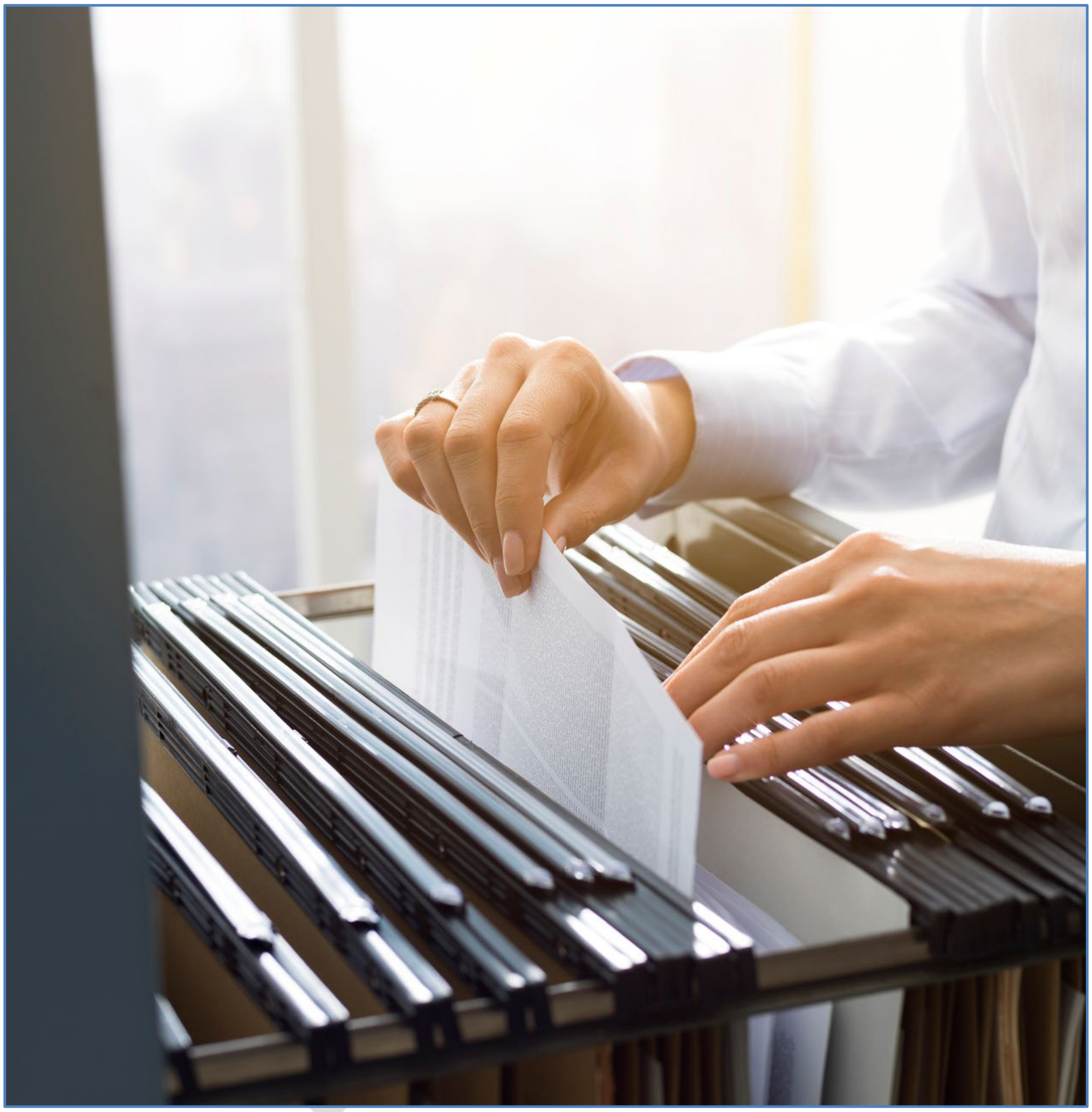
UNENE
University Network of Excellence in Nuclear Engineering

FEBRUARY 2023



RESEARCH HISTORY

of UNENE-Sponsored University Programs

TABLE OF CONTENTS

ACRONYMS

ALARA	As Low As Reasonably Achievable
AR	Attenuated Reflectance
CASL	Consortium for Advance Simulation of Light Water Reactors
CHF	Critical Heat Flux
COG	CANDU Owners Group
CNL	Canadian Nuclear Laboratories
CNSC	Canadian Nuclear Safety Commission
CRD	Collaborative Research and Development
CS	Carbon Steel
CT	Calandria Tube
CTF	COBRA-TF
DAS	Distributed Antenna Systems
DCPD	Direct Current Potential Drop
DHC	Delayed Hydride Cracking
DOE	Department if Energy
EBSD	Electron Backscatter Diffraction
ECCS	Emergency Core Cooling System
EDX	Energy Dispersive X-ray
EPR	Electron Paramagnetic Resonance
EPRI	Electric Power Research Institute
ESC	End Shield Cooling
ETH	Swiss Federal Institute of Technology
FAC	Flow-Accelerated Corrosion (FAC)
FEG	Field Emission Gun
FEM	Finite Element Model
FHS	Fuel Handling System
FIB	Focused Ion Beam
FM	Fuelling Machine
FPGA	Field-Programmable Gate Array
FTIR	Fourier Transfer Infrared
HCSG	Helical Coil Steam Generator
HQP	Highly Qualified Personnel
IAEA	International Atomic Energy Agency
ICP	Inductively Coupled Plasma

IRC	Industrial Research Chair
IWSN	Industrial Wireless Sensor Network
IX	Ion Exchange
IXR	Ion Exchange Resins
L&ILW	Low and Intermediate Level Wastes
LOCA	Loss of Coolant Accident
MCNP	Monte Carlo N-Particle Transport
MNR	McMaster Nuclear Reactor
MSR	Molten Salt Reactors
MUZIC	Mechanistic Understanding of Zirconium Corrosion
NCSU	North Carolina State University
NEA	Nuclear Energy Agency
NGS	Nuclear Generating Station
NOP	Neutron Over Power
NPCTF	Nuclear Power Plant Process Control Test Facility
NPP	Nuclear Power Plant
NSERC	National Sciences and Engineering Research Council
NWMO	Nuclear Waste Management Organization
OCCAM	Ontario Center for the Characterisation of Advanced Materials
OECD	Organisation for Economic Co-Operation and Development
OES	Optical Emission Spectrometer
OPEX	Operating Experience
OPG	Ontario Power Generation
ORF	Ontario Research Fund
ORNL	Oak Ridge National Laboratory
PNERP	Provincial Nuclear Emergency Response Plan
PT	Pressure Tube
PWR	Pressurized Water Reactor
R&D	Research and Development
RMTL	Reactor Materials Testing Laboratory
RRS	Reactor Regulating System
SAB	Service Area Bridges
SCC	Stress Corrosion Cracking
SCWR	Super Critical Water Reactor
SEM	Scanning Electron Microscopy
SG	Steam Generator

SMNR	Small Modular Reactor
SS	Stainless Steel
SSRT	Slow Strain Rate Testing
TEM	Transmission Electron Microscopy
UAM	Uncertainty in Analysis and Modelling
UFC	Used Fuel Container
UNENE	University Network for Excellence in Nuclear Engineering
UTSG	U-tube Steam Generator
VR/AR	Virtual Reality/Augmented Reality
VHTR	Very High Temperature Reactor

INTRODUCTION

1.1 OVERVIEW

UNENE has compiled this companion document that will summarize the history of UNENE-sponsored university programs, to provide further background to our member capabilities. For current projects please see the UNENE University Capabilities Directory 2023 here.

