Hindawi Publishing Corporation
Science and Technology of Nuclear Installations
Volume 2015, Article ID 143767, 9 pages
http://dx.doi.org/10.1155/2015/143767

Review Article

CANDU Safety R&D Status, Challenges, and Prospects in Canada

W. Shen[1] and F. Doyle[2]

[1] *Canadian Nuclear Safety Commission, 280 Slater Street, Ottawa, ON, Canada K1P 5S9*
[2] *CANDU Owners Group, 655 Bay Street, 17th Floor, Toronto, ON, Canada M5G 2K4*

Correspondence should be addressed to W. Shen; wei.shen@cnsc-ccsn.gc.ca

Received 10 June 2014; Accepted 29 October 2014

Academic Editor: Bo Wook Rhee

In Canada, safe operation of CANDU (CANada Deuterium Uranium; it is a registered trademark of Atomic Energy of Canada Limited) reactors is supported by a full-scope program of nuclear safety research and development (R&D) in key technical areas. Key nuclear R&D programs, facilities, and expertise are maintained in order to address the unique features of the CANDU as well as generic technology areas common to CANDU and LWR (light water reactor). This paper presents an overview of the CANDU safety R&D which includes background, drivers, current status, challenges, and future directions. This overview of the Canadian nuclear safety R&D programs includes those currently conducted by the COG (CANDU Owners Group), AECL (Atomic Energy of Canada Limited), Candu Energy Inc., and the CNSC (Canadian Nuclear Safety Commission) and by universities via UNENE (University Network of Excellence in Nuclear Engineering) sponsorship. In particular, the nuclear safety R&D program related to the emerging CANDU ageing issues is discussed. The paper concludes by identifying directions for the future nuclear safety R&D.

1. Introduction

1.1. Importance of Nuclear Safety Research. Nuclear energy deployment must be based on a firm technical understanding to ensure safety at every stage of the life cycle, from development to decommissioning and waste management. Nuclear power programmes have required a continued investment in safety research both by industry—to meet its responsibility for ensuring safe operation—and by government to ensure that the regulatory organization has the competence and independence to discharge its responsibility. The current safety record as well as success of nuclear power worldwide is built upon a foundation of research. Such research has been sponsored by governments and industry and has led to innovative designs, safer and more reliable plant operation, and improved operating plant efficiency.

In recent years, funding for long term strategic activities such as research, preserving corporate knowledge and maintaining technical expertise, has been reduced in many countries. Industry funding by the designers and operators has been reduced on the assumption that the research needed for the initial design of plants has been completed, with absence of commitment to build new plants and a highly competitive market place which make it difficult to support long term programmes such as research.

Safety research has never lost its importance, but its scope and emphasis have changed as potential challenges to safety have arisen. Past successes in safety research have permitted the nuclear industry to grow, maintaining public confidence through well founded designs and operating limits and through sound regulatory practices. However capabilities need to be maintained by both the industry and the regulatory organization to ensure the safety of nuclear plants is not compromised.

1.2. Nuclear Safety Research and Development (R&D) in Canada. Canada has a long and proud history regarding the development of the well established CANDU—PHWR (pressurized heavy water reactor) technology. Safe operation of CANDU reactors is supported by a full-scope program of safety R&D in key technical areas. Nuclear R&D in the 1940s and 1950s was directed towards basic heavy-water reactor technology (physics, control, fuel, chemistry, etc.). As basic technology became established, progressively more emphasis was placed on safety R&D. Major safety R&D programs started in the late 1970s and early 1980s and many have continued to the present. Key nuclear R&D programs, facilities, and expertise are retained in addressing the following two main areas.

(i) Unique features of the CANDU such as fuel, physics, fuel channels, and moderator. Physically realistic models used in the CANDU safety analysis are built based on solid understanding of phenomena gained from experiments.

(ii) Generic technology areas common to CANDU and LWR (light water reactor) such as world-class work in hydrogen ignition and detonation and iodine behaviour. Both industry and the regulatory body work cooperatively with the international community in areas of mutual interest.

Basically, the R&D program required for due diligence in CANDU safety is dominated by AECL (Atomic Energy of Canada Limited) and COG (CANDU Owners Group), while the R&D program required for innovation and advancement of CANDU designs to further enhance safety, economic, fuel cycle flexibility, and fuel sustainability is dominated by the nuclear vendor (CANDU Energy Inc.) with the underlying technology and support provided by AECL. The regulator does a small amount of independent and confirmatory safety research and reviews and critiques the industry R&D program. Over the years, CANDU safety issues [1] have carried over from gaps in knowledge in the original design, or discovered through R&D and experience, either as a plant event or as an evolving understanding. Resolving the CANDU safety issues identified by the Canadian Nuclear Safety Commission (CNSC) is one of key drivers for the industry's ongoing nuclear safety R&D programs.

Canada is one of few nations that have exported reactor technology—CANDU based designs are used in Argentina, Korea, India, Pakistan, Romania, and China. It should be noted that, as a vendor nation that has exported CANDU technology to other countries, it is expected that Canada will continue to maintain an adequate nuclear R&D infrastructure in all aspects of the technology required to support CANDU reactors and their services worldwide. This is an expectation for the CANDU nations that may not yet have the domestic expertise required to independently support their CANDU nuclear safety programmes.

