduce or eliminate cumbersome and expensive computation in the time history method. The research will develop accurate methods for seismic fragility analysis of systems, structures, and components (SSCs) by considering multiple ground motion parameters (GMP) to ensure that SSCs in nuclear power plants (NPPs) are seismic qualified in a cost-effect way. It is critical for Seismic Margin Assessment (SMA) and Seismic Probabilistic Risk Assessment (SPRA).

Research Team

In 2015, two PhD students (Zhaoliang Wang and Bo Li) graduated. Dr. Zhaoliang Wang is working at CNSC and Dr. Bo Li continues working as a post-doctoral fellow. Four PhD students (Wei Jiang, Zhen Cai, Yang Zhou, and Xiaojun Yu) were working in the projects under this CRD.

Progress

Some significant progresses in 2015 are highlighted in the following.

Direct Method for Generating Floor Response Spectra

The purpose of this study is to develop a method of generating FRS that overcomes the deficiencies of the time history method and preserves the advantages of conventional response spectrum analysis for structures. A direct spectra-to-spectra method is analytically developed for the generation of FRS without introducing spectrum-compatible time histories as intermediate seismic input or performing time history analyses. Only the information required in a conventional response spectrum analysis for structural responses, including prescribed ground response spectra (GRS) and basic modal information of the structure (modal frequencies, mode shapes, and participation factors), is needed. The concept of t-response spectrum is proposed to determine the responses in the tuning case when the secondary system is resonant with the supporting structure. Furthermore, a new modal combination rule (called FRS-CQC), which fully considers the correlation between the responses of the secondary system and the supporting structure, and the correlation between modal responses of the structure, is derived based on random vibration theory. The direct method developed is both efficient and accurate, giving a complete probabilistic description of FRS peaks, and accurate FRS comparable to those obtained from time history analysis using a large number of spectrum-compatible time histories.

The direct method provides an efficient and accurate method for determining seismic demand, used in seismic design, SMA, and SPRA. It has been successfully applied in the Point Lepreau NGS project by Candu Energy Inc.

Scaling Method for Generating Floor Response Spectra

A scaling method, based on the proposed direct spectra-to-spectra method, is further developed for generating FRS in a situation when the modal information of structure is not available. A system identification technique is carried out to recover the modal information of equivalent significant modes of the structure from existing GRS-I and FRS-I. Scaling factors are then determined in terms of the equivalent modal information along with the GRS-I and GRS-II. The proposed scaling method can scale FRS to various damping ratios when the interpolation method recommended in standards are not applicable, and can also consider the large variations in the spectral shapes between GRS-I and GRS-II. The scaling method provides an accurate, efficient, and economical method for generating FRS, which is important to refurbishment projects of existing NPPs and critical for new build in feasibility analysis, budgeting, scheduling, bidding and tendering, and procurement of important equipment.

Seismic Fragility Analysis Considering Multiple Ground-Motion Parameters

Seismic fragility is the probability of failure of an SSC for a given ground motion parameter (such as peak ground acceleration) level. Seismic fragility analysis (FA) is widely used to determine seismic capacities of SSCs of NPPs. Some inherent deficiencies, due to the use of a single GMP, have been observed in engineering practice:

(1) Different reference response spectral shapes give inconsistent seismic capacity of SSCs;

(2) Reference response spectra introduce noticeable spectral shape variability, which decreases seismic capacity estimate of SSCs;

(3) UHS implies that the maximum spectral accelerations at all frequencies occur simultaneously for a given earthquake scenario, introducing extra conservatism.

To overcome these shortcomings, seismic fragility analysis considering multiple GMPs, which are spectral accelerations at significant vibration frequencies of SSCs, is proposed to reduce the influence of spectral shape, and release seismic margin in current seismic assessment. A large number of fictitious response spectra, which consider all possible combinations of spectral acceleration values of GMPs, are used as input GRS. Spectral shape variability is greatly reduced, leading to increased estimates of seismic capacities of SSCs. High Confidence of Low Probability of Failure (HCLPF) capacity considering multiple GMPs is derived; using multiple GMPs can significantly increase HCLPF capacity estimate of SSCs. By considering multiple GMPs, the method improves the fragility analysis methodology, which is critical in SMA and SPRA, by providing better prediction of seismic responses of structures, more accurate estimate of seismic capacities of SSCs, and more accurate assessment of seismic risk. This project is on-going. The results of Probabilistic Seismic Hazard Analysis (PSHA) is being incorporated to develop Equivalent HCLPF capacities and to employ equivalent fragility surfaces in SPRA.

Generating Spectrum-Compatible Time Histories

In many earthquake engineering applications, such as evaluation of response of inelastic structures or generation of floor response spectra, time history analysis may be required, which ground motions as input. Two algorithms to generate spectrum-compatible time histories based on two approaches recommended by USNRC Standard Review Plan 3.7.1 were developed. Hilbert-Huang Transform technique is used to analyze frequency contents and amplitudes of seed motions. Through adjusting the frequency contents and amplitudes of seed motions, spectrum-compatible time histories are obtained. The first algorithm is to generate tri-directional time histories compatible with multi-damping target design spectra (GRS or FRS). The second algorithm is to generate tri-directional time histories compatible with single-damping target design spectra. Time histories generated by these two algorithms satisfy stringent requirements and well match target response spectra; they are applicable to generate time histories for seismic analysis of nuclear structures and facilities.