Appendices A thru N are below.

APPENDICIES A TO N

APPENDIX A - ONTARIO TECH UNIVERSITY – NUCLEAR-RELATED PROGRAMS

A synopsis of nuclear related faculty experts, programs and activities is presented below:

DEPARTMENT OF ELECTRICAL, COMPUTER AND SOFTWARE

Dr. Vijay K. Sood, Department Chair and Associate Professor

Research Areas: HVDC transmission, FACTS, microgrids, renewable energy integration, distributed generation, smart grid

Dr. Ahmad Barari, Associate Professor

Research Areas: Advanced manufacturing technologies, digital manufacturing, precision manufacturing, measurement uncertainty, 3D coordinate metrology, additive manufacturing and rapid prototyping of sculptured surfaces, manufacturing surface integrity, surface quality, surface tribology, reverse engineering, surface reconstruction, structural design optimization, topology optimization, FEA-based design optimization

Dr. Akramul Azim, Associate Professor

Research Areas: Real-time systems, embedded software, safety-critical systems, internet of things, software verification and validation, software quality and testing, applied machine learning, cybersecurity

Dr. Ali Grami, Associate Professor

Research Areas: Satellite communications, digital communications

Dr. Jing Ren, Associate Professor

Research Areas: Haptics and virtual reality, robotics and control, image processing, soft computing

Dr. Khalid Elgazzar, Associate Professor

Research Areas: Canada Research Chair (Tier II) in internet of things, internet of things, ubiquitous computing, real-time data analytics, distributed systems, intelligent software systems, mobile computing, cloud and edge computing

Dr. Langis Roy, Professor

Research Areas: Integrated antennas, microwave integrated circuits, micro/nanoelectronics, wireless power transfer, wireless sensors, reconfigurable components, cybersecurity principles

Dr. Masoud Makrehchi, Associate Professor

Research Areas: Natural language processing, artificial intelligence, machine learning, text and data mining, social computing, mining social networks and complex systems, network science, moral artificial intelligence

Dr. Mikael Eklund, Professor

Research Areas: Autonomous systems (robotic vehicles, smart sensors for assisted living), nonlinear system identification and control, health informatics, pervasive and mobile computing

Dr. Min Dong, Professor

Research Areas: Statistical signal processing, wireless communication systems and networks, learning techniques, optimization and control applications in cyber-physical systems

Dr. Mohamed El-Darieby, Associate Professor

Research Areas: Software systems engineering, software process management, software analysis, design, computer systems, cloud computing, internet of things, pervasive computing, data engineering, big data, artificial intelligence, applications areas, connected and autonomous vehicles, smart agriculture, intelligent transportation systems, smart city and infrastructure

Dr. Mohamed Youssef, Associate Professor

Research Areas: Propulsion systems for the automotive and innovative technologies like hyperloop, power train for new drives like water pumps, railway Electromagnetic Compatibility (EMC), railways traction substation design planning, and commissioning, power electronics applications for the Information Technology (IoT), power electronics applications in the innovative renewable energy resources, power supply design for the oil/gas, power systems operation and stability

Dr. Qusay Mahmoud, Associate Dean and Professor

Research Areas: Software systems and security, mobile computing and middleware, cybersecurity

Dr. Ramiro Liscano, Professor

Research Areas: Pervasive and mobile computing (service discovery and security management), distributed computing (peer-to-peer, web services, service-oriented architectures, GRID services), sensor networks (interoperability between wireless and internet- based sensing)

Dr. Ruth Milman, Associate Professor

Research Areas: Systems control theory, model predictive control systems, optimization, nonlinear control, constrained systems, control systems

Dr. Sanaa Alwidian, Associate Professor

Research Areas: Software engineering, goal-oriented requirements engineering, model-based system engineering, software evolution and analysis, artificial intelligence and its application to software engineering, mobile ad hoc networks, natural language processing

Dr. Shahram ShahbazPanahi, Professor

Research Areas: Array processing, co-operative communications, detection and estimation, dynamic spectrum access, smart antennas, statistical signal processing, wireless communications

Dr. Sheldon Williamson, Professor and Canada Research Chair (Tier II) in Electric Energy Storage Systems for Transportation Electrification

Research Areas: Autonomous mobility/transportation, batteries, charging, electric energy storage systems, electric machines, motor drives, power electronics, renewable energy systems, transportation electrification

Dr. Tarlochan Sidhu, Professor

Research Areas: Smart grid, renewable energy, power systems, power system protection, power system automation, active distribution systems, microgrids, substation automation

Dr. Walid Morsi Ibrahim, Professor

Research Areas: Smart grid, power and energy systems, artificial intelligence and data analytics, cyber-physical security, energy automation and management

Dr. Ying Wang, Professor

Research Areas: RF/microwave circuits and systems, millimeter-wave technology, antennas and antenna arrays, microwave filters and multiplexers, computer-aided design of RF circuits

DEPARTMENT OF MECHANICAL AND MANUFACTURING

Dr. Atef Mohany, Department Chair and Professor

Research Areas: Aeroacoustics, fluid-structure interaction, flow-induced vibration and noise, turbulent flows, structural dynamics, and noise and vibration control

Dr. Amirkianoosh Kiani, Associate Professor

Research Areas: Laser materials processing, micro/nano manufacturing, nano energy materials, nano opto-electronic materials, nano sensing materials

Dr. Bale Reddy, Professor

Research Areas: Thermodynamics, energy systems, biomass, solar energy

Dr. Brendan MacDonald, Associate Professor

Research Areas: Fluid mechanics, thermodynamics, sustainable energy, Stirling engines, external heat engines, microfluidics, capillary-driven flows

Dr. Ebrahim Esmailzadeh, Professor Emeritus

Research Areas: Mechanical vibration, active vibration control, nonlinear vibrations, vehicle dynamics, structural dynamics, nonlinear and discrete control systems, dynamics and vibration of MEMS and NEMS

Dr. Ghaus Rizvi, Professor

Research Areas: Advanced manufacturing, additive manufacturing, advanced composite development, bio-composites, tissue engineering, nano-composites, lightweight materials, material characterization

Dr. Hossam Kishawy, Dean, Professor

Research Areas: Manufacturing, high-speed machining, modelling and optimization, finite element modelling, residual stress and stress analysis

Dr. Ibrahim Dincer, Professor

Research Areas: Sustainable energy technologies, renewable energy technologies, hydrogen energy and fuel cell technologies, carbon capturing technologies, energy storage technologies, community and district energy systems, alternative/sustainable fuel technologies, energy conversion, conservation and management technologies, integrated energy systems, energy, environment and sustainability policies and program implementation techniques.

Dr. Jana Abou-Ziki, Assistant Professor

Research Areas: Precision manufacturing of miniature components, Spark Assisted Chemical Engraving (SACE), surface engineering, electroforming, advanced manufacturing, electrochemical fabrication, machine learning, additive manufacturing.

Dr. Kamiel Gabriel, Professor

Research Areas: Hydrogen, boiling and two-phase flows, energy conservation, fluid physics and heat transfer at reduced gravity (microgravity space sciences), heat-recovery systems and thermos-fluids in power plants.