2. Nuclear Safety R&D Conducted by COG

2.1. Overview of COG R&D Program. Formed in 1984 to improve the performance of CANDU stations worldwide through member collaboration, COG is a not-for-profit corporation with voluntary funding from CANDU-owning utilities and AECL. The COG R&D Program and the Industry Standard Toolset (IST) Program are sponsored by the Canadian Utilities Ontario Power Generation (OPG), Bruce Power (BP), and New Brunswick Power Nuclear Corporation (NBPN); by Societatea Nationala Nuclearelectrica S.A (SNN-SA) of Romania; and by AECL. Hydro Quebec had sponsored the program for about three decades prior to the end of the service of its Gentilly-2 CANDU 6 reactor. Since 2012, the Korea Hydro and Nuclear Power Company (KHNP) has started to sponsor two of COG's R&D programs, namely, Safety and Licensing, and IST.

The current COG R&D program comprises five distinct programs: (i) fuel channels, (ii) safety & licensing, (iii) health, safety & environment, (iv) chemistry, materials & components, and (v) IST. The major suppliers to the five R&D programs have been AECL, CANDU Energy, Kinectrics, AMEC NSS, and Stern Laboratories. There are a number of organizations with specialized capabilities that are also used as suppliers on an as-needed basis.

Over the years, COG R&D programs have supported the safe, reliable, and efficient operation of CANDU reactors. With the sustained R&D funding in recent years, the industry has been able to maintain the infrastructure needed to support the emerging CANDU ageing issues (more discussions can be found in Section 8.1).

2.2. Fuel Channels R&D. The fuel channels R&D program addresses the issue of fuel channel life cycle management through technical support for fitness for service (CSA N285.8) [2] while also reducing the conservatism in models to predict deformation, corrosion, and deuterium ingress. The current R&D program includes but is not limited to the following areas:

(i) assessment of the risk of cracking from in-service flaws,

(ii) deuterium ingress,

(iii) hydride blister avoidance,

(iv) fitness-for-service guidelines,

(v) deformation,

(vi) assessment of fracture toughness of pressure tubes at end-of-life.

2.3. Safety and Licensing R&D. The safety and licensing R&D program addresses issues related to the safety design basis and safe operating envelope of existing nuclear plants and has a strong focus on supporting the resolution of outstanding generic safety and licensing issues. In part, this work also supports safety assessments for new plant designs and assists in maintaining the core capabilities, scientific expertise, and the infrastructure necessary for an ongoing nuclear safety R&D program. There are four disciplines under this program: containment and severe accidents, fuel and fuel channels and fuel NOC (normal operating condition), physics, and thermalhydraulics. The current R&D program includes but is not limited to the following areas:

(i) fuel channel integrity,

(ii) hydrogen behaviour in containment,

(iii) fuel and fission product (FP) behaviour in accidents,

(iv) critical heat flux,

(v) research supporting safety analysis software,

(vi) severe accident R&D.

Table 1: List of COG IST codes in four disciplines.

Code group (discipline area)	Computer codes
Containment and severe accident	GOTHIC, SMART, ADDAM, MAAP-CANDU
Thermalhydraulics	ASSERT-PV, MODTURC_CLAS, TUF, CATHENA
Physics	RFSP, WIMS, DRAGON, DOORS/ORIGEN, MCNP
Fuel and fuel channels	ELESTRES, ELOCA, SOPHAEROS, SOURCE, TUBRUPT

2.4. Health, Safety, and Environment R&D. The health, safety, and environment R&D program addresses issues related to radiation monitoring, radiation protection, and dosimetry, including the establishment of the risks of radiation exposure to workers, the public, and the environment. Aspects of ecological impact; emission, environmental, and waste management; and techniques for monitoring emissions and the environment, managing spills, and pollution prevention are also addressed. The current R&D program includes but is not limited to the following areas:

(i) external and internal dosimetry,
(ii) radiation monitoring,
(iii) environmental impacts and biodiversity,
(iv) occupational radiation protection,
(v) environmental management systems,
(vi) waste management and pollution prevention.

2.5. Chemistry, Materials, and Components R&D. The chemistry, materials, and components R&D program covers a diverse range of issues that can impact on the safe, reliable, and efficient operation of the major CANDU systems and their auxiliaries, such as the primary heat transport (PHT), moderator, steam generators, heat exchangers, emergency core cooling, and containment. This includes optimizing the chemistry control regimes and understanding material ageing effects in order to predict, manage, and mitigate component degradation on key components, such as pressure tubes, feeders, and steam generators, and hence improve safety and reliability and extend the asset life. There is also a strong focus on smaller, but no less important, components, such as valves, cables, sealants, lubricants, and other organically based materials. The current R&D program includes but is not limited to the following areas:

(i) chemistry,
(ii) containment boundary degradation,
(iii) improved components, materials, maintenance, and processes,
(iv) reactor vessel and piping material degradation,
(v) steam generators and heat exchangers integrity and cleaning.

2.6. Industry Standard Toolset (IST). The COG IST program is a consolidation of the qualification, development, maintenance, and support activities on different computer codes used for the design, safety analysis, and operational support of CANDU reactors. Currently there are 16 IST codes in the following four disciplines as listed in Table 1:

(i) containment and severe accident [3],
(ii) thermalhydraulics [4],
(iii) physics [5–8],
(iv) fuel and fuel channels [9, 10].

2.7. Joint Projects. In addition to the above five distinct programs, the industry provides significant funding through COG for participation in EPRI's nuclear sector R&D program and for COG-organized joint projects such as fuel channel fracture toughness at the end of life, pressure tube material surveillance, fuel channel life management, and LLOCA (large-break loss-of-coolant accident) analytical solution. A brief illustration about the COG joint projects on the LLOCA analytical solution is provided below for demonstration purposes.