Interaction with Industry

Our research team has been working very closely with the Department of Engineering Analysis, Candu Energy Inc. by working on projects of their immediate interest and providing training.

Publications

Journal Papers:

1. Bo Li, Wei-Chau Xie, Mahesh D. Pandey, "Newmark Design Spectra Considering Earthquake Magnitudes and Site Categories," *Earthquake Engineering and Engineering Vibration*.
2. Wei Jiang, Bo Li, Wei-Chau Xie, Mahesh D. Pandey, 2015, "Generate Floor Response Spectra, Part 1: Direct Spectra-to-Spectra Method," *Nuclear Engineering and Design*, 293, 525-546, doi:10.1016/j.nucengdes.2015.05.034.
3. Bo Li, Wei Jiang, Wei-Chau Xie, Mahesh D. Pandey, 2015, "Generate Floor Response Spectra, Part 2: Response Spectra for Equipment-Structure Resonance," *Nuclear Engineering and Design*, 293, 547-560, doi:10.1016/j.nucengdes.2015.05.033.

Conference Publications:

1. Shunhao (Sean) Ni, Zhen Cai, Wei Liu, and Wei-Chau Xie, 2015, "Seismic Fragility Analysis for Structures, Systems, and Components of Nuclear Power Plants: Part I — Issues Identified in Engineering Practice," *SMiRT-23 (Structural Mechanics in Reactor Technology)*, August 10-14, 2015, Manchester, UK.
2. Zhen Cai, Shunhao (Sean) Ni, Wei Liu, Wei-Chau Xie, and Mahesh D. Pandey, 2015, "Seismic Fragility Analysis for Structures, Systems, and Components of Nuclear Power Plants: Part II — Use of Multiple Ground-Motion Parameters," *SMiRT-23 (Structural Mechanics in Reactor Technology)*, August 10-14, 2015, Manchester, UK.

Western University – David Shoesmith /Sridhar Ramamurthy CRD

CRD Title: Mechanical and Chemical Indicators for SCC in Alloy 800 Steam Generator Tubing

<u>Overview</u>

As nuclear power stations approach their design life, one of the greatest concerns to the operators is corrosion of steam generator (SG) heat exchanger tubing, which can take several forms, such as pitting, thinning and stress corrosion cracking (SCC). Nickel-based Alloy 600 (A600) tubes have proven to be susceptible to corrosion in the operating environment. In fact, SCC of A600 tubing is the single most important reason that nuclear SGs are replaced. In US PWR nuclear stations, Alloy 690 (A690) has been introduced as a replacement or A600 tubing. So far, thermally treated A690 tubes appear to be highly resistant to SCC in PWR environments; no in-service failures have been reported in more than 16 years of operating experience. Yet there has been no solid scientific explanation for the improved performance; most observers conclude that it is related to the effect of the higher chromium. In contrast to US practices, station operators in Canada and Europe have been replacing A600 with Alloy 800 (A800); this is an alloy high in both nickel and iron with more characteristics of an austenitic stainless steel than a nickel alloy. Until recently, there had been no reports of SCC in A800; however, cracking of A800 has recently been reported in Europe and A800 is also not immune to cracking under laboratory conditions; under certain chemical conditions, such as in caustic and lead-containing solutions, cracking has been reported. In addition, advanced CANDU designs specify higher outlet temperatures, which will again likely accelerate SCC. As with A690, there has not been a comprehensive comparative study of the processes leading to crack initiation in any of the major alloys used in heat exchanger tubes in the world's nuclear power stations.

During the first year of this project, research focused on understanding the oxide film properties on A600 and A800 specimens exposed to room temperature 0.1M $Na_2S_2O_3$ (pH=6.5) solution. Based on the extensive electrochemical data and the results from the surface analytical measurements, a model for the oxide film growth was developed. During the second year of the project, research continued on understanding the oxide film development at higher temperatures, up to 90 ºC. In addition to sodium thiosulphate solution (known to cause SCC in A600 tubing), experiments were also performed in sodium sulphate solution (which does not cause SCC). Moreover, the oxide films formed on stressed A600 and A800 C-ring specimens exposed to an acid sulphate solution at 315 ºC (from U of T) was also characterized.

During the current and third year of the project, work continued on A600 and A800 specimens exposed to room temperature, 60 and 90 ºC solutions with a view of understanding the chemistry of the oxide film formed at these temperatures and to determine whether the solution composition has any effect on the oxide film chemistry. Experiments were conducted using a modified electrochemical procedure, designed to remove the effect of pre-formed surface film on the electrochemical behaviour. The results from 90 ºC experiments are important because this temperature is close to that experienced during the shut down of the boiler. In addition, based on the request from UNENE, some limited electrochemical experiments were also performed on A690 specimens under the same conditions to determine the electrochemical behavior of A690 compared to A600 and A800 tubing materials. Highlights of the results from these measurements are presented in the next section.