Dr. Marc A. Rosen, Professor

Research Areas: Poly-generation (cogeneration, trigeneration, etc.), district energy, efficiency improvement, electricity generation, energy, environmental impact assessment and reduction, exergy analysis, geothermal energy, heat transfer, hydrogen energy and fuel cells, integrated energy systems, modelling and simulation of energy systems, renewable energy, solar energy, sustainable energy and sustainability, wind energy, thermal energy storage, thermodynamics

Dr. Martin Agelin-Chaab, Associate Professor, Graduate Program Director

Research Areas: Bluff body/ground vehicle aerodynamics, turbulent flows and jets, vehicle and battery thermal analyses, sustainable energy systems

Dr. Ramona (Haniyeh) Fayazfar, Associate Professor

Research Areas: Advanced manufacturing (additive manufacturing, micro and nano fabrication), smart materials (nanostructured composites/hybrid materials, multifunctional composites), advanced coatings and surface engineering, electrochemical synthesis of nanostructured materials, electro catalysts and energy storage devices (batteries, supercapacitors), biosensors and wearables for point-of-care diagnostics and health monitoring

Dr. Remon Pop-Iliev, Professor, Former NSERC Senior Chair in Innovative Design Engineering (2005-2018)

Research Areas: Processing functionally graded polymeric composites and nanocomposites, fabrication of biodegradable nanocomposites for bone tissue regeneration, manufacturing multifunctional nanocomposite fibers, rapid rotational foam molding, innovative design engineering education

Dr. Sayyed Ali Hosseini, Assistant Professor

Research Areas: Advanced manufacturing, metal additive manufacturing, machining difficult- to-cut materials, design and optimization, material behavior

Dr. Yuelei Yang, Teaching Professor

Research Areas: Sustainability, computer-aided design, thermal-fluid systems, interfacial phenomena

DEPARTMENT OF AUTOMOTIVE AND MECHATRONICS

Dr. Scott Nokleby, Associate Dean and Professor

Research Areas: Robotics, mechatronics, mechanisms, automation, advanced kinematics of robots and mechanisms, redundant manipulator systems, mobile-manipulator systems, mechanism and robot design, optimal design

Dr. Greg Rohrauer, Associate Professor

Research Areas: Advanced composite materials, analysis and design of composite pressure vessels, materials testing, alternate-fuelled and hybrid vehicles development, vehicle dynamics, manufacturing technology and application

Dr. Haoxiang Lang, Associate Professor

Research Areas: Mechatronics, autonomous robotics, visual serving and advanced controls, machine learning

Dr. Jaho Seo, Assistant Professor

Research Areas: Autonomous mobile machine, construction equipment, electro-hydraulic systems, safety control, sensing and monitoring, and agricultural machinery

Dr. Matthew Harker, Associate Professor

Research Areas: Mechatronics, robotics, inverse problems, engineering geometry, scientific computing, measurement theory, control theory, engineering design, machine vision

Dr. Meaghan Charest-Finn, Assistant Professor

Research Areas: The integration of machine learning methods, multi-physics systems, model predictive controller and method with correction parameter, model predictive control systems, and methods

(PCT Application): international application number, industrial process optimization system, and method (PCT application)

Dr. Moustafa El-Gindy, Professor

Research Areas: Road and off-road vehicle simulation, dynamics simulation and FEA, truck driving simulator laboratory for heavy vehicle

Dr. Xianke Lin, Assistant Professor

Research Areas: Electrified mobility: advanced modeling and control for lithium-ion batteries and powertrain, autonomous driving: HD mapping, perception, localization, navigation, and motion control, artificial intelligence and machine learning-enabled diagnostics and prognostics for internet of things applications

Dr. Yuping He, Professor

Research Areas: Autonomous driving, vehicle system dynamics, vehicle chassis design, vehicle active safety systems, automated design synthesis, modelling and simulation, driver- hardware-in-the-loop real-time simulations, application of multidisciplinary design optimization, mechatronic systems

Dr. Zeinab El-Sayegh, Assistant Professor

Research Areas: Autonomous vehicles, tire mechanics, vehicle dynamics, terra-mechanics

1. FACILITIES OUTSIDE OF THE FACULTY OF ENGINEERING AND APPLIED SCIENCE

Multi-disciplinary research at Ontario Tech's other research centres can bring important applications for greater operational efficiency, resilience, security, safety and social license to the nuclear and energy sector. Institutes within the university, outside of the Engineering faculty include:

A. INSTITUTE FOR CYBERSECURITY AND RESILIANCE

The Institute for Cybersecurity and Resilient Systems at Ontario Tech University is a multi-disciplinary, global centre for cybersecurity research, innovation, teaching, and outreach.

The institute explores and solves critical questions with research that has technological, financial, legal, ethical, and social implications to privacy, security and trust.

B. ADVANCED NETWORKING TECHNOLOGY AND SECURITY RESEARCH LABORATORY

The Advanced Networking Technology and Security Research Laboratory at the university is home to state-of-the-art research and development of technologies for next-generation networks and critical infrastructures. It includes a security testing facility funded by the Canada Foundation for Innovation, a private research cloud environment and a software-defined networking test bed.

C. DIGITAL LIFE INSTITUTE

The Digital Life Institute is a community of researchers examining the human and social dimensions of digital technologies, advancing our understanding of their impact on humans. It is a hub for the critical analysis of digital technologies, an international network of interdisciplinary scholars interested in the social implications of disruptive technological advancement.

D. SOCIAL RESEARCH CENTRE

The Social Research Centre at Ontario Tech is an interdisciplinary, social science research unit and training centre housed within the Faculty of Social Science and Humanities. The centre offers a variety of research services to university faculty and administrators, and external clients looking to do research primarily in the Durham Region.

E. MATERIALS CHARACTERIZATION FACILITY

Focused on science, technology, and innovation, the Materials Characterization Facility (MCF) provides access to a variety of resources and services to support research activities and development in materials science.

Modern instrumentation integrated at the MCF is operated by a multidisciplinary team of experts to support comprehensive analysis at the micro to the nanoscale, promoting the development of novel materials and technologies. MCF provides opportunities for researchers from diverse backgrounds, including Ontario Tech faculty and students, as well as external partners to explore, learn and successfully collaborate.

APPENDIX B - MCMASTER UNIVERSITY – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

B1.0 IRC

To be addressed, if applicable, in next version

B2.0 RCPS

B2.1 RCP: IMPROVED UNDERSTANDING OF INTER-SUBCHANNEL THERMAL MIXING

- Lead: Marilyn Lightstone
- Period: 2011.01.01 – 2013.12.31

Industry Issue and Problem Statement

Nuclear safety analysis is often performed to determine the consequence of a loss of coolant accident or other event on the fuel integrity and to determine subsequent fission product release. Thermal-hydraulic analyses rely on accurate modeling of the heat transfer and fluid flow within the fuel rod bundle geometries. Due to the typically long simulation times for accidents and the complex geometries of the rod bundles and their appendages, subchannel methods (such as that used in ASSERTPV) are often in employed. With these methods, the governing equations for heat transfer and fluid flow are integrated over a subchannel and averaged quantities are determined. As a result of the spatial averaging or integration, the fine structures of the flow are not resolved. This approach therefore requires many empirical correlations to represent the complex exchange mechanisms across the gap between the subchannels.

Research Program Completion

Computational Fluid Dynamics (CFD), when used with an appropriate turbulence model, provides fine resolution of the fluid flow and heat transfer within a geometry, however, requires much greater computational effort than a sub-channel method. As such, CFD has been employed as a valuable tool for studying the complex flows in rod bundle geometries and for developing physics-based correlations of fluid mixing for use in subchannel codes.