LLOCA is a design basis accident (DBA) that is postulated to occur as a result of a sudden failure of a large diameter pipe in the heat transport system (e.g., a reactor inlet or outlet header, pump suction, or discharge pipe). Due to the existence of a large positive coolant void reactivity (CVR) coefficient, the initial phase of the event is characterized by a large power pulse combined with a severe degradation in core cooling. LLOCA not only represents the most severe accident scenario within the CANDU DBA set, but also plays a key role in establishing certain design requirements of the special safety systems such as shutdown systems, emergency core cooling, and containment. Difficulties of characterizing the CVR coefficient, fuel behaviour in a large power pulse, and fuel behaviour at high temperature following high energy deposition and difficulty in validating computer codes for such conditions have led to the formulation by the CNSC of several category-3 CANDU safety issues (Canadian Nuclear Safety Commission defines category-3 issues as follows: "*The issue is a concern in Canada. Measures are in place to maintain safety margins, but further experiments and/or analyses are required to improve knowledge and understanding of the issue, and to confirm the adequacy of the measures*." [11]). The LLOCA safety margin issue has led over the years to deratings, more restrictive limits on operational parameters, and design changes.

In 2008, a joint industry/CNSC LLOCA working group was established to identify possible options for a resolution path to address the issues associated with LLOCA safety margin in existing CANDU reactors. Two resolution strategies (risk control measures) were evaluated by the working group: a composite analytical approach (CAA) [12]

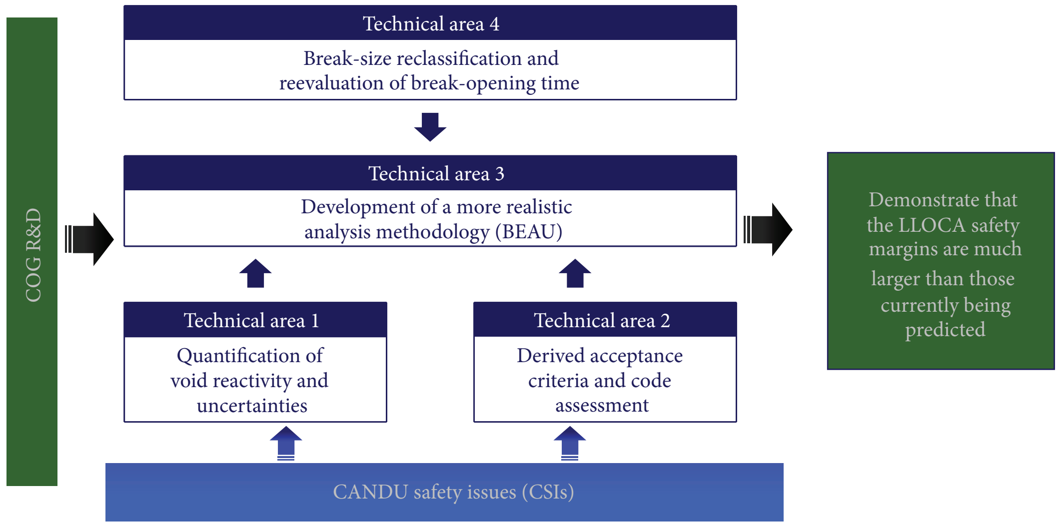


Figure 1: Illustration of composite analytical approach [4].

and a design change approach which includes changes to operational practices, modifications to the shutdown systems, and implementation of the low void reactivity fuel (LVRF). The industry chose to focus its efforts on the development of the CAA and a COG joint project (JP-4367) was established by the industry to implement the CAA and establish the plans for design change as a contingency.

The CAA approach, as illustrated in Figure 1 [12], involves consolidating a number of individual approaches in a manner that alleviates reliance on any single analytical method or activity. Using this multilayered approach, the objective of this composite solution is to use a variety of reinforcing analytical approaches such that they complement one another to collectively form a robust solution. The CAA approach involves four technical areas (TA) with objectives as follows.

(i) TA1: reevaluation of the uncertainty associated with the CVR and kinetics parameters.

(ii) TA2: reevaluation of LLOCA DAC (derived acceptance criteria), accounting for the available experimental database and uncertainties.

(iii) TA3: further development and application of BEAU (Best estimate and uncertainty) analysis methodology to provide a more realistic representation of the margins.

(iv) TA4: reclassification of different break sizes into DBA and beyond design basis accident (BDBA) categories according to the break probability, implementation of a more realistic model for break opening characteristics.

As indicated in Figure 1, each technical area relies upon industry R&D performed by the COG in addition to analyses and assessments performed within the LLOCA joint project. Note that activities in TA1 and TA2 have been identified as ones which must be completed regardless of the resolution strategy (CAA or design change). Completion of these two fundamental activities will contribute to resolving the LLOCA associated CANDU safety issues.

3. Nuclear Safety R&D Conducted by AECL (Including CANDU Energy)

3.1. AECL R&D Program. AECL is a Canadian federal Crown corporation and Canada's largest nuclear science and technology laboratory. AECL developed the CANDU reactor technology starting in the 1950s and in October 2011 licensed this technology to CANDU Energy Inc. Until October 2011, AECL was also the vendor of CANDU technology worldwide, providing services to nuclear utilities around the world. Its business activities included the design and construction of nuclear reactors and related products, services, life extension, decommissioning, and waste management, as well as the supply of medical radionuclides.

