

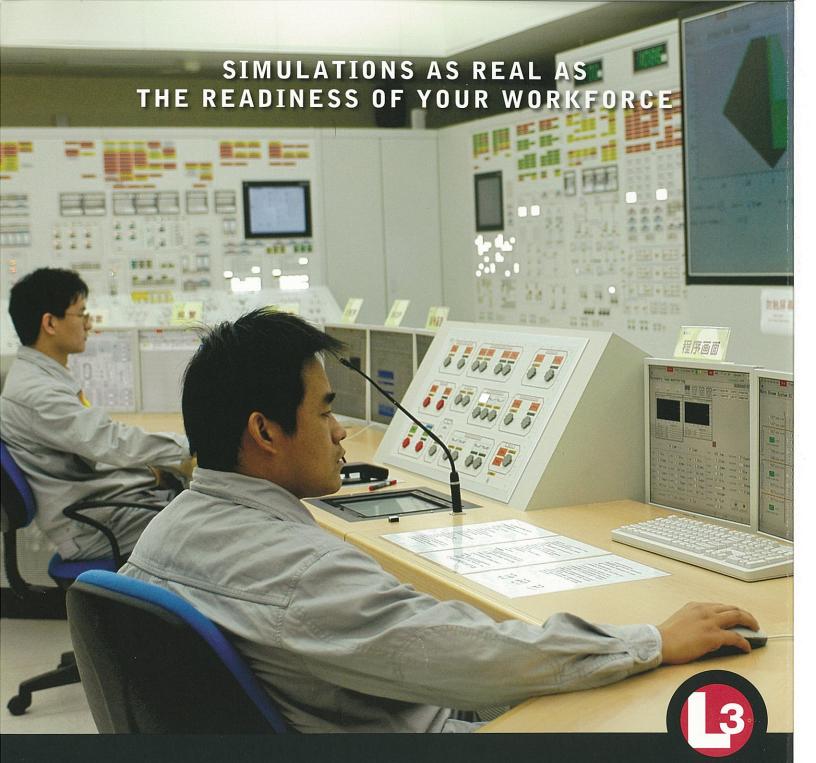
CANADIAN NUCLEAR SOCIETY

# 

LA SOCIÉTÉ NUCLÉAIRE CANADIENNE

MARCH 2015 MARS VOL. 36, NO.1

- CNA Conference and Trade Show
   CNS Bulletin Survey Findings
- New Publisher for the CNS Bulletin
   Endpoint





L-3's superior training environments use Orchid® simulation products to give plant operators the skills to handle any emergency response situation. No matter how complex or dangerous, any scenario can be reproduced, monitored and varied — realistically and in real time. To see how more than 40 years of expertise in advanced simulation can make a very real difference to you today and tomorrow, visit www.L-3com.com/MAPPS.

### **Nuclear Speak 101**



As in any scientific discipline a language evolves that is based on a set of esoteric terms including jargon that are only understood by colleagues and professors. The nuclear industry is no different. However, given the public controversy over such things nuclear there is much more public dialogue about nuclear issues than other sci-

entific and technical issues. With the language spoken by nuclear professionals based on scientific knowledge rather than in human emotional terms it is no wonder that the public does not understand what nuclear professionals are saying. Unfortunately, those opposed to nuclear speak in a language that is easily understood by the public, based on human emotional terms and leaving out boring technical truth. They scare people.

Case in point: A small amount of tritium leaked from the NRU reactor and entered the Ottawa River. It was a trivial amount posing no threat to the public. However, Gordon Edwards framed it this way: the unit of radioactivity for tritium is the Becquerel; AECL just released 13 trillium Becquerels! That sounds like an enormous amount, sure to scare people.

When nuclear professionals speak to the public they tend to confuse people. A cartoon appeared in a Toronto newspaper shortly after the accident at Three Mile Island, where one reporter is asking the other "What's so noble about those gases?" Recently Dr. Nancy Covington, an anti-nuclear activist (and a medical professional) claimed in a Chronicle Harold article that uranium mining

exploration releases cancer-causing radon gas that will seep into people's homes. It prompted a quick response from CNSC President Dr. Michael Binder who said the statement was false and put the issue into perspective by explaining how gases behave in open air and noting natural radon background levels. Of course, Dr. Covington left out the fact that drilling a well for drinking water or ploughing a farm to plant crops also releases radon gas. But Dr. Covington expressed her view in a language that was easy to understand and served her goal of scaring the public with no use of science whatsoever.

There has been considerable debate in letters to the editor of the CNS Bulletin (last four issues including this one) about how best for nuclear professionals to communicate with the public. We all seem to agree that we don't do it very well, but there is disagreement on how we should. We understand the technical details, but we should probably seek to better understand human emotional nature and what drives decisions. When buying a car we often research the specifications - fuel economy, horsepower, torque, safety rating, 2-door or 4-door, 0-100 km time, etc. - but in the end we buy a car "because we like it!" So do we need to find a way to communicate in a manner that makes the public "like" nuclear power and deep geological repositories? Do we need to learn to speak in plain language instead of "nuclear speak"?

Bruce Power CEO Duncan Hawthorne has been very successful in gaining public support and confidence for nuclear energy, possibly because he has an admirable ability to speak in plain language. We should listen to him more often.

### In This Issue

This year's Canadian Nuclear Association conference and trade show attracted some 600 delegates and 100 students. Both Federal and Provincial political leaders expressed strong support for nuclear power, with Ontario Energy Minister Bob Chiarelli noting that nuclear provided 60% of Ontario's electricity. He added that the province's principal priority was the refurbishment of the Darlington and Bruce stations. A summary of the conference is the lead item for this edition of the CNS Bulletin.

We are also providing four technical papers, one

submitted directly to the CNS Bulletin and three from recent conferences.

Our new publisher, Colin Hunt, has compiled the Canadian and CNS News. The CNS News includes a message from our president, Jacques Plourde, and a "Meet the Publisher" article providing some background about our new Publisher.

Last but never least, Jeremy Whitlock answers a little girl's question in a Letter to Endpoint.

As I write this it is the first day of spring, and I say "good riddance to Old Man Winter!"

### From The Publisher



2015 is bringing significant changes to the Canadian Nuclear Society (CNS) and to its CNS Bulletin. It is with deep regret that we note the retirement of two long-standing pillars of the CNS: Bulletin Publisher Fred Boyd, and CNS Office Manager Denise Rouben.

WETHER

Mr. Boyd has guided the CNS Bulletin for a quarter century since assuming control in 1990. He has been the fourth publisher of the Bulletin after its founding in 1980 by John Hewitt. His immediate predecessors were David Mosey and Jatin Nathwani, both in the 1980s. Initially a 28-page mimeograph production, under Mr. Boyd the Bulletin was transformed into a fully type-set, colour production with a target page content of 56 pages.

His efforts transformed the Bulletin into the high quality publication CNS members see regularly four times per year. Intended for the general reader, he has shaped the Bulletin into its current mix of general news, technical articles, upcoming CNS events, and opinion designed to provide items of interest to all members of the Society. His introduction of advertising into the Bulletin more than 10 years ago has helped to defray its costs of production as well as providing Canada's nuclear institutions and industries a venue for showcasing their products and services to CNS members.

Noteworthy over the years is that the Bulletin has never shied away from controversy within our industry. Under the guidance of Mr. Boyd, the Bulletin has provided and will continue to provide information and commentary on the current issues of the day from the perspective of the CNS.

Also retiring from active work for the CNS has been its first Office Manager Denise Rouben. Ms. Rouben's contributions to the CNS have been enormous. Prior to incorporation in 1998, all of the administrative needs of the Society were performed by staff at the Canadian Nuclear Association (CNA). Incorporation meant full physical independence for the CNS. It was Ms. Rouben who created the CNS office in Toronto. It was Ms. Rouben who established the office procedures which now sustain the CNS as an institution.

Not limited to just the CNS office, Ms. Rouben has contributed extensively to establishing the administration and support for nearly all of the various CNS conferences and courses over the past years. Her unfailing support and attention to detail have been of

vital importance to the success of the CNS in all of its conferences. In achieving this, she established strong relations with a large number of volunteers from other organizations to make CNS events a success.

Bulletin readers should also note two important CNS Conference advertisements in this issue: the CNS Annual Conference starting May 31 in Saint John, NB; and the Fire Safety and Emergency Preparedness Conference starting June 17 in Mississauga, ON. With respect to the former, this conference represents the first time that the CNS and the Organization of Canadian Nuclear Industries (OCI) have teamed up for the CNS Annual Conference. During the conference OCI will also be holding one of its Supplier Day events. It is anticipated that holding the two events together will draw both support and attendance for both. CNS President Jacques Plourde and OCI President Ron Oberth are to be commended for their initiative.

Also noteworthy in 2015 will be the Fire Safety and Emergency Preparedness Conference. This will be the first new conference of its kind, and it will bring to the CNS an entirely new group of topics, companies and areas of interest. It is the hope of this author that the conference will mark the beginning of an entirely new conference series for the CNS, the first such in many years. CNS Program Committee Chair Tracy Pierce is to be thanked for her efforts to develop this event.

C.G.H.

### Contents -

Editorial1	
CNA Conference and Exhibition 5-7,39	
Letter to The Editor 8	
Materials Research with Neutron Beams from a Research Reactor	
A Novel Approach to the Production of Medical Radioisotopes: The Homogeneous Slowpoke Reactor	
Muon Tomography with Momentum  Measurements for Fast Detection of  Nuclear Materials at Ports of Entry 28	
Whither LNT?	
Canadian News	
Canada's New Nuclear Liability and Compensation Act Proclaimed 40	
Extended Operation of the NRU 40	
Pickering 5 Sets Unit Production Record 41	
Cameco Reports Uranium Production from Cigar Lake 41	
Atucha 2 Achieves Full Power 42	
Japan to Close Three Old Reactors 42	
CNS News	
From the President 43	
Meet the Publisher 45	
Denise Rouben and Fred Boyd Retire 45	
Council Considers Changes to CNS Bulletin 45	
News from Branches 46	
Calendar	
Endpoint	

#### ~ Cover Photo ~

Aerial view of the Pickering Nuclear Generating Station.

Photo courtesy of Ontario Power Generation

### LIBRARY

Canadian Nuclear Safety Commission

AYR 1 6 2015 N/18 920 BIBLIOTHÉQUE

Commission canadienne de sûreté nucléaire



### ISSN 0714-7074

The Bulletin of the Canadian Nuclear Society is published four times a year by:

The Canadian Nuclear Society c/o AMEC NSS Limited 700 University Avenue, 4th Floor Toronto, ON M5G 1X6 Telephone (416) 977-7620 e-mail: cns-snc@on.aibn.com

Le Bulletin SNC est l'organe d'information de la Société Nucléaire Canadienne.

CNS provides Canadians interested in nuclear energy with a forum for technical discussion. For membership information, contact the CNS office, a member of the Council, or local branch executive. Membership fee for new members is \$82.40 per calendar year, \$48.41 for retirees, free to qualified students.

La SNC procure aux Canadiens intéressés à l'énergie nucléaire un forum où ils peuvent participer à des discussions de nature technique. Pour tous renseignements concernant les inscriptions, veuillez bien entrer en contact avec le bureau de la SNC, les membres du Conseil ou les responsables locaux. Les frais d'adhésion par année de calendrier pour nouveaux membres sont 82.40\$, et 48.41\$ pour retraités.

#### Editor / Rédacteur

Ric Fluke

Tel. (416) 592-4110

e-mail: richard.fluke@amecfw.com

**Publisher** 

Colin Hunt

Tel./Fax (613) 742-8476

e-mail: colin.hunt@rogers.com

The comments and opinions in the CNS Bulletin are those of the authors or of the editor and not necessarily those of the Canadian Nuclear Society. Unsigned articles can be attributed to the editor.

Copyright, Canadian Nuclear Society, 2014

Printed by The Vincent Press Ltd., Peterborough, ON

Canada Post Publication Agreement #1722751



# Nuclear Qualified, Certified and Energized

E.S. Fox Ltd. has been in business for eighty years, designing and building major power projects throughout Canada and around the world.

As a single source of industrial construction, fabrication and engineering solutions, our integrated mechanical, electrical and civil departments ensure we adhere to, control and execute all your design requirements.

E.S. Fox Fabrication has held ASME Nuclear N, NPT, NA and NS Certifications since 2010, one of a select few Canadian Nuclear suppliers to hold these qualifications. We are also a key supplier of EPC construction and maintenance services to major nuclear power producers in the country.

For the better part of a century, E.S. Fox has achieved and continues to foster a reputation for the highest quality workmanship, engineering excellence, timely project completion and operational efficiency. We strive to be your contractor of choice.

TO LEARN MORE, CALL US AT (905) 354-3700, OR VISIT US AT ESFOX.COM



80 Years Of Integrated Construction Solutions

THESE STAMPS ARE TRADEMARKS OF THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS AND THE NATIONAL BOARD OF BOILER AND PRESSURE VESSEL INSPECTORS, RESPECTIVELY.



### **CNA Conference and Exhibition**

### Federal and Provincial Ministers support nuclear power in Canada

By COLIN HUNT

The annual Canadian Nuclear Association (CNA) winter conference and trade show featured two prominent federal and provincial ministers at the Westin Hotel in Ottawa, Feb. 25-27, 2015. The conference drew over 600 delegates, and an additional 100 students.



Speaking during the morning of Feb. 26, Federal Natural Resources Minister Greg Rickford reinforced the federal government's support for nuclear power in Canada. He noted the strong contribution that nuclear electricity generation has played in Canada, reducing greenhouse gas emissions by 29 per cent

between 2005 and 2012. With the addition of hydro generation, Mr. Rickford stated that Canada has one of the cleanest electricity systems in the world.

He noted that the federal government has provided strong support for nuclear power. It has committed \$1.2 billion into waste remediation and cleanup at AECL sites and in Port Hope. He also indicated that the restructuring of AECL's commercial reactor division had been strongly positive for the Canadian industry.

It was in foreign affairs where the government had achieved much recent progress. The enhanced memorandum of understanding with China has resulted in a high degree of co-operation between SNC Lavalin Nuclear (Candu Energy Inc.) and the China National Nuclear Corporation (CNNC). This enhanced co-operation with China could be seen in two areas. The first was to develop new CANDU fuel cycles, and the second was partnership in new reactor construction, specifically in Romania and Argentina. Rickford noted that Cameco Corporation is now supplying uranium to China.

The federal government has also achieved additional nuclear bilateral agreements with the United States and India.

Minister Rickford also discussed the future of Chalk River Laboratories (CRL). Now incorporated as a division of AECL called Canadian Nuclear Laboratories (CNL), he indicated that four consortia have submitted proposals for operation of the site. He stated that all are experienced in laboratory site operation, and that a decision on the successful bid will be made this year.

However he expressed strong support for the future of CRL.

"Make no mistake, Canada's nuclear future will continue to run through Chalk River."

He added that all of the government's policies over the past nine years have been devoted to establishing a solid base for Canada's nuclear industry.

With respect to current operations, Minister Rickford stated that the government had extended the production of radioisotopes at CRL to 2018 from its original cessation date of 2016. He said that a variety of other Canadian nuclear institutions have been making strong progress towards replacing the supply from Chalk River, noting in particular the work at TRIUMF in British Columbia, University of Sherbrooke in Quebec, and at Canadian Light Source in Saskatchewan. He stated that the federal government had spent \$60 million on non-reactor isotope production

Minister Rickford also was pleased to announce that the new Energy Safety and Security Act would receive Royal Assent on Thursday, February 27, 2015. The new statute replaces the old 1976 Nuclear Liability Act, and provides Canada's nuclear industry with a fully updated liability regime for all nuclear facilities.



Speaking as the keynote speaker on Friday, February 27, Ontario Energy Minister Bob Chiarelli also expressed strong support for nuclear power. He noted that Ontario received well over 60 per cent of its electricity from nuclear power in 2014. He indicated that Ontario was continuing to benefit from more than four decades of safe, reliable nuclear generation.

At this time, Minister Chiarelli stated that the province's principal priorities right now were the upcoming refurbishments of the Darlington and Bruce NPSs. He noted that it was vital that these projects proceed on time and on schedule. And in addition, the impact of these projects on Ontario's economy would be large, billions of dollars and more than a decade of work would be required for them.

Minister Chiarelli was blunt about the virtues of refurbishment. "Refurbished capacity costs 50 per cent of what new generating capacity would cost."

But for Minister Chiarelli, nuclear was of much more significance than producing electricity.

"Nuclear power doesn't just power the Ontario economy, it drives it."

He noted the Ontario-based companies that have developed international businesses supplying goods and services around the world in fields as diverse as robotics, plant component and services.

However, the Minister stated that engagement by the federal government was essential for the success of Canada's nuclear industry.

"The nuclear industry needs a renewed commitment from the federal government and from Ontario." Minister Chiarelli said. "We the Ontario government are ready to come to the table with industry and with the federal government."



The various themes of the two ministers were echoed in the conference opening remarks of Bruce Power President and CEO Duncan Hawthorne. He noted that Ontario has some of the best performing nuclear plants in the world. He stated that Ontario's nuclear plants have achieved the goal of highly

successful and reliable operation. And he noted that many other countries are looking to nuclear power to displace fossil fuels. He cited the example of Saudi Arabia which is studying the introduction of nuclear for power generation following the example of the United Arab Emirates.

But Mr. Hawthorne cautioned that there is one significant area of improvement still remaining.

"It is generally true that any nuclear construction project runs late. We have ticked the box on successful operation; now what we need to do is tick the box on project execution."

Mr. Hawthorne stated that Canada's industry must demonstrate its ability to execute projects to a predictable schedule and for a competitive price. He noted that Canada's industry has the skills to achieve this, both in terms of engineering project management and in the ability to secure the social licence to build and operate.



Following Minister Rickford on Thursday, February 26, was Dr. Leslie Dewan. Co-founder and CEO of Transatomic Power, she spoke to the conference about her company's developments of a new molten salt reactor technology. Her presentation outlined significant differences from the old molten salt technology developed in the 1960s at Oak

Ridge, Tennessee. In particular, different materials allowed a much lower level of fuel enrichment than was the case at Oak Ridge. She also noted that significant changes to both the salt and the moderator resulted in much higher fuel burnup than was formerly the case, significantly reducing the inventory of transuranics in used fuel.

She also contrasted the regulatory regimes of the United States and Canada. Because of differences in philosophy, Dr. Dewan said it was her impression that the regulatory regime in Canada was more flexible and more welcoming of new reactor technology than that in the United States.

Dr. Dewan was followed by Dr. Matthew Nisbet. His talk concerned attitudes to climate change and methods of framing both technology issues and the debate over climate change.



The theme of climate change was continued by the lunch speaker, Dr. James Hansen. Formerly with the Goddard Institute of Space Studies with NASA, Dr. Hansen voiced strong support for the use of nuclear power to displace the use of fossil fuels in electricity generation and other applications. He noted with

regret the opposition of much of the environmental community to the use of nuclear power.



The first speaker of Friday morning's session was Dr. Michael Binder, President and CEO of the CNSC. Dr. Binder spoke of the CNSC and industry's response in Canada to the Fukushima accident in 2011.

Dr. Binder observed that one of the principal challenges in Canada for the regulator was public out-

reach. Because of geography, it could be difficult consulting with the public on nuclear project regulation particularly where both the site under review and the population were in remote areas.

The final morning of the conference was continued with a strong panel on environmental infrastructure. The speakers were Hugh MacDiarmid of Terrapower, Ken Nash of the Nuclear Waste Management Organization, and Bob Walker of CNL. Mr. MacDiarmid noted the developments his startup



company is making in the development of small modular, molten salt reactors. Mr. Nash commented on the state of Canada's program for the long term management of used nuclear fuel. Of particular interest was the fact that other nations are looking favourably at the Canadian model, noting in particular the recommendations of the recent US government Blue Ribbon Panel. A particular strength of the Canadian model is its flexibility both in terms of time and in terms of materials that can be accommodated.

The final speaker of the morning was Canada's



Commissioner of the Environment and Sustainable Development Julie Gelfand. She outlined the results of her recent audit of the government's climate change policy and program. She noted that based on current policies and progress, Canada was unlikely to achieve the government's stated targets.

Following Ms. Gelfand, CNA President and CEO John Barrett formally closed the conference.

### Scenes from The Conference









### Letter to The Editor

Reply to Robert Dixon's Letter to the Editor, December 2014 edition of the CNS Bulletin.

Unfortunately, Robert Dixon's Letter to the Editor misses the mark. His statement that my suggested solutions have "all been used by senior AECL staff for decades ..." is, at best, only partially correct. The nuclear industry's public communication has generally been done by technical people, like him, who embrace scientific accuracy and abhor telling stories and using analogies and comparisons. The success of their approach correlates to progress in nuclear waste disposal and getting new reactors in Ontario.

Crucially, the nuclear industry has not compared radioactive wastes and their disposal to other hazardous wastes, other than fleetingly. This comparison should have been pursued vigorously, with passion and ingenuity. For example, the Nuclear Waste Management Office could have included a surface disposal facility similar to the Swan Hills Treatment Centre for hazwaste as one of their main disposal options.

Sadly, nuclear matters and radioactive materials, including waste, have been placed on a pedestal and the public believes they are extraordinarily deadly – even evil– and uniquely different from other materials and hazards. This (mis)belief is so well entrenched it will require Herculean efforts to change. Dixon's solution is to "study the concept of acceptability from first principles." Agreed, but the first principles are those that I suggested initially: speak plainly avoiding technical talk and jargon. Also, focus on comparisons and analogies that are readily comprehensible.

Hans Tammemagi

### **2015 Nominations for CNS Council**

Members of the Canadian Nuclear Society (CNS) will elect the Society's governing Council for 2015-16 at the upcoming Annual General Meeting. That meeting will be held prior to the beginning of the 35th Annual CNS Conference, on Sunday, May 31, 2015 in Saint John, New Brunswick.

Members of the CNS wishing to stand for election to the CNS Council or its Offices are asked to inform the CNS Office in writing or by email (cns-snc@on.aibn.com ) by Thursday, April 30, 2015.

Members wishing to stand for election to Council are encouraged to read the document "Council Roles and Responsibilities" posted in the Members' documents section of the CNS website. This document will also be sent to all members by email.

Members are also encouraged to bring other candidates to the attention of the CNS Office.