The ultimate goal of the research is to develop improved models of thermal fluid mixing for subchannel codes such as ASSERT-PV. Much of the work completed to-date has direct application to the increased mixing that occurs with the gap vortical flows. The lower Re number work has a more indirect outcome to industry through a more basic understanding of the phenomena, although the stability work has application to Reynolds numbers up to the full-scale fuel channels and is important in determining the development time of this enhanced mixing/heat-transfer within the real bundles and fuel channels.

The complex nature of the underlying flow indicates that further studies should be performed to assess the impact of subchannel shape, appendages, number of fuel pins and flow rates. Directly based on the results from this UNENE/CRD project, additional work is being done by our group with Candu Energy on the effect of appendages and fuel pins on the enhancing mixing.

APPENDIX C - ONTARIO TECH UNIVERSITY – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

C1.0 IRC

To be addressed, if applicable, in next version

C2.0 RCPS

C2.1 RCP: INVESTIGATION OF THE DYNAMIC RESPONSE OF CANDU FUEL BUNDLE DUE TO ACOUSTIC PRESSURE PULSATIONS IN THE HTS PIPING SYSTEM

- Lead: Atef Mohany, Ontario Tech University; Marwan Hassan, University of Guelph
- Period: 2016.07.01 – 2019.06.30

Industry Issue and Problem Statement

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 systems and to numerically simulate the dynamic response of CANDU fuel bundles due to acoustic pressure pulsations. This research focuses on designing and testing a series of acoustic dampers aimed at use in industrial installations. The numerical simulation of the CANDU fuel bundle are performed using INDAP (Incremental Nonlinear Dynamics Analysis Program) which is an in-house general purpose finite element program capable of simulating the nonlinear dynamics of nuclear and power equipment subjected to fluid excitations.

Research Program Completion

The experimental part of this project is conducted using two different experimental loops. Acoustic pressure pulsations were excited at 150 Hz which is similar to that generated by the primary heat transport pumps in some CANDU reactors. The results show that the use of multiple passive control devices in strategic locations along the pipeline achieved a pressure pulsation suppression of 25 dB.

The numerical part of this project, the simulation was performed on a CANDU fuel bundle with 37 fuel elements. The 37 rods of the CANDU fuel bundle were coupled with the two endplates by utilizing common 74 nodes between the beam element and plate element. The fluid flow is simulated using a pseudo turbulence forces, motion dependent forces, as well as forces due to acoustic pressure pulsations. Some of the locations of the maximum stresses correspond to the location where end-plate cracks were observed.

C2.2 RCP: ADVANCEMENT OF SENSOR ARRAY PROCESSING AND MIMO SIGNAL PROCESSING FOR NON-DESTRUCTIVE TESTING

- Lead: Shahram Shahbazpanahi
- Period: 2011.01.01 – 2015.12.31

Industry Issue and Problem Statement

The RCP proposed to study the applications of sensor array processing and multiple input multiple output (MIMO) imaging to ultrasonic non-destructive testing (NDT) in nuclear power plants. The objective of the project is to apply MIMO imaging and sensor array signal processing techniques to the development of new design tools for the ultrasonic non-destructive testing of nuclear power plants and systems therein. The project will investigate MIMO signal processing methods for imaging, array calibration techniques, wideband and vector sensor processing tools as well as high-resolution and distributed source (reflector) localization approaches.

Research Program Completion

The following four inventions were developed:

1. Ultrasonic Imaging for Non-Destructive Testing Using Correlation Receiver

   Using an ultrasonic transduce array, a method was developed to extract, from the array signals, the location and shape of the upper surface of a test sample which has been immersed in water. The location and shape of this surface is crucial in imaging the inside of the sample. The proposed correlation-based surface imaging method performs well in our experiments.

2. Ultrasonic Imaging for Non-Destructive Testing using Distributed reflector Modelling.

   The upper surface of the material under test not only produces a strong interference on the received signal by reflecting the probing signal, but also has an effect on the signature of all the points inside the material under test. Therefore, a precise model for this surface will result in a precise localization of the cracks inside the material under test. In this work, we model the reflectors as spatially distributed reflectors. That is, we model the reflectors as distributed reflectors consisting of infinite number of point reflectors. In order to localize the reflectors, a shape for the reflector is considered and the parameters of this shape are estimated using a covariance fitting approach. Computer simulation has been used to show the performance of this Covariance Fitting approach. The simulation shows the accuracy of the approach. The model has a low computational complexity.

3. Ultrasonic Imaging for Non-Destructive Testing using MUSIC and Capon Techniques

Previous studies in non-destructive testing (NDT) mostly focus on applying the traditional delay and- sum (DAS) technique for imaging defects in solid materials. However, the DAS-based approaches are independent of the second order statistics of the data, therefore, they provide lower resolution and have inferior interference suppression capabilities, as compared to high-resolution techniques such as the well-celebrated multiple signal classification (MUSIC) and Capon techniques. In this RCP, MUSIC and Capon methods were applied to NDT applications, thereby exploiting the second order statistics (SOS) of the data. Different from traditional MUSIC and Capon approaches, we take the mode conversion phenomenon into account and develop MUSIC- and Capon-based imaging techniques which exploit the additional information that are present in all propagating modes to the advantage of imaging procedure- a problem not previously addressed in the context of NDT applications. Both the numerical simulations as well as data validation show that the proposed SOS-based approaches perform better compared to the DAS-based imaging algorithms in terms of root mean square error (RMSE) and also provide higher resolution, and better side-lobe suppression capabilities. In addition, the proposed MC-MUSIC and MC-Capon methods provide higher resolution images as compared to their standard mode-neglecting counterparts.

4. Ultrasonic Imaging for Non-Destructive Testing using Beamforming and Phase Shift -Migration

In this RCP, we are dealing with immersed objects in water. This case is different from the contact situation, where there is no gap between transducers and the object to be imaged. When we are imaging objects immersed in water, the difficulty that arises is that the speed of wave in passing through different layers changes. In such scenarios, traditional algorithms developed for contact cases cannot be applied directly. A method was developed based on phase shift migration and delay and sum beamforming:

- In phase shift migration, we compensate for different velocities that wave experiences while passing through different layers. This algorithm has been implemented in frequency domain.
- In the delay and sum beamforming algorithm approach to multilayer case, different time-of-flights from each transducer element to each point in the region of interest are compensated and then a summation is performed on all the aligned observations to form the image.

These delays in multilayer imaging scenarios cannot be calculated easily. The way we tackle this problem, is by introducing a root-mean-square (RMS) velocity and replacing our multilayer situation with just one layer where the speed of wave in this layer is RMS speed. This algorithm has been implemented in time-domain.

C2.3 RCP: IMPROVED CANDU CORE HOMOGENIZATION AND BENCHMARK MODELS

- Lead: Eleodor Nichita
- Period: 2014.04.01 – 2018.03.31

Industry Issue and Problem Statement

The broad objective of this proposal is twofold:

1. To develop a new, more accurate, method for calculating the neutron power distribution in a nuclear reactor by using advanced homogenization methods and
2. 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.

Research Program Completion

- Global-local iterations using discontinuity factors

  As part of this project, a new global-local iteration model was developed for CANDU lattices, whereby cross sections and discontinuity factors are generated using nonreflective node-boundary conditions. The advanced homogenization based on global-local iterations has the potential to allow better accuracy of full-core neutronics calculations and allows the computation of individual pin powers.