AECL has been undertaking a strong R&D program for over six decades including operating a nuclear-licensed site with extensive research facilities. Over the years, AECL's R&D program has supported the design and licensing basis for existing CANDU nuclear power plants, the development of new reactor concepts, and the development of products and services for commercialization to nuclear utilities worldwide. In October 2011, the Federal Government completed the first phase of AECL restructuring with the divestiture of its CANDU Reactor Division (i.e., industrial/vendor arm of AECL) to CANDU Energy Inc. Since then AECL has been focusing its nuclear research focuses on the following areas:

(i) nuclear and radioactive material management,

(ii) irradiation and postirradiation services,

(iii) nuclear safety, security, and risk management,

(iv) radiation biology, radioecology, and dosimetry,

(v) materials and chemistry in nuclear applications,

(vi) advanced nuclear fuels and fuel cycles,

(vii) systems engineering,

(viii) advanced computing, modelling, and simulation,

(ix) hydrogen and hydrogen isotopes management,

(x) environmental remediation and nuclear waste management.

The Federal Government is now moving forward on the next phase of restructuring of AECL's Nuclear Laboratories as a Government-Owned Contract-Operated (GoCo) model. During the restructuring process, AECL continues its daily operations and R&D activities focusing on its new mandates:

(i) addressing the government's legacy liabilities obligations (for waste and decommissioning) through dedicated funding,

(ii) supporting the government's nuclear role and responsibilities through Federal S&T (science and technology) funding,

(iii) ensuring third party access to AECL's facilities, but with S&T services moving to full cost recovery.

Being part of the Federal Nuclear S&T Committee, the CNSC is being engaged with other federal agencies to ensure that AECL's nuclear research after restructuring supports the government's nuclear role and responsibilities which include research and testing to support the CNSC in identifying safety issues and developing and applying nuclear safety and regulatory standards. Hence the CNSC is in a position to confirm research activities needed at AECL to meet CNSC needs and the facilities and capabilities required for safe and effective regulation of the nuclear sector. As a consequence, AECL is expected to be engaged more with the CNSC to strategically align with prioritized regulatory objectives. The changes in the AECL laboratory's role are, in fact, a significant opportunity for the CNSC to shape the direction of future nuclear safety research.

3.2. CANDU Energy R&D Program. After privatizing the industrial/vendor arm of AECL, CANDU Energy's (CE) R&D program is mainly focused on the continuing support for the design, safety analysis, and licensing of its flagship product—EC6 (Enhanced CANDU 6) [13]. Building on proven high performance of the CANDU 6 design, the EC6 design meets up-to-date Canadian regulatory requirements, including post-Fukushima lessons learned. The EC6-related R&D program covers the following areas: generic action items and CANDU safety issues, confirmatory testing and analysis program for the SSCs (systems, structures, and components) with the design changes, test program for end shield heat transfer, use of TSUNAMI methodology to determine reactor-physics code biases and uncertainties, and so forth.

In collaboration with Chinese utility partners since 2008, CE has been actively developing the natural uranium equivalent (NUE) fuel to be fully implemented in Chinese CANDU reactors at Qinshan [14–16]. The NUE fuel contains a combination of recycled uranium (RU) and depleted uranium (DU) that simulates natural uranium (NU) behaviour. The project for full-core implementation of NUE fuel in Qinshan CANDU reactors was approved by China National Nuclear Corporation (CNNC) in 2011. The preliminary safety assessment indicates that the conversion of both Qinshan CANDU units to NUE fuel would not impose significant negative impact on existing licensing and operating basis.

The advance of the NUE full-core implementation project resulted in the initiation of two other R&D programs which are being actively conducted at CE: one R&D program is the exploration of higher burnup CANDU reactor fuel with the advanced fuel CANDU reactor (AFCR) which is an EC6-based design optimized for alternative fuels, including RU and thorium fuels. CANDU Energy and partners jointly showed that the CANDU 6 reactor design can efficiently use high burnup RU and LEU-Th fuel with minimal changes. The other R&D program is the development of CANMOX fuel design for the disposition of United Kingdom (UK) plutonium stockpiles with EC6 reactors. A feasibility study for UK's Nuclear Decommissioning Authority (NDA) has been completed. CE is now further developing the CANMOX proposal with UK stakeholders.

4. Nuclear Safety Research Conducted by the CNSC

It is recognised that the practices of regulatory organisations vary from country to country and that the degree to which regulatory-sponsored research is conducted and utilised in the regulatory process also varies. However, in general, the role of research sponsored by regulatory organisations is to provide those organisations with the capability and expertise to assess reactor safety issues, review designs, and perform their various other functions, independent from those seeking regulatory approval or promoting nuclear energy. Such independent capability and expertise provides the regulatory organisation with a deeper understanding of the activities it regulates. This deeper understanding can result in insights that contribute to the quality, timeliness, and thoroughness of the regulatory review, confidence in the information provided by the industry, or identification of potential safety issues that may have gone undetected.