For further information regarding nominations and election to the CNS Council, contact:

Adriaan Buijs, CNS Past President: buijsa@mcmaster.ca Colin Hunt, CNS Secretary: colin.hunt@rogers.com CNS Office: cns-snc@on.aibn.com

### MoVeo NEW portable, battery operated videoscope system The lightweight MoVeo is designed to be a complete solution for the demanding needs of RVI in applications in aviation, aerospace, power generation, wind energy, pipe inspection. When portability and a bright, crisp, high resolution image is needed MoVeo is an excellent cost effective solution. The MoVeo features: » Optimal mobility and flexibility with different OD's and lengths » Interchangeable direct 0° and side view 90° tips » A large integrated 5 inch LCD Screen » A powerful LED light source » Precise 4 way articulation of the distal tip from 0° to 150° » A Multi-functional case that can act as work station www.hoskin.ca Vancouver | Burlington | Montreal 604-872-7894 905-333-5510 514-735-5267

# Materials Research with Neutron Beams from a Research Reactor

by JOHN ROOT and DANIEL BANKS<sup>1</sup>

[Ed. Note: The following paper was presented at the 3rd International Technical Meeting on Small Reactors, November 5-7 2014 in Ottawa.]

### **Abstract**

Because of the unique ways that neutrons interact with matter, neutron beams from a research reactor can reveal knowledge about materials that cannot be obtained as easily with other scientific methods. Neutron beams are suitable for imaging methods (radiography or tomography), for scattering methods (diffraction, spectroscopy, and reflectometry) and for other possibilities. Neutron-beam methods are applied by students and researchers from academia, industry and government to support their materials research programs in several disciplines: physics, chemistry, materials science and life science. The arising knowledge about materials has been applied to advance technologies that appear in everyday life: transportation, communication, energy, environment and health. This paper illustrates the broad spectrum of materials research with neutron beams, by presenting examples from the Canadian Neutron Beam Centre at the NRU research reactor in Chalk River.

### 1. Research Reactors Produce Neutron Beams

Nuclear research reactors enable continuous fission of uranium-235, each atomic nucleus breaking into smaller atomic nuclei of various sizes and a few free neutrons. Neutrons are neutral subatomic particles that persist outside the usual confines of an atomic nucleus, eventually decaying into a proton, electron and neutrino with a half-life of about 15 minutes. A steady flux of neutrons diffuses throughout the core volume of a research reactor. Neutrons scatter from the atomic nuclei of other materials in the core of the reactor, including fuel, structural components and especially from materials with low atomic mass, such as hydrogen, deuterium, water, heavy water, graphite, or methane. These light materials efficiently moderate neutron speeds from the initial high energies of fission to 'thermalized' energies. The temperature of the moderator material determines the equilibrium spectrum of neutron energies. If the moderator is room-temperature water or heavy water, most of the neutrons settle into a 'thermal spectrum' with speeds in the range of 1000 m/s to 4000 m/s. If the moderator is very cold, for example liquid hydrogen

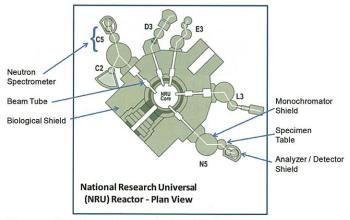
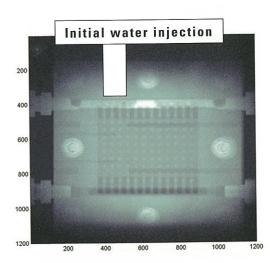


Figure 1: Plan view of the NRU research reactor, showing the core, biological shield, beam tubes and external components that comprise six neutron spectrometers, labelled C2, C5, D3, E3, L3 and N5.

with a temperature of about -250 oC, the neutron speeds would be slower, most of them in the range of 200 m/s to 1000 m/s, and labelled as "cold neutrons". Neutrons are small enough that they exhibit both particle-like and wave-like behaviours. Cold neutrons in a liquid hydrogen moderator have longer wavelengths, most of them in the range of 0.4 to 2.0 nm, whereas thermal neutron wavelengths in a water moderator mostly fall in the range of 0.1 to 0.4 nm.

The core of a research reactor is typically surrounded by a thick wall – the biological shield that protects personnel in the working area around the reactor from the radiation emitted by fission and decay processes inside the reactor core. By simply opening a beam tube through the biological shield, neutrons and other radiation can escape from the core into the working area. Additional external shielding and other components can be placed in line with the beam tube to separate a stream of neutrons of a chosen wavelength and direct that 'monochromatic' neutron beam towards a specimen of material. The way the neutron beam is scattered from the specimen reveals crystalline structures or nanostructures as well as intermolecular vibrations, magnetic structures and magnetic excitations.

Canadian Neutron Beam Centre, Chalk River Laboratories, Chalk River, Ontario, Canada



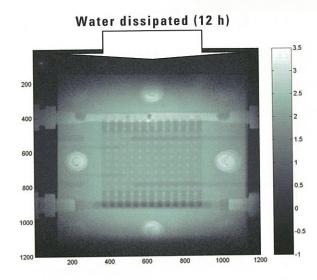


Figure 2: Neutron radiographs of a prototype hydrogen fuel cell, showing dissipation of injected water (light patch in upper horizontal channel) after 12 hours. The images were taken at the NRU reactor.

### 2. Neutron Beams Probe Materials

The reason why materials researchers are interested to probe specimens with neutron beams, is the unique way that neutrons interact with matter. Neutrons are neutral particles, and mainly interact with the nuclei of atoms via the strong, short-ranged, nuclear force, not through any long-ranged Coulomb forces with the charged electron cloud that occupies the vast majority of an atom's volume. From the viewpoint of a neutron, matter is mostly empty space, the nucleus at the centre of each atom being a pin-point compared to the wavelength of the neutron, which is similar to the distances between atoms and molecules. The interaction of the neutron with atomic nuclei varies erratically with atomic size, and isotope. Also, while neutrons are electrically neutral, they carry a magnetic moment, and therefore interact with any magnetic structures or excitations that appear at the molecular level of materials. The way neutrons interact with matter frequently reveals features of materials that are challenging to study with other scientific probes of materials, such as light, X-rays, or electrons, all of which interact strongly with atomic electrons, rather than the nucleus.

The "Big Three" strengths of neutron beam methods are listed here:

- (1) Neutrons penetrate deeply into most materials (millimetres, centimetres) even though the energies of thermal neutrons are a million times lower than X-rays of similar wavelength i.e. thermal neutrons are completely non-destructive probes of materials in bulk or at depth.
- (2) Neutrons reveal magnetic structures that appear in many innovative materials that have high technological impact or potential to revolutionize technologies, including colossal magneto-resistors for

- information storage, high-temperature superconductors to maximize energy efficiency, high-field permanent magnets for miniaturization of electric motors, and advanced quantum materials.
- (3) Neutrons distinguish among isotopes of a given atom, which enables researchers to adjust the contrast and visibility of molecular features through isotope substitution in complex biological structures, as well as to detect light atoms in the presence of heavy atoms, for example lithium ions in battery materials, or hydrogen in a metal matrix.

### 3. Neutron Imaging

The easy penetration of neutrons through most materials, along with their high sensitivity to hydrogen, opens

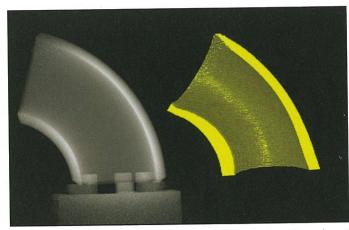


Figure 3: A single neutron radiograph of a bent steel pipe (~ 70mm diameter) is compared to a tomographic reconstruction from several neutron radiographs, revealing the thickening of the pipe wall on the intrados of the bend. Images were collected with a Mar345 image-plate detector on the N5 neutron beam at the NRU reactor in Chalk River.

up possibilities for imaging the interior structures of many objects, and revealing complementary details that might be comparatively difficult to see with X-rays. Neutron radiography is directly analogous to X-ray radiography, which is familiar in the form of dental X-rays - images of bone with darker features where softer tissue or regions of decay provide contrast with the general background. X-ray absorption increases uniformly with atomic size, with heavy-metal fillings absorbing more than calcium-loaded bone, which in turn absorbs more than the metal-free tissue of the gums. An image made with neutrons would reveal different light and dark regions, the hydrogen-rich proteins in the gums absorbing and scattering far more neutrons away from the transmitted beam than the heavy metal fillings. Neutron and X- ray radiography images are not necessarily 'negatives' of each other, but if there are structural features inside an object that contain a lot of hydrogen, such as water, oil, plastic or biological materials, neutrons may reveal them more readily than X-rays against a background of heavier materials, such as metals or ceramics. At neutron beam laboratories around the world, the technology for neutron radiography is continuously advancing with respect to spatial resolution and speed of image capture. The first stroboscopic neutron radiography demonstration was made in 2002 as a collaboration of FRM II (Munich), the ILL (Grenoble), the University of Heidelberg and the Paul Scherrer Institute (Switzerland), in which a four-piston BMW engine was probed to reveal the distribution of lubricant at various points in the operating cycle, with the high flux neutron beam line H9 at the Institut Laue Langevin (ILL), delivering exposure times of the order ~100ms.

By rotating the specimen to acquire a series of neutron radiographs, the internal structures of the object can be reconstructed in a three-dimensional model. This method, called neutron tomography, is completely analogous to computer-assisted tomographic scanning (CAT- scanning) familiar in clinical imaging, where gamma rays are transmitted through a patient in several directions to form a three-dimensional picture of internal organs and disease structures. However, again, the easy penetration of neutrons into most materials and special sensitivity of neutrons to light atoms, especially hydrogen, provides opportunities for image contrast that might reveal internal structure details not so easily distinguished by X-rays or gamma rays.

### 4. Neutron Scattering

While neutron imaging reveals structural information on a large scale, neutron scattering exploits the abilities of neutrons to probe structures and dynamics of materials at the level of inter-atomic distances or nanostructures. Whether a sample is composed of a hard material (metals, alloys, ceramics) or a soft material (polymers, biological membranes, vesicles) or a complex mixture (metal-matrix composites, colloids, emulsions), neutrons

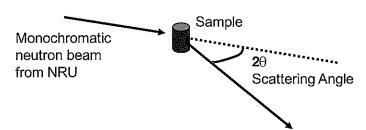
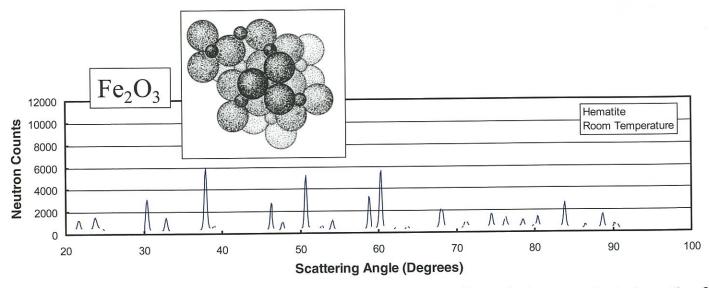


Figure 4: A beam of neutrons, with initial direction, shape and wavelength, enters a sample of material. The neutrons are scattered into various directions and their energies (wavelengths) are shifted by interaction with atomic nuclei or magnetism in the sample at the length scale of intermolecular distances (nanometres).

can extract information about distances, molecular-interaction energies and magnetism, often while the sample is simultaneously held in scientifically or technologically relevant conditions (temperature, pressure, stress, chemical environment). A neutron beam, prepared with initial direction, cross-section, magnetic polarization and energy (ie wavelength or velocity), directed into a sample, will produce scattered neutrons over a range of scattering angles and a range of scattered-neutron energies, and possible change of polarization, all of which can be characterized with suitable detection equipment. The changes in scattered neutron direction and energy can be analyzed to reveal the underlying crystalline or nanostructures of the material as well as the available excitations in the material, such as phonons or magnons.

A familiar manifestation of neutron scattering is neutron diffraction. As with X-ray diffraction, neutrons can diffract from single crystals, powders and polycrystalline solid materials. The easy penetration of neutrons into most materials ensures that neutron diffraction probes the entire volume of a specimen, yielding bulk-average information, and enabling the possibility of non-destructive mapping of the interior of a specimen. Neutrons can penetrate through the walls of a furnace or other specimen environment, to probe a sample that is held within, at conditions of interest. The structural information extracted by neutron diffraction reveals distances between the atomic planes that comprise crystals, the occupancy of crystal sites by various atoms or isotopes, distortions of the crystal lattice due to applied or residual stresses, crystal-lattice damage, statistical distributions of crystal orientations in a poly-crystal, and average microstructural grain sizes.

A second category of structural analysis by neutron scattering is provided by a method called reflectometry. Similar to the way fibre optics transmit light over long distances with minimal loss of intensity through 'total internal reflection' at the surfaces of each fibre, neutrons are also totally reflected at surfaces or interfaces, when scattering angles are very low. As the neu-



**Figure 5:** A neutron powder diffraction pattern from iron oxide (hematite) was collected on the C2 diffractometer at the NRU reactor. The pattern of peak intensities and scattering angles is a fingerprint of the underlying crystal structure. The C2 instrument has a single, curved, 800-channel position-sensitive detector that acquires the full diffraction pattern in a single setting, providing resolution and throughput that is highly competitive among neutron beam laboratories in North America.

tron scattering angle increases, there comes a point where neutrons partially penetrate the interface and enter the material in the next layer. Reflection may then occur at the next interface, as well, and the two neutron waves, reflected from each surface, interfere with each other to create a pattern of intensity oscillations as a function of scattering angle. When this reflectivity pattern is analyzed, the thickness of each interface, its roughness and the atomic or isotopic composition can be extracted, averaging over a comparatively large surface area (~cm 2) with a depth resolution and range in the scale of nanometres. Neutron reflectometry measurements can be performed on

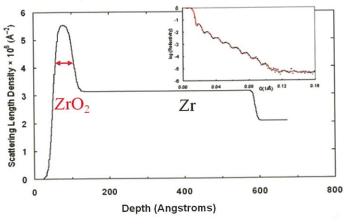


Figure 6: A neutron interference pattern (inset), collected with the D3 neutron reflectometer at the NRU reactor is modelled to extract a profile of composition versus depth, here revealing that the native oxide on a zirconium metal surface is about 50 Angstroms (5 nm) thick.

specimens while they are exposed to electrochemical conditions, hydrogen at selected pressures and temperatures, or magnetic fields to reveal new knowledge about corrosion, absorption of gases, polymeric coatings for medical implants, structures in biological membranes, superconductivity, spintronic materials and much more.

The final major category of neutron scattering methods is a form of spectroscopy, where both the new direction (momentum) of neutrons is determined after scattering, as in diffraction, as well as the new energy of the neutrons is determined after scattering. The change in energy from incident to scattered neutron arises by exciting lattice vibrations or waves of magnetism within the specimen. Measurements of neutron inelastic scattering, help to inform fundamental ideas about dynamic processes in condensed states of matter: solids, liquids, interacting spins and lattice vibrations. Although neutrons are neutral particles they have a magnetic moment and a beam of neutrons can be polarized, setting all neutrons in a 'spin-up' state before entering the specimen. A neutron-polarizing analyzer can then detect how many neutrons have changed polarization to the 'spin-down' state because of interaction with magnetic structures or dynamics in the specimen. Polarized-neutron inelastic scattering provides the most detailed insights about magnetic excitations in condensed matter, enabling researchers to be certain that features in the measured spectrum are due either to magnetic or to crystal-lattice 'nuclear' vibrations. An excellent introduction to neutron inelastic scattering and applications to characterize magnetic spin excitations is found in reference 1.

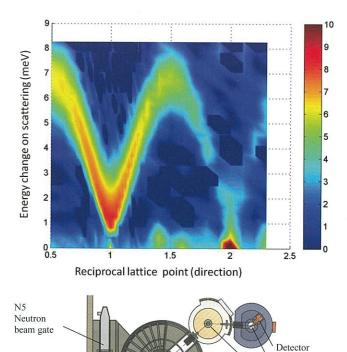


Figure 7: A neutron inelastic scattering map (dispersion) from a specimen of manganese fluoride, shown above, was collected with the N5 triple-axis neutron spectrometer at the NRU reactor, shown below. Crystals diffract the neutron beam to select incident neutron energy (monochromator) and the scattered energy (analyzer) of neutrons that reach the detector.

Analyzer

Specimen

Monochromator

### Neutron Beam Methods Contribute to Science and Technology

The knowledge of structures and dynamics of materials at the molecular and nanoscale can be applied to any scientific discipline that involves materials: physics, chemistry, materials engineering, life science, or earth science. The knowledge arising from neutron beam measurements has been applied to many technologies important for daily life, and linked to several industry sectors: nuclear energy, oil & gas, aerospace, automotive, materials production and other manufacturing. Neutron scattering measurements provide insights into the condition of materials during exploration of fundamental properties, through development of new technologies to full scale material processing, to manufacturing, service performance and ultimate failure - spanning the full range of 'technology readiness levels' and beyond. The following examples are drawn from the Canadian Neutron Beam Centre (CNBC)

at the NRU reactor at Chalk River Laboratories, and are explained more fully in an Annual Report to the Canadian scattering community [2].

### 5.1 Basic Research

Research at the leading edges of scientific knowledge is the foundation for game-changing technologies of the future, and the basis to revolutionize ideas about the nature of our world. Past examples of scientific breakthroughs of this calibre include the theories of relativity, and quantum mechanics, and the realizations of nuclear energy, neutron-scattering, lasers or transitors from these new ideas. Researchers leading in these breakthroughs were recognized with Nobel Prizes. Today, an important scientific frontier is attempting to understand the phenomenon of high-temperature superconductivity and related quantum materials. The scientific importance of this research domain is demonstrated through publication in the most highly cited scientific journals, and through awards bestowed by scientific societies. Examples of high-impact journals that recently published research enabled by neutron scattering at the CNBC include Nature Communications [3-4], Physical Review Letters [5-10], and Nature Materials [11]. CNBC collaborators Walter Hardy, Doug Bonn, and Ruixing Liang from the University of British Columbia were awarded the 2005 Brockhouse Canada Prize for Interdisciplinary Research in Science and Engineering. Bruce Gaulin (McMaster University) and Bill Buyers (CNBC), much of whose research has been enabled through the CNBC's neutron beam facilities and expertise, were both inducted as Fellows of the Neutron Scattering Society of America in 2014 for seminal and sustained contributions to fundamental research in solid-state physics, and leadership in the field of neutron-scattering in North America.

### 5.2 Application-driven research

On the next level forward, many scientists study materials because they are candidates for overcoming barriers to new technologies. For example, an environmentally-friendly alternative to fossil fuels may be hydrogen, because it only produces water and energy when it is combined with oxygen. One hurdle to cross on the way to a future 'hydrogen economy', where vehicles are powered by hydrogen, is to better store and release hydrogen safely, efficiently and cost- effectively. Pressurized storage tanks might be an option in the short-term, but the targets for capacity and efficiency set by the US Department of Energy will require the development of hydrogen-storage materials that concentrate hydrogen in the solid state, such as metal hydrides or more exotic metal-oxide framework materials. Neutron scattering methods are especially effective for characterizing candidate hydrogen-storage materials because neutrons are

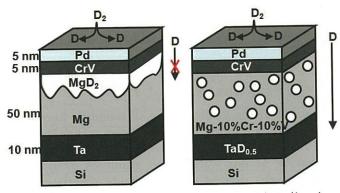


Figure 8: Illustration of hydride formation (in the form of deuterium, D) in thin films of magnesium in which a blocking layer forms (left), and of magnesium-chromium-vanadium in which the hydrogen moves more freely (right).

very sensitive to hydrogen within metals.

Magnesium has a very high storage capacity for hydrogen (7.6 wt.%), but it's practical application is limited by its slow response in accepting and releasing the hydrogen. The slow response is due in part to a build-up of magnesium hydride at the surface, which blocks further movement of the hydrogen in and out of the magnesium film. Recently, Prof. D. Mitlin (U of Alberta) achieved much higher rates of hydrogen absorption and desorption in magnesium when a combination of other metals was added (chromium and vanadium). He needed neutron scattering to understand the cause of this improved performance to guide further development and accessed the CNBC to undertake neutron reflectometry measurements while the storage material was exposed to hydrogen and subjected to relevant temperatures. The measurements proved that the addition of chromium and vanadium was impeding the formation of the blocking layer of magnesium hydride, therefore enabling faster movement of hydrogen through the material.

The elucidation of the underlying mechanism led to an examination of the effect of adding other metals like chromium and iron together to the magnesium. This alloy turned out to be another promising hydrogen storage system, in which the blocking layer is prevented in a manner similar to the magnesium-chromium vanadium system. [2, 12]

A second example of application-driven science is in the domain of health-related molecular biophysics. The human body is a complex system, with thousands of molecules in every cell performing different functions. There is much to be learned yet in how these molecules provide their functions, because they reside in or interact with cell membranes, an environment which is problematic to study with many common scientific techniques. Neutron beams are used to study these molecules, because they are effective yet gentle probes of delicate samples that require carefully controlled environments. The ability of neutrons to penetrate inside equipment to hold mem-

branes in biologically relevant conditions of temperature, pH and humidity, to probe these soft materials with absolutely no destructive effect, and, by isotopic substitution of hydrogen with deuterium enhance the contrast and visibility of selected portions of the molecules of interest is a powerful combination to reveal new knowledge about processes in health-related sciences.

The molecule known as Vitamin E is the only essential nutrient for which no one knows how it delivers a benefit. A scientific understanding of the function of Vitamin E could be applied to optimize vitamin supplements. However, Vitamin E is difficult to study in clinical trials because the effects of vitamin E only become apparent over long time scales. Instead, using neutrons at the CNBC, a research team from Brock University has been able to pin-point the location of vitamin E's anti-oxidant activity at the interface of a model membrane with its aqueous environment. They have been able to show that a significant body of research on vitamin E, that is, its oxidation kinetics and its products, must revisited, taking into consideration the physical properties of the model membrane, and are now suggesting that vitamin E supplements may be ineffective, in fact. [2] The same research team has also applied neutron scattering methods at the CNBC to understand an anti-microbial agent, known as "chlorhexidine," which is commonly used in personal hygiene products, such as soaps, contact lens solutions, and mouthwashes. Chlorhexidine disrupts bacterial membranes to kill the bacteria. The further insights from neutron scattering measurements about the interaction of chlorhexidine with cell membranes may open a pathway towards a patentable, membrane-based drug delivery system. [2]

### 5.3 Technology development

Engineers perform research to solve specific industrial challenges along the way to improving technologies, from developing new alloys with more desirable properties to improving manufacturing processes. Such research is often done either directly for industry, or with university researchers who are collaborating with industry partners.

Pipeline owners need to prevent failures by using the best scientific methods available to interpret inspection data and inform decisions about, for example, whether to replace a small section of pipeline, which may cost over a hundred thousand dollars.

To help solve challenging problems like this, the global pipeline industry pools resources through the Pipeline Research Council International.