- Investigation of a partial-cell homogenization model

  One potential way to reduce homogenization-related errors for neutronics calculations is to use smaller homogenization regions which can be homogenized either using simple flux weighting or using the super-homogenization (SPH) approach. 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. The possibility of using partial-cell homogenization was therefore investigated.

- Development of CANDU benchmarks

  Possible concepts, configurations and size for full-core and partial-core benchmarks have been discussed with the technical advisory committee and two benchmark models have been developed. The developed benchmarks (track 3) will be very useful for industry code verification, as will the newly-implemented DONJON capacity to account for position-dependent delayed-neutron fractions.

C2.4 RCP: DEVELOPMENT OF NEW FUEL CHANNEL INSPECTION TOOLS FOR INCREASED INSPECTION SPEED

- Lead: Scott Nokleby
- Period: 2012.02.01 – 2016.04.30

Industry Issue and Problem Statement

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.

This project addressed these shortcomings by developing two new inspection tools.

1. The first tool to be developed will 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 NonDestructive Examination (NDE) tests in the extremely demanding, high temperature, high-flux core environment and, therefore, must be radiation hardened and total dose fault tolerant.
2. The second tool to be developed will 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).

Research Program Completion

The development of the new inspection system is proceeded on three fronts.

1. First is 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 have been investigated and an initial concept has been proposed. A simple proof-of-concept prototype was built to verify the design concept. A more rigorous prototype was developed that allowed testing of the concept under design pressures.
2. The second avenue of investigation was the development of a robotic crawler that will move the inspection head in the channel. Concept generation and selection have been performed and proposed design concept has been 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 has been completed and a proof-of-concept prototype has been built.

3. 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 has been built that allowed for the testing the accuracy of different localization techniques. In addition, a Kalman filter approach for fusing the data from the three encoders mounted on the system was developed.

In addition to the above:

- Modeling the reactor in MCNP was completed in order to determine flux levels that the proposed crawler will experience. The modeling data was used in the detailed design of the crawler as well as the online inspection system.
- A new flaw replication tool was developed that can be used in-situ

APPENDIX D - POLYTECHNIQUE MONTRÉAL – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

D1.0 IRC

To be addressed, if applicable, in next version

D2.0 CRDS

To be addressed, if applicable, in next version

APPENDIX E - QUEEN'S UNIVERSITY – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

E1.0 IRC

tbd

E2.0 RCPS

E2.1 RCP: MEASUREMENT OF NEAR-SURFACE RESIDUAL STRESS IN CANDU FEEDER PIPES USING MAGNETIC NON-DESTRUCTIVE EVALUATION TECHNIQUES

- Lead: Lynann Clapham
- Period: 2005 – 2008

Industry Issue and Problem Statement

The objective of the proposed work is to develop a magnetic non-destructive evaluation (NDE) probe for measuring residual stresses in CANDU feeder pipes. These feeder pipes, which are typically mild steel with a 60mm diameter OD with a 7mm wall thickness, transport heavy water coolant into and out of fuel channels in CANDU nuclear reactors. Residual stresses (strain) in these feeders have become a concern after cracks were discovered in some bend regions. The two magnetic NDE techniques that are being investigated in this project are based on Magnetic Barkhausen Noise (MBN) and Magnetic Flux Leakage (MFL) principles.

Research Program Completion

The project was split into two complementary projects:

1. Develop an MBN probe for residual strain measurement in CANDU feeder tubes.
2. Develop an MFL probe for residual strain measurement in CANDU feeder tubes.

E2.2 RCP: DELAYED HYDRIDE CRACKING IN ZIRCONIUM DURING HEAT-UP AND AT LOW TEMPERATURE

- Lead: Mark Daymond

- Period: 2008 – 2011

Industry Issue and Problem Statement

To be addressed, if applicable, in next version

Research Program Completion

To be addressed, if applicable, in next version

E2.3 RCP: AGING OF INCONEL X-750 SPACER MATERIAL

- Lead: Zhongwen Yao
- Period: 2013.06.01 – 2017.05.31

Industry Issue and Problem Statement

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' Ni3[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.

Research Program Completion

The main objective of this project was 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 examined 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.

APPENDIX F - ROYAL MILITARY COLLEGE – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

F1.0 IRC

To be addressed, if applicable, in next version

F2.0 RCPS

F2.1 RCP: COMPREHENSIVE MODEL OF EDDY CURRENT BASED PRESSURE TUBE TO CALANDRIA TUBE GAP MEASUREMENT

- Lead: Thomas Krause
- Period: 2014.07.01 – 2018.12.31

Industry Issue and Problem Statement

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 (~80 C) surrounding the fuel channels. Four annulus spacers separate the hot PT from the cool CT, to prevent contact and thereby, potential formation of hydride blisters on the PT, which can lead to cracking. In-reactor gap monitoring is performed from within the PT by an eddy current (EC) probe that is sensitive to CT proximity. The 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. Gap measurement accuracy can be improved by correctly compensating for all the essential parameters that may affect the inspection outcome. These parameters include PT wall thickness, PT and CT resistivity, and probe lift-off from the PT surface. The relative effects of various parameters can be evaluated by application of a comprehensive model of EC response to changes in gap. Analytical models that account for driver and pickup coil interaction with the PT and CT have been developed for an axially symmetric representation of PT to CT gap as a layered infinite planar structure. A semi-analytical model has been developed by approximating the PT inside the CT as two concentric tubes. While this concentric tube model accounts for PT curvature exactly, it allows the CT to have a variable radius of curvature in order to vary gap. The concentric tube model allows rapid determination of response to gap and a means of accurately evaluating sensitivity to variation in essential parameters. A full three-dimensional (3D) finite element method (FEM) model of transmit-receive EC response to changes in PT to CT gap has also been developed for evaluating gap measurement accuracy. The 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 were:

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 (completed).
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 (in progress).
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 (laboratory portion has been completed).
5. Use models to explore effects of variable in-reactor measurement conditions (completed).
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 (in progress).

Research Program Completion

A semi-analytical model that accounts for PT curvature and approximates the PT-CT configuration in fuel channels as concentric tubes has been developed. In this concentric-tube model the gap is varied by changing the curvature of the CT. Model results show excellent agreement with both experimental and 3D FEM model results. RMSE in the 0 to 5 mm gap range, the expected range of minimum gap at the bottom of the fuel channel, is less than 0.1 mm, and at maximum gap relative error is 1% for a 4.2 kHz excitation frequency.

In the coming year development of inverse models based on analytical planar and semi-analytical concentric-tube models will be investigated for the simultaneous extraction of gap, resistivity and PT wall thickness from experimental gap data. In addition, the effect of LISS nozzles on gap measurement will continue to be investigated experimentally.

F2.3 RCP: MOLYBDENUM-BASED OXYGEN SENSORS AND ANALYSIS FOR INTACT AND DEFECTIVE FUEL STUDIES

- Lead: Emily Corcoran
- Period: 2012.06.01 – 2018.11.30

Industry Issue and Problem Statement

The main objectives of the RCP are to conduct research in the following three areas, namely:

1. Alternative Be-replacement Brazing Materials:

   The toxic nature of the beryllium (Be) brazing material currently used in the CANDU fuel bundle manufacturing process may be a significant risk to human health, which has been emphasized by the proposal of new regulations that promote reduced occupational exposure. A change in brazing material presents significant challenges to CANDU fuel manufacturers because this is a substantial change to the fuel bundle design. Thermodynamic studies of replacement Bebrazing materials will assist the nuclear industry in the identification of the best alternative material by further narrowing the field through the use of thermodynamic modeling of the short-listed candidate materials (as defined by the nuclear industry).