Program Results /Highlights

The results presented here are divided into three parts: (a) summary of the results from 60 and 90 ºC experiments using the modified electrochemical procedure, (b) preliminary results from the experiments on A690 specimens and (c) further results from the characterization of the A600 and A800 C-ring specimens subjected to cracking experiments.

(1) Composition of the Oxide Films formed on A600 and A800 at 60 ºC and 90 ºC

Electrochemical experiments were performed in deaerated 0.1M $Na_2S_2O_3$ (pH=6.5) and 0.1M Na_2SO_4 (pH=6.1) solutions. Based on the trends observed in the previous experimental data, the procedure for the electrochemical measurements was revised slightly to include a cathodic cleaning step prior to polarization or impedance measurements. This step involved polarizing the specimen at -1 VAg/AgCl for 10 min to remove any surface films or artefacts arising from the polishing and other specimen preparation procedures. All the electrochemical measurements were repeated using this modified procedure. This was followed by the characterization of the oxide films formed at various applied potentials, namely the equilibrium corrosion potential (E_{corr}), passive regions and transpassive regions where passive film breakdown occurs. The oxide films were characterized using surface analytical techniques such as scanning electron microscopy coupled with energy dispersive X-ray (SEM/EDX) analysis, X-ray photoelectron spectroscopy (XPS), and scanning Auger microscopy (SAM).

The results from the electrochemical measurements indicated that the solution composition has a more pronounced effect on the corrosion behavior compared to the test temperature or alloy composition. Potentiodynamic polarization measurements indicated that both A600 and A800 have a narrower passive range and higher passive current density in thiosulphate solution compared to in sulphate solution. However, no significant differences in the electrochemical polarization behavior were observed between A600 and A800 in experiments conducted at 60 ºC and 90 ºC yielded similar measurements. An example of the differences in the electrochemical behavior is shown in Figure 1, which presents the results from the electrochemical impedance spectroscopy (EIS) measurements on A800 at 90 ºC in the two solutions of interest. In this figure, the magnitude of impedance is plotted as a function of the frequency of the applied a.c. signal; in general, greater impedances represent greater

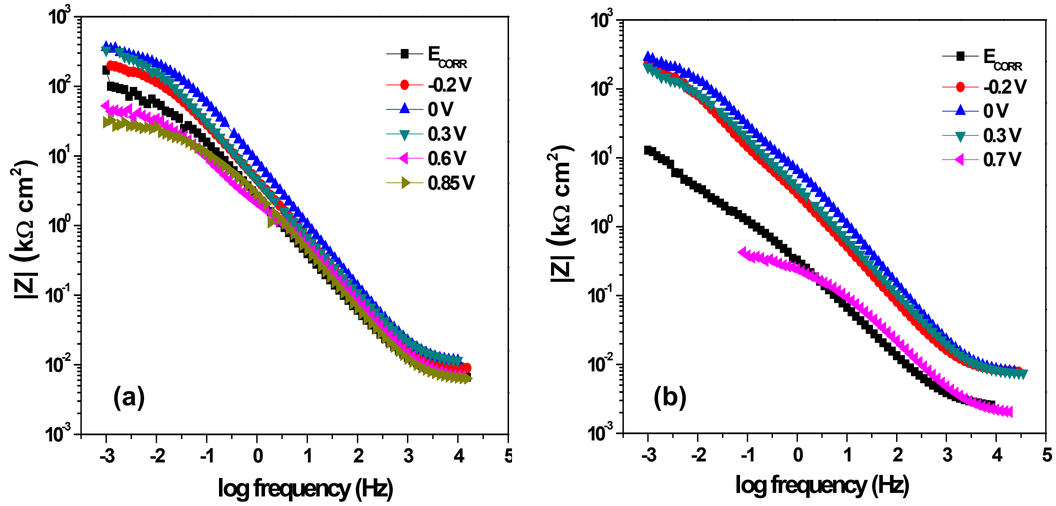


Figure 5. Data from electrochemical impedance spectroscopy measurements performed on A800 specimens in deaerated 0.1 Na_2SO_4 (a) and 0.1M $Na_2S_2O_3$ (b) solutions at 90 ºC.

resistance to corrosion. Impedance plots from several different applied potentials, ranging from the corrosion potential (Ecorr) to the passive (-0.2 and 0.3 VAg/AgCl) and transpassive (0.6 to 0,85 VAg/AgCl) regions, are presented in this figure. This figure shows that the decrease in the impedance from the passive to transpassive (film breakdown) region is an order of magnitude in the sulphate solution compared to nearly three orders of magnitude in the thiosulphate solution, indicating that the thiosulphate solution promotes the passive film destabilization much more readily compared to the sulphate solution.