Researchers from Queen's University are working with GdF Suez to help interpret pipeline inspection data from a technique called Magnetic flux leakage (MFL). Their research seeks to develop a library that maps MFL data to specific kinds of defects and conditions of stress around the defect—factors which influ-

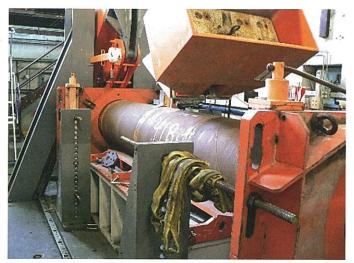


Figure 9: GdF Suez lab simulates dents produced by a backhoe. Stress data obtained by neutron diffraction, will be useful to the industry in making hundred thousand-dollar decisions about how to manage pipelines that have sustained mechanical damage, for example, as a result of a backhoe digging in the wrong place.

ence the likelihood of failure. MFL is sensitive to the loss of metal from corrosion or mechanical damage, which could be caused by a backhoe digging in the wrong place, for example. Thus, GdF Suez produced dents and gouges in full-sized, pressurised sections of pipe, mimicking the damage caused by a backhoe.

Prof. Clapham's research group mapped the stress around these gouges with neutron diffraction at the CNBC, and is comparing those actual, measured stresses to computer simulations and the (more indirect) experimental data provided through the MFL signal. The group aims to find correlations that can be used to determine if an MFL inspection signal in the field was produced by mechanical damage, and to estimate the level of risk represented by the damage. That data will serve industry as scientific input into decision-making about how to manage affected pipelines [2].

An example of improving manufacturing practices is a collaboration between Nemak (a Canadian automobile engine manufacturer), Ryerson University, and the CNBC, each of whom contributed their own tools and expertise in metallurgy, mechanical testing and computer modelling. Nemak's objective was to find the best way to make V-6 aluminum engine blocks. These engines have extremely low tolerance for distortion in the shape of the cylinder holes in the block. Stress relief methods are used after casting the block to increase dimensional stability, and yet each manufacturing step comes with its own costs and impacts on the materials properties. To improve the cost-effectiveness of manufacturing, the collaborative team needed to better understand the factors contributing to dimensional instability.

The CNBC applied neutron beams in several studies to



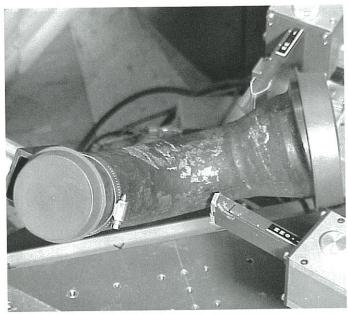
Figure 10: Nemak prototype engine block installed on the L3 neutron stress scanner at the NRU reactor.

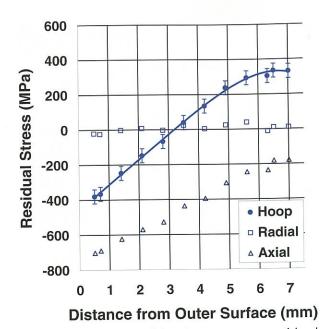
map the stress distribution and microstructure in new aluminum alloys as well as engine blocks following the application of stress-relief such as a heat treatment. The CNBC also developed and implemented some new experimental technologies to observe microstructural evolution during solidification of the alloys as would occur during casting of an engine block. The new knowledge obtained by neutron diffraction may be suggesting a way to simplify the current heat treatment practice, without compromising reliability of the final product. Practical validation is needed; however, if proven, a simplification in manufacturing process could reduce production time, reduce energy usage, and save millions per year on the manufacturing processes [1].

### 5.4 Applied Research 'in the field'

Industry sometimes needs timely access to neutron beams to solve immediate problems and determine how to manage on-going issues. A primary example was a highly impactful line of research on pipe cracking over a 15 year period that began with an urgent failure analysis and grew to qualify better maintenance and prevention techniques.

In January 1997, the Pt. Lepreau Generating Station (PLGS) was shut down for repair of a heavy-water leak from a through-wall crack in a feeder outlet bend. A second such incident occurred in March 2001. These outages together cost about \$10M in repairs, inspections, and related work, plus about \$50M to replace the lost electricity. NB Power and Atomic Energy of Canada Ltd. (AECL) carried out urgent failure analyses, which included non-destructive stress measurement by neutron diffraction at the CNBC. In both cases, the residual stress from the manufacture of the bend was found to be nearly at the point of yielding. With a clear understanding of the cause





**Figure 11:** Crossed neutron beams pinpoint locations inside the wall of a bent steel feeder, to scan residual stress versus depth below the outer surface, non-destructively. The measurements reveal increasing tensile stress towards the inner surface of the pipe, which could accelerate the growth of through-wall axial cracks.

of the failure, of which the neutron-beam stress-scans were a part, NB Power was able to assure the regulator in both instances that the PLGS could be restarted safely, thus avoiding further unplanned down time costs.

The industry needed to better understand the factors driving the degradation, which bends were most at risk, and how to manage the risk of cracking. The industry collectively funded, among other activities, significant efforts to measure the distribution and magnitude of residual stresses at feeder pipe bends using the CNBC frequently from 2001 to 2008, and most recently in 2011. Residual stress measurements by neutron diffraction constituted a valuable input into this research over this period that together had the following cumulative impacts [13]:

- increased assurance for nuclear regulators to relicense CANDU reactors
- timely assurance for continued construction of CANDU reactors at Qinshan, China,
- assistance in multi-million-dollar decisions about strategies to manage the cracking, avoiding tens of million-dollar costs due to unplanned down time,
- saving significant outage time and inspection resources during planned maintenance outages,
- enhanced safety requirements in regulatory documents for new reactors,
- high confidence that feeder cracking of the types seen at PLGS and Gentilly-2 will not be life-limiting factors for existing CANDU reactors once they are refurbished, and
- qualification of an innovative welding method that is now entering the marketplace.

## 6. Enabling Frontier Science and Technology

For industrial and government researchers, the ability to apply neutron beam methods to characterize hard materials, such as metals, alloys and composites will continue to be valuable in the foreseeable future, as reliability of hard-material components underlies safe, economic operations of our infrastructure, including power plants, pipelines, bridges, cars, airplanes, ships, and railroads. Industries with low tolerance for failure need to know, with certainty, the properties of the materials they use in critical components. Neutrons beams are unrivalled in their ability to directly and non-destructively determine stress, texture, and other properties deep inside metallic components, and the CNBC has led the way in this area. More examples of current impacts arising from industrial projects at the CNBC are found in its recent activity report. [2]

On the other hand, strong growth in the interdisciplinary areas of biochemistry and biophysics is driving the evolution of tools from physics and chemistry to understand the soft materials that appear in life sciences, polymers and the emerging nanotechnologies that promise major impacts in health, environment and energy sectors. Neutron beam facilities outside of Canada have been advancing their capabilities in recent decades to enable frontier contributions to science and technology of soft materials, including cold-neutron sources in their research reactors and building neutron-beam instruments that are optimized to reveal nanometre-scaled structures and lower-energy excitations. Lacking a cold

neutron source, the NRU reactor can only support a limited subset of soft materials research in niche areas where contributions are competitive with those of the twenty or so other neutron beam facilities around the world. To reach a world-class level of enabling science and technology of soft materials, contributing across the full range of technology readiness in Canada, would require an investment to upgrade the NRU reactor substantially or to replace it with a modern neutron facility featuring a compact, high-flux core, a cold source, stateof-the-art beam optics and expanded instrument suite fed by cold-neutron guides. Examples of recent national investments of this type can be found in Germany (FRM-II, Munich, opened in 2002), Australia (OPAL, opened in 2007) ), and the United States of America (NIST Center for Neutron Research, upgrades currently underway).

### 7. Conclusion

This paper has summarized how a research reactor generates neutron beams, and how neutron beams probe materials of all kinds, revealing knowledge that cannot be obtained easily by other scientific methods. Even with the limitations of the NRU reactor, a medium-flux source of thermal neutrons alone, Canadians have access there to facilities and expertise that support leading-edge science and technology over the full range of technology readiness levels and beyond – supporting innovation with nuclear methods for broad social and economic impacts, both in the short term and in years to come.

### 8. References

- Z. Yamani, Z. Tun, and D.H. Ryan, "Neutron scattering study of the classical antiferromagnet MnF2: a perfect hands-on neutron scattering teaching course", Can. J. Phys. 88: 771-797 (2010).
- 2. Activity report 2011-2013 to the Canadian Institute for Neutron Scattering available at websites for the Canadian Neutron Beam Centre http://neutrons.ca, as well as the Canadian Institute for Neutron Scattering website http://www.cins.ca
- Quantum oscillations of nitrogen atoms in uranium nitride. Aczel, A. A.; Granroth, G. E.; MacDougall, G. J.; Buyers, W. J. L.; Abernathy, D. L.; Samolyuk, G. D.; Stocks, G. M.; Nagler, S. E.. Nature Communications, 3, 2012-10-09 http://dx.doi.org/10.1038/ncomms2117.
- 4. Carrier localization and electronic phase separation in a doped spin-orbit-driven Mott phase in Sr3(Ir1xRux)2O7. Chetan Dhital, Tom Hogan, Wenwen Zhou, Xiang Chen, Zhensong Ren, Mani Pokharel, Yoshinori Okada, M. Heine, Wei Tian, Z. Yamani, C. Opeil, J. S. Helton, J. W. Lynn, Ziqiang Wang, Vidya Madhavan and Stephen D. Wilson. Nature Communications 5,

- 2014-02-25 http://dx.doi.org/10.1038/ncomms4377.
- Study of the Ground State Properties of LiHoxY1-xF4 Using Muon Spin Relaxation J. Rodriguez, A. A. Aczel, J. P. Carlo, S. R. Dunsiger, G. J. MacDougall, P. L. Russo, A.T. Savici, Y. J. Uemura, C. R. Wiebe and G. M. Luke. Physical Review Letters 105: 107203-1 to -4 (2010).
- Effect of uniaxial strain on the structural and magnetic phase transitions in BaFe2As2. Dhital, Chetan; Yamani, Z.; Tian, Wei; Zeretsky, J.; Sefat, A. S.; Wang, Ziqiang; Birgeneau, R. J.; Wilson, Stephen D.. Physical Review Letters, 108 (8), 2012-02-22, p. 1. 087001-1-087001-4.
- Competing ferri- and antiferromagnetic phases in geometrically frustrated LuFe2O4. de Groot, J.; Marty, K.; Lumsden, M. D.; Christianson, A. D.; Nagler, S. E.; Adiga, S.; Borghols, W. J. H.; Schmalzl, K.; Yamani, Z.; Bland, S. R.; de Souza, R.; Staub, U.; Schweika, W.; Su, Y.; Angst, M.. Physical Review Letters, 108.
- Coexistence and competition of the short range incommensurate antiferromagnetic order with superconducting state of BaFe2-xNixAs2. Luo, Huiqian; Zhang, Rui; Laver, Mark; Yamani, Zahra; Wang, Meng; Lu, Xingye; Wang, Miaoyin; Chen, Yanchao; Li, Shiliang; Chang, Sung; Lynn, Jeffrey W.; Dai, Pengcheng. Physical Review Letters, 108 (24), 2012-06-12, p. 247002-1-247002-5.
- Magnon Breakdown in a Two Dimensional Triangular Lattice Heisenberg Antiferromagnet of Multiferroic LuMnO3. J. Oh, M.D. Le, J. Jeong, J-H Lee, H. Woo, W.-Y. Song, T.G. Perring, W.J.L. Buyers, S.-W. Cheong and J.G. Park. Physical Review Letters 111: 257202 (2013).
- Phonon Lifetime Investigation of Anharmonicity and Thermal Conductivity of UO2 by Neutron Scattering and Theory. Judy W.L. Pang, William J.L. Buyers, Alexandr Chernatynsky, Mark D. Lumsden, Bennett C. Larson and Simon R. Phillpot. Physical Review Letters 110, 157401 (2013).
- Spatially Homogeneous Ferromagnetism of (Ga, Mn)As. S. R. Dunsiger, J. P. Carlo, T. Goko, G. Nieuwenhuys, T. Prokscha, A. Suter, E. Morenzoni, D. Chiba, Y. Nishitani, T. Tanikawa, F. Matsukura, H. Ohno, J. Ohe, S. Maekawa and Y. J. Uemura. Nature Materials 9: 299-303 (2010).
- 12. Effect of alloying magnesium with chromium and vanadium on hydrogenation kinetics studied with neutron reflectometry. Kalisvaart, Peter; Luber, Erik; Fritzsche, Helmut; Mitlin, David. Chemical Communications, 47 (14), 2011-04-14, p. 4294-4296.
- D. Banks, R. Donaberger, B. Leitch, R.B. Rogge. Stress Analysis of Feeder Bends Using Neutrons: New Results and Cumulative Impacts. The 19th Pacific Basin Nuclear Conf. PBNC2014-186.

# A Novel Approach to the Production of Medical Radioisotopes: The Homogeneous Slowpoke Reactor

by H.W. BONIN, J.W. HILBORN<sup>1</sup>, G.E. CARLIN<sup>2</sup>, R. GAGNON & P. BUSATTA<sup>3</sup>
Royal Military College of Canada, Kingston, Ontario Canada K7K 7B4 bonin-h@rmc. ca

[Ed. Note: The following paper was submitted by the authors to the CNS Bulletin.]

### Abstract

In 2009, the unexpected 15-month outage of the Canadian NRU nuclear reactor resulted in a sudden 30% world shortage, with higher shortages experienced in North America than in Europe. Commercial radioisotope production is from just eight nuclear reactors, most being aging systems near the end of their service life. This paper proposes a more efficient production and distribut ion model. Tc-99m unit doses would be distributed to regional hospitals from ten integrated "industr ia I radiopharmacies", located at existing licensed nuclear reactor sites in North America. At each site, one or more 20 kW Homogeneous SLOWPOKE nuclear reactors would deliver 15 litres of irradiated aqueous uranyl sulfate fuel solution daily to industrial-scale hot cells, for extraction of Mo-99; and the low-enriched uranium would be recycled. Purified Mo-99 would be incorporated in large Mo-99/Tc-99m generators for extraction of Tc-99m five days a week; and each automated hot-cell facility would be designed to load up to 7,000 Tc-99m syringes daily for road delivery to all of the nuclear medicine hospitals within a 3-hour range. At the current price of \$20 per unit dose, the annual gross income from 10 sites would be approximately \$360 million.

The Homogeneous SLOWPOKE reactor evolved from the inherently safe SLOWPOKE-2 research reactor, with a double goal: replacing the heterogeneous SLOWPOKE-2 reactors at the end-of-core life, enabling them to continue their primary missions of research and education, together with full time commercial radioisotope production. The Homogeneous SLOWPOKE reactor was modelled using both deterministic and probabilistic reactor simulation codes. The homogeneous fuel mixtur e is a dilute aqueous solution of low-enriched uranyl sulfate containing approximately 1 kg of U-235. The reactor is controlled by mechanical absorber rods in the beryllium reflector.

Safety analysis was carried out for both normal operation and transient conditions. The most severe transient simulated resulted from a 5.87 mk step positive reactivity insertion to the reactor starting at critical, steady state, and 20 C. Peak temperature, 83 C, and peak power, 546 kW, were reached 5.1 seconds after the reactivity insertion. However, the power fell rapidly after the peak, and remained below 20 kW thereafter. Both the temperature and void coefficients were

significant ly more negative than the corresponding coefficients in the present SLOWPOKE-2 reactors. The transient simulations showed that the maximum temperature and power never damaged the reactor; and thermal-hydraulics calculations showed that natural convection was sufficient to ensure adequate reactor cooling in all situations.

### Global Medical Isotope Shortage

An estimate of the combined demand for Mo-99 in Canada and the USA for the year 2008 was 6,000 six-day Curies (Ci) per week, of which 72% came from the NRU reactor. [1] The Mo-99 is produced from HEU targets, and after removal of uranium, it is shipped to Nordion in Kanata, Ontario. Nordion further purifies the material and sends it to Lantheus in the USA for manufacture and distribution of Mo-99/Tc-99m generators. The 15 month shutdown of NRU in 2009-2010 caused an overall global isotope shortage of approximately 30%, with North America experiencing higher shortages than Europe. [1] A recent reference estimates current North American demand to be 5,000 six-day Curies of Mo-99 per week, produced by 8 reactors; and all of the reactors except one irradiate HEU targets. The same reference estimates the corresponding Tc-99m demand to be approximately 15 million unit doses per year. [2]

# 2. Production & Direct Delivery of Tc-99m Unit Doses from SLOWPOKE Reactor Sites

An alternative to the complex system of manufacturing and distributing small Mo-99/Tc-99m generators to hundreds of radiopharmacies in regional hospitals, is the manufacture and direct distribution of Tc-99m unit doses to regional hospitals from 10 "industrial" radiopharmacies, located at existing licensed sites in North America. A 20 kW homogeneous SLOWPOKE reactor at each of the 10 radiopharmacy sites would deliver 15 litres of irradiated Uranyl Sulfate fuel solution daily

<sup>1.</sup> Atomic Energy of Canada Ltd (retired)

<sup>2.</sup> Ontario Power Generation

<sup>3.</sup> Officers in the Canadian Forces

to industrial-scale hot cells for extraction of Mo-99, which would be incorporated in large Mo-99/Tc-99m generators for elution of Tc-99m five days a week; and the Low-Enriched-Uranium (LEU) in solution would be recycled. Fortuitously, the 66 hour half-life of Mo-99 allows the replenishment of Tc-99m in the generators over a growth period of approximately 20 hours.[3] It is conceivable that any SLOWPOKE 2 research reactor could be converted to homogeneous core operation, by replacing the fuel-rod core unit with a cylindrical tank of the same diameter.[4] The homogeneous SLOWPOKE would be designed to operate unattended, but remotely monitored at the security office within the SLOWPOKE site. Each automated hot-cell facility would be designed to load up to 7,000 Tc-99m syringes for daily delivery to all of the Nuclear Medicine hospitals within a 3 hour average range by road transport. Typically, the delivered doses would be in the range 10 to 30 mCi, at each hospital, ready for immediate use. Assuming an average delivered dose of 25 mCi at the hospital and 5 x 52 irradiation days per year, it is estimated that 10 SLOWPOKE sites could deliver up to 350,000 unit doses per week, or 18 million unit doses per year, to approximately 500 hospitals in North America.

The two day shutdown period with reduced staff would be used for plant maintenance and radioactive waste management, but it could also be used to produce and supply Mo-99/Tc-99m generators to any of the other radiopharmacies experiencing shortages or unplanned shutdowns. An additional two day irradiation would add 37 % to normal weekly production at a single site. [Please see Appendix 1] With backup supply available from neighbouring sites, one SLOWPOKE reactor at each site would be adequate, although local demand conditions may justify the operation of more than one Homogeneous SLOWPOKE reactors at a given site. One option would be to locate the radiopharmacies at existing nuclear power plant sites close to large metropolitan centres. In North America the largest are: Mexico City, New York, Los Angeles, Chicago, Dallas-Fort Worth, Houston, Toronto, Washington, Seattle and Miami. If small, low-temperature, unpressurized reactors producing medical isotopes were located at nuclear power plant sites, they could be an important component of the utilities' public information and outreach programs. It has taken decades to overcome the negative image of commercial nuclear reactors following Chernobyl and Three Mile Island. The public will always need credible assurance that the benefits of nuclear power and medical isotopes far outweigh the risks, both real and perceived.

### 3. Design of the Homogeneous SLOWPOKE reactor

In this work, a homogeneous nuclear reactor is proposed as an alternative for the production of radioisotopes such as 99Mo which is chosen here as a representative of several radioisotopes that can be extracted from the irradiated homogeneous fuel mixture of the Homogeneous SLOWPOKE reactor for medical as well as non-medical applications. The extraction of radioisotopes from a homogeneous fuel-moderator mixture has many advantages [5] such as simplicity and minimal amounts of radioactive waste incurred. There are no requirements to produce and transport highly enriched uranium targets that represent safety and security issues. In heterogeneous reactors, the Mo-99 atoms produced in the driver fuel elements remain in the solid fuel, and only the Mo-99 produced in the targets is recovered. The reader may obtain a good description of a suitable Mo-99 extraction process from the reactor homogeneous fuel solution by consulting the work of Cheng et al. [6]. Homogeneous reactors are those reactors for which there are no physical barriers between the fuel and the moderator. Several advantages are provided by homogeneous reactors, such as the ease of construction of the reactor avoiding the need of fuel assembly design, fuel cladding and fabrication, the high fuel burnup, and, more important, the possibility of processing the fuel mixture on-line to remove the fission products and extract the wanted radioisotopes. Homogeneous reactors have a natural tendency to achieve inherent safety since these reactors most often display strong negative temperature coefficients of reactivity and very strong negative void reactivity coefficients.

"SLOWPOKE" is an acronym for Safe LOW-POwer (K) Critical Experiment. It is a 20 kW unpressurized, pool-type reactor, intended primarily for university research. In its current version, the SLOWPOKE-2 nuclear research reactor, depicted in Figure 1, is a small, low power, pool-type reactor based on a core assembly of nearly 200 fuel rods made of UO<sub>2</sub> fuel pellets with a 20% initial enrichment [7]. The reactor core is essentially a large-diameter fuel bundle, its size being slightly larger than a 925-g can of coffee.

The SLOWPOKE-2 nuclear reactor is inherently safe. Inherent safety is defined by the International Atomic Energy Agency as follows: "Inherent Safety refers to the achievement of safety through the elimination or exclusion of inherent hazards through the fundamental conceptual design choices made for the nuclear plant. Potential inherent hazards in a nuclear power plant include radioactive fission products and their associated decay heat, excess reactivity and its associated potential for power excursions, and energy releases due to high temperatures, high pressures and energetic chemical reactions. Elimination of all these hazards is required to make a nuclear power plant inherently safe. For practical power reactor sizes this appears to be impossible. Therefore the unqualified use of "inherently safe" should be avoided for an entire nuclear power plant or its reactor." [8].

The following safety principles must be adhered to. Any positive power transients (from causes such as the sudden withdrawal of the control rod) result in the reactor always remaining in a physical state such that the equipment and the fuel are not damaged. In particular, fission products and other radioactive contaminants are never released into the primary coolant and the environment. As an additional measure of safety, the SLOWPOKE-2 reactor design restricts a maximum excess reactivity to +4.0 mk. This ensures that a sudden and complete withdrawal of the control rod from the core cannot cause a prompt criticality excursion. Other safety principles include the following: no uranium fuel needs to be stored on site, strong negative temperature and void reactivity coefficients, natural circulation of water coolant through the core at atmospheric pressure, double containment of the reactor core, core sub-critical in water (i.e. to become supercritical, it needs both the beryllium reflector and the immersion in water), top beryllium reflector with adjustable thickness to keep the excess reactivity at or below +4.0 mk, and single motor-driven control rod operating between -1.5 mk and +4.0 mk. The fuel assembly is a single bundle, consisting of 200 Zircaloyclad fuel rods containing 1100 grams of U-235 in the form of LEU ceramic pellets. An annular beryllium reflector surrounds the core, and beryllium plates are added periodically to the top reflector to compensate for uranium burn-up. Water coolant inside the aluminum container vessel is separate from the pool water. Orifices in the top and bottom reflectors allow water to circulate upwards through the core by natural convection. Heat from the circulating water in the

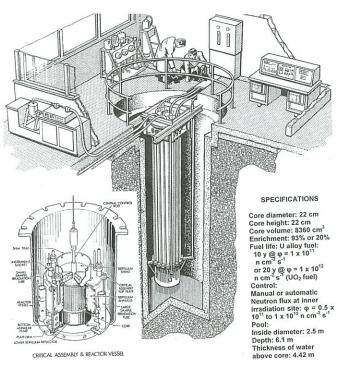
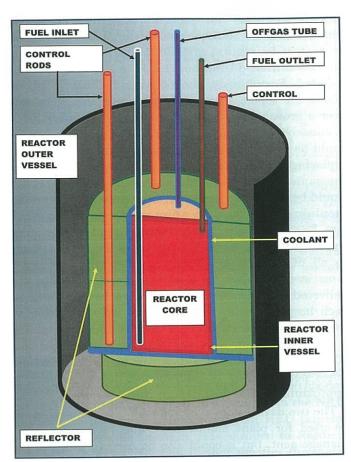


Figure 1: SLOWPOKE-2 reactor pool and facility [9].