2. Investigations of Stress Corrosion Cracking of Nuclear Fuel Bundles

   Fuel failures in Canadian reactors observed following sustained power ramps in the early 1970's led to the development of improved refueling strategies, as well as the development of technology to mitigate fuel-sheath Stress-Corrosion Cracking (SCC) with the introduction of an interlayer coating on the inner bore of the fuel sheath. Thermal expansion of fuel pellets during a power ramp can generate the required stress/strain to initiate a crack in the protective oxide layer that is formed on the fuel sheathing. Fission products (e.g., iodine) released from the fuel pellets corrodes the fuel sheathing. Currently, a thin layer of CANLUB (graphite material) is applied to the inner surface of fuel sheathing to mitigate the SCC phenomena, but how CANLUB mitigates SCC is not well understood. Further, there is a concern with the sustainability of the supply of CANLUB material. Other candidate materials may be identifiable and could be substituted if a better understanding of how CANLUB mitigates SCC was available.

3. Investigation of Mo-U-O Compounds for the Characterization of Nuclear Fuel

   The relationship between oxygen partial pressure (pO_2) and $UO_{2\pm x}$ is significant as it relates to thermal performance and operational integrity of nuclear fuel. The relationship between pO_2 and $UO_{2\pm x}$ is well understood, measured and modelled. However, the relationship between pO_2 and $UO_{2\pm x}$ and fission/activation products is not well characterized and is often estimated. The scope of this project is to understand fundamentally the relationship between pO_2 and $UO_{2\pm x}$ with mixtures of oxides, with a special focus on molybdenum (Mo). Emphasis is placed on Mo as it can exist as a metal, an oxide or a compound (e.g., $UMoO_6$) depending on the pO_2. It is believed that a clear understanding of the relationship between pO_2, $UO_{2\pm x}$ and Mo can support the development of an oxygen sensor. As Mo is the key pO_2 buffering material, an understanding of its behaviour is fundamental in any thermodynamic model of nuclear fuel. The activities outlined in this proposal will provide a new technique that utilizes the Mo/MoO_2 content as a gauge in estimating the fuel oxygen potential in high burn-up and doped fuel found in advanced fuel esigns, as well as defective fuel.

Research Program Completion

- Alternative Be-replacement Brazing Materials:

  A preliminary review of the thermodynamic data of the prospective brazing materials has focussed on the Ni-Be-Zr system. A Charpy impact test was developed suitable for investigating specific to CANDU fuel element geometry and over 200 tests were completed. A methodology was established for fusing foils of some of the candidate alternative brazing materials to Zircaloy-2 substrates.

- Investigations of Stress Corrosion Cracking (SCC) of Nuclear Fuel Bundles

  Static loaded C-ring experiments were completed to determine if commercial polysiloxane coatings are suitable CANLUB replacements and to develop alternative SCC mitigating strategies utilizing alkali metal-oxygen additives and slightly oxidizing environments. A Dynamic Loading Apparatus (DLA) has been designed and prototype built. Completed Activities included qualification of the DLA at 300 C and repetition of the static C-ring experimentation with dynamic loading conditions.

- Investigation of Mo-U-O Compounds for the Characterization of Nuclear Fuel

  Thermogravimetric analysis on MoO2+x and UMoO6 systems were performed at RMCC. Data gathered from this experimentation assisted the thermodynamic modeling of U-Mo-O model, which will contribute to improvements in the RMCC nuclear fuel thermodynamic model. Efforts contined to reduce/oxidize 4-addative SIMFUEL solid samples and to determine the stability of molybdenum in the oxide and metallic phase as a function of oxygen partial pressure using SEM-WDX.

The goals of the CRP research are to assist the ongoing work of the nuclear industry, namely:

- COG WP22229: Replacement of Be as Brazing Metal for CANDU Fuel
- COG WP22230: Electron Probe Analysis of Mo in Defected Fuel and
- COG WP22331: Out-Reactor Instrumented Defective Fuel Experiment.

APPENDIX G - UNIVERSITY OF GUELPH – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

G1.0 IRC

Cases with Realized Outcomes to Industry

G1.1 PWR CHEMISTRY (EPRI FUNDED):

A major study with independent funding from EPRI to quantify the thermodynamics of borate ion pairing and polyborate formation up to 350 o C has been completed. Thermodynamic and transport property data for boric acid, borates and polyborates are needed to model the chemistry in fuel deposit crevices of pressurized water reactors (PWRs) under the "hideout" conditions that lead to crud-induced power shifts. Boric acid is also used in CANDU moderator systems. EPRI has funded a comprehensive study at Guelph using the laboratory's unique high-precision flow-through AC conductance instrument and Raman spectroscopic techniques to identify the major borate and polyborate species, and to measure their limiting conductivities and thermodynamic formation constants from 25 o C up to ~350 o C.

The results are being incorporated into a new database for the EPRI chemical modelling software MULTEQ, CHEMWORKS and BOA to model boron "hideout" under PWR fuel deposits so that the onset of crud-induced power shifts can be predicted and avoided.

G1.2 MODELLING CANDU COOLANT CHEMISTRY:

Over the past three years, we have contributed to the development of new databases for the solubility of magnetite, nickel and cobalt ferrites in the EPRI chemical equilibrium modelling software MULTEQ.

G1.3 HOT CONDITIONING CHEMISTRY:

Research from the group contributed to a study by Kinetrics, funded by OPG, to provide general expertise and modelling input on the most appropriate primary coolant chemistry for hot start-up of refurbished CANDU reactors.

G1.4 CONTAMINATION OF MORPHOLINE BY DISSOLVED CO2:

Experimental and modelling studies were carried out to resolve questions raised by OPG about possible CO_2 contamination of morpholine, and the effect of dissolved CO_2 on secondary coolant chemistry during outages and normal operation under the "Organic Solutes" project. The work indicated that the situations of potential concern occur during start-up after outages. A COG Report was submitted

G2.0 RCPS

G2.1 RCP: PREDICTIVE MODELS FOR D2O ISOTOPE EFFECTS ON IONIZATION AND METAL HYDROLYSIS UNDER CANDU REACTOR COOLANT CONDITION

- Lead: Peter Tremaine
- Period: 2013.07.01 – 2016.06.30

Industry Issue and Problem Statement

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 cogeneration 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.

Research Program Completion

Tremaine's UNENE RCP 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. 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 D2O isotope effects on chemical equilibria under extreme conditions of temperature and pressure.

Tremaine's other research uses state-of-the-art instruments to determine ionization and association constants for simple acids, bases, dissolved metals, and organic complexes under near-critical and super-critical conditions that will be encountered in the Generation IV CANDU Supercritical Water-cooled Reactor ("SCWR"). The projects include the construction of highpressure 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.

G2.2 RCP: THERMODYNAMIC DATA AND MODELS FOR COOLANT AND MODERATOR CHEMISTRY UNDER CANDU OPERATING CONDITIONS

- Lead: Peter Tremaine
- Period:

Industry Issue and Problem Statement

To be addressed, if applicable, in next version

Research Program Completion

To be addressed, if applicable, in next version

G2.3 RCP: D20 ISOTOPE EFFECTS ON HYDROLYSIS AND IONIZATION EQUILIBRIA IN HIGH TEMPERATURE WATER

- Peter Tremaine
- 2009 – 2012

Industry Issue and Problem Statement

CANDU nuclear reactors are a uniquely Canadian technology in that their design is based on the use of heavy water in a closed loop to transfer heat from the reactor core to the steam generator. Optimizing primary coolant chemistry requires detailed models for the chemical behaviour of metal oxides, dissolved gases and pH-control additives at temperatures as high as 300°C, using data determined in light water systems. The methods now used to correct these models for the differences between light-water and heavy-water systems are based entirely on room temperature studies.