Composition of the oxide films formed at different potentials was also determined using the surface analytical techniques. These are similar to the measurements performed last year, except that the modified electrochemical methodology was used to grow the oxide films. The results from these measurements are similar to those obtained without cathodic cleaning, i.e. the oxide film consists of mainly Cr, Ni and Fe oxides/hydroxides at Ecorr and in passive range, while the dominant corrosion product in transpassive range is Fe oxides/hydroxides. For A800, With the increase in temperature, it appears that Fe can be readily oxidized to form deposits of iron hydroxides, especially in the transpassive region. Significant amounts of Cr_2O_3 species were detected within the oxide film in the transpassive region. In contrast, A600 specimens exhibited lower amounts of iron-species and, as a consequence, lower level of Cr_2O_3 species in the transpassive region. Decreasing amounts of Cr_2O_3 has increased the susceptibility A600 specimens to enhanced corrosion in the transpassive region in the thiosulphate solution.

(2) Preliminary Results from Experiments on A690 Tubing

Alloy 690 (A690) SG tubing is being extensively used in PWR reactors and is also being considered for use in Canadian nuclear power plants. As a result, UNENE was interested in the electrochemical behaviour of A690 tubing and requested that some preliminary experiments be performed under the conditions similar to those employed for the examination of A600 and A800 specimens. Electrocehmical measurements, including potentiodynamic polarization and electrochemical impedance spectroscopy, were performed in deaerated 0.1M Na_2SO_4 and 0.1M $Na_2S_2O_3$ solutions using the revised methodology. Figure 2 presents the polarization plots for the three alloys in room temeprature solutions. In the 0.1M Na_2SO_4 solution (Figure 2, left), all three alloys exhibited a well-defined passive region. However the passive current density for A690 is half an order of magnitude greater compared to the other two alloys. A800 appeared to exhibit the lowest crrent density. The potential at which the passive film break down occurs (transpassive region) is similar for A600 and A690 alloys and A800 maintained better passivity at higher potentials. The corresponding results from the 0.1M $Na_2S_2O_3$ solution (Figure 2, right) show that there is no siginificant difference in the electrochemical behaviour among the three alloys. Current densities in the passive region are similar and A800 exhibited a better corrosion resistance in the transpassive region.

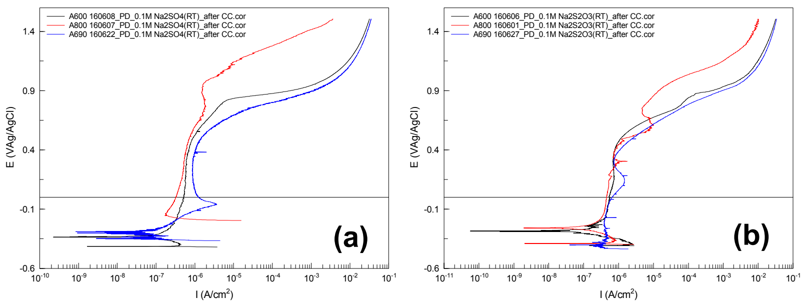


Figure 2. Potentiodynamic polarization plots for A600 (black), A800 (red) and A690 (blue) specimens exposed to room temperature deaerated 0.1M Na_2SO_4 (a) and 0.1M $Na_2S_2O_3$ (b) solutions.

Figure 3 presents the polarization plots in deaerated 0.1M $Na_2S_2O_3$ solution maintained at 60 °C (left) and 90 °C (right). This figure shows that at both temperatures, the passive film is not stable and break downs in the passive film, corresponding to an increase in the current desities, were observed at ~ 0 VAg/AgCl and at higher potentials. The current densities in the passive region are lower for A600 compared to A800 and A690. However, A690 appeared to exhibit much better corrosion protection (lower curents) at the higher potentials, especially in the transpassive region. In this potentiual range, ~ 0.25 to 1.0 VAg/AgCl, A600 is the most susceptible to corrosion, followed by A800 and A690 exhbited currents an order of magnitude or lower than those for A600.

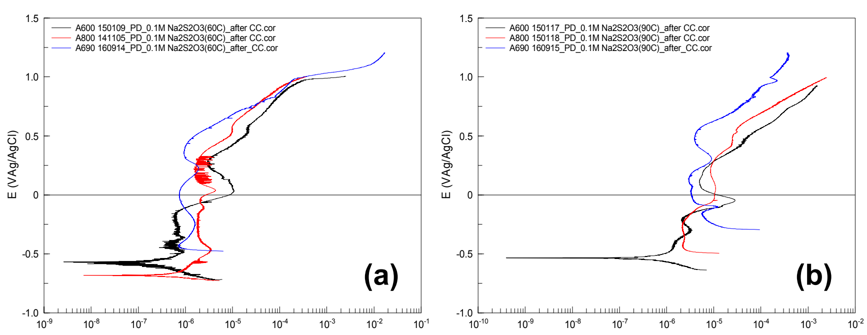


Figure 3. Potentiodynamic polarization plots for A600 (black), A800 (red) and A690 (blue) specimens exposed to deaerated 0.1M $Na_2S_2O_3$ solution at 60 °C (a) and 90 °C, solutions.