**Figure 2:** Simple representation of the Homogeneous SLOWPOKE reactor.

container vessel is conducted through the container wall to the outer pool, and the pool water is cooled by an immersed coil supplied by city water. A single thermocouple monitors and records the core outlet temperature. The reactor is controlled, automatically or manually, by a single motor-driven cadmium absorber rod, located on the central axis of the fuel assembly. The control rod is worth 5.5 mk. Electrical signals from a self-powered neutron detector automatically control both startup and steady state operation over the range 5% to 100% full power. By physically limiting the excess reactivity to a small value less than prompt critical, and relying on the negative temperature and void coefficients as the primary safety mechanisms, it has been experimentally demonstrated that conventional electro-mechanical safety devices are unnecessary. Moreover, the skilled tradesmen normally required to test and maintain the safety devices are unnecessary; and because of the simple control system and inherent safety, there is no need for a full-time operator in the reactor room in automatic operation. This translates in significant savings in both capital and operating costs.

The Homogeneous SLOWPOKE core consists in a cylindrical vessel filled with a homogeneous aque-

Table 1: Characteristics of the final Homogeneous SLOWPOKE design.

Characteristic	Zircaloy-2 model type (Mark IIa)	Stainless Steel Type 347 model type (Mark IIb) 48.8 cm				
Core height	48.8 cm					
Core radius	10 cm	10 cm				
Core vessel thickness	3 mm	3 mm				
Vessel material	Zircaloy-2	Stainless Steel Type 347				
Control rod material and radius Control rod cladding thickness	Cadmium 1.50 mm Al 2 mm	Cadmium 2.25 mm Al 2 mm				
Control rod worth: 5 x 2 mm rods within inner sites 2 x 3.8 mm within inner sites	3.4 mk* - (-6.6 mk**) =10.0 mk 4.0 mk* - (-3.5 mk**) =7.5 mk	4.5 mk* - (-3.5 mk**) = 8.0 mk 4.0 mk* - (-3.3 mk**) =7.3 mk				
Fuel volume (in core) at 40 oC	15.331 L	15.331 L				
Reflector annulus: inner radius	11 cm	11 cm				
Reflector annulus: outer radius	21 cm	21 cm				
Beryllium radial reflector height	49.75 cm	49.75 cm				
Beryllium/Graphite radial reflector height	22.0 cm (Be) + 27.0 cm (C)	_				
Beryllium radial reflector thickness (extension part)	10 cm	10 cm				
Graphite radial reflector thickness (extension part)	10 cm	-				
Bottom reflector dimensions	Diameter: 28 cm; Height: 11 cm	Diameter: 28 cm; Height: 11 cm				
Fuel	uranyl sulfate solution in water	uranyl sulfate solution in water				
Fuel enrichment	20%	20%				
Fuel concentration	1.4575 ± 0.0061 mol kg-1	1.7058 ± 0.0033 mol kg-1				
U-235 Mass (in core)	994.2 g	1149 g				
k <sub>arr</sub>	1.0039 ± 0.001	1.0038 ± 0.001				
Thermal power	20 kW	20 kW				
Operating temperature at steady state	40 oC	40 oC				
*: Control rod fully withdrawn	**: Control rod fully inserted					

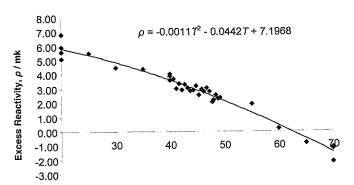
ous uranyl sulfate solution, as shown in Figure 2. This vessel is referred to as the inner reactor vessel. The inner vessel has the same diameter as of the SLOWPOKE-2 reactor core in order to fit within the cavity in the annular beryllium reflector annulus left when the core of a SLOWPOKE-2 reactor is removed at its end-of-core life. However, the height of the core is about twice its diameter. The Homogeneous SLOWPOKE reactor can be located on university campuses or within nuclear research centres and can fulfill and continue the same mission as for the SLOWPOKE-2 reactor, i.e. being a source of neutrons for Neutron Activation Analysis (NAA) and neutron radiography, among others, in support of educational programs and research. Moreover, the Homogeneous

SLOWPOKE reactor can accomplish the extra mission of producing radioisotopes for applications in nuclear medicine and many other domains. For the Homogeneous SLOWPOKE nuclear reactor, particular attention is given to the homogeneous fuel mixture and associated potential corrosion and erosion problems for the reactor vessel and the heat transport conduits. The extraction of the wanted radioisotopes and other fission products must be done outside the reactor core. A significant amount of the irradiated fuel mixture thus represents radiation protection hazards which can be addressed using well known and proven technology and methods. In the present study, an aqueous uranyl sulfate solution (UO<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O) is proposed and the corrosion power of this solution as

well as the possibility of precipitation are addressed. The radiation-induced decomposition of the moderator (water) is also considered as it may lead to the accumulation of gases which could become explosive mixtures of hydrogen and oxygen. The Homogeneous SLOWPOKE reactor has been designed as an inherently safe nuclear reactor, like the present SLOWPOKE-2 research reactors. Therefore, it can be operated continuously in automatic mode by crews of Certified Operators with relatively minimal training, resulting in substantial savings in operation costs.

### 4. Design Methodology

The full details of this research may be found in three theses written by graduate students at the Royal Military College of Canada [10-12]. The Homogeneous SLOWPOKE reactor was simulated on computer with the MCNP 5 (Monte Carlo N-Particle) code [13] which is a general-purpose, continuous energy, generalized-geometry, time-dependent, coupled neutron/photon/electron Monte Carlo transport code. For fissile systems, MCNP 5 has the ability to calculate the effective multiplication factor ker as an eigenvalue. The cross sections used with MCNP 5 were provided by the ENDF/B-V library and were adjusted to the temperatures by interpolating within the database and also by calculating the homogeneous mixture density for the temperature modeled. Table 1 provides the dimensions of the reactor. The results obtained with the MCNP 5 code were then compared with the results obtained by running a computer model of the reactor with the deterministic code WIMS-AECL Release 2-5d [14]. Because WIMS-AECL performs the simulation in two dimensions only, the axial buckling needs to be adjusted until the value of the effective multiplication factor obtained with WIMS-AECL matches the value of  $k_{\rm eff}$  calculated by MCNP 5. Both codes then do agree very well on other results, such as the thermal and fast neutron distributions, the power density distributions and the nuclear reaction rates including the production rates of isotopes such as 99Mo. The analysis then concentrated on the effects of the temperature on the reactivity of the reactor, on the control rod worth and the determination of the potential for inherent safety for this reactor concept. The simulations were carried out by varying the temperature of the reactor using both MCNP 5 and WIMS-AECL, using the ENDF/B-VI library and 89 groups of neutron energy. Figure 3 presents the effects of the temperature on the excess reactivity of the reactor and confirms the large negative coefficient of reactivity due to the temperature at high temperatures, which is an essential, but not sufficient, requirement for inherent safety. A more elaborate analysis was then performed with MCNP 5 and with the WIMS-AECL Version 3.1 [15]. Several materials compositions were investigated, with Table 1 presenting the retained selections. The



**Figure 3:** Excess reactivity estimated by individual Zircaloy-2 MCNP-5 models with a molality of 1.4575 mol kg<sup>-1</sup>, normal operating fuel solution level, at various temperatures.

fuel solution molality was adjusted within the final reactor configurations in order to yield excess reactivity values similar to those of the original SLOWPOKE-2 reactor (~3.8 mk). In order to determine the molality of the uranyl sulfate aqueous solution, the maximum allowable 20% uranium enrichment was maintained throughout this study. For that excess reactivity of 3.8 mk, the solution molality obtained was 1.46 mol kg¹ and 1.70 mol kg¹ for the model with the Zircaloy-2 reactor inner vessel and the model with the 347 Stainless Steel reactor inner vessel, respectively.

Water within the reactor vessel was maintained at the expected reactor operating temperature of 313 K (40 °C), this being the maximum value for the temperature foreseen in normal operation at steady state. As for the pool water temperature, a value of 293 K (20 °C) was assigned for this water. An air-filled plenum was included in the reactor inner vessel above the fuel mixture surface and was modeled as water-saturated air at 313 K (40 °C). As a result of continuous operation of the reactor, the composition of this air plenum changes since hydrogen and oxygen accumulate in significant concentrations following radiolysis of fuel-water mixture. Gaseous radioisotopes also gradually accumulate in the air plenum such as 41Ar and 135Xe. The design of the reactor addresses the issue of removing these gases by including a gas removal system. Two final models were retained for further studies: one with the reactor inner vessel made with Zircaloy-2 (Mark IIa) and the other with 347 Stainless Steel (Mark IIb). The characteristics of both models are presented in Table 1. While the stainless steel inner vessel appears to be the least expensive alternative for the reactor design, additional beryllium reflectors and higher fuel solution concentrations would be needed in addition to more cadmium control rods. The control rod system was designed as a cluster of cadmium rods that would slide in guide tubes located in the radial reflector. This option is justified since the thermal neutron flux in the radial reflector is almost equal to the value at the axis of the

**Table 2:** Tabulated estimation of the reactivity coefficient due to the void fraction  $(\alpha_v)$  at various temperatures with calculation performed for a several fuel solution void fractions, using the "microbubble voiding" model.

Model Type	Temperature (°C)	Curve-fitted Polynomial	x at ο=0	$\alpha_{V=\partial\rho}$	αν at x = (mk void-1)		
	1.07	ρ(x) (mk) (Note a)	ρ=0 (Note b)	(mk void-1)	0.05	0.20	
	20	-0.0654x² -4.5055x+5.755	0.0130	-0.1308x - 4.5055	-4.51	-4.53	
Zircaloy-2	40	-0.0622x² -4.6007x+3.6995	0.0080	-0.1244x - 4.6007	-4.61	-4.63	
	70	-0.0674x² -4.5479x+1.5541	n/a	-0.1348x - 4.5479	-4.55	-4.57	
Stainless	20	-0.0677x² -4.7863x+5.7520	0.0120	-0.1254x - 4.7863	-4.79	-4.81	
Steel Type	40	-0.0720x² -4.7391x+3.7298	0.0080	-0.1440x - 4.7391	-4.75	-4.77	
347	70	-0.0788x² -4.6455x-1.9309	n/a	-0.1576x - 4.6455	-4.65	-4.68	

Notes

- a) the void fraction (**x**) used for Table 2 is expressed simply as the fraction of the volume occupied by void. Since the Homogeneous SLOWPOKE reactor core volume is 15.331 L, then a volume fraction of 0.01 (1%) is simply 0.15331 L or 153.31 cm<sup>3</sup>. Therefore, the reactivity per void fraction unit, if the unit is 1% void fraction, would be, for example, -4.51 mk void<sup>-1</sup> = -4.51 mk (153.31 cm<sup>3</sup>)<sup>-1</sup> = -2.94 x  $10^{-2}$  mk cm<sup>-3</sup>.
- b) neglecting the negative void fraction solution, except at  $T=70^{\circ}$ C, where both solutions are negative. Void solutions which are x < 0 have no physical meaning, therefore at  $70^{\circ}$ C, the reactor is already subcritical, hence the use of "not applicable" (n/a) for the void fraction for which the reactor becomes subcritical.
- c) Of course, for reactor temperatures of 20, 40 and 70 °C, there is no voiding due to ebullition. The data presented here are obtained from the aqueous uranyl sulfate solution's density for the various temperatures and used in the "microbubble voiding" model. The interpretation is that of the reactivity that would be obtained if a void fraction (x) is created artificially by means other than natural boiling in the homogeneous fuel mixture.

core. The fabrication of the inner reactor vessel is then much easier and the fuel mixture volume is increased. Several control rod configurations were then investigated, with the control rod locations chosen at inner irradiation sites selected such as to ensure as much azimuthal uniformity as possible. In some of the models, the radius of the control rods was increased in order to free up more inner sites for NAA. The best configurations obtained had 2 x 3.8 mm rods and 3 x 3.2 mm rods for the reactor with a vessel made of Zircaloy-2 and 347 Stainless Steel, respectively. A 5-rod cluster arrangement minimized the variations of the thermal neutron flux in the azimuthal direction and the results for this configuration appear in Table 1.

### 5. Safety Analysis

A safety analysis was implemented aiming, among other goals, at confirming the Homogeneous SLOWPOKE reactor as being inherently safe. The reactivity coefficients due to the temperature and the void fraction were determined from a series of simulations of the reactor using MCNP 5. Distributions

of the excess reactivity of the reactor as a function of the temperature of the fuel-moderator solution were obtained through multiple runs of MCNP 5. For some key temperatures such as 20 °C, 40 °C, 70 °C and 90 °C, multiple runs were carried out and the reactivity recorded. Figure 3 above presents a typical distribution for a reactor with a Zircaloy-2 reactor inner vessel under normal operation. This figure was obtained from 36 MCNP 5 runs.

The reactivity coefficient due to the void fraction was determined using various approaches to simulating voiding. One of these approaches, referred to as "microbubble voiding", consisted in mimicking the void fraction by simply decreasing artificially the density of the homogeneous fuel solution. A second mode of voiding consisted in inserting two spherical bubbles within the reactor core according to a centred geometry, and then in varying the radii of these bubbles. A variant consisted in using 49 actual spherical bubbles and in varying their radii. Yet another mode consisted in using a single void cylinder of varying dimensions and centered within the reactor core. A sample of the results are presented in Table 2 for the case of the

microbubble model at different temperatures, as the investigation determined that the microbubble model was the most conservative method for determining the reactivity coefficient due to the void fraction. All of the results show that voiding produces a strong negative reactivity, bringing the reactor to a subcritical state well before the temperature of the homogeneous fuel mixture becomes close to levels that would damage the reactor and its components.

A third component of the safety analysis consisted in examining the thermal-hydraulics of the reactor system in order to provide answers to questions such as whether natural convection remains sufficient to ensure the cooling of the reactor in normal and abnormal operating conditions. In order to fully confirm inherent safety, modelling of the Homogeneous SLOWPOKE reactor through several transient states was carried out [12] and the results demonstrate that the Homogeneous SLOWPOKE reactor is indeed inherently safe from simulations in non-steady state conditions. Using the software COMSOL Multiphysics [16] to carry out the thermal-hydraulics simulations, this study has shown that natural convection is sufficient to cool down the reactor, even following severe transients. Figure 4 illustrates the results of several transients to which the reactor was submitted and shows how the reactor responds to these transients without developing excessive temperatures. The pronounced self-regulating nature of the Homogeneous SLOWPOKE reactor is demonstrated, with the temperatures kept well below the boiling point of the aqueous uranyl sulfate solution.

### 6. Discussion

In order to validate the results of the reactor physics calculations, an actual Homogeneous SLOWPOKE reactor needs to be built and tested, which is not (yet) the case here. The next best approach to acquire confidence in the results of the simulations is to use two very different reactor simulation codes considered reliable in the nuclear industry: MCNP 5 and WIMS-AECL. MCNP 5 is an improved version of MCNP 4A which was used by Pierre [17] for his successful model of the heterogeneous LEU-fueled SLOWPOKE-2 reactor at RMC, with the results of his simulations in very good agreement with the commissioning data obtained by the AECL commissioning team when the reactor was installed in 1985. WIMS-AECL is an Industry Standard Tool currently used in the industry for the support of existing CANDU reactors and the development of Generation III and IV reactors. The authors' experience [18] with WIMS-AECL allows them to estimate the accuracy within ±5% (at most), with an extra 1% added for the fact that here the simulation is carried out with a two-dimension model.

In order to further verify the numerical results, MCNP 5 was tested against two benchmark homo-

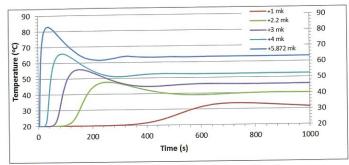


Figure 4: Average core temperature during various power transients initiated at t = 0 s. (Mark IIa model).

geneous reactor cases found in the Nuclear Energy Agency's International Handbook of Evaluated Criticality Safety Benchmark Experiments [19-20]: the LEU-SOL-THERM-002 and the LEU-SOL-THERM-004 cases. The LEU-SOL-THERM-002 system considers a 174 L (34.3990 cm inner radius) sphere of low enriched (4.9%) uranium oxyfluoride (UO,F,) solution. The experiments using this system to calculate  $k_{_{\rm eff}}$  were part of a series of measurements performed at Oak Ridge National Lab during the 1950's. The spherical reactor is constructed of 1/16 in. thick aluminum and supported by only the top and bottom overflow and feed tubes. Experiments 1 and 2 determined the uranium concentration and chemical composition of the fuel solution with which the sphere is critical when completely filled with and without a water reflector, respectively. Experiment 3 used the same fuel solution as Experiment 2, however, a water reflector was employed and the fuel solution was brought to the level of criticality. In this case, the sphere was 83% filled when criticality was achieved.

For the MCNP model, the feeder and overflow tubes were not included to simplify the geometry and the space outside of the 15 cm thick water reflector is considered to be a void space. The temperature of the solution is assumed to be 298K (25 °C) and the temperature of the water reflector is assumed to be 300K (27 °C). The results of the simulations for the benchmark cases are reported at Refs. [4] and [21]. For each experiment tested using MCNP 5, the resulting  $k_{\rm eff}$  value is found to be within 1% error of the benchmark  $k_{\rm eff}$  value. The slight discrepancy between the MCNP 5 values found here and the MCNP values found in the report may be explained from a different number of Monte Carlo iterations used in the benchmark report or from slight differences in nuclide values used in the report calculations.

As for the LEU-SOL-THERM-004 case, it was experimentally tested on the Static Experiment Critical Facility (STACY) in 1995 at the Tokai Research Establishment of the Japan Atomic Energy Research Institute. The STACY reactor is a cylindrical stainless steel tank (150 cm length by 60 cm diameter) filled with 10% enriched uranyl nitrate solution and is water reflected. The fuel solution level in the tank

was adjusted to find criticality with various uranium concentrations in the solution ranging from 225 to 310 gU L-1. The details of this experiment are reported in Refs. [4] and [20-21]. All calculated MCNP 5 results here are again within 1% error of the benchmark experimental results, providing good agreement. The discrepancy between the MCNP 5 and the benchmark results comes likely from the inability to use the Continuous-Energy JENDL-3.2 cross section for MCNP 5 results calculated here. However, using the Continuous Energy ENDF60 W-184 cross section table, more accurate results were found.

Replacing the solid fuel core of the SLOWPOKE-2 reactor with liquid fuel for the Homogeneous SLOWPOKE reactor affects the reactivity calculation in five important ways: no self-shielding in the liquid fuel/moderator; no separate temperature reactivity coefficients for fuel and moderator/coolant; an additional power-dependent void coefficient from radiolytic hydrogen and oxygen gas bubbles; neutron absorption in the inner vessel wall and the light water gap between the inner vessel wall and the inner wall of the reflector; and increased neutron leakage because of increased height and core volume. The neutronic analysis is considerably more complex and better tools than the 2-D WIMS-AECL exist and should be used for the continuation of the present research. A challenging follow-up of the present research would consider the development of a simulation tool coupling the neutronic calculations with a thermal-hydraulic model producing accurate temperature/void/delayed neutron distributions.

### 7. Conclusion: The Way Ahead

In this section, major similarities between the existing SLOWPOKE-2 reactor and the proposed Homogeneous SLOWPOKE reactor are listed and areas of future work outlined as follows:

- Replacing a solid fuel core is much more difficult than draining a liquid fuel solution from a tank and refilling an empty tank.
- Integrity of solid fuel sheaths a safety issue similar to integrity of a fuel tank and associated pipes and valves.
- Pressure in the SLOWPOKE-2 reactor container vessel during transients a minor safety issue versus pressure in the much smaller thin-walled tank which is an important issue.
- For the SLOWPOKE-2, weekly purging of gases during shutdown represents a minor safety issue; for the Homogeneous SLOWPOKE reactor, continuous purging the gas plenum may be needed, although future research may conclude that daily purging may be sufficient.
- Recombiner not required versus need of a recombiner as essential for safety. (It is to be noted that an

- AECL Chalk River team earned the Canadian Nuclear Society's John S. Hewitt Team Achievement Award in 2003 award for their design of a hydrogen recombiner.)
- Proven through-core convection cooling system versus unproven external cooling of tank surface.
- Much experience with water chemistry versus little Canadian experience with uranium aqueous solutions although experience exists in several countries.
- Build-up of long term fission products and plutonium in solid fuel elements is similar to fission products in two or three tanks of recycled fuel solution during total core life.
- Steady state full power reactivity loads measures versus reactivity loads not fully quantified in the research done so far.
- Reactivity load due to radiolytic gas negligible for SLOWPOKE-2, but not yet quantified for the Homogeneous SLOWPOKE reactor. Further research needs to be done both experimentally and via computer simulation to determine the behaviour in the aqueous fuel solution of important fission products such as xenon-135 and samarium.
- SLOWPOKE-2 uses only one control rod while the Homogeneous SLOWPOKE used a cluster of up to five control rods that slide (in unison) in guide tubes within the beryllium reflector.

SLOWPOKE-2 is licensed for a maximum of +4 mk excess reactivity ensuring for about 12 hours of continuing operation at full power. The Homogeneous SLOWPOKE reactor has been designed with this +4 mk maximum excess reactivity for the moment, but further research has to be carried out to determine the reactivity that would allow continuous 2-day operation.

This research on the design of the Homogeneous SLOWPOKE reactor has produced indeed encouraging results such that the construction of a prototype reactor may be considered as not far in the future.