Research Program Completion

Tremaine's UNENE CRD grant involved a laboratory study to provide fundamental data and understanding for the difference in ionization constants between H2O and D2O, for simple acids and bases at the extreme temperatures and pressures encountered in nuclear reactors (250 to 300°C and 10 MPa).

1. The first phase developed high precision AC conductance, densimetry, and UV-visible methods to measure the deuterium isotope effect on acid-base ionization. These state-of-the-art instruments, constructed of inert materials to withstand the corrosive conditions that exist in high temperature water, allow one to measure differences in the chemical equilibrium constants in H2O and D2O under identical conditions, directly.
2. The second phase used these instruments, and a new custom-made Raman spectrometry system, to measure data for three model systems.
3. The third, and final, phase extended these studies to more systems and develop a practical model for estimating the magnitude of D2O isotope effects on metal hydrolysis and metal oxide solubility, under CANDU operating conditions.

The project contributed to research aimed at extending the lifetime of existing reactors by providing criteria for optimizing primary circuit pH to reduce feeder tube thinning. It will make a long-term contribution to Canada's leadership role in heavy water technology by providing a fundamental understanding of D2O isotope effects on chemical equilibria under extreme conditions of temperature and pressure.

APPENDIX H - UNIVERSITY OF NEW BRUNSWICK – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

H1.0 IRC

To be addressed, if applicable, in next version

H2.0 RCPS

To be addressed, if applicable, in next version

APPENDIX I - UNIVERSITY OF REGINA – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

I1.0 IRC

To be addressed, if applicable, in next version

I2.0 RCPS

To be addressed, if applicable, in next version

APPENDIX J - UNIVERSITY OF SASKATCHEWAN – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

J1.0 IRC

To be addressed, if applicable, in next version

J2.0 RCPS

To be addressed, if applicable, in next version

APPENDIX K - UNIVERSITY OF TORONTO – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

K1.0 IRC

To be addressed, if applicable, in next version

K2.0 RCPS

K2.1 RCP: LIQUID FILM DRYOUT AND IBIF IN CANDU FUEL CHANNELS

- Lead: Masahiro Kawaji
- Period: 2007 – 2010

Industry Issue and Problem Statement

The objectives of this research project were to obtain fundamental information on:

1. Vapour bubble buildup and venting in a horizontal CANDU fuel channel Intermittent Buoyancy Induced Flow (IBIF phenomenon) following a loss of forced circulation during reactor outages.

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

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

2. The effect of pressure tube sagging on the venting of steam during IBIF incidents, and
3. The liquid film dryout phenomenon leading to Critical Heat Flux (CHF) under steady state operation and certain accident conditions such as a loss of reactor regulation accident.

   In the liquid film dryout study, the objectives and scope were:

- To study the behaviour of a thin film of water flowing on metal rods simulating the uranium fuel rods used in CANDU reactors.
- To study the stability of a thin liquid film, break-up and dry-out phenomena by measuring the liquid film thickness profile on the rod surface near a gap between the consecutive rods using a Laser Confocal Displacement Meter (LCDM) as a function of liquid and gas flow rates and gap width.

The information collected would be useful for devising viable technologies to enable the CANDU reactor designers and operators to extend the applicability of the existing experimental data on the IBIF phenomena and liquid film dryout and gain additional safety margins (or return to full-power) and operational flexibility (i.e., shorter reactor outages).

Research Program Completion

- Intermittent Buoyancy Induced Flow (IBIF) Study

  Experiments have been conducted using a IBIF flow loop:

  - Effect of Air Injection Location on Venting Time
  - Parametric Effects
    - Combined Effect of Feeder Water Level and Air-Injection Rate on the Venting Time
    - Effect of Multiple Air Injections on the Venting Time
    - Effect of Pressure Tube Sagging on the Venting Time
    - Oscillatory behaviour

  New insights have been gained into the Intermittent Buoyancy-Induced Flow (IBIF) phenomena and liquid film dryout in CANDU reactor fuel bundles. The average venting time data showed that small sagging of the pressure tube in the middle by 12.5 mm (0.5 inch) and 50.8 mm (2-inches) could cause significant reductions in the venting time by 8% and 14%, respectively, compared to the horizontal pressure tube. Thus, neglecting the effect of sagging phenomena on pressure tube venting would lead to a conservative estimate of safety margins.

- Liquid Film Dryout Study

  Experiments have been conducted using the Liquid Film Experiment Apparatus:

  - Ridge Size Measurements
  - Effect of Gap Distance on Liquid Film Breakage
  - Liquid Film Breakage and Formation of Dryout Region
  - Liquid Film Formation after the Gap

In the liquid film dryout study, the thin film profile was measured to be highly non-linear near the gap between the rods and there was a sharp reduction in the thickness just after the edge of the rod. An instantaneous film thickness after the gap could often reach zero thickness indicating the breakage of the liquid film. However, the dry-out condition existed temporarily, and the rod surface became again wetted and covered by the liquid film. At relatively small gap widths the liquid film breakage was not observed due to the formation of a liquid bridge between the adjacent edges of the consecutive metal rods. The time-averaged thickness of the liquid film decreased with an increase in the gap size, due to an increased intensity of the liquid film breakage. Within the investigated range of system parameters, the gap size above which the breakage would start to occur was approximately 5 mm.

APPENDIX L - UNIVERSITY OF WATERLOO – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

L1.0 IRC

To be addressed, if applicable, in next version

L2.0 RCPS

L2.1 RCP: SEISMIC RISK ANALYSIS OF NUCLEAR PLANTS

- Lead: Wei-Chau Xie
- Period: 2014.09.01 – 2017.12.31

Industry Issue and Problem Statement

The objectives of this research are:

- to develop comprehensive methodologies for the accurate determination of floor response spectra (FRS);
- to develop methods for accurate estimates of seismic fragility of systems, structures, and components (SSCs) by considering multiple ground motion parameters (GMPs) to ensure that SSCs in nuclear power plants (NPPs) are seismically qualified in a costeffective way; and
- to generate drift-free, consistent, and spectrum-compatible ground motion time histories for various dynamic analyses of NPP structures.

The outcomes are critical for Seismic Margin Assessment (SMA) and Seismic Probabilistic Risk Assessment (SPRA) of nuclear power plants.

Research Program Completion

- A Direct Method for Generating FRS Considering Soil-Structure Interaction

  A methodology is developed for generating FRS considering the effect of dynamic soil-structure interaction based on the substructure technique and the direct spectra-to-spectra method developed in this RCP. FRS with 50% and 84% Non-Exceedance Probability (NEP) given by the method agree extremely well with the FRS obtained from a large number of time history analyses

- Seismic Fragilities Analysis Using Multiple Ground Motion Parameter

  Seismic fragility analysis (FA) has been widely used to evaluate seismic capacities of SSCs in NPPs. An improved seismic FA method, which overcomes the problems in traditional seismic FA by using multiple GMPs, was proposed. It gives more realistic seismic capacity and fragility estimates of SSCs. By incorporating vector-valued probabilistic seismic hazard analysis, weighted seismic capacities and fragilities are represented by a selected GMP, which can be readily applied in traditional SMA and seismic PSA. Results indicate that, by using multiple GMPs, the improved FA methodology could uncover the excessive conservatism in the traditional method, resulting in more accurate estimates of seismic capacity and fragility of SSCs and more accurate assessment of seismic risk in NPPs.