Finally, Figure 4 presents the EIS plots obtained in deaerated room temeprature room temperature 0.1M Na_2SO_4 (a, c, and e) and 0.1 M $Na_2S_2O_3$ (b, d, and f) solutions at corrosion potential, Ecorr (a and b), passive (c and d) and transpassive (e and f) regions. In 0.1M Na_2SO_4 solution, there is no significant difference in the corrosion behaviour of the three alloys at Ecorr (a) and in the passive (c) regions. However, in the transpassive region (e), A690 exhibited much greater impedances compared to A800 and A600 samples. A600 sample is the most susceptible to corrosion; at low frequencies, the impedances were two orders of magnitude lower compared to A690 specimen. In contrast, for the 0.1M $Na_2S_2O_3$ solution measurements, no significant differences were observed among the three alloys at Ecorr (b) and passive regions (d), while A690 appears to be slightly more susceptible to corrosion in the transpassive

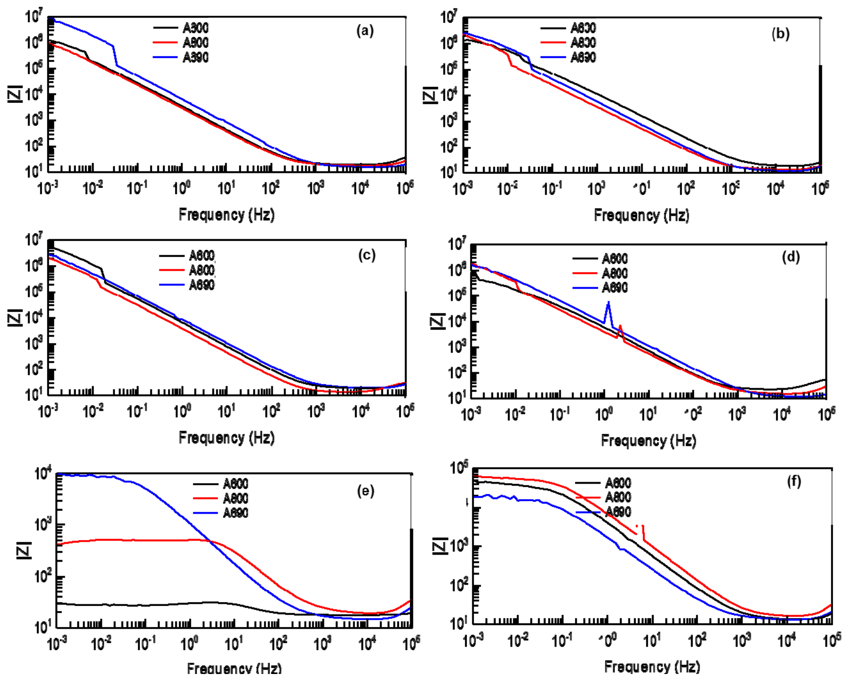


Figure 4. EIS data collected from A600 (black), A800 (red) and A690 (blue) specimens in deaerated room temperature 0.1M Na_2SO_4 (a, c, and e) and 0.1 M $Na_2S_2O_3$ (b, d, and f) solutions, at corrosion potential, Ecorr (a and b), passive (c and d) and transpassive (e and f)

region. In this region, A800 exhibited the greatest impedance. This observation is also consistent with the potentiodynamic plots for room temperature measurements shown in Figure 2(b), which shows that, in the transpassive region (~0.7 VAg/AgCl), A800 exhibited the lowest current density.

The results presented in this section suggest that the behaviour of A690 is similar to A600 and A800 in the room temperature solutions. However, at 60 and 90 °C, A690 consistently exhibited greater corrosion resistance, especially in the transpassive region. Thus, the higher Cr concentration of A690 has some beneficial effects on the corrosion behaviour of A690, especially in the regions where passive film break down can occur.

(3) Results from Characterization of Cracked C-ring Specimens

Further work continued on characterizing the A600 and A800 stressed C-ring specimens exposed to an acid sulphate solution at 315 ºC under potentiostatic control in Professor Roger Newman's laboratory at U of T. Surface analytical measurements were performed to determine the changes in the oxide film composition as a function of alloy composition and exposure time. XPS and ToF-SIMS measurements were complemented by the focused ion beam analysis (FIB), laser Raman spectroscopy and X-ray diffraction (XRD) measurements. These measurements indicated that the oxide film formed on A800 C-ring sample after 60 hours of exposure to the sulphate chemistry is enriched in Fe and Cr and S also incorporated into the oxide layer. Such Fe incorporation in the oxide film was not observed on the A600 specimen and, as a result, the oxide film is porous and thicker compared to that on the A800.

Cases with Realized outcomes to Industry

The most significant outcome of this project is the mechanistic understanding of how the oxide films evolve on A600 and A800 materials and the determination of why A600 is more susceptible to corrosion compared to A800 under the operating conditions. Experiments at 315 °C in a pressure vessel or the laboratory electrochemical measurements ranging from room temperature to 90 C (representing the plant shut down condition) have indicated that the greater Fe content of A800 has enabled the incorporation of Fe into the oxide film, especially at the outer layers of the oxide film; this has preserved the underneath Cr_2O_3 to a greater extent, thus providing additional corrosion protection for A800. Greater Cr content of A690 also appeared to enhance the corrosion protection especially at 60 and 90 °C under transpassive conditions where oxide film break down occurs.

With further measurements, information from this project can subsequently be used to determine the role of various species (such as dissolved oxygen) on the oxide film stability during the shutdown or start up conditions. Such experiments are expected to define the boundary conditions within which the SG material is expected to exhibit a stable behaviour with improved resistance to corrosion.