To generate knowledge and information to support CNSC staff in its regulatory activities, a dedicated research and support program oversees the execution of objective driven research, in line with short, medium, and long term regulatory priorities. All regulatory-sponsored research is categorised according to a research area where, at present, research needs to exist in the following eight areas: human performance management, safety analysis, physical design, fitness for service, radiation protection, environmental protection, waste management, and safeguards and nonproliferation. For example, research on aging systems, structures, and components would fall under the "fitness for service" research area. For illustrative purposes, Figure 2 summarizes the "safety analysis" research area of the CNSC research and support program. It should be noted that regulatory research is not intended to duplicate what is industry's responsibility, but rather to provide a check on its completeness and quality

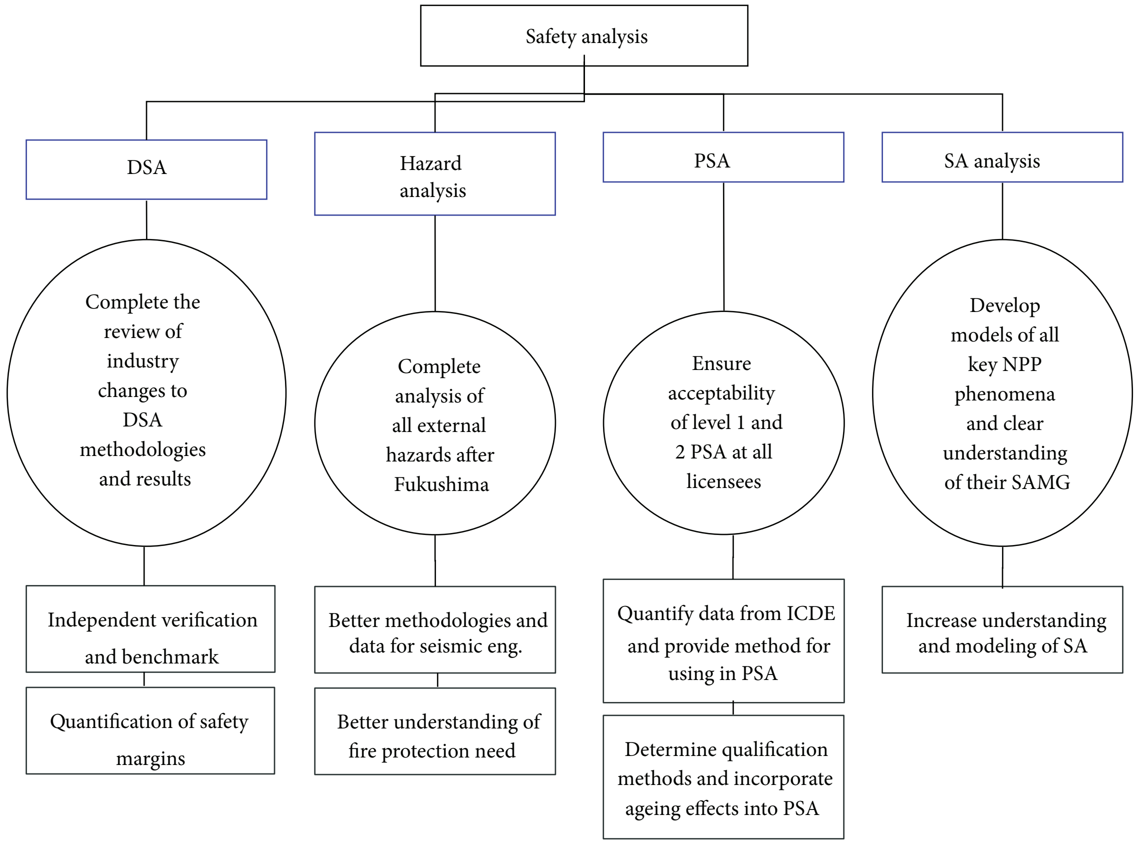


Figure 2: Illustration of CNSC research and support program in the safety analysis area.

in an independent fashion. This capability and expertise by the regulator is fundamental to public confidence as well as contributing to safety by enhancing the efficiency and effectiveness of regulatory programs.

5. Nuclear Safety R&D Conducted by Universities via UNENE Sponsorship

University involvement in CANDU R&D is considered important for the development and retention of the R&D capabilities that the nuclear industry will require to support the CANDU plants for the long term future. The University Network of Excellence in Nuclear Engineering (UNENE) [17] was launched in 2002 as an alliance of universities, utilities, research, and regulatory agencies (members are shown in Figure 3) dedicated to the support of education and research in nuclear engineering. The UNENE initiative has resulted in the establishment of the following six industrial research chairs (IRCs) in Ontario:

(i) Advanced Nuclear Materials (Queen's University);

(ii) Control, Instrumentation and Electrical Systems (University of Western Ontario);

(iii) Health Physics and Environmental Safety (University of Ontario Institute of Technology);

(iv) Nuclear Safety Analysis (McMaster University);

(v) Corrosion and Materials Performance in Nuclear Power Systems (University of Toronto);

(vi) Risk-Based Life Cycle Management (Waterloo University).

These IRCs became anchors for establishing research programs and competent research teams within their respective universities. Industry funding of the IRC programs has also served to leverage additional funds from federal and provincial research grants, thus widening the scope and size of these programs.

UNENE has also created small collaborative R&D (CRD) grants to universities to support research projects of interest to the CANDU Industry, as proposed by existing faculty members at Canadian universities. The CRD topics are closely tied to the IRC programs such as seismic risk analysis, subchannel mixing, D2O chemistry, stress corrosion cracking (SCC) in Alloy 800, nondestructive testing (NDT) sensors for feeders, thermalhydraulics, and delayed hydride cracking (DHC).