### References

- [1] Mohamed Zakzouk, "The 2009-2010 Medical Isotope Shortage: Cause, Effects and Future Considerations", Library of Parliament Publication No. 2009-04-E, Ottawa (revised Nov. 2010).
- [2] Anton Khlopkov and Miles Pomper with Valeriya Chekina, "Ending HEU Use in Medical Isotope Production: Options for Russian-U.S. Cooperation", Center for Energy and Security Studies, February 24, 2014, Moscow.
- [3] Ernest Rutherford, James Chadwick, and C.D. Ellis, "Radiations from Radioactive Substances", Cambridge University Press, Cambridge, 1951, pp.10-13.
- [4] H.W Bonin, J.W.Hilborn, G.E.Carlin, R.Gagnon & P.Busatta, "Homogeneous SLOWPOKE Reactors for

- Replacing SLOWPOKE -2 Research Reactors and the Production of RadioIsotopes", Proceedings of the 3rd International Technical Meeting on Small Reactors, Ottawa, Ontario, Canada, 2014, November 5 -7.
- [5] R.M. Ball, V.A. Pavshook and V.Ye. Khvostionov, "Present Status of the Use of LEU in Aqueous Reactors to Produce Mo-99", Int. Meeting on Reduced Enrichment for Research and Test Reactor, Sao Paulo, Brazil, 18-23 Oct. 1998.
- [6] W.L. Cheng, C.S. Lee, C.C. Chen, Y.M. Wang & G. Ting, "Study on the Separation of Molybdenum-99 and Recycling of Uranium to Water Boiler Reactor", Appl. Radiat. Isot, Vol. 40, No. 4, pp. 315-324 (1989).
- [7] R.E. Kay, J.W. Hilborn, and N.B. Poulsen, "The Self-Limiting Power Excursion Behaviour of the SLOWPOKE Reactor, Results of Experiments and Qualitative Explanation", AECL-4770, January 1976. (Available on-line: GOOGLE AECL-4770, The Self-Limiting Behaviour of the SLOWPOKE Reactor).
- [8] International Atomic Energy Agency (1991), Safety Related Terms for Advanced Nuclear Plants, Document #: IAEA-TECDOC-626.
- [9] "SLOWPOKE", Leaflet #IND. 64 5/75, Atomic Energy of Canada Limited, 1975.
- [10] P.J.F. Busatta, "Homogeneous SLOWPOKE Reactor - Feasibility Study of Transforming the SLOWPOKE-2 Reactor for Homogeneous Fuel for the Production of Commercial Radio-Isotopes", Master's degree thesis, Royal Military College of Canada, Kingston, Ontario, Canada, June 2005.
- [11] R.L. Gagnon, "Safety Analysis of a Homogeneous SLOWPOKE Reactor", Master's degree thesis, Royal Military College of Canada, Kingston, Ontario, Canada, May 2009.
- [12] G. E. Carlin, "A Thermalhydraulic Study and Transient Analysis of the Homogeneous SLOWPOKE Reactor", Master's degree thesis, Royal Military College of Canada, Kingston, Ontario, Canada, June 2013.

- [13] "MCNP A General Monte Carlo N-Particle Transport Code, Version 5, Volume I: Overview and Theory", X-5 Monte Carlo Team, Diagnostics Applications Group, Los Alamos National Laboratory, 2003.
- [14] S.R. Douglas, "WIMS-AECL Release 2-5d Users Manual"; Reactor and Radiation Physics Branch, Chalk River Laboratories (July 2000).
- [15] G. Jonkmans, "WIMS-AECL Version 3.1 User's Manual, Rev. 1", Reactor and Radiation Physics Branch, Chalk River Laboratories, Chalk River, Ontario, Canada, 2006.
- [16] COMSOL Inc. (2013), "COMSOL Multiphysics User's Guide, Version 4.3", Burlington, MA., U.S.A., www.comsol.com.
- [17] M.J.R. Pierre & H.W. Bonin, "Monte Carlo Simulation of the LEU-Fueled SLOWPOKE-2 Nuclear Reactor Using MCNP 4A", Nuclear Technology, 125, Jan 1999, pp. 1-12.
- [18] C. Cole & H.W. Bonin, "The Near Boiling Reactor: Design of a Small, Inherently Safe, Nuclear Reactor to Extend the Operational Envelope of the Victoria-Class Submarine", Nuclear Technology, 159, July 2007, pp. 1-14.
- [19] Nuclear Energy Agency (2012), "International Handbook of Evaluated Criticality Safety Benchmarks Experiments Volume IV", NEA/NSC/DOC(95)03/IV, LEU-SOLOTHERM-002.
- [20] Nuclear Energy Agency (2012), "International Handbook of Evaluated Criticality Safety Benchmarks Experiments Volume IV", NEA/NSC/DOC(95)03/IV, LEU-SOLOTHERM-004.
- [21] G.E. Carlin, "MCNP5 Benchmark Simulations Using the International Handbook of Evaluated Criticality Benchmarks", Research Report, Royal Military College of Canada, Document RMC-CCE-GEC-13-1, July 2013.

### Appendix 1

### Direct Distribution of Tc-99m Unit Doses from a 20 kW Homogeneous SLOWPOKE Reactor Site

#### Assumptions:

Industrial radiopharmacy for production and distribution of isotopes operates 7 days /week;

SLOWPOKE reactor for Mo-99/Tc-99m production normally operates 5 days /week;

Unit doses of Tc-99m delivered Monday to Friday to regional hospitals within 3 hours by road;

Mo-99 production from a fission reactor: 51 Ci/kW at equilibrium (12 days, 95% equilibrium);

Reactor irradiation time: 22 hr/day, 20.6% equilibrium, 5 days/week, 52 weeks/year.

### Process and Delivery:

Cool for 1 hr after shutdown, then drain reactor tank to hot-cell: 10 min;

Refill reactor from second tank and restart SLOWPOKE: 50 min;

After draining the tank extract Mo-99: 1 hr; loss of Mo-99 in chemical extraction: 15%;

Mo-99 decay factor for reactor cooling, draining and chemical extraction; 2 hr: 0.98;

Waiting time for Tc-99m growth: approximately 20 hr;

Unit dose production and packaging at the SLOWPOKE reactor site; 4 hr decay factor: 0.630;

Average delivery time 3 hr; Tc-99m decay factor: 0.71; Unit syringe doses delivered to the hospital radiopharmacies contain: 25 mCi = 0.925 GBq;

Price per unit syringe dose of Tc-99m not including delivery: \$20.

Daily and Weekly Tc-99m Unit Dose Production: Lantheus table shows daily elutions of generators in

Lantheus table shows daily elutions of generators in units of mCi Tc-99m/initial Ci of Mo-99;

Total Tc-99m production during the third week and following weeks: 11,206 mCi [Please see Appendix. 2]; Average daily elution during third week:11,206 mCi/5 = 2,241 mCi /initial Ci of Mo-99;

Number of unit doses: 20 kW x 51 Ci Mo-99/kW x 0.206 equilibrium Mo-99 x 0.85 Mo -99; extraction loss x 0.98 Mo-99 decay x 0.63 Tc-99m decay x 0.71 Tc-99m decay x 2,241 mCi Tc-99m/initial Ci Mo-99 x 1 unit dose/25 mCi Tc-99m =  $7.018/\text{day} \times 5 = 35.090/\text{week}$ .

Gross Annual Income from Tc-99m Unit Doses Five Days per Week.

 $35,090 \times \$20 = \$702,000$  per week x 52 weeks = \\$36.5 million per year from each reactor.

Additional Weekly Income from Two-Day Weekend Irradiation

(46 hour irradiation, 38.3% Mo-99 equilibrium); (0.383/0.206) x 7,018 x \$20 = \$261,000 per week = 37% increase in weekly income.

# Appendix 2 Daily Tc-99m Elutions from Mo-99/Tc-99m Generators Lantheus Table: mCi Tc-99m per initial Ci Mo-99

Gen	Mon	Tue	Wed	Thur	Fri	Sat Sun	Mon	Tues	Wed	Thur	Fri	Sat Sun	Mon	Tues	Wed	Thur	Fri
1	662	541	422	328	255		120	93.0	72.2	56.1	43.6						
2		662	541	422	328		154	120	93.0	72.2	56.1						
3			662	541	422		198	154	120	93.0	72.2						
4				662	541		255	198	154	120	93.0		43.6				
5					662		328	255	198	154	120		56.1	43.6			
6							662	541	422	328	255		120	93.0	72.2	56.1	43.6
7								662	541	422	328		154	120	93.0	72.2	56.1
8									662	541	422		198	154	120	93.0	72.2
9										662	541		255	198	154	120	93.0
10											662		328	255	198	154	120
11													662	541	422	328	255
12														662	541	422	328
13															662	541	422
14																662	541
15																	662

(Assuming 85% elution efficiency)

### Notes

- 1. The homogeneous SLOWPOKE reactor normally operates five days a week for Mo-99 production, and shuts down two hours per day to change tanks and restart.
- 2. Mo-99/Tc-99m generators are added daily, and in the table above they are numbered 1 to 15 for the first 3 weeks.
- 3. Generators are rejected after Monday and Tuesday elutions of 43.6 mCi, and Friday elutions of 43.6, 56.1 and 72.2.
- 4. Daily Tc-99m elutions can continue week after week, exactly the same as in the third week after the very first elution.
- 5. 8 generators will be available each Monday, Tuesday and Wednesday, 9 will be available on

Thursday, and 10 on Friday.

- As shown in the table, a new generator is added each week-day; and during the week five depleted generators are removed - one on Monday and Tuesday, and three on Friday.
- 7. Total Tc-99m elutions per 5-day week: 11, 206 mCi per initial Ci Mo-99.
- 8. Average daily Tc-99m elution: 2,241 mCi per initial Ci Mo-99.
- 9. If additional Mo-99 is required, the reactor can be operated for one or two extra days at the end of the week. (See Appendix 1)
- 10. Lantheus data: Google "Lantheus Imaging Tc-99m Chart Sunday" http://www.lantheus.com/

# Muon Tomography with Momentum Measurements for Fast Detection of Nuclear Materials at Ports of Entry

A. ERLANDSON¹, V. ANGHEL¹, J. ARMITAGE², F. BAIG¹, K. BONIFACE¹, J. BOTTE², K. BOUDJEMLINE³, D. BRYMAN⁴, J. BUENO⁴, E. CHARLES³, T. COUSINS⁵, P.-L. DROUIN⁶, G. GALLANT³, R. GAZIT⁴, D. GODIN¹, V. V. GOLOVKO¹, C. HOWARD⁶, R. HYDOMAKO⁶, C. JEWETT¹, G. JONKMANS¹, Z. LIU⁴, S. NOEL⁵, A. ROBICHAUD², T. J. STOCKIˀ, M. THOMPSON¹, D. WALLER⁶

[Ed. Note: The following paper was presented at The 19th Pacific Basin Nuclear Conference (PBNC 2014) Hyatt Regency Hotel, Vancouver, British Columbia, Canada, August 24-28, 2014. Muon technology is currently being use to map the location of the melted core of the Fukushima reactor.]

### **Abstract**

Muon tomography uses naturally occurring high energy cosmic ray particles called muons to statistically reconstruct 3D images of targets analogously to techniques widely used in medical physics. The Cosmic Ray Inspection and Passive Tomography (CRIPT) detector is a Canadian initiative that has demonstrated that the concept of tomography can be applied to cargo using cosmic ray muons. The unique aspect of the CRIPT detector is its use of muon momentum information which decreases the scanning time required to reconstruct an image. The CRIPT detector is currently operating at Atomic Energy of Canada Limited's (AECL) Chalk River Laboratories.

### Introduction

The cross border transport of illicit nuclear material, specifically fissile material, is a major concern for governments in the post 9/11 world. The International Atomic Energy Agency (IAEA) records incidents where attempts were made to illegally traffic nuclear material. The Incident and Trafficking Database (ITDB) shows that this activity persists and that in some cases kilogram quantities1 of fissile material have been seized at ports of entry [1]. In some cases the fissile material is highly enriched uranium2 (HEU) or plutonium, both of which are considered to be weapons grade materials.

Presently the Canada Border Services Agency (CBSA) uses a system called RADnet [2] that consists of radiation sensitive portals, gamma imaging, intelligence, and visual inspection to examine all cargo entering Canada. The degree to which the cargo is inspected depends on whether radioactivity is initially detected. If the radiation is shielded the portal monitors may not detect anything. In this case, if a secondary screening is pursued, the gamma imaging process would only reveal a dense object or shadow. Cargo often consists of either raw or manufactured dense materials and

in order to fully determine the nature of the gamma image anomaly a visual inspection would be required. The "de-stuffing" of a cargo container requires the container to be set aside. This method of inspection is the most time consuming and can result in exposure if nuclear materials are discovered by agents that were not detected beforehand. The restrictions on inspection are compounded by the economic constraints which require a fast and steady flow of commercial cargo into and out of the country. It is therefore prudent to investigate additional techniques to inspect cargo such as muon tomography [3].

In order to be a viable inspection method the technique must be both fast and accurate. 30 second scan times and false positive rates of less than 1% are considered to be desirable when considering muon tomography as an interrogation technique [3]. Muon tomography is sensitive to special nuclear materials<sup>3</sup> where other technologies are not, however, the time required to reconstruct an image is limited by the natural flux of muons which is roughly 1 cm-2 min-1. This can be balanced by making improvements in the detection time rather than the image reconstruction time. If detection can be done to a high degree of confidence the time constraint on inspection is no longer an issue. It is the goal of this paper to demonstrate that improvements to the detection time are possible while maintaining a low false alarm rate by utilizing aspects unique to the Cosmic Ray Inspection and Passive Tomography (CRIPT) detector [4].

### 1. Muon Physics

The Earth is constantly bombarded by high energy particles from both galactic and inter-galactic space. These particles are typically protons but can also include any elements synthesized by stars [5]. Protons have

<sup>50</sup> kg of 85% enriched 235U is sufficient for a critical mass

<sup>2</sup> Enrichment beyond 20% is considered highly enriched.

<sup>3</sup> Materials which are fissile are considered to be special nuclear materials.

<sup>1</sup> Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

<sup>2</sup> Physics Department, Carleton University, Ottawa, Ontario, Canada

<sup>3</sup> Canada Border Services Agency, Ottawa, Ontario, Canada

<sup>4</sup> Advanced Applied Physics Solutions, Vancouver, British Columbia,

<sup>5</sup> International Safety Research, Ottawa, Ontario, Canada

<sup>6</sup> Defense Research and Development Canada, Ottawa, Ontario,

an energy range from less than 1 GeV to over 100 GeV though the flux varies with energy. The protons have enough energy to create particle showers in the upper atmosphere producing muons which are the most abundant constituent of cosmic rays at sea level [5].

Muons are second generation leptons and have a mass 206 times greater than that of the electron. Cosmic ray muons have a wide momentum spectrum with a mean of 3-4 GeV/c though the majority of muons have momentum less than 8 GeV/c. The angular distribution of muons is primarily vertical and is well described by  $\cos^2 \emptyset \theta$  where  $\theta$  is the zenith angle<sup>4</sup>. Muons in this energy regime are also highly penetrating. That is to say they can pass through a substantial amount of dense material without being absorbed and with minimal deflection [5].

When muons interact with matter it is generally by multiple Coulomb scattering from nuclei. The distribution of scattering angles from nuclei with atomic number Z is well approximated by a Gaussian distribution with a mean of 0 and a width given by Equation (1) [5]:

$$\sigma_{\theta} = \frac{13.6 MeV}{\beta cp} \sqrt{x/X_0} \left[ 1 + 0.038 \ln(x/X_0) \right]$$
 (1)

where  $\beta c$  is the velocity of the muon, p is the momentum, and x /  $X_0$  is the material thickness in units of radiation length. The dependence on Z is not immediately clear until the definition of the radiation length,  $X_0$ , is examined as shown in Equation (2):

$$X_0 = \frac{716.4 \,\mathrm{g \, cm^{-2}} A}{Z(Z+1) \ln(287/\sqrt{Z})} \tag{2}$$

where A is the atomic mass of the material.

Therefore elements with higher atomic numbers have smaller radiation lengths<sup>5</sup> whereas lighter elements have longer radiation lengths<sup>6</sup>. Since the width of the scattering angle distribution depends inversely on radiation length, materials with higher atomic numbers can be distinguished from materials with lower atomic numbers by measuring the width of the distribution as shown in Equation (1).

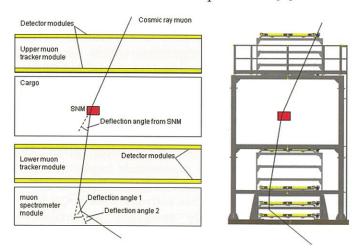
### 2. The CRIPT detector

The CRIPT detector is a prototype muon tomography system based upon particle detection technology used in modern particle physics experiments [6]. It uses scintillating strips with fiber-optic readout coupled to multipixel photomultipliers to track muons. The detector is able to reconstruct muon tracks with a

hit position resolution of 3 mm [4]. The detector concept is shown in Figure 1. Muon tomography relies on tracking muons before and after they enter a volume of interest. The details of what happened in the volume can be reconstructed by examining the differences in the track angles.

The detector consists of six sub-detectors which are divided into three tracking levels. The three tracking levels are the upper, lower, and spectrometer as shown in Figure 2. Collecting position information at each tracking level allows one to not only reconstruct the track of the muon but to also infer its momentum. Scattering is simple to infer as the incoming and outgoing tracks will not be collinear. The momentum reconstruction requires knowledge of scattering through a finite thickness of a known material.

The width of the scattering distribution, Equation (1), is a function of the muon momentum. Therefore the muon momentum information can be used to supplement both the image reconstruction and detection of targets. CRIPT uses two momentum detectors each with a 10 cm thick iron absorber to infer the muon momentum. The momentum reconstruction is done with a maximum likelihood method taking the reconstructed positions, the thickness of the absorber, and the scattering angles into account. The likelihood function can use information based on measured momentum data from other experiments [7].



**Figure 1:** Left: Muon tracking concept including momentum estimation. Right: Technical concept for the entire tomography system.

# Image reconstruction – muon tomography

Muon tomography refers to the reconstruction of 3D images of a volume of interest by using measurements outside of this volume. Images produced by muon tomography specifically rely on the physics and instrumentation described above.

<sup>4</sup> With respect to the vertical direction.

<sup>5</sup>  $X_0$  (lead) = 6.36 g cm<sup>-2</sup> [4]

<sup>6</sup>  $X_0$  (AI) = 24.01 g cm<sup>-2</sup> [4]



Figure 2: CRIPT tracking layout.

Image reconstruction done with CRIPT data uses several techniques. The first is a Point of Closest Approach (PoCA) [8] algorithm which determines the point at which the muon scattered by finding the midpoint of the line that minimizes the distance between the incoming and outgoing tracks. The PoCA points are then scaled by the angle that separates the two tracks in three dimensions. The second technique is called Scattering Density Estimation (SDE). The SDE algorithm has been successfully implemented in AECL's Scattering Density and Image Reconstruction Software (SDIRS) [9]. This software uses PoCA information to geometrically determine approximately where scattering happened in 3D while simultaneously using probabilistic analysis to determine the scattering density of the material. The scattering density is defined in Equation (3):

$$\lambda = \frac{\sigma_{\theta}^2}{x} \left[ \frac{\beta cp}{(\beta cp)_0} \right]^2 \tag{3}$$

where x is the length of material,  $\beta cp$  is the product of the muon speed and momentum and  $(\beta cp)_0$  is the average speed multiplied by the average momentum for cosmic ray muons.

The main shortfall of the PoCA technique is that it assumes a single point of scattering in material when this is unlikely to be the case. The total angular deflection of a muon through material is a cumulative effect of many small angle scattering events. This causes the PoCA points to be smeared in all spatial dimensions and results in a degraded image.

The scattering density is a useful way to describe materials with different atomic numbers because it is spatially accurate and sensitive to momentum information while being characteristic of the material properties and not as dependent on statistics as PoCA.

### 3.1 Detection Time

The most relevant aspect of muon tomography development to border security is the speed and accuracy with which dense materials can be detected. An experiment was designed and performed to begin to quantify the results of including momentum information in material detection. The experiment was performed on a cube of lead bricks<sup>7</sup> with dimensions 20x20x20 cm<sup>3</sup> which was placed in the centre of the imaging volume. This configuration was also simulated with the CRIPT Monte Carlo code which is built with GEANT4 [10] in order to validate the method.

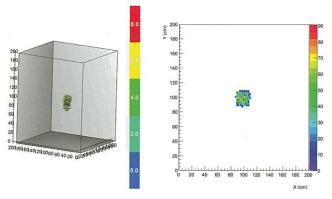
The Monte Carlo replicates the same geometry and physical processes that occur in the CRIPT detector and the data are analyzed using the same analysis software as real data. A reconstructed image using simulated data of the lead target is shown in Figure 3. This data set is limited mostly by statistics as the data set consist of 300000 muon events. The Monte Carlo results produce a PoCA image that accurately describes the physical dimensions of the lead target.

The reconstructed image from real data is shown in Figure 4. The object appears8 to have a cross sectional area of roughly 20x20 cm2 and a height of roughly 20 cm. The edges of the target image are slightly blurred which is an artifact of the PoCA technique. Figure 5 shows the median scattering angles for voxels in fig. 4 where there is detected scattering occurring above the noise threshold. It can be seem that by aggregating these angles over a finite number of voxels and comparing the distribution to these same voxels when no target is present allows one to quantify the amount of scattering resulting in this region. The mean of the median angle distribution is 2 times that of the no target case. This, coupled with the RMS of the lead target distribution being 4 times as large as the no target case, is strong quantitative evidence that the PoCA method is reliably able to reconstruct images based on muon multiple scattering.

The SDE method was used to determine the false alarm rates from this data set. The Receiver Operating Characteristic (ROC) curve is a statistical measure of how often a target is correctly detected. In order

<sup>7 8000</sup> cm<sup>3</sup> has a mass of 90.7 kg

<sup>8</sup> After cuts to the data based on PoCA angles and noise thresholds.



**Figure 3:** Left: 3D Monte Carlo PoCA image. Right: Top down Monte Carlo image. (Note: Colour scale is in arbitrary units.)

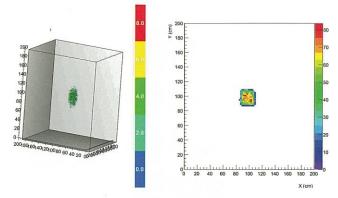
to construct the ROC curves the data are broken up into temporal subsets and analyzed against data where there is no target present. The length of the subsets is arbitrary but is ultimately statistics limited. The smaller the length of the subsets the less data there will be which increases the uncertainty of the results. The goal here is to minimize the length of the time subsets while still maintaining an extremely low false alarm rate<sup>9</sup>. The likelihood of correct detection is increased when more information is given to the SDE algorithm.