Research Facilities and Equipment

A high temperature reactor was built for the steam/H_2 oxidation experiments conducted for this project. This reactor is being used by the project personnel from this research project to conduct experiments under conditions simulating the primary side of the steam generator. In addition, this steam/H_2 reactor is also extensively used by Professor Newman's group at the University of Toronto (UofT). His group has been studying the internal oxidation of several nickel-based alloys under various conditions and at different length of exposure times. This work is being carried out as part of Professor Newman's UNENE/NSERC Industrial Research Chair (IRC) program. In addition, two researchers from Canadian Nuclear Laboratories (CNL) have also been recently using this steam/H_2 reactor to grow oxide films under various humidity levels at different temperatures. Thus the facility developed for this CRD project is useful to other members of UNENE as well.

Current HQP

For the current year, one summer student (100%), one research associate (50%) and one staff scientist (20%) were trained at Surface Science Western. In addition, one Master's student, one PhD student and a senior Research Associate from UofT were trained on the use of Steam/H_2 reactor and were able to perform experiments on their own.

HQP that Graduated

1 Research Associate, 50% on this project.
1 Research Assistant, 25% on this project
2 Summer Students, 100% on this project.

Publications /Journal Papers

Major publications for the past two years from Professor Shoesmith's group are given below.

1. N. Ebrahimi, He, X., Noël, J. J., Zagidulin, D., Bachhav, M., Marquis, E., and Shoesmith, D. W., "The Advantage of Atomic Probe Tomography in Investigationof the Role of Iron Content on Crevice Corrosion Behaviour of Grade-2 Titanium", *Corrosion 2016*. NACE, Vancouver, BC, Canada, 2016.
2. J. Turnbull, Szukalo, R., Behazin, M., Zagidulin, D., Ramamurthy, S., Wren, J. C., and Shoesmith, D. W., "Corrosion of Copper Coated Nuclear Waste Containers in Aerated Nitric Acid", *Corrosion - Aqueous Gordon Research Conference*. New London, NH, 2016.
3. J. Turnbull, Szukalo, R., Behazin, M., Zagidulin, D., Ramamurthy, S., Wren, J. C., and Shoesmith, D. W., "Corrosion of Copper Coated Nuclear Waste Containers in Aerated Nitric Acid", *NACE Southern Ontario Student Section*. London, ON, 2016.
4. J. Turnbull, Behazin, M., Zagidulin, D., Ramamurthy, S., Wren, J. C., and Shoesmith, D. W., "Corrosion of Copper Nuclear Waste Containers by Nitric Acid", *Corrosion 2016*. Vancouver, BC, 2016.
5. T. Standish, Chen, J., Jacklin, R., Jakupi, P., Ramamurthy, S., Keech, P. G., and Shoesmith, D. W., "Corrosion of Copper-Coated Steel High Level Nuclear Waste Containers Under Permanent Disposal Conditions", *Electrochim. Acta*, vol. 211, pp. 331-342, 2016.
6. T. Standish, Chen, J., Jacklin, R., Jakupi, P., Ramamurthy, S., Zagidulin, D., Keech, P., and Shoesmith, D., "CORROSION OF COPPER-COATED STEEL HIGH LEVEL NUCLEAR WASTE CONTAINERS UNDER PERMANENT DISPOSAL CONDITIONS", *Electrochimica Acta*, vol. 211, pp. 331 - 342, 2016.
7. J. Chen, Wang, J. - Q., Han, E. - H., Ke, W., and Shoesmith, D. W., "Effect of Hydrogen on Corrosion and Stress Corrosion Cracking of AZ91 Alloy in Aqueous Solutions", *Acta Metallurgica Sinica (English Letters)*, vol. 29, no. 1, pp. 1 - 7, 2016.
8. M. Goldman and Shoesmith, D. W., "The Effect of Sulphide on the Corrosion of Carbon Steel in Neutral to Slightly Alkaline Environments ", *NACE Corrosion 2016*. Vancouver, 2016.
9. T. Standish, Zagidulin, D., Ramamurthy, S., Nelson, A., Keech, P. G., and Shoesmith, D. W., "The Evolution of Galvanic Corrosion on Copper-Coated Carbon Steel Determined by In-Situ X-ray Microtomography", *Corrosion 2016*. Vancouver, BC, 2016.