6. Nuclear R&D on Canadian SCWR

The super-critical water reactor (SCWR) is one of six candidate reactor concepts selected by the Generation-IV International Forum (GIF) [18] for meeting GIF design goals, which include enhanced safety, resource sustainability, economic

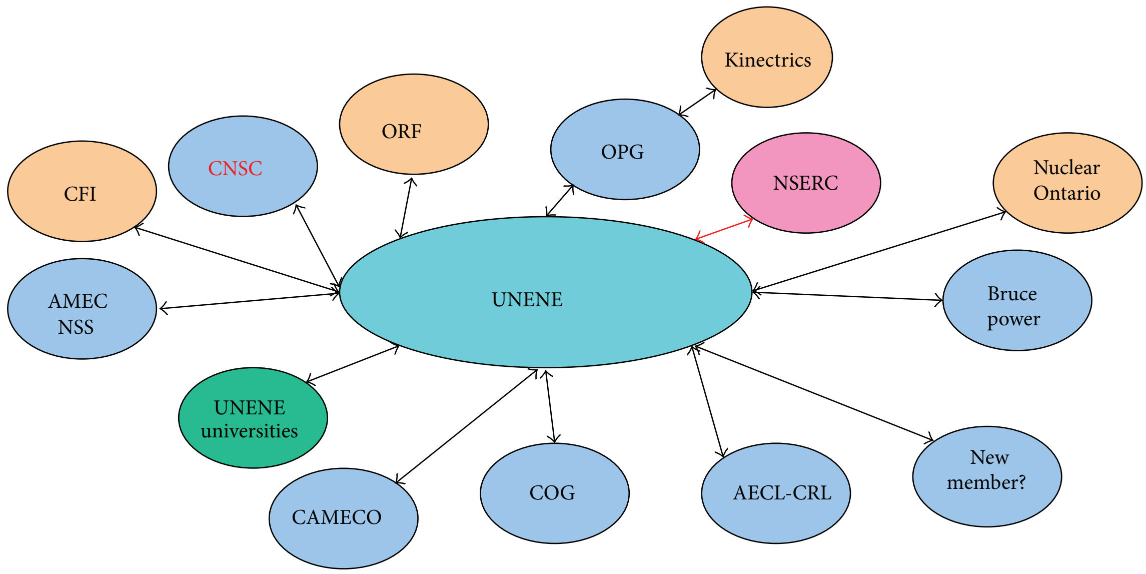


FIGURE 3: UNENE—an industry-university partnership.

benefit, and proliferation resistance. As a member of GIF, Canada is developing a pressure-tube type SCWR, which has the potential to fulfil all major GIF goals. A national program has been established in Canada to support R&D studies for the Canadian SCWR design. It covers key areas of interest (such as thermalhydraulics, safety, materials, and chemistry) to participants in the GIF SCWR designs. Administrated under NRCan (Natural Resource Canada) and networked with 20 Canadian universities and laboratories, AECL is leading the design of the Canadian SCWR, which evolves from the well-established CANDU reactor [19–21].

7. Canadian Nuclear Safety R&D Facilities

Nuclear safety R&D spans a range of activities, from small-scale laboratory work for developing the fundamental understanding to large-scale demonstrations, with extensive mathematical modelling of the various phenomena. These activities require large, specialized active facilities such as hot cells, research reactors, laboratories, and radioactive materials handling equipment. It is costly and also takes time to establish and operate such nuclear research facilities. Only governments have the resources to establish and maintain these facilities, and established nuclear power countries usually maintain at least one national nuclear laboratory for R&D in nuclear safety. This infrastructure is part of the government obligation when the nuclear power is deployed.

Most of Canada's nuclear safety experiments have been done at AECL's Chalk River Laboratories (in-reactor and ex-reactor tests as shown in Figure 4) and Whiteshell Laboratories (ex-reactor tests) with full-scale water CHF (critical heat flux) and some ex-reactor tests having been done at Stern Laboratories. The Whiteshell Laboratories R&D facilities have been gradually decommissioned with the exception of a few facilities such as RD-14 M and LSVCF (large scale vented combustion facility). Notwithstanding the ongoing restructuring of AECL Nuclear Laboratories, AECL envisions to continue to offer the needed level of nuclear safety R&D facilities to the CANDU community.

8. R&D Program to Support Ageing CANDU Reactors

8.1. Industry's Ageing Management Strategy. Ageing of a CANDU nuclear power plant poses additional safety challenges on the plant safety. This is represented by increased probability of common-cause failures, impact of HTS ageing on fuel performance in NOC, and reduction over time of safety margins for certain DBAs. Industry's ageing management strategy includes a number of initiatives and projects (including R&D programs) whose objective is to delay or preclude the need to derate:

(i) addressing root cause of ageing through steam generator cleaning and improving pressure tube (PT) data collection;

(ii) changing operating conditions and/or procedures;