ROC curves for 1 minute and 30 second subsets of real data are shown in Figure 6. It can be seen that the inclusion of momentum information improves the false alarm rate. The false positive fraction (FPF) for the momentum-inclusive curve stays closer to the 0 on the FPF axis. It can be seen that when including momentum on 1 minute scan intervals the false alarm rate decreases by 1~2% for high true positive fractions (TPF). An ideal detector would produce a ROC curve with a 0 FPF for all values of the TPF up to 1. It is also useful to note that the area under the curves (AUC) is improved by 1.2% and 2.5% for 1 minute and 30 seconds respectively by including momentum. This metric is meaningful to compared with a perfect ROC curve of this nature which would have an AUC of 1.

### 3.2 Imaging

One key aspect of the experimental plan for the CRIPT detector at Chalk River is to apply muon tomography to nuclear fuel and waste in order to determine the applicability of this technology to non-proliferation and waste characterization.

A preliminary experiment involving the geometry of nuclear fuel was conducted using a mock fuel bundle. This bundle is a 36 element modified CANDU reactor bundle filled with steel<sup>10</sup> instead of natural uranium. The housing of each fuel pin is a zirconium alloy of



**Figure 4:** Left: 3D PoCA image of lead target. Right: Top down PoCA image. (Note: Colour scale is in arbitrary units.)

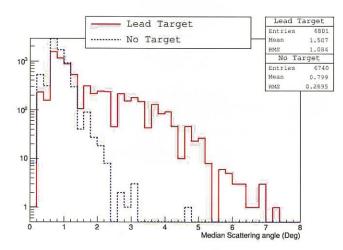


Figure 5: Median scattering angle distribution curves for lead target and no lead target.

negligible thickness compared to the steel. The bundle is approximately 50 cm in length with a diameter of approximately 10 cm. Each fuel pin is approximately 1 cm in diameter and they are situated in concentric

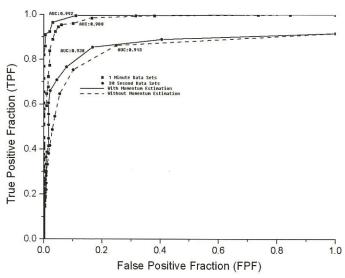


Figure 6: ROC curves for a lead target.

<sup>9</sup> The smaller the time subset the faster detection occurs.

<sup>10</sup>  $X_0$  (Iron)  $\approx$  13.84g cm<sup>-2</sup> which is the main constituent of steel [4].

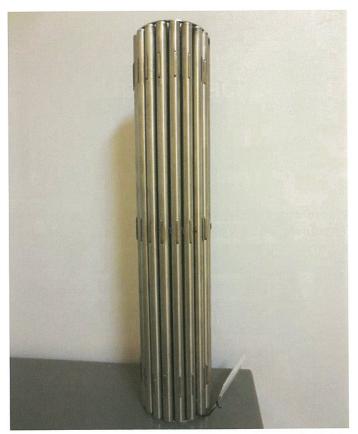


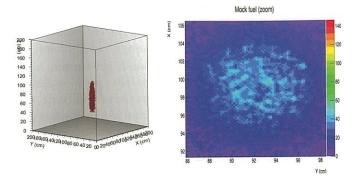
Figure 7: Mock fuel bundle - side view.



**Figure 8:** Mock fuel bundle - cross sectional view. Note: The central element was removed from the bundle referenced in this paper.

rings of 6, 12, and 18 elements. The mock bundle is shown in Figure 7 and Figure 8. The bundle has a weight of slightly less than 22.7 kg.

The configuration was to stand the bundle upright in the detector. This trial consisted of a weeklong<sup>11</sup> exposure of the bundle in order to determine some



**Figure 9:** Left: 3D PoCA image which accurately describes the physical dimensions of the mock bundle. Left: Zoomed top down projection. (Note: Color scale is in arbitrary units.)

limitations of the PoCA technique as far as image resolution is concerned. After ~24 hours of data aquisition the image quality appears to become optimal. The reason for the excessive exposure in this case was to be able to apply more strict cuts on the data in order to better estimate the physical dimensions of the bundle. The PoCA image produced is shown in Figure 9. The results are promising insofar as imaging without time-constraint is concerned. Since the steel mock bundle produced good results it is expected that a bundle with natural uranium will produce similar results due to the higher atomic number of uranium compared to iron.

### 4. Conclusion

Including momentum information in the determination of the presence of dense material has yielded favourable results. It has also been shown that the CRIPT detector is capable of reconstructing images of targets to a very good degree of spatial accuracy. The measurement of muon momentum<sup>12</sup> is a unique feature to the CRIPT detector. The CRIPT project will continue to experiment on nuclear material at Chalk River in order to provide valuable industry relevant information regarding the suitability of muon tomography for quickly detecting nuclear materials.

The CRIPT project spans many years and much progress has been made not only to optimizing detector performance from an instrumentation perspective but also to pushing the concept of muon tomography to a level where it is a demonstrably reliable technique for security and safeguards applications. The ability to both quickly and reliably detect dense material coupled with the ability to produce detailed tomographic images that characterize materials based on muon multiple scattering are goals being sought after. The CRIPT detector was able to produce images only months after initial commissioning and the results of this paper were again produced months are re-commissioning at a new site.

<sup>11 ~44</sup> million events

<sup>12</sup> For use in muon tomography.

Progress is continuous in the development of new algorithms to analyze muon tomography data and future results will be forth coming.

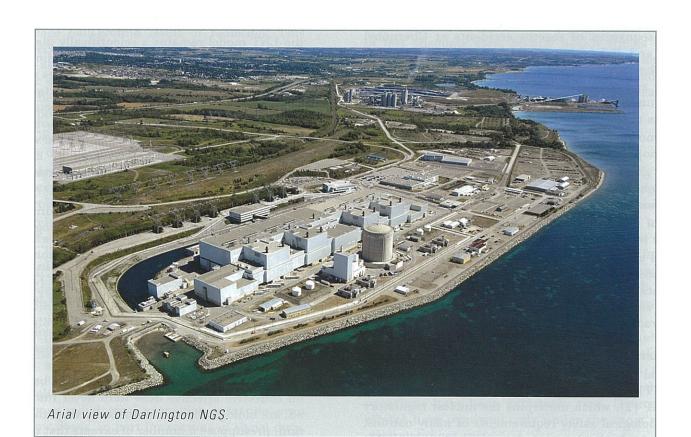
### 5. Acknowledgment

This work was supported, in part, by the Chemical Biological Radiological and Nuclear Research and Technology Initiative (CRTI) under project CRTI 08-0214RD.

### 6. References

- [1] http://www-ns.iaea.org/security/itdb.asp
- [2] http://www.cbsa-asfc.gc.ca/agency-agence/reports-rapports/ae-ve/2009/exam-eng.html
- [3] V. Anghel et al., International Conference on Advancement in Nuclear Instrumentation, Measurement Methods, and their Application, Belgium, June 6-9, 2011.
- [4] G. Jonkmans et al., CRIPT project preliminary results of imaging special nuclear materials with

- cosmic rays, Proceedings of the Institute for Nuclear Material Management (INMM) 54th annual meeting, Palm Desert, CA, July 14-18, 2013.
- [5] J. Beringer et al., (Particle Data Group), Review of particle physics, Phys. Rev. D86, 010001 (2012).
- [6] MINERĐA Collaboration, The MINERĐA Technical Design Report, MINERĐA-doc-700-v28, December 2006.
- [7] S. Haino et al., (BESS collab.), Phys. Lett. B594, 35 (2004).
- [8] S. Riggi et al., Muon tomography imaging algorithms for nuclear threat detection inside large volume containers with the Muon Portal detector, arXiv.org: 1307.0714, 2013.
- [9] G. Jonkmans et al., Nuclear waste imaging and spent fuel verification by muon tomography, Annals of Nuclear Energy, 53, 267-273, 2013.
- [10] Agostinelli, S. et al, GEANT4 a simulation took kit, Nucl. Instr. Meth. A506, 250-303, 2003.



CNS Bulletin, Vol. 36, No. 1

### Whither LNT?

by D.J. HIGSON

[Ed. Note: The following paper was presented at The 19th Pacific Basin Nuclear Conference (PBNC 2014) Hyatt Regency Hotel, Vancouver, British Columbia, Canada, August 24-28, 2014.]

### **Abstract**

UNSCEAR and ICRP have reported that no health effects have been attributed to radiation exposure at Fukushima. As at Chernobyl, however, fear that there is no safe dose of radiation has caused enormous psychological damage to health; and evacuation to protect the public from exposure to radiation appears to have done more harm than good. UNSCEAR and ICRP both stress that collective doses, aggregated from the exposure of large numbers of individuals to very low doses, should not be used to estimate numbers of radiation-induced health effects. This is incompatible with the LNT assumption recommended by the ICRP.

### Introduction

Grossly exaggerated estimates of the radiological consequences of reactor accidents at Chernobyl (1986) and Fukushima (2011) have been propagated by the news media and by anti-nuclear pressure groups, and the public has been exposed to unrealistic and unnecessary concerns about radiological risks. This has created:

- an atmosphere of dread and panic amongst the adjacent populations;
- grave concerns about the safety of nuclear power throughout Japan, with extended shut-down of operable nuclear power stations;
- fear of nuclear power amongst many people elsewhere in the world

It also appears very likely that some of the emergency actions taken to protect the public from exposure to radiation in both cases have done more harm than good. I say "appears" because it is controversial how much radiological detriment was averted by these actions – although it is certain that evacuation, in particular, caused many deaths and much suffering.

Central to all these matters is the linear no-threshold (LNT) dose-response assumption recommended by the ICRP [1], which underpins the nuclear regulatory and radiological safety requirements of many nations. Unfortunately, it also gives lay people an unsuitable tool with which to form their opinions and it provides a base for anti-nuclear propaganda.

# 1. The Findings and Recommendations of ICRP and UNSCEAR

Two recent reports - one by UNSCEAR [2] and the other by an ICRP Task Group [3,4] - have been published in the aftermath of the Fukushima accident. Both state that no health effects have been observed that can be attributed to radiation exposure, either among workers or the general public.

Both these reports [2,3] stress that collective doses, when aggregated from the exposure of large numbers of individuals to very low doses, should not be used to estimate numbers of radiation-induced health effects within a population – either retrospectively or prospectively. In its 2007 recommendations [1], the ICRP had said:

"[The] Commission emphasises that whilst the LNT model remains a scientifically plausible element in its practical system of radiological protection .... the Commission judges that it is not appropriate [because of uncertainty on health effects at low doses] .... to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people over very long periods of time ....

"Collective effective dose is an instrument for optimisation, for comparing radiological technologies and protection procedures ....

".... because the assumptions implicit in the calculation of collective effective dose (e.g., when applying the LNT model) conceal large biological and statistical uncertainties .... the computation of cancer deaths based on collective effective doses involving trivial exposures to large populations is not reasonable and should be avoided. Such computations based on collective effective dose were never intended, are biologically and statistically very uncertain, presuppose a number of caveats that tend not to be repeated when estimates are quoted out of context, and are an incorrect use of this protection quantity."

UNSCEAR [2] has now restated this as follows:

".... the Scientific Committee does not recommend multiplying very low doses by large numbers of individuals to estimate numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels."

#### UNSCEAR also says:

".... an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure .... health effects in an individual that are known to be associated with radiation exposure — such as radiation-inducible malignancies ("stochastic" effects) — cannot be unequivocally attributed to radiation exposure ...."

"An increased incidence of stochastic effects in a population could be attributed to radiation exposure through epidemiological analysis .... [only if] .... the increased incidence of cases of the stochastic effect were sufficient to overcome the inherent statistical uncertainties.

"In general, increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation. This is because of the uncertainties associated with the assessment of risks at low doses, the current absence of radiation-specific biomarkers for health effects and the insufficient statistical power of epidemiological studies."

UNSCEAR recognises that its position is incompatible with the assumption of LNT, and also states that:

- "Extrapolation from acute to chronic and fractionated exposures" is a factor that can dominate the uncertainty in projecting risk.
- The relationship between dose and response "from moderate- or high-dose to low- dose exposures .... may not be linear".

The ICRP [1,3] appears not to acknowledge the incompatibility of the LNT assumption with some of its other recommendations. However, González et al [4] state that the ICRP, as well as UNSCEAR and others, strongly urge that the misuse of collective dose should be avoided while recognising that:

".... collective dose is a very useful concept which decision-making bodies may use to impose radiological protection measures even at low doses, in part for reasons of social duty, responsibility, utility, prudence and precaution. But the distinction between prudent practices for radiological protection and the misuse of protection concepts to attribute adverse health effects is not always clearly enunciated and a much better approach is needed."

On this matter, UNSCEAR itself [2] says:

"The Scientific Committee notes that public health bodies need to allocate resources appropriately, and that this may involve making projections of numbers of health effects for comparative purposes. This method, though based upon reasonable but untestable assumptions, could be useful for such purposes provided that it were applied consistently, the uncertainties in the assessments were taken fully into account, and it were not inferred that the projected health effects were other than notional."

Nevertheless, it is important that radiation protection measures imposed by public health bodies should do more good than harm. At Fukushima, the real harm to the public has been from the social upheaval, trauma and physical risks of evacuation, the consequences of other emergency measures, and fears and misunderstandings about radiation effects. At both Chernobyl [5] and Fukushima [2-4], these have been far more damaging to public health than the radiation itself. At Fukushima, evacuation caused more than 1000 deaths [6] including elderly people taken from their homes and nursing homes to places of less adequate care. Mental health effects such as depression, anxiety, anger and stigma have had grave consequences in Japan including many suicides. The fear of radiation appears to be at least as great as the fear of tsunamis.

#### 2. Interpretation

Neither UNSCEAR nor ICRP defines clearly what is meant by "very small", "low", "very low" and "trivial" doses in the LNT-context. This is crucial to the responsible evaluation of the health effects of nuclear plant accidents and is important because fears of radiation – aggravated by irresponsible estimates of the consequences of accidents – have distorted public opinion on nuclear safety. Hence, although nuclear power generation has in fact proved to be very safe, it is feared by many.

Although there have been accidents in the nuclear industry when radiation exposure of workers has been at levels at which tissue reactions ("deterministic" effects) have been experienced, these occasions have been extremely rare. Deterministic effects have occurred only under the most extreme circumstances, viz:

 There were 134 cases of acute radiation sickness (ARS) at Chernobyl (28 being fatal) out of many thousand cases of significant exposure to radiation.

- No worker at Fukushima incurred ARS.
- By far the majority of significant accidental exposures of workers in the nuclear industry have been well below levels that could give rise to deterministic effects.
- No member of the public has incurred any form of deterministic health effect due to an accident in the nuclear power industry.

The highest accidental exposures of the public have been protracted, at rates initially greater than natural background levels but falling rapidly to be within the global range of natural background radiation.

UNSCEAR [2] states that "increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation". Numerical values are not quoted but "typical ... average ... levels" is plural, implying that this does not mean just the global average of about 2 mSv/y. Could it mean the average levels in areas around nuclear plant sites, which might be a lot more than the global average – perhaps 10 mSv/y? This needs to be clarified.

### 3. The relationship of risks to doses and dose rates

The relevant ICRP recommendation [1] - the LNT model - is that cancer risks observed at acute doses greater than 500 mSv should be extrapolated proportionally to low doses and low dose rates, such as the average background rate of about 2 mSv/y in Australia, subject only to reduction by a dose and dose rate effectiveness factor (DDREF) of 2. I find it hard to accept that this adequately accounts for the difference between the effects of acute doses from atomic bomb explosions and chronic exposure to natural background radiation because:

- With the possible exception of exposures to elevated levels of radon (see below), there is no reason, apart from the LNT assumption itself, to believe that there are risks from chronic exposures to natural background radiation up to at least 10 mSv/y. I actually believe that this extends to at least 100 mSv/y, although the small numbers of people exposed to such extreme levels are not sufficient to make observations statistically significant [7]. If the LNT model is valid, however, adverse health effects should be evident at such high dose rates\*.
- Experiments on dogs exposed to chronic D-radiation have shown that lifespan was reduced only when the dose rate was greater than 700 mGy/y [6].
- The main reason for believing that there are risks to adults from exposure to acute doses less than about

- 100 mSv (perhaps 10-20 mSv in utero) appears also to be the LNT assumption itself.
- Observations of biological effects at the cellular and molecular level have been reported "even at very low levels of radiation exposure. However, the presence of such biological indicators in samples taken from an individual does not necessarily mean that the individual would experience health effects due to the exposure" [2].

There is significant evidence from animal experiments of beneficial health effects, including reduced incidences of cancer, from exposure to doses up to 100 mSv [e.g. reference 9]; and consistent indications of similar effects on humans [10,11].

#### 4. Risks from radon?

I am mentioning radon because UNSCEAR has focussed attention on natural background radiation and more than half the exposure to background radiation in many parts of the world is due to the inhalation of radon in homes. This has no relevance to accidents and any effects of radon are due to alpha-radiation, which is unlikely to be an issue in nuclear reactor accidents. However, any change in the application of the LNT model could be significant in the assessment of risks from radon.

I presented a review of the risk of lung cancer from radon at the ARPS-35 conference in Adelaide (2010). This was updated, presented as a poster at IRPA-13 (2012) and should be available on the IRPA-13 WebSite as a full paper. The position is briefly as follows.

Outdoors in the open air, levels of radon range from about 1 to more than 100 Bq m-3 worldwide. Radon accumulates in enclosed spaces, notably in caves, underground mines and dwellings. Sometimes, but very rarely in Australia, it reaches levels in homes and workplaces at which it causes a significant risk of lung cancer—particularly for smokers, because there appears to be synergism between radon and tobacco smoke. For concentrations greater than 200 Bq m-3, there are risks as shown in Table 1.

Some average levels of radon in homes are:

- 11 Bq m<sup>-3</sup> in Australia
- 21 Bq m<sup>-3</sup> in Britain
- 55 Bq m<sup>-3</sup> in 27 countries of the European Union.

At concentrations less than 100 Bq m-3, there are no confirmed health effects of radon, although both harmful and beneficial effects have been clai-

<sup>\*</sup> Footnote: Kendall *et al* [8] have reported an association between natural background radiation and childhood leukaemia in Great Britain, but have not shown that there is a causal relationship. No such association has been observed in relation to areas of high natural background radiation [7].

Table 1: Risks of lung cancer death from domestic exposure to high levels of radon for 75 years.

Concentration of radon in air	200 Bq m <sup>-3</sup>	800 Bq m <sup>-3</sup>
Risk reported by Darby et al for smokers [12]	0.03	0.12
Risk reported by Darby et al for non-smokers [12]	0.0012	0.0048
Risk estimated according to the ICRP's recommendations#	0.07	0.29

# ICRP [13] recommends a risk coefficient of 8x10-10 per Bq h m-3 at all levels of radon, without reference to smoking habits. The estimates in this table are based on the number of hours in a 75-year lifetime and a home occupancy factor of 0.7.

med. If there is an effect on health, it is too small to be statistically significant. Again, the ICRP's LNT-recommendation is the only reason for a belief that there are risks from radon at these levels. Nevertheless, dwellings with a mean of 64 Bq m-3 have been targeted for remediation in Britain, to reduce radon levels; in the US, the EPA recommends the consideration of remediation for homes testing down to 74 Bq m-3, as there is said to be no "safe" level of radon.

In Britain, estimates of the numbers of deaths from radon related lung cancers have been used to evaluate the cost-effectiveness of remedial measures. Seventy percent of these deaths are estimated to be in homes where the radon levels are below 50 Bq m-3. In the US, the EPA estimated that 21,100 lung cancer deaths in 1995 were related to indoor radon exposure. In 2011, the EPA estimated the average cancer mortality risk from natural background radiation in the US to be about 0.44%. All these estimates would now appear to be inconsistent with the recommendations of the ICRP (2007) and UNSCEAR (2012), quoted earlier in this paper.

In NSW Australia, there is on-going controversy over the need to decontaminate an area in Hunters Hill where harbour-side homes have been built on tailings left over from the processing of radioactive minerals about 100 years ago. In one of these homes, the maximum measured level of radon is 174 Bq m-3. Measured levels in all other homes are less than 43 Bq m3 [14]. Although these radon levels are on the high side for Australia, they are not unusual on the global scale; the level at which remediation is recommended in Australia is 200 Bq m-3. The maximum external and internal gamma and beta dose rate that could be incurred from the industrial waste at Hunters Hill is 0.7 mSv/y [14], which is well within the natural range in Australia and less than the 1 mSv/y dose limit for the general public.

#### 5. Conclusions

Responsible agencies recognise that the LNT model has been misused to calculate grossly exaggerated health effects of radiation exposure from the reactor accidents at Chernobyl and Fukushima.

These abuses have ignored the ICRP's recommendation that it is not appropriate to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people.

This might not be considered surprising, since the ICRP continues to recommend use of the LNT model and does not define clearly what it means by "very small" radiation doses in this context.

UNSCEAR has now taken the position that risks from such exposures should not be estimated using the LNT model to estimate numbers of radiation-induced health effects "within a population exposed to incremental doses at levels equivalent to or lower than natural background levels". This implies chronic exposures without providing specific numerical guidance on relevant dose rate levels or total doses to individuals.

Guidance from ICRP is needed on the range of application for the linear dose- response relationship – which clearly should no longer be extrapolated unconditionally down to zero dose and dose rate – so that national regulations relating to radiation protection and nuclear safety can be amended appropriately. It is important to ensure that emergency measures imposed by public health bodies should do more good than harm.

Guidance from ICRP should be general in application, as the implications of the current LNT recommendation are not restricted to the consequences of accidents.

#### References

- [1] J. Valentin (Editor), "The 2007 recommendations of the International Commission on Radiological Protection", Annals of the ICRP: Publication 103, Elsevier, 2007.
- [2] United Nations General Assembly, Sixty-seventh session, Supplement No. 46 "Report of the United Nations Scientific Committee on the Effects of Atomic Radiation" UNSCEAR's fifty-ninth session (21-25 May 2012)
- [3] International Commission on Radiological Protection. "Report of ICRP Task Group 84 on initial lessons learned from the nuclear power plant accident in Japan vis-à-vis the ICRP system of radiological protection", 22 November 2012.
- [4] A.J. González et al, "Radiological protection issues arising during and after the Fukushima nuclear reactor accident", J. Radiol. Prot. Vol. 33, 2013, pp. 497-571.
- [5] The Chernobyl Forum report, "Chernobyl Legacy: Health, Environmental and Socio- economic Impacts", 2005.
- [6] J.M. Cuttler, "Remedy for radiation fear discard the politicized science". Dose- Response (Prepress), 2014.
- [7] J.H. Hendry et al, "Human exposure to high natural background radiation: what can it teach us about radiation risks?", J. Radiol. Prot. Vol. 29, 2009, pp. A29-A42.
- [8] G.M. Kendall et al, "A record-based case-control study of natural background radiation

- and the incidence of childhood leukaemia and other cancers in Great Britain during 1980–2006",. Leukemia, Vol. 27, 2013, pp. 3–9.
- [9] R.E.J. Mitchel, "Cancer and low dose responses in vivo: Implications for radiation protection", presented at the 15th Pacific Basin Nuclear Conference, held in Sydney, Australia, October 2006.
- [10] United Nations Scientific Committee on the Effects of Atomic Radiation, "Adaptive responses to radiation in cells and organisms", Document A/AC.82/R.542, approved 11 March 1994.
- [11] D.J. Higson et al, "Effects of low doses of radiation: Joint statement from ...... participants at the 15th Pacific Basin Nuclear Conference, sessions held in Sydney, Australia, Wednesday 18 October 2006", Dose-Response, Vol. 5, No. 4, 2007, pp. 259-262.
- [12] S. Darby et al, "Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies", BMJ, January 2005, pp. 330: 223.
- [13] C.H. Clement (Editor), "Lung cancer risk from radon and progeny and statement on radon", Annals of the ICRP: Publication 116, Elsevier, 2010.
- [14] R. Blackley, "Radiological survey of Nelson Parade, Hunters Hill", ANSTO report for NSW Department of Health and NSW DECC, 8th June 2009.