10. T. Standish, Zagidulin, D., Ramamurthy, S., Nelson, A., Keech, P. G., and Shoesmith, D. W., "The Evolution of Galvanic Corrosion on Copper-Coated Carbon Steel Determined by In-Situ X-ray Microtomography", *Gordon Research Conference: Corrosion - Aqueous*. New London, NH, 2016.
11. T. Standish, Zagidulin, D., Ramamurthy, S., Nelson, A., Keech, P. G., and Shoesmith, D. W., "Galvanic Corrosion of Copper-Coated Carbon Steel for Used Nuclear Fuel Containers", *NACE Southern Ontario Student Section Meeting*. London, ON, 2016.
12. T. Standish, Zagidulin, D., Ramamurthy, S., Nelson, A., Keech, P. G., and Shoesmith, D. W., "Galvanic Corrosion of Copper-Coated Carbon Steel for Used Nuclear Fuel Containers", *6th International Workshop on Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems*. Toronto, ON, 2016.
13. Z. Zhu and Shoesmith, D. W., "Hydrogen Peroxide Decomposition on SIMFUEL in Carbonate Solutions", *Spent Fuel Workshop 2016*. Stockholm, Sweden, 2016.
14. Z. Zhu and Shoesmith, D. W., "Hydrogen Peroxide Decomposition on Simulated Spent Fuel (SIMFUEL) in Carbonate Solutions", *NACE CORROSION*. VANCOUVER, 2016.
15. N. Ebrahimi, Jakupi, P., Noël, J. J., Zagidulin, D., and Shoesmith, D. W., "The Influence of Microstructure and Composition on the Crevice Corrosion of Ni-Cr-Mo Alloys", *Corrosion 2016*. NACE, Vancouver, BC, Canada, 2016.
16. J. Turnbull, Behazin, M., Zagidulin, D., Ramamurthy, S., Wren, J. C., and Shoesmith, D. W., "Radiolytic Corrosion of Copper Nuclear Waste Containers by Nitric Acid", *The 6th International Workshop on Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems*. Toronto, ON, 2016.

A. K. Mishra, Zhang, X., and Shoesmith, D. W., "The Role of Copper on the Crevice Corrosion Behavior of Nickel-Chromium-Molybdenum Alloys in Aggressive Solutions", *Corrosion*, vol. 72, no. 3, pp. 356 - 367, 2016.

17. N. Ebrahimi, Noël, J. J., Rodríguez, M. A., and Shoesmith, D. W., "The self-sustaining propagation of crevice corrosion on the hybrid BC1 Ni–Cr–Mo alloy in hot saline solutions", *Corrosion Science*, 2016.
18. N. Ebrahimi, Jakupi, P., Korinek, A., Barker, I., Moser, D. E., and Shoesmith, D. W., "Sigma and Random Grain Boundaries and Their Effect on the Corrosion of the Ni-Cr-Mo Alloy 22", *Journal of The Electrochemical Society*, vol. 163, no. 5, pp. C232 - C239, 2016.
19. M. R. Asmussen, W. Binns, J., Partovi-Nia, R., Jakupi, P., and Shoesmith, D. W., "The stability of aluminum-manganese intermetallic phases under the microgalvanic coupling conditions anticipated in magnesium alloys", *Materials and Corrosion*, vol. 67, no. 1, pp. 39 - 50, 2016.
20. , *Corrosion*, 2015.

Interactions / Consultations to Industry

The results from this research project have been presented to the UNENE community during the May 5, 2015 RAC and December 16, 2015 R&D Workshop meetings. A poster was also presented during the 2015 December R&D workshop by the Research Associate involved in this project. The results from this project were also showcased to the industry members from OPG, CNL and Bruce Power during the 2015 December R&D workshop. In addition, students from Professor Shoesmith's group also participated in the student poster session during the December RAC meeting.

In addition to this project, Professor Shoesmith has extensive interactions with the nuclear industry, mainly through the Nuclear Waste Management Organization (NWMO). In addition to sponsoring his chair program, NWMO is also funding major projects on copper coated steel containers for long-term nuclear waste storage and on radiolytic corrosion of copper. He has also been involved with various international efforts on nuclear waste storage. Some of his research projects have been sponsored by GM (magnesium corrosion), TransCanada Pipelines (pipeline corrosion), Amec U.K. (titanium corrosion) and SKB (copper corrosion). He has also been involved in reviewing papers and reports related to the corrosion of nuclear waste storage containers.

AUDITOR'S REPORT 2015

Grant Thornton

Independent auditor's report

Grant Thornton LLP
Suite 501
201 City Centre Drive
Mississauga, ON
L5B 2T4

T +1 416 366 0100
F +1 905 804 0509
www.GrantThornton.ca

To the Board Members of the
University Network of Excellence in Nuclear Engineering

We have audited the accompanying financial statements of University Network of Excellence in Nuclear Engineering, which comprise the statements of financial position as at March 31, 2015, and the statements of operations, changes in net assets and cash flows for the year then ended, and a summary of significant accounting policies and other explanatory information.

Management's responsibility for the financial statements

Management is responsible for the preparation and fair presentation of these financial statements in accordance with Canadian accounting standards for not-for-profit organizations and for such internal control as management determines is necessary to enable the preparation of financial statements that are free from material misstatement, whether due to fraud or error.

Auditor's responsibility

Our responsibility is to express an opinion on these financial statements based on our audits. We conducted our audit in accordance with Canadian generally accepted auditing standards. Those standards require that we comply with ethical requirements and plan and perform the audit to obtain reasonable assurance about whether the financial statements are free from material misstatement.