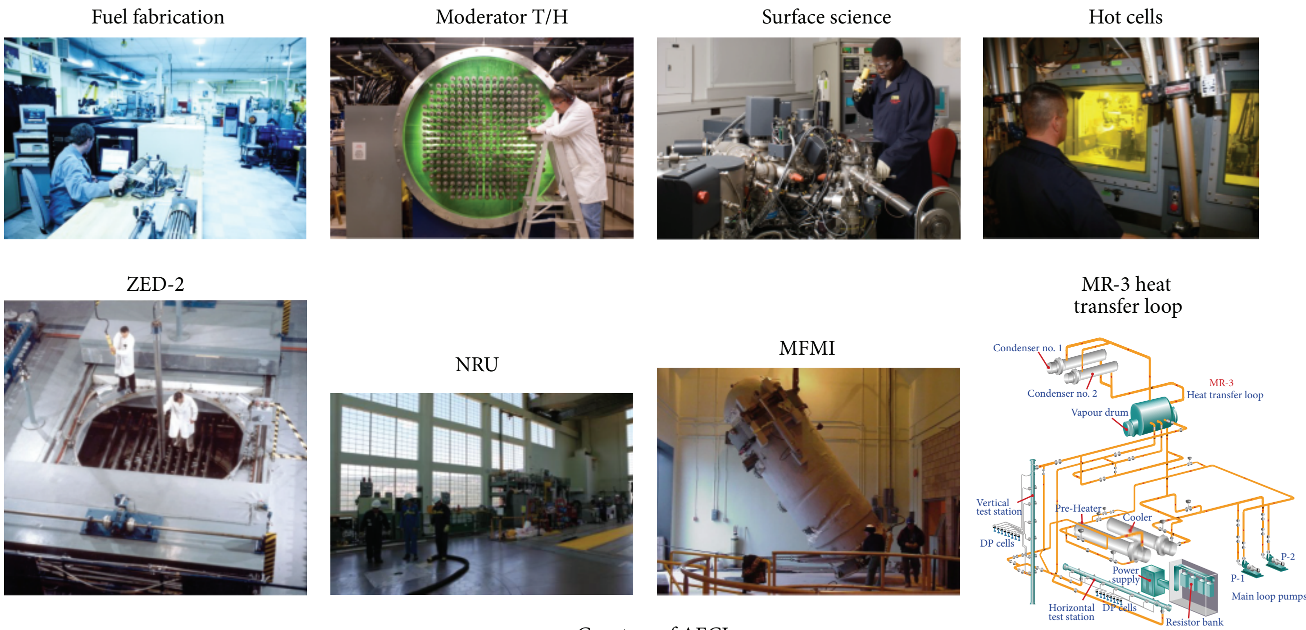
(iii) changing the CHF correlation methodology;

(iv) using a new NOP (neutron overpower protection) analysis methodology to demonstrate extra margin in the required NOP trip set points;

(v) adopting a new fuel bundle design with higher dryout powers (37M fuel bundle project);

(vi) changing the shutdown system effectiveness criteria by demonstrating that the previous criterion is overly conservative (joint CNSC/COG ITP project on derived acceptance criteria).

Among these initiatives and projects, design change such as the 37M fuel bundle project makes physical improvement to the fuel thermalhydraulic performance and offsets partially the erosion of safety margin [22, 23].



Courtesy of AECL

Figure 4: AECL nuclear safety R&D facilities.

8.2. Regulator's Ageing Oversight Strategy. The CNSC's response to early signs of CANDU reactor ageing followed "regulation-by-feedback" process, to ensure that when component degradation was discovered, licensees investigated the degradation, assessed its safety impact, and adjusted controls to mitigate further degradations. The CNSC has adopted a comprehensive and systematic strategy to ageing management which includes regulatory requirements and documents [24], adequate research, implementation plan, and compliance verification. The CNSC requires the Canadian utilities to have ageing management programs in place to ensure long-term safe operation of CANDU plants.

The CNSC also actively participates in national and international initiatives related to plant degradation such as cooperation with OECD-NEA and IAEA, participation in the IGALL (International Generic Ageing Lessons Learned) Project, initiation of joint CNSC and Industry R&D activities in supporting current industry initiatives related to plants' life extension and long-term operation.

9. Summary and Recommendations

The Canadian nuclear R&D program has a long and proud history starting from the pioneer R&D activities that led to the original CANDU design to today's R&D activities. Safe operation of CANDU reactors is supported by a full-scope program of safety R&D in key technical areas. Key nuclear R&D programs, facilities, and expertise are maintained in order to address the unique features of the CANDU as well as generic technology areas common to CANDU and LWR. The R&D program required for due diligence in CANDU safety is dominated by AECL and COG, while the R&D program required for innovation and advancement of CANDU designs to further enhance safety, economic, fuel cycle flexibility, and fuel sustainability is dominated by the nuclear vendor (CANDU Energy Inc.) and supported by AECL. University involvements in CANDU R&D, through six UNENE Industrial Research Chairs, constitute an important contribution to the development and retention of the R&D capabilities that the nuclear industry will require to support the CANDU plants for the long-term future. Finally, to generate knowledge and information to support CNSC staff in its regulatory activities, a dedicated CNSC research and support program oversees the execution of objective driven research, in line with short, medium, and long term regulatory priorities.

As a vendor nation that has exported CANDU technology to other countries, it is expected that Canada will continue to maintain an adequate nuclear R&D infrastructure in all aspects of the technology required to support CANDU reactors and their services worldwide. Government policy (at various levels) continues to support CANDU reactors as an important long term source of energy, contributing to the overall energy supply mix in Canada. The restructuring of AECL Nuclear Laboratories represents an important shift in Canada's nuclear landscape, which industry and the CNSC will follow very closely. The CNSC, along with other stakeholders, is actively engaged in the process and every effort will be made to ensure that Canada continues to benefit from the high level of nuclear competence and capacity it has now for the foreseeable future. Notwithstanding the ongoing restructuring of AECL Nuclear Laboratories, AECL envisions to continue to offer the needed level of nuclear safety R&D services to the CANDU community.

Future nuclear safety R&D directions would include but not be limited to the following areas: regulatory compliance, development tools for CNSC independent verification, improved operation margin (e.g., design modifications), plant life cycle management and plant life extension, computer code development and qualification, and severe accident management.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The information in this paper is based on material from COG, AECL, CANDU Energy Inc., CNSC, and UNENE. The authors would like to thank M. Couture, D. Serghiuta, Y. Guo, K. Dewar, M. Ducic, and D. Tello from CNSC and B. Rouben from UNENE for their fruitful feedback and comment on this paper.