#### More Scenes from The CNA Conference and Exhibition



Opening Day at the CNS Booth.



Morning Climate Change Panel.



Olympian Skeleton Gold medalist Jon Montgomery.



Afternoon Technology Panel.



Friday morning Environmental Panel.

### **CANADIAN news**

(Compiled by Colin Hunt from open sources)

### Canada's New Nuclear Liability and Compensation Act Proclaimed

Canada's new Nuclear Liability and Compensation Act, Bill C-22, was given Royal Assent on Thursday, February 26, 2015. The new statute replaces the 1975 Nuclear Liability Act.

It changes a number of items in the older statute, while preserving and enhancing existing principles. The changes include increasing the liability cap nuclear operators must carry as insurance. Under the previous regime, a cap of \$75 million was set. Under the new legislation, the new liability cap starts at \$650 million, rising to \$1 billion three years after coming into force.

The statute also defines a compensation limitation period, up to 10 years after the event of an accident or incident for which compensation is sought.

Unlike the previous statute, the new act provides for specific compensable damages including bodily injury or death, damage to property, economic losses, psychological trauma and reasonable remediation measures to mitigate environmental damage.

The new statute also makes provisions for geographic location. An operator is liable for damage that occurs within Canada. It also permits liability by an operator in any nation which has accepted the International Atomic Energy Authority's (IAEA) Convention on Supplementary Compensation for Nuclear Damage, or any other state-to-state agreement with the government of Canada with respect to injury or damage from nuclear material.

The statute preserves and enhances the principle of absolute liability of a nuclear operator. No proof of tort is required. This now includes any act of terrorism as defined by the Criminal Code.

The statute also preserves the principle of exclusive liability. In the event of a compensable event, no operator has the right of recourse against any individual other than one who intentionally caused the event by either deliberate act or omission.

The passage of Bill C-22 marks the fifth time that the government has attempted to pass this act. The previous four attempts failed for reasons unrelated to the bill itself, but were mostly the result of procedural events such as remaining as unfinished business at the end of a session of Parliament.

#### **Extended Operation of the NRU**

The government of Canada has authorized the extension of medical radioisotope production for nearly two more years. Minister of Natural Resources Greg Rickford announced that production at the NRU would continue until March 31, 2018.

In 2000, the government decided that production would end on October 31, 2016. NRU is an important source of Molybdenum-99, the precursor to Technitium-99m, and it has been responsible for about 40 per cent of total world production. Tc-99m is an important radioisotope used in medical diagnostics.

Subsequent to its decision, the government pursued a strategy of securing alternate supplies. However, the project to develop dedicated production reactors for Tc-99m, the two 10 MW MAPLE reactors at Chalk River Laboratories, was abandoned in 2008. The government had subsequently committed some \$60 million to support development of alternate, non-reactor sources.

Entering service in 1957, the 135 MWt NRU has been Canada's principal research reactor. It has been a key part of Canada's nuclear physics and engineering research program for more than 50 years.

Canadian Nuclear Laboratories (CNL) expects to continue full operation of the NRU until 2018. At that time, it is expected that the reactor will be shut down and placed in safe storage prior to decommissioning.

#### Bruce Power Commits \$58 million to Bruce 1

Bruce Power will be spending \$58 million during the maintenance outage of Bruce Unit 1. Unit 1 was removed from service for a planned maintenance Bruce Power will be spending \$58 million during the maintenance outage of Bruce Unit 1. Unit 1 was removed from service for a planned maintenance outage on January 30, 2015. That marked the completion of 91 days of con-



tinuous operation of all four Bruce A nuclear reactors, a record performance since 1981.

Bruce Unit 1, along with Bruce Unit 2, was returned to service in 2012 after an extensive refurbishment program. It was shut down by the former Ontario Hydro in 1998. Unit 2 was shut down in 1996 after lead contamination was discovered in the steam generators.

### Pickering 5 Sets Unit Production Record



Pickering Unit 5 was shut down for a maintenance outage on Jan. 12, 2015. The shutdown capped a record run for the reactor of 523 days of consecutive power generation. It marks the longest continuous operation of any Pickering reactor since 1994, when Unit 7 operated for 892 days continuously.

During its 45 years of operation, the Pickering nuclear station has produced about 750 TWh, enough electricity to power the whole of Ontario for at least five years. With six current operating reactors, Pickering has a total production capability of 3,100 MW and produces approximately 14 per cent of Ontario's annual electricity needs.

#### Cameco Reports Uranium Production from Cigar Lake

Cameco Corporation's Cigar Lake uranium mine in northern Saskatchewan produced 0.34 million pounds of uranium concentrate during 2014. Mining operations began at Cigar Lake in March, 2014, and the first concentrate was packaged at the McClean Lake mill in October.

Cameco indicated that it expected to produce between six and eight million pounds of uranium from Cigar Lake in 2015.

Cigar Lake is operated by Cameco and owned by Cameco, AREVA Resources Canada, Idemitsu Canada Resources Ltd., and Tepco Resources Inc.



### Wolsong 1 Receives Restart Permission

The Nuclear Safety and Security Commission (NSSC) of South Korea granted permission on February 27 for the restart of the CANDU Wolsong 1 reactor. Its operating licence has been granted for a seven-year duration.

The reactor was shut down in 2009 for a full refurbishment program. As South Korea's second oldest reactor, Wolsong 1 entered service in 1983. Its refurbishment program included fuel channel replacement and upgrades to all major system components including steam generators and turbo-generators. The work was complete by 2011, and the unit resumed electricity production in July with a power rating of 657 MW.

However its operating licence expired near the end of 2012. Renewal of its operating licence was delayed in the wake of the Fukushima Daiichi accident while the reactor underwent a series of tests. The tests were completed in October 2014 with the conclusion that the reactor was safe to operate until November 2022 provided that some engineering improvements are made over the long term.

### New Isotope Production Agreement by Nordion

Nordion and its parent company Sterigenics International have signed an agreement with General Atomics and the University of Missouri Research Reactor Centre (MURR) for the production of Molybdenum-99. The production will use low-enriched uranium targets.

At 10 MWt, the MURR is the largest university research reactor in the United States. It currently produces a range of medical and industrial radioisotopes, and it is the largest such producer in the US.

Nordion has indicated that production at MURR should begin in 2017. Production at the NRU in Chalk River, Ontario was originally to terminate in 2016, but its production was extended to 2018 to cover a potential supply shortfall. Production of Mo-99 must be done on a continuous basis, as the isotope has a half-life of only six hours.

#### Atucha 2 Achieves Full Power

The Argentinian Atucha 2 nuclear power reactor achieved 100 per cent of rated power during its commissioning on February 19, 2015. Completion of Atucha 2 makes it the third power reactor to be built in Argentina, raising the proportion of electricity supplied by nuclear in that country to 10 per cent.

Atucha 2, rated at 692 MWe, was originally ordered and construction started in the 1980s. Like Atucha 1, the reactor was originally designed by Siemens. These two reactors have the distinction of being the only non-CANDU or non-CANDU based design for heavy water-moderated power reactors in the world.

The Argentinian nuclear power program experienced a revival in 2006 when the government announced a \$3.5 billion strategic plan for the country's nuclear power sector. Along with Atucha 1 and Embalse, Argentina now has 1627 MWe of nuclear generation. The country is also a source of Molybdenum-99 and Cobalt-60 medical radioisotopes.

#### Argentina and China Agree To Build Fourth Reactor

The governments of Argentina and China have signed an agreement on February 9, 2015 to build a fourth reactor in Argentina.

Nucleoelectrica Argentina holds the rights to CANDU technology. It will be the designer, builder and operator of the new reactor to be built at the Atucha site. The China National Nuclear Company (CNNC) will supply equipment, goods and services for the project.

The CANDU design reactor will be 800 MWe capacity, and construction is expected to extend over about eight years.

### Japan to Close Three Old Reactors

Kansai Electric Power Company and Japan Atomic

Power Company(JAPC) have decided to close permanently three of Japan's oldest nuclear power reactors. Kansai will be closing Mihama Units 1 and 2, while JAPC will be shutting permanently its Tsuruga 1 reactor.

Mihama 1 and 2 are PWR type reactors that entered service in 1970 and 1972, respectively. Tsuruga 1 is a 341 MW BWR type reactor which entered service in 1970. These along with all the other reactors in Japan's nuclear reactor fleet were shut down in the wake of the Fukushima earthquake and tsunami.

Japan's Nuclear Regulation Authority (NRA) has received requests from the owners of 19 of Japan's 48 reactors for permission to restart. Approval has been granted for four of them, Sendai 1 and 2 and Takahama 3 and 4. No requests have been made to restart any reactor in Japan more than 30 years old. There is thus reason to expect that more permanent closure decisions will be forthcoming.

# Construction of Chernobyl Confinement Structure Nearing Completion

Work on the New Safe Confinement structure at the Chernobyl nuclear power station in Ukraine is nearing completion, according to the European Bank for Reconstruction and Development (EBRD). However, the project needs approximately 100 million Euros in additional funding.

This project is to provide a new containment structure for Chernobyl Unit 4, an RBMK type reactor destroyed by a power surge and steam explosion in April 1986. Construction of the new cover has taken place in two large sections, and when complete, they will be moved over the ruined reactor and joined. Construction has taken place over the past four years. Total cost of the project is approximately 2.15 billion Euros.

The new structure has a lifespan of at least one hundred years. It includes a ventilation system designed to keep the interior free of corrosion, a technology building also functioning as a control centre, and cranes and other equipment to enable decommissioning work on the reactor.



### **CNS news**



#### From the President

How time flies! Already nearing the end of my term as President with one more Council meeting ahead, then the AGM. And so much left to do!

It has been busy times indeed at the CNS. Thanks to Adriaan Buijs and his Past-Presidents Committee,

we now have a new President-Elect, Paul Thompson from NB Power. Due to an unfortunate event a number of years ago, Paul had to leave Council at the start of his term as President, but he is now back to finish the job! Welcome, Paul - and congratulations!

Succession planning needs to be an important part of our business at CNS. One way to approach it is to double up as committee chairs and other Council positions. The Nuclear Operations & Maintenance Division, for example, now has two co-chairs: Aman Usmani of Amec Foster Wheeler and Polad Zahedi of OPG. This will help share the load in that division, and ensure more continuation for the future.

Speaking of succession, we recently celebrated the retirement of two wonderful persons devoted to the CNS for many, many years: Denise Rouben (Office Manager) and Fred Boyd (Bulletin Publisher, Photographer, Reporter, etc, etc). To make sure that Fred really takes his well deserved retirement, we secured a replacement in the person of Colin Hunt, our new Bulletin Publisher. As for Denise, she has graciously agreed to have her company support our office operations until we select a new person to the role.

On another note, I have had the pleasure to visit three Branches so far (Bruce, New Brunswick and Chalk River), and I must say that those were very pleasant and engaging events. I always say that the local branches are key to delivering the 'good news message' on nuclear, and I must say that I was impressed by the cross-section of people (knowledge, experience, age) involved in our branch programs. Thank you for giving me the opportunity to bring my perspective on the industry and the CNS. Now it's on to the Ottawa Branch in April!

Interesting isn't? The strength of the CNS is in its members. It's all about people working on a common cause!

I cannot sign off without a 'plug' for the Annual Conference in Saint John NB, May 31 – June 3. We are shooting for the best AnnCon yet! And we need you there, engaged with our industry partners. Here are some highlights (thanks to our hard-working Organizing Committee) that you will not want to miss:

- The CNS Annual Meeting, where you have the chance to speak up and elect your officers and Council members.
- A Conference co-hosted by the CNS and NB Power, in the historical City of Saint John.
- A huge presence by the Nuclear Waste Management Organization (NWMO).
- A technical program with about 100 papers presented in three half-day timeslots divided into five streams.
- · A plenary program that is next to none.
- A trade show, with over 40 vendors, including for the first time at our conferences: an OCI Supplier Event with NB Power.
- The first ever 'Harold A. Smith' Lecture, our lecturer none other than Pierre Tremblay of CNP.
- A student poster conference, with over 45 registrants to date.
- The presentation of the CNA-CNS honours and awards, with recipients for 8 of the 9 awards this year.
- A banquet with New Brunswick as the theme (food, entertainment, etc)

...and much, much more.

Please sign up and join us in Saint John.

Pour mes amis du Nouveau-Brunswick, je voudrais mentionner que notre force, ce sont nos membres qui travaillent très fort pour vous apporter des évènements tels que la conférence annuelle à Saint-Jean, du 31 mai au 3 juin. Voici quelques points saillants:

- Notre AGA, où vous aurez la chance de prendre la parole et élire vos représentants.
- Une conférence ou la SNC partage les devoirs d'hôte avec Énergie NB.
- Une présence importante de 'Nuclear Waste Management Organization'.
- Des séances plénières et techniques très intéressantes et pour tous les goûts.
- Un exposition de nos fournisseurs, avec plus de 40 kiosques, et un évènement spécial avec Point Lepreau.
- La première lecture 'Harold A. Smith' par Pierre Tremblay de CNP.
- Une conférence où les étudiants présentent leurs projets sur affiches.
- · La présentation des prix et honneurs SNC-ANC
- Un banquet où nous goûterons les mets et la musique du NB.

Inscrivez vous dès maintenant, et au plaisir de vous voir à Saint Jean.



#### Meet the Publisher

Replacing a legend is never easy. For a quarter of a century, Fred Boyd, a true pioneer of Canada's nuclear industry, has been the publisher, editor, principal reporter and advertising manager of the CNS Bulletin. This past December, he

stepped down from the helm of a publication that he shaped into the leading society journal that it is.

So it's probably reasonable that most of our readers want to know just who's coming on board to succeed him as the fifth publisher of the Bulletin. After all, as members of the Canadian Nuclear Society, this is your publication.

To start with, Fred and I have known each other for many years. I met Fred very shortly after I joined the staff of the Canadian Nuclear Association in 1992. Before very long, we found our views very similar on the various aspects of Canada's nuclear industry, science and technology. If there were any differences, they were largely ones of Fred having a stronger grasp of the science, technology and history of the industry and my having an appreciation of the politics and policy behind our industry.

In fact many of the contacts I have made over the years within the nuclear industry were the result of long discussions over time with Fred. And these contacts served me well during the more than 18 years with the CNA. Throughout I was involved with government interventions, public and media affairs, and publications, lots of publications. There were several that were prominent. The first was the quarterly news publication of the CNA called Nuclear Canada. First in print, later electronic, Nuclear Canada finally disappeared about a decade ago.

The second major publication was and continues to be Nuclear Canada Yearbook. This was an annual publication started in 1976 by then-Office Manager at the CNA Jim Weller. Indeed, some of you may remember Jim; he's still very much a retired member of the CNS today. While larger and with a high quality production press run, the Yearbook remains much the same format as Jim created. The Yearbook consists of three principal sections: an editorial front section, a middle section consisting of industry data, organizations and Canada's nuclear licensees, and a back section listing products and services provided by Canada's nuclear industries.

The Yearbook continues to this day, now a publication of the CNS.

After I departed from the CNA in 2010, the CNA indicated that it would cease production of the Yearbook. The Council of the CNS wanted the Yearbook to continue, and it asked me if it could be

continued as a CNS publication. The first of the CNS editions came out in June, 2011, and it has continued to do so ever since.

In 2012, I was asked to stand for office for election to the CNS Council and to serve as Secretary for the Society. This was no small step. In the CNS, the Secretary is one of the Officers of the Society. I had served as Board Secretary for the CNA for 15 years, and that served as good preparation for the responsibilities to the CNS.

This became a particularly demanding role in 2013. The federal government had passed its new Not For Profit Corporations Act that year. The new statute would require significant by-law changes to all not-for-profit corporations. As Secretary, it was my job to function as go-between among the CNS Council, the drafting committee of the CNS Council, and the CNS's lawyers drafting the legal text and eventually submitting the new by-laws and Application for Continuance to Industry Canada.

However, aside from Secretary, the CNS was also quick to make use of other skills. During the term of President John Roberts in 2012-13, the CNS Council decided that its voice should be heard in public hearings on topics related to nuclear science and technology. The first such intervention was the Request for Expressions of Interest by the federal government on the future of Chalk River Laboratories in 2013. This was followed more recently by interventions by the CNS in the relicensing of the Pickering NGS and in the joint environmental assessment hearings on Ontario Power Generation's Deep Geologic Repository for low and medium-level radioactive wastes at Bruce.

So, all of the above is a short outline of who your new Bulletin Publisher is and what he's been up to. But nuclear matters are not purely confined to publications and CNS Council. Fred and I still routinely discuss things twice a week during summers out on the golf course. So if any of you are ever in Ottawa and want a short round, you know whom to contact.

Colin Gerard Hunt



#### Denise Rouben and Fred Boyd Retirement

By Colin Hunt

A gathering was held on the evening of Thursday, March 5 to commemorate the retirement of two long-serving members of the Canadian Nuclear Society: Office Manager Denise Rouben, and CNS Bulletin Publisher Fred Boyd. The event was attended by more than 20 friends, family and members of the CNS Council.

Ms. Rouben has served as the Office Manager of the CNS since its incorporation in 1998. During that time she has provided support to many CNS events including all of the Society's annual conferences and most of its technical conferences and courses. Her work was instrumental in establishing the first CNS office at the CANDU Owners Group (COG). She also managed the two subsequent moves of the CNS office prior to arriving at its current location with AMEC-Foster Wheeler at 700 University Avenue in Toronto.

Her work over the past 17 years has been deeply appreciated by all members of the CNS. A search for Ms. Rouben's replacement is in progress.

Also commemorating retirement was the Publisher of the CNS Bulletin, Fred Boyd. Mr. Boyd has been the publisher of the CNS Bulletin since 1990. For a quarter-century, he has written and edited the CNS Bulletin, establishing the editorial standards and appearance of the CNS Bulletin in the form in which it is seen today, one of Canada's leading print publications on nuclear news, science and technology and opinion.

In addition to the editorial content and direction, Mr. Boyd also introduced commercial advertising for the first time into the CNS Bulletin. In recent years, Mr. Boyd has been joined by Richard Fluke as Editor in 2008.

Mr. Boyd remains a member of the CNS Council. In his role as publisher of the CNS Bulletin, he has been succeeded by Colin Hunt, CNS Secretary and publisher of the CNS Nuclear Canada Yearbook.



Left to right: Fred Boyd, Denise Rouben, CNS President Jacques Plourde.

Photo credit Ruxandra Dranga

### Council Considers Changes to CNS Bulletin

By Colin Hunt

With the impending retirement of Mr. Boyd, CNS Council considered in 2014 the future of the CNS Bulletin as a publication. In specific, the Council considered the question of whether or not the Bulletin should be converted into a purely electronic publication. The reason was that in the 21st century more and more publications are vanishing as printed publications and being converted into electronic magazines, accessible in on-line editions or downloadable files.

In exploring this question, the Council saw a mockup of how an electronic magazine version of the Bulletin could look. In discussing the matter in 2014,

the Council decided that the membership of the CNS should be consulted. Accordingly, Council Members Adriaan Buijs, Jeremy Whitlock and Ruxandra Dranga designed and sent out a readership survey early in 2015 to all members of the CNS. The results were received and presented to the CNS Council at its meeting on March 6, 2015.

The results were interesting and showed some division among CNS members. Some expressed preference for an electronic magazine. However, a majority favoured continuation of the print publication, many of them strongly so. In general, the membership expressed considerable satisfaction with the Bulletin's current editorial mix.

It is the view of this author that the two choices, printed vs. electronic, are not truly equivalent. Any CNS member can read a printed magazine. However, a purely electronic publication may well be inaccessible to many of the Bulletin's readers. Approximately a quarter of the total CNS membership replied to the survey, and this author and the CNS Council regard the result as highly statistically significant.

In view of the results of the survey, the CNS Council accordingly decided unanimously at its March 6 meet-

ing that the Bulletin will continue as a print publication. However, this author indicated that the Bulletin could be placed on the CNS website in the Members Section in pdf form only. During the summer of 2015, it is the project of this author to place many of the back issues of the Bulletin as well on the CNS website.

#### News from Branches

Ed. Note: most of this report is based on submissions to CNS Council on Friday, January 9, and Friday, March 6, 2015

#### BRUCE Branch - John Krane

The CNS Bruce Branch hosted a dinner meeting / presentation on Monday December 15, 2014. After many informal discussions on the state of the nuclear industry in Canada, Jacques Plourde, Canadian Nuclear Society President gave us an interesting and wide ranging presentation on the "Canadian Nuclear Society and Industry Update".

The CNS Bruce Branch is sponsoring two \$50 prizes at the Bluewater District Regional Science Fairs in **April**. Three members of the Bruce Branch will act as judges at both of the Junior and Senior Fairs.

#### NEW BRUNSWICK Branch - Derek Mullin

The NB Branch hosted a Seminar on Tuesday, 24th February, 2015. The title of the presentation was "Looking Back Over 40 Years", presented by Jacques Plourde, CNS President.

In his presentation Jacques' talk looked back over the last 40 years; he provided a CANDU\* industry update, a CNS update covering some objectives and events and also discussed CNS partnerships.

#### SHERIDAN PARK Branch - Raj Jain

The CNS Sheridan Park Branch organized a seminar on Wednesday, February 25, 2015. Dr. V. G. Snell's presentation was titled "Risk and Fear".

#### TORONTO Branch - Andrew Ali

The Canadian Nuclear Society's Toronto branch in conjunction with the University of Toronto's Astronomy and Space Exploration Society hosted a presentation by Nicholas Sion entitled "Are Humans Ready to Land On Mars?" on Friday, November 21.

The presentations covered a wide range of topics associated with human space travel to Mars and

amongst them were radiological and nuclear considerations associated with deep space exploration.

On Wednesday, February 25th 2015, the CNS Toronto Branch in collaboration with NAYGN, held a seminar on "The Long-Term Management of Canada's Used Nuclear Fuel" presented by Neale Hunt, from NWMO.