An audit involves performing procedures to obtain audit evidence about the amounts and disclosures in the financial statements. The procedures selected depend on the auditor's judgment, including the assessment of the risks of material misstatement of the financial statements, whether due to fraud or error. In making those risk assessments, the auditor considers internal control relevant to the entity's preparation and fair presentation of the financial statements in order to design audit procedures that are appropriate in the circumstances, but not for the purpose of expressing an opinion on the effectiveness of the entity's internal control. An audit also includes evaluating the appropriateness of accounting policies used and the reasonableness of accounting estimates made by management, as well as evaluating the overall presentation of the financial statements.

Grant Thornton

We believe that the audit evidence we have obtained is sufficient and appropriate to provide a basis for our audit opinion.

Opinion

In our opinion, the financial statements present fairly, in all material respects, the financial position of University Network of Excellence in Nuclear Engineering as at March 31, 2015, and the results of its operations and its cash flows for the year then ended in accordance with Canadian accounting standards for not-for-profit organizations.

Grant Thornton LLP

Mississauga, Canada
September 24, 2015

Chartered Accountants
Licensed Public Accountants

University Network of Excellence in Nuclear Engineering
Statement of Financial Position

As at March 31	2015	2014
Assets		
Current		
Cash	$ 1,113,737	$ 1,314,467
Portfolio investments	1,003,890	507,598
Receivables	31,997	133,547
	2,149,624	1,955,612
Property and equipment (Note 3)	1,428	2,183
	$ 2,151,052	$ 1,957,795
Liabilities		
Current		
Accruals	$ 35,593	$ 22,092
Net assets		
Unrestricted	2,115,459	1,935,703
	$ 2,151,052	$ 1,957,795

Commitments (Note 4)

On Behalf of the Board

____________________ Director ____________________ Director

See accompanying notes to the financial statements.

University Network of Excellence in Nuclear Engineering
Statement of Operations and Changes in Net Assets

For the Year Ended March 31	2015	2014
Revenue		
Fees	$ 1,815,000	$ 1,545,000
Education revenue	21,155	21,314
Workshops and courses	30,287	38,951
Interest income	16,935	12,926
Other income	2,000	-
	1,885,377	1,618,191
Expenses		
Administration fees	242,762	238,948
Bank charges	262	193
Depreciation	755	940
Insurance	3,726	3,726
Office	60,313	43,666
Professional fees	11,184	11,685
Research expenditures	1,363,000	868,000
Workshops and courses	23,619	73,977
	1,705,621	1,241,135
	179,756	377,056
Unrealized (loss) on investments	-	(2,429)
Excess of revenue over expenses	$ 179,756	$ 374,627

Net assets		
Beginning of year	$ 1,935,703	$ 1,561,076
Excess of revenue over expenses	179,756	374,627
End of year	$ 2,115,459	$ 1,935,703

See accompanying notes to the financial statements.

University Network of Excellence in Nuclear Engineering
Statement of Cash Flows

For the Year Ended March 31	2015	2014
Increase (decrease) in cash and cash equivalents		
Operating activities		
Excess of revenue over expenses	$ 179,756	$ 374,627
Depreciation	755	940
Unrealized loss on investments	-	2,429
	180,511	377,996
Changes in non-cash operating working capital		
Receivables	101,550	265,020
Accruals	13,501	(7,462)
	295,562	635,554
Investing activities		
Purchase of portfolio investments	(1,000,000)	(506,750)
Proceeds on redemption of portfolio investments	503,708	500,052
	(496,292)	(6,698)
Net (decrease) increase in cash and cash equivalents	(200,730)	628,856
Cash and cash equivalents		
Beginning of year	1,314,467	685,611
End of year	$ 1,113,737	$ 1,314,467

See accompanying notes to the financial statements.

BOARD OF DIRECTORS AND OFFICERS

Voting Members and Directors

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Western University

Paul Spekkens
Board Vice-Chair
OPG

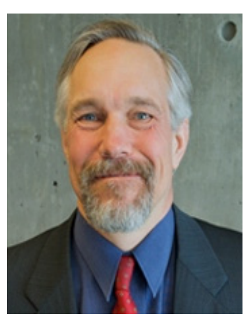
Gary Newman
Bruce Power

Bill Kupferschmidt
CNL

John Preston
McMaster U

Brian Surgenor
Queen's U

George Bereznai
UOIT



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AMEC Foster Wheeler


Fred Dermarkar
(COG President)


Chary Rangacharyulu
U of Saskatchewan


Mehrdad Saif
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Sermet Kuran
SNC-Lavalin

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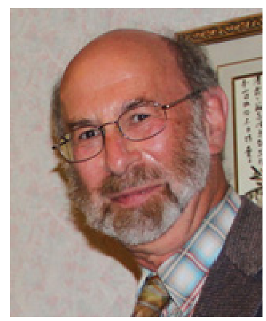

Victor Snell
Program Director

Jim Findlater
Accountant

Lori Cole
Administration

University Network of Excellence in Nuclear Engineering
Department of Engineering Physics
McMaster University
Hamilton, ON, Canada L8S 4L7
www.unene.ca

University Network of Excellence in Nuclear Engineering
Réseau D'Excellence Universitaire en Génie Nucléaire

WWW.UNENE.CA

Department of Engineering Physics
McMaster University
1280 Main Street West,
Hamilton, ON, L8S 4L7 Canada