APPENDIX M - UNIVERSITY OF WESTERN ONTARIO – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

M1.0 CONTROL INSTRUMENTATION AND ELECTRICAL SYSTEMS

M1.1 IRC

To be addressed, if applicable, in next version

M1.2 RCPS

To be addressed, if applicable, in next version

M2.0 RADIATION-INDUCED CORROSION

M2.1 IRC

To be addressed, if applicable, in next version

M2.2 RCPS

M2.2.1 RCP: STUDY OF THE EFFECT OF HELIUM, IRRADIATION, AND TEMPERATURE ON THE EMBRITTLEMENT OF INCONEL X-750 CANDU GARTER SPRING SPACERS

- Lead: Dr. Robert Klassen
- Period: 2014.12.23 – 2017.12.22

Industry Issue and Problem Statement

To be addressed in next version

Research Program Completion

To be addressed in next version

M2.2.2 RCP: MECHANICAL AND CHEMICAL INDICATORS FOR SCC IN ALLOY 800 STEAM GENERATOR TUBING

- Lead: Dr. David Shoesmith/Dr. Sridhar Ramamurthy
- Period: 2013.04.01 – 2016.03.31

Industry Issue and Problem Statement

Steam generator (SG) tubing plays an important role in heat transfer from the primary side to the secondary side of the nuclear reactor. SG tubing made from Alloy 600 (Ni-rich alloy) has proven to be susceptible to corrosion, especially to stress corrosion cracking (SCC). As a result, A600 has been replaced with either A690 (Cr-rich) in the USA or A800 (Fe-Ni-rich) in Canada.

The major objective of this UNENE-funded NSERC RCP project is to understand the differences in the corrosion behaviour of A600 and A800 SG tubing materials, especially the properties of the oxide layer formed on A600 and A800, and how these differences affect their cracking behaviour.

During the first year of this project, research focused on understanding the oxide film properties on A600 and A800 samples exposed to room temperature 0.1M Na2S2O3 (pH=6.5) solution. Based on the 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).

Research for the third year of the project will focus on three aspects:

1. extending the laboratory-based electrochemical measurements to temperatures up to 180 ºC,
2. performing scoping experiments under selected shutdown and start-up conditions typically encountered in a CANDU reactor,
3. further investigating the role of applied/residual strain on oxide film properties. A major outcome of this project will be the development of a comprehensive database of oxide film properties on the A600 and A800, which will identify the effect of solution composition (especially the trace amounts of contaminants present during the shutdown or start-up conditions), operating temperature and the role of strain in the material. It is also expected that the results from these experiments may help to define boundary conditions for the stakeholders in which the A800 material is expected to be stable and resistant to corrosion

Research Program Completion

The experimental results are divided into two parts:

- Results obtained from the laboratory-based electrochemical experiments.

  Electrochemical experiments have been performed in deaerated 0.1M Na2S2O3 (pH=6.5) and 0.1M Na2SO4 (pH=6.1) solutions.

- Results from the characterization of the A600 and A800 C-ring samples subjected to cracking experiments.

  A600 and A800 stressed C-ring samples were exposed to an acid sulphate solution at 315 ºC under potentiostatic control in Roger Newman's laboratory at U of T. Samples were removed after 12 hours of exposure (close to crack initiation for A800) and after 60 hours (cracks propagated to ~ 60 µm in A800). These samples were characterized as part of the project work scope to determine the oxide film composition and how the composition compared to those formed during laboratory electrochemical experiments.

Based on the results obtained from the laboratory-based electrochemical measurements performed at room temperature to 90 ºC and the analysis of the C-ring samples exposed to the acid sulphate chemistry at 315 ºC, the incorporation of Fe into the oxide layer on A800 is the most critical step in improving the corrosion resistance of this material compared to that of A600. It appears that the presence of Fe (or Fe oxides) helps to stabilize and preserve the Cr oxides on the sample surface even in the trans-passive region where significant corrosion is expected to occur. Improvement in corrosion resistance could be attributed to the formation of a stable Fe2Cr2O4 phase on the A800.

Significant progress has been made on understanding why A800 exhibits improved corrosion resistance compared to A600. Incorporation of Fe into the oxide layer and the subsequent formation of a compact and stable film appears to be the primary factor for improved corrosion resistance of A800. Experiments conducted under the shutdown and restart conditions and the role of various species (such as dissolved oxygen) on the oxide film stability were investigated. 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.

M2.2.3 RCP: MICRO-INDENTATION STUDIES OF THE LOCAL DUCTILITY OF ZR-2.5NB CANDU PRESSURE TUBES

- Lead: Dr. Robert J. Klassen
- Period: 2007 – 2011

Industry Issue and Problem Statement

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

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

Research Program Completion

1. Spherical micro-indentation testing of Zr-2.5Nb material

   Spherical micro-indentation tests were performed at 25 C in the radial-, axial-, and transverse-directions of a non-irradiated Zr-2.5Nb pressure tube off-cut. Pyramidal micro-indentation hardness tests were performed on sectioned spherical indentations to map the variation in hardness, and hence the variation in the equivalent plastic strain, around the indentation. Similar tests were performed on spherical indentations made at 100, 200, 300, and 400 C. Knowing the distribution of plastic strain around spherical indentations made in pressure tube material in the three orthogonal directions at various temperatures will provide benchmark data against which researchers can assess the accuracy of their finite element models.

2. Micro-indentation creep testing of non-irradiated Zr-2.5Nb

   Constant-force indentation creep tests, of one hour duration, were performed at indentation depths of h0 = 0.1, 0.5, 1.0, 5.0, 8.0, and 10.0 µm in the radial-, axial-, and transverse-directions of non-irradiated Zr-2.5Nb pressure tube material at temperatures of 25, 100, 200, 300, and 400 C.

   The magnitude of the measured plastic strain and activation energy of the obstacles suggests that the obstacles controlling the creep rate of Zr-2.5Nb at 25 C are dislocation / dislocation or dislocation/grain boundary interactions. This was confirmed by TEM micrographs of foils that were extracted from directly below crept micro-indentations using focused ion beam milling.

3. Micro-indentation creep testing of ion-irradiated Zr-2.5Nb

   Constant-force indentation creep tests (of one hour duration) were also performed on Zr-2.5Nb pressure tube material that was irradiated with 8.5 MeV Zr+ ions to levels corresponding to 5 and 30 displacements per atom (dpa) at a depth of about 3 µm. The results indicates that the ion damage induces a population of crystal defects into the Zr-2.5Nb that directly affect the activation energy associated with creep deformation.

4. Micro-indentation strain rate change tests of non-irradiated Zr-2.5Nb

   Pyramidal micro-indentation tests were performed, at room temperature, to indentation depths of 2 µm and 10 µm on the non-irradiated and ion-irradiated Zr-2.5Nb samples. Periodically during the tests the indentation strain rate was changed suddenly by a factor of ten to assess the effect of irradiation hardening on the strain rate sensitivity of the hardness of Zr-2.5Nb.

APPENDIX N - POLYTECHNICA UNIVERSITY OF BUCHAREST – COMPLETED RESEARCH PROGRAMS

A synopsis of completed R&D activities are presented below:

N1.0 IRC

To be addressed, if applicable, in next version

N2.0 RCPS

To be addressed, if applicable, in next version