References

[1] "Generic safety issues for nuclear power plants with pressurized heavy water reactors and measures for their resolution," Tech. Rep. TECDOC-1554, IAEA, 2007.

[2] CSA Standard, "Technical requirements for in-service evaluation of Zirconium alloy pressure tubes in CANDU reactors," Canadian Standards Association N285.8-10, CSA, 2010.

[3] S. M. Petoukhov and P. M. Mathew, "Status of MAAP4-CANDU code development and simulations of severe core damage accidents for a generic CANDU plant," in *Proceedings to the Technical Meeting on Severe Accident and Accident Management Toranomon Pastoral*, Tokyo, Japan, March 2006.

[4] B. N. Hanna, "CATHENA: a thermalhydraulic code for CANDU analysis," *Nuclear Engineering and Design*, vol. 180, no. 2, pp. 113–131, 1998.

[5] D. Altiparmakov, W. Shenb, G. Marleau, and B. Rouben, "Evolution of computer codes for CANDU analysis," in *Proceedings of Advances in Reactor Physics to Power the Nuclear Renaissance (PHYSOR '10)*, Pittsburgh, Pa, USA, May 2010.

[6] D. Altiparmakov, "New capabilities of the lattice code WIMS-AECL," in *Proceedings of the International Conference on the Physics of Reactors (PHYSOR '08)*, pp. 635–642, Interlaken, Switzerland, September 2008.

[7] G. Marleau, A. Hébert, and R. Roy, "A user guide for DRAGON 3.06," Report IGE-174 Rev. 7, École Polytechnique de Montréal, Québec, Canada, 2008.

[8] W. Shen and P. Schwanke, "Evolution of RFSP 3.5 for CANDU analysis," in *Proceedings of the 33rd Annual Conference of the Canadian Nuclear Society (CNS '12)*, pp. 1277–1288, Saskatoon, Canada, June 2012.

[9] H. H. Wong, E. Alp, W. R. Clendening, M. Tayal, and L. R. Jones, "ELESTRES: a finite element fuel model for normal operating conditions," *Journal of Nuclear Technology*, vol. 57, pp. 203–212, 1982.

[10] A. F. Williams, "The ELOCA fuel modelling code: past, present, and future," in *Proceedings of the 9th International CNS CANDU Fuel Conference*, 2005.

[11] "2010 Annual CNSC staff report on the safety performance of canadian nuclear power plants," in *Proceedings of the CNSC Technical Document for Public Meeting*, CMD:11-M46, 2011.

[12] P. Purdy, "A composite analytical solution for large break LOCA," in *Proceedings of the International Conference on Future of Heavy Water Reactors (HWR-FUTURE '11)*, Ontario, Canada, October 2011.

[13] J. Hopwood, "A robust reactor," *Nuclear Plant Journal*, vol. 32, no. 1, 2014.

[14] H. Z. Fan, T. Laurie, A. Siddiqi et al., "Safety assessment to support NUE fuel full core implementation in CANDU reactors," in *Proceedings of the 12th International Conference on CANDU Fuel*, Kingston, Canada, September 2013.

[15] C. M. Cottrell, M. Boubcher, M. J. Chen, Z. H. Zhang, and S. Kuran, "Natural uranium equivalent (NUE) fuel: full core use of recycled uranium and depleted uranium in CANDU reactors," in *Proceedings of the 21st International Conference on Nuclear Engineering (ICONE '13)*, Chengdu, China, July-August 2013.

[16] M. J. Chen, Z. H. Zhang, and Z. L. Meng, "CANDU position and prospect in China," in *Proceedings of the 26th Canadian Nuclear Sociate Annual Conference*, Toronto, Canada, June 2013.

[17] B. A. Shalaby, V. G. Snell, and B. Rouben, "UNENE: an update on nuclear education and research," in *Proceedings of the 31st Annual Conference of the Canadian Nuclear Society*, Toronto, Canada, May 2010.

[18] U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, "A technology roadmap for generation IV nuclear energy systems," Tech. Rep. GIF-002-00, 2002.

[19] C. K. Chow and H. F. Khartabil, "Conceptual fuel channel designs fro CANDU—SCWR," *Nuclear Engineering and Technology*, vol. 40, no. 2, pp. 139–146, 2008.

[20] L. K. H. Leung, M. Yetisir, W. Diamond et al., "A next generation heavy water nuclear reactor with supercritical water as coolant," in *Proceedings of the International Conference on Future of Heavy Water Reactors (HWR-Future '11)*, Canadian Nuclear Society, Ottawa, Canada, October 2011.

[21] W. Shen, "Assessment of the traditional neutron-diffusion core-analysis method for the analysis of the Super Critical Water Reactor," *Annals of Nuclear Energy*, vol. 45, pp. 1–7, 2012.

[22] Y. Guo, "Regulatory review of the CANDU Fuel Modification program in Canada," in *Proceedings of the 12th International Conference on CANDU Fuel*, Kingston, Ontario, Canada, September 2013.

[23] K. Shaheen, M. E. Shawkat, A. I. Popescu, and H. Hasanein, "Assessing the impact of the 37M fuel bundle design on fuel safety parameters," in *Proceedings of the 12th International Conference on CANDU Fuel*, Kingston, Ontario, Canada, September 2013.

[24] CNSC Regulatory Document, "Aging Management for Nuclear Power Plants," RD 334, 2011.