The seminar was well attended by over 50 people, composed of CNS members, university students and AMEC NSS employees.

#### **UOIT Branch** - Terry Price

The UOIT Branch of the CNS branch hosted **Dr.** Jeremy Whitlock on October 30<sup>th</sup> for his presentation "75 Years of Fission". Since then, the branch has gone into hibernation for exams; however, we will soon be exiting from this and we are looking forward to an exciting 2015.

#### WESTERN Branch - Jason Donev

The Western Branch is planning on holding its first ever 'book club' event where a significant fraction of the branch reads the same book. The current intention is to read Half-Lives by **Tammemagi and Jackson**.

Michael Taylor did a geiger counter demonstration to the public at the Telus Spark centre in Calgary.

**Aaron Hinman** prepared questions for the Earth Sciences for Society meeting, which he will attend.

**Duane Bratt** and **Jason Donev** have helped a graduate student, **Laura Johnson** to do research on how improving policy could improve the ability of the nuclear industry to operate.

**Jason Donev** presented to Let's Talk Energy with the museum of Science and technology.

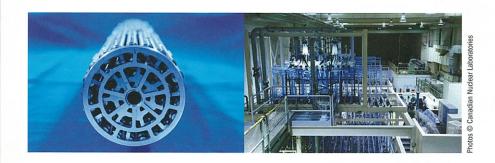
Jason Donev has joined the Nuclear Science Week committee and has started approaching Canadian institutions about doing events for the week.





### International Nuclear Components Conference

November 1-4, 2015 · Delta Meadowvale Hotel and Conference Centre · Mississauga, Ontario, Canada



Mississauga, Ontario will be the place to be for all interested in the hardware of nuclear power systems. For decades, the Canadian Nuclear Society has presented a series of conferences on steam generators and heat exchangers. INCC 2015 will continue that tradition, while expanding the scope of the conference to address other plant components.

This year's event will include topics of interest that are applicable to the new construction, ongoing maintenance and plant refurbishment of all types of power reactors.

The conference will highlight state-of-the-art technology and innovation, while keeping its strong links and importance to operating utilities and their ongoing needs.

#### **Call for Abstracts of Presentations and Posters**

The Technical Program Committee invites those involved with nuclear power plant major components to submit 300-word abstracts of proposed oral and poster presentations. Details are on the conference website.

#### Key features include:

- All major plant components: steam generators, heat exchangers, reactor components;
- Engineering design, fitness for service, life cycle and life extension;
- Science, technology and innovation within academic, nuclear research and engineering development sectors;
- · Aspects of plant repair and refurbishment.

#### Who should attend:

#### All those involved with:

- · Scientific research and technological innovation;
- Component manufacturers;
- · Utility and contract engineering services;
- · Government regulators;
- · Students entering the nuclear industry.

#### **Technical Scope**

- · Non-Destructive Evaluation
- Life extension, refurbishment and replacement (including, for the first time, craning and rigging)
- Life cycle management and asset management programs
- · Nuclear plant chemistry
- Degradation of materials, component aging, and advanced inspection/evaluation techniques
- · Fitness-for-service assessments
- Engineering Change Control (ECC)

#### **Important Dates**

Abstract Submission: March 25, 2015
Full Paper Submission: August 30, 2015
Early Bird Registration: September 25, 2015

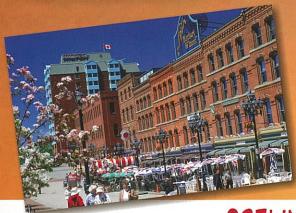
### ·SAINT JOHN 2015·

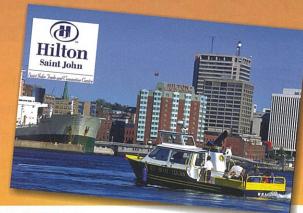
Nuclear Innovation through Collaboration La collaboration facilitant l'innovation nucléaire



In June 2015, join us in Saint John, NB as we embrace all aspects of renewal and growth in Canada's vital nuclear science & technology sector.

35<sup>th</sup> Annual CNS Conference
39<sup>th</sup> CNS/CNA Student Conference
Saint John, NB • May 31 - June 3, 2015
HILTON SAINT JOHN / SAINT JOHN TRADE AND CONVENTION CENTRE





### PRELIMINARY PROGRAM

#### SUNDAY, MAY 31

- 15:00 CNS Annual General Meeting
- 17:00 Conference registration
- 18:00 Opening Reception

#### MONDAY, JUNE 1

- 08:00 Opening addresses Jacques Plourde, CNS Gaëtan Thomas, NBPower
- 08:15 Plenary: "Nuclear Power Utility Collaboration to Improve Lifetime Performance"
- 10:30 Plenary: "Performance Improvement"
- 12:00 Luncheon & Annual Harold A. Smith Lecture (Pierre Tremblay, CNP)
- 14:00 "Nuclear for Everyone" seminar (pre-registration required) OCI-NBPower Supplier Event Parallel Technical Sessions
- 17:30 Student Poster Session & Wine and Cheese Reception

#### **TUESDAY, JUNE 2**

- 08:00 Panel Discussion: "Transportation of Used Nuclear Fuel" (NWMO)
  - OCI-NBPower Supplier Event Parallel Technical Sessions
- 12:00 Luncheon & Honours and Awards Ceremony
- 14:00 Plenary: "Enterprise Risk Management"
- 16:00 Plenary: "Vendor Role in a Continuously Improving Industry"
- 18:30 Conference Banquet

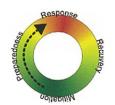
#### WEDNESDAY, JUNE 3

- 08:00 Plenary: "Waste Management and Decommissioning"
- 10:15 Plenary: "Developing Technologies and Resources"
- 12:00 Luncheon & Guest Speaker: "Toth Anniversary of Controlled Fission in Canada" (John Hilborn)
- 14:00 Panel Discussion: "International Developments in Used Nuclear Fuel Repositories" (NWMO)
  - Parallel Technical Sessions
- 17:00 Close of Conference

www.cnsconference2015.org







#### Canadian Nuclear Society Société Nucléaire Canadienne

### 1<sup>st</sup> Technical Meeting on Fire Safety and Emergency Preparedness for the Nuclear Industry

#### Delta Meadowvale Hotel & Conference Centre Mississauga, ON, June 17 – 19, 2015

http://cns-snc.ca/events/fsep-2015/

The 1st International Meeting on Fire Safety and Emergency Preparedness will provide a forum for nuclear professionals to network and communicate changes presently impacting the industry. It is an opportune time as the new standard, CSA N393 Fire Protection for Facilities that Process, Handle or Store Nuclear Material is approved for use. This standard may affect facility licenses as early as 2014. It is expected that CSA N393 will be included in a broader range of facility licenses and will replace NFPA 801 Standard for Fire Protection for Facilities Handling Radioactive Materials in existing licenses.

The conference is intended to attract participants from various sectors of the nuclear industry relating to power reactors, research reactors, nuclear laboratories, mines, processing, storage and handling facilities, decommissioned nuclear facilities, nuclear medicine and transportation of nuclear materials.

#### **Plenary Speakers**

Raoul Awad, Directorate of Security and Safeguards, Canadian Nuclear Safety Commission Claude Bouchard, Section Head, Radiation Protection Bureau, Health Canada Jim Coles, Director, Emergency Management & Fire Protection, Ontario Power Generation John Collin, Director, Emergency and Protective Services, Bruce Power Steve Hall, Deputy Chief of Training, FESTI Dave Nodwell, Manager, Planning & Exercises, Emergency Management Ontario John Osborne, General Manager, Isotope Reliability/Project, Canadian Nuclear Laboratories Wade Parker, Director of Fire, Emergency Preparedness, Security and Training, New Brunswick Power Frank Saunders, VP, Nuclear Oversight and Regulatory Affairs, Bruce Power

#### **Honorary Chair**

Greg Rzentowski, Director General of Power Reactor Regulation, Canadian Nuclear Safety Commission

#### **Sponsors**





Conference Chair: Tracy L. Pearce

Canadian Nuclear Laboratories Chalk River Laboratories 1-800-377-5995 x 44084 tracy.pearce@cnl.ca **Technical Chair:** 

Rudy Cronk Professional Loss Control 3413 Wolfedale Road, Suite 6, Mississauga, ON

1-800-675-2755 rcronk@plcfire.com

#### Calendar

#### 2015

May 25-May 27 4th Climate Change Technology

Conference (CCTC-2015) Hotel Omni, Mont-Royal website: www.cns-snc.ca

May 31-June 3 CNS 2015 Annual Conference

Saint John Hilton and Conference Centre

website: www.cns-snc.ca

June 7-June 11 ANS Annual Meeting

San Antonio, Texas

website: www.ans.org/meetings

June 17-June 19 1st International Technical Meeting on

Fire Safety and Emergency Preparedness

for the Nuclear Industry Delta Meadowvale Hotel and

Conference Centre, Mississauga, ON

website: www.cns-snc.ca

Aug. 9-13 17th International Conference on

**Environmental Degradation of Materials** 

in Nuclear Power Systems -

**Water Reactors** 

Fairmont Chateau Laurier Hotel, Ottawa, ON

website: www.cns-snc.ca

Aug. 30-Sept. 5 Nuclear Reactor Thermal Hydraulics

(NURETH-16)

Chicago, USA

website: www.cns-snc.ca

Oct. 18-Oct. 20 7th International Conference on Simulation

**Methods in Nuclear Engineering** 

Ottawa, ON

website: www.cns-snc.ca

Nov. 1-Nov. 4 International Nuclear Components

Conference Mississauga, ON

website: www.cns-snc.ca

#### Recent IAEA Publications

### Root Cause Analysis Following an Event at a Nuclear Installation: Reference Manual

IAEA TECDOC 1756 — Subject Classification: 0612-Safety analysis

IAEA-TECDOC-1756 (ISBN:978-92-0-110014-6) 18.00 Euro;

Language: English - Date Published: 2015

In the case of an event at a nuclear installation it is important to accurately determine the root causes, in order to allow corrective actions to be implemented to address them and prevent their recurrence. There are different analysis tools, techniques and methods available which can be used to evaluate the root causes of events and this publication presents a comprehensive reference manual of them and allows organizations to deepen their knowledge of these instruments. In addition, it also provides new organizations with a broad overview of the root cause analysis process. The present manual is also intended to provide guidance to all organizations establishing a new process for root cause analysis, especially in countries embarking upon a nuclear power programme.

## Methodology for the Systematic Assessment of the Regulatory Competence Needs (SARCoN) for Regulatory Bodies of Nuclear Installations

IAEA TECDOC 1757 - Subject Classification: 0614-Legal and governmental aspects

IAEA-TECDOC-1757 (ISBN:978-92-0-110514-1) 18.00 Euro;

Language: English - Date Published: 2015

This publication provides guidance for competence needs assessment (CNA) and offers a step by step approach to develop competence profiles for specific regulatory tasks. It explains how to analyse existing and required regulatory competences in order to identify gaps and thus training and competence needs. It also provides guidance on the development and implementation of tools and programmes to address these gaps in conjunction with IAEA Safety Reports Series No. 79 on Managing Regulatory Body Competence.

#### Yes, Virginia, There is Still Science

by JEREMY WHITLOCK

(with apologies to Francis Pharcellus Church, 1839-1906)

#### DEAR ENDPOINT:

I am eight years old. Some of my little friends say there is no more Science.

Papa says, "If you see it in The CNS Bulletin, it's so." Please tell me the truth: is there still Science?

Virginia, New York City

#### DEAR VIRGINIA.

Your little friends are wrong. They have been affected by the disheartenment of a disheartened age. They think that nothing can be which is not comprehensible by little minds with the power to decide what is, and what is not. All minds are little, Virginia: in this great universe of ours, Man is a mere insect - an ant, in his intellect, as compared with the boundless world about him.

Yes, Virginia, there is still Science. It exists as certainly as wonderment and delight and curiosity exist. Science is not a deliverable. It is not a goal,

nor a milestone, nor a key performance indicator. Science is an outlook - an enquiry of Nature, and a challenge to be as patient as possible in listening to the answer.

Science is as playful as a child pushing over a rock with a stick, and as courageous as a result that isn't expected. Science is neither fettered nor directed, and transcends all attempts to do so. Lawyers, bureaucrats, and politicians may define glorious and encompassing structures that suit their respective needs, and these structures may indeed limit discourse, but they can never limit enquiry.

This does not mean that Science is without process, Virginia. Quite the contrary, Science without process is aimless observation. Today information may flow in increasing volumes and directions, and empower citizen rapporteurs by the millions through social media outlets with increasing reach and immediacy, but devoid of the testable proposition there can be no enhancement of knowledge.

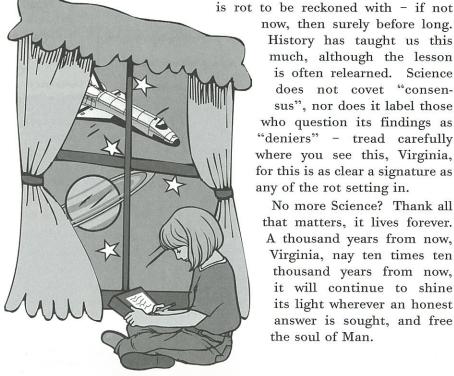
Alas! How dreary would be the world if there were no There would be no exploration, no innovation. We would define our endpoints before we started, and draw great satisfaction from plain-sight milestones along the way, like stepping stones across safe waters on a sunny day. Our success would be applauded for its mediocrity, and we would be supremely unlikely to find new waters and unfamiliar stones.

No more Science? There might as well be no more light. It has been Science that has led Mankind around every unknown corner, and advanced us to every sublime new land. Once there, it may be that Science has taken a back seat to other pressing and prominent practicalities, but the torchlight to innovation and betterment has invariably been Science, and respect thereof by authorities keenly aware of the order in which such things usually happen.

Science informs Policy - not the other way around, in a sustainable society. Where your friends may have told you differently, you can be sure that there

> now, then surely before long. History has taught us this much, although the lesson is often relearned. Science does not covet "consensus", nor does it label those who question its findings as "deniers" - tread carefully where you see this, Virginia, for this is as clear a signature as any of the rot setting in.

No more Science? Thank all that matters, it lives forever. A thousand years from now, Virginia, nay ten times ten thousand years from now, it will continue to shine its light wherever an honest answer is sought, and free the soul of Man.



#### 2014-2015 CNS Council • Conseil de la SNC

#### Executive / Exécutif

President / Président e-mail

Past President / Président sortant e-mail

Ist Vice-President / Iier Vice-Président

2nd Vice-President / 2ième Vice-Président Treasurer / Trésorier

Secretary / Secrétaire

Financial Administrator / Administrateur financier e-mail

> Executive Director / Directeur exécutif e-mail

Communications Director / Directeur des communications e-mail

Jacques A. Plourde......905-441-2776

jap-performance@rogers.com

Adriaan Buijs...... 905-525-9140 x24925 buijsa@mcmaster.ca

Paul Thompson . . . . . . . . 506-659-6234 pthompson@nbpower.com

Peter Ozemoyah .......289-288-0490 x249 pozemoyah@tyne-engineering.com

Mohamed Younis . . . . . . . 416-592-6516 mohamed.younis@amecfw.com

Colin G. Hunt.........613-742-8476

colin.hunt@rogers.com Ken L. Smith......905-828-8216

unecan@rogers.com

Ben Rouben . . . . . . . . . . . . . 416-663-3252 roubenb@alum.mit.edu

Jeremy Whitlock..........613-584-3311 x44265

whitlockj@cnl.ca

Members-at-Large / Membres sans portefeuille

Parva Alavi. Frederick C. Boyd . . . . . . . . . 613-823-2272 Daniel Gammage . . . . . . . . . . . . . . . . . 519-621-2130 x 2166

Kris K. Mohan ...... 905-332-8067 Dorin Nichita......905-721-8668 

John G. Roberts . . . . . . . . . . . . . . . . 519-361-5898 Ben Rouben . . . . . . . . . . . . . . . . . 416-663-3252 

Jeremy Whitlock . . . . . . . . . . . . . . . . . 613-584-3311 x 44265 Syed Zaidi ...... 905-763-9860 John Barrett, CNA 613-237-4262 barretti@cna.ca

#### CNS Committees / Comités de la SNC

Program / Programme

e-mail

WiN Interface / Interface avec WiN

popovic@rogers.com

mohamed.younis@amecfw.com

Branch Affairs / Chapitres locaux Syed Zaidi.....

smh@zaidi.net

COG Interface / Interface avec COG

Frank W. Doyle...........416-595-1888 x156 frank.doyle@candu.org

Education and Communications / Éducation et communications 

Membership / Adhésion

Finance / Finances

Mohamed Younis . . . . . . . . . . . . . . . . . . 416-592-6516 Bulletin

colin.hunt@rogers.com

Colin Hunt . . . . . . . . . . 613-613-742-8476

Past Presidents / Anciens présidents Adriaan Buijs...........905-525-9140 x24925 buijs@mcmaster.ca

Honours and Awards / Prix et honneurs 

International Liaison Committee / Liaisons internationales mohank@sympatico.ca

fboyd@sympatico.ca

Internet / Internet

Adriaan Buijs......905-525-9140 x24925

Inter-society Relations / Relations inter-sociétés

Young Generation / Jeune génération

Scholarship / Bourses

Mohamed Younis . . . . . . . . . . . . . . . . . . 613-592-2256 

drangar@cnl.ca

pozemoyah@tyne-engineering.com

adriaan.buijs@sympatico.ca

rahim.lakhni@amecfw.com

mohamed.younis@amecfw.com

#### Technical Divisions / Divisions techniques

• Nuclear Science & Engineering / Science et génie nucléaires

Elisabeth Varin

514-953-9790

varine@gmail.com

• Fuel Technologies / Technologies du combustible

To 2014 October 7:

From 2014 October 8: Paul Chan

613-541-6000 x6145

paul.chan@rmc.ca

dgammage@babcock.com

· Design and Materials / Conception et matériaux

519-621-2130 x2166 Daniel Gammage

Environment & Waste Management / Environnement et gestion des déchets

905-599-9534 Parva Alavi parvaalavi@gmail.com

• Nuclear Operations & Maintenance/ Exploitation nucléaire et entretien de centrale Aman Usmani 416-217-2167 aman.usmani@amec.com

905-839-6746 x4029 Polad Zahedi

polad.zahedi@opg.com

 Medical Applications and Radiation Protection/Applications médicales et protection contre les rayonnements Nick Sion 416-487-2740 sionn@sympatico.ca

Fusion Science and Technology / Science et technologie de la fusion

Blair Bromley 613-584-3311 x43676 bromleyb@cnl.ca

CNA Liaison / Agent de liaison avec l'ANC

613-237-4262 barrettj@cna.ca John Barrett

CNS Bulletin Publisher / Éditeur du Bulletin SNC

613-742-8476 colin.hunt@rogers.com Colin Hent

CNS Bulletin Editor / Rédacteur du Bulletin SNC Ric Fluke

416-592-4110 rfluke@sympatico.ca

CNS Office Manager / Bureau de la SNC

Denise Rouben 416-977-7620 denise.rouben@sympatico.ca Bob O'Sullivan 416-977-7620 cns-snc@on.albn.com

#### **Branches / Chapitres locaux**

John Krane 519-361-4286 Bruce

jck@bmts.com

Chalk River Scott Read 613-584-3311 scott.ad.read@gmail.com

Jacques Plourde 905-441-2776 **Darlington** 

Derek Mullin

jap-performance@rogers.com

Golden Horseshoe David Girard

girarddj@gmail.com

506-650-3374

Manitoba Jason Martino

**New Brunswick** 

905-525-9140

204-753-2311 x62229 martinoj@cnl.ca

dmullin@nbpower.com

Ottawa Pickering

Québec

HOIT

Western

Ken Kirkhope Leon Simeon

ken.kirkhope@cnsc-ccsn.gc.ca 905-839-1151 x2520

leon.simeon@opg.ca Michel Saint-Denis 514-875-3452

michelstdenis@videotron.qc.ca

Sheridan Park Raj lain Toronto

Terry Price

raj.jain@candu.com andrew.ali@amecfw.com Andrew Ali

terry.price@uoit.ca 403-210-6343 Jason Doney imdonev@ucalgary.ca

#### CNS WEB Page - Site internet de la SNC

For information on CNS activities and other links - Pour toutes informations sur les activités de la SNC

http://www.cns-snc.ca



# Exporting Canadian expertise. Importing quality jobs.

International exports of CANDU® nuclear technology represent new high-tech jobs for Canadians.

In fact, with each CANDU reactor we build abroad, Canada gains about 35,000 person-years of work and a \$3.5 billion boost to the economy.

We are pursuing a number of promising opportunities to provide nuclear power to countries that are looking to meet an increasing demand for energy and a desire for cleaner air. As a leading full-service nuclear technology and EPC company, we provide complete integrated solutions that meet global market needs.

The opportunities are out there, and we're ready to meet them.





www.snclavalin.com/nuclear





Canadian Nuclear Laboratories

Laboratoires Nucléaires Canadiens











### APPLYING ADVANCED SCIENCE TO A COMPLEX WORLD.

Canadian Nuclear Laboratories is a world leader in nuclear science and technology; with a proud history of innovation and a world of opportunity ahead. Operating today as a trusted and experienced partner, Canadian Nuclear Laboratories offers unique abilities and solutions across a wide range of industries.

With ongoing investment in new facilities and a sharper mandate, Canadian Nuclear Laboratories is positioned for the future. A new performance standard reinforced with a strong safety culture underscores every activity.

Actively involved with industry-driven research and development in nuclear, automotive, aerospace, defence, security and life sciences, we provide solutions to keep these sectors competitive internationally.

Leverage our expertise and facilities to improve the competitiveness of your organization through innovative research and development. For more information visit www.cnl.ca or contact commercial@cnl.ca.

#### NOUS APPLIQUONS DES PRINCIPES SCIENTIFIQUES DANS UN MONDE COMPLEXE.

Les Laboratoires Nucléaires Canadiens sont un chef de file mondial en technologie et en sciences nucléaires qui offrent des capacités et des solutions uniques dans une gamme d'industries. En participant activement à des travaux de recherche et de développement dirigés par l'industrie dans les domaines du nucléaire, des transports, de la technologie propre, de l'énergie, de la défense, de la sécurité, et des sciences de la vie, nous offrons des solutions qui maintiennent la compétitivité de ces secteurs sur la scène internationale.

Grâce à des investissements réguliers dans de nouvelles installations et un mandat précis, les Laboratoires Nucléaires Canadiens sont bien placés pour l'avenir. Une nouvelle norme de rendement appuyée par une solide culture de la sécurité est au cœur de toutes nos activités.

Tirer parti de notre expertise et de nos installations pour accroître la compétitivité de votre organisme au moyen d'efforts novateurs en recherche et en développement. Pour obtenir de plus amples renseignements, visitez www. cnl.ca ou écrivez à commercial@cnl.ca.