CANADA

By W.J. Garland, V.G. Snell and B. Rouben

1. Background History

Nuclear research and development in Canada started in the 1940s as a responsibility of the federal government. An engineering design team was established at Chalk River, Ontario, to carry out research on heavy-water-moderated lattices. A zero-energy heavy-water-moderated research reactor, ZEEP, was built and achieved criticality in September 1945; it was in fact the first man-made operating reactor outside the USA. In 1947, the 20-MW heavy-water-moderated National Research Experimental reactor (NRX) started up. It served as one of the most valuable research reactors in the world, and provided the basis for Canada's development of the very successful CANDU series of pressurised-heavy-water reactors (PHWR) for power generation.

Atomic Energy of Canada Limited (AECL) was established in 1952 as a federal Crown Corporation. It has both a public and a commercial mandate. AECL has overall responsibility for Canada's nuclear research and development programme (its public mandate) as well as for the Canadian reactor design (CANDU), engineering and marketing programme (its commercial mandate). . Nuclear energy in Canada is a $5-billion-per-year industry, representing about 150 firms, 21,000 direct jobs and 10,0000 indirect jobs, and ~$1.2 billion in exports – the value to the country's economy is much higher than the research and development funding provided by the federal government.

The CANDU nuclear reactor system was developed by AECL in close collaboration with the Canadian nuclear industry, and in particular with Ontario Hydro (now Ontario Power Generation). Currently, Canada operates 17 CANDU reactors, which contribute 16% of the country's current electricity consumption. There are also 12 CANDU reactors operating abroad (in Argentina, China, India, Korea, Pakistan and Romania). See Figure 1 – the localities shown in red are where the CANDU plants are located. AECL is now developing the "third-generation plus" Advanced CANDU Reactor (ACR-1000), and also has the leading role internationally in developing the Generation IV Supercritical-Water-Cooled Reactor (SCWR).

- 17 operating CANDU reactors in Canada & 12 abroad
- Provide 16% of Canada's electricity

Figure 1 - Nuclear Reactors in Canada

Canada also initiated or contributed to other important applications of nuclear science and technology:

- The cobalt-60 therapy machine was developed in 1952 by Dr. Harold Johns.
- Canada has for many decades provided the lion's share of medical radionuclides to the world market. These have been produced mostly in the NRU reactor at Chalk River Laboratories, NRU has served Canada extremely well in this regard
- NRU has also performed a key role in supporting the power reactor programme for fuel and materials research over the last 52 years

2. Demands for Nuclear Engineers

The economic health of the nuclear industry has a strong effect on the status of nuclear education in the country. In the 1980s, the number of students studying or graduating with degrees having nuclear content stayed relatively constant, as did the number of teaching staff. But from the early 1990s, for about 15 years, there was not a high level of investment by the nuclear industry in university research, and not a high level of hiring of graduates, which resulted in the near vanishing of nuclear programmes and nuclear-engineering professors.

In contrast, in the last few years, with a number of activities to refurbish aging reactors and with the looming renaissance in the nuclear industry, the job market for new graduates with a nuclear-engineering background has improved significantly.

Current **annual** demand for new engineers and scientists (of all disciplines) in the Canadian nuclear industry are approximately as follows:

- by the electric utilities, ~250-300
- by AECL, ~70
- by mining companies, ~60
- in total, by all sectors of the nuclear industry, 400-500.

3. Educational System and Institutions Involved in Nuclear Education

The list below identifies the main Canadian universities which offer programs in nuclear engineering or engineering physics, or in closely related disciplines with application in the nuclear industry, such as chemical engineering, mechanical engineering, control and instrumentation, nuclear science and radiation, and health physics. All the universities listed offer Bachelor's, Master's, and Ph.D. degrees.

- McMaster University: http://www.mcmaster.ca
- Queen's University: http://www.queensu.ca
- University of Ontario Institute of Technology: http://www.uoit.ca
- University of Saskatchewan: http://www.usask.ca
- University of Toronto: http://www.utoronto.ca
- University of Waterloo: http://www.uwaterloo.ca
- University of Western Ontario: http://www.uwo.ca
- École Polytechnique de Montréal: http://www.polymtl.ca
- University of New Brunswick: http://www.unb.ca
- Royal Military College: http://www.rmc.ca
- University of Guelph: http://www.uoguelph.ca

McMaster University and the University of Ontario Institute of Technology have instituted course-based “Nuclear Technology Diploma” programs for working professionals who want to broaden their knowledge in certain nuclear topics (for example, reactor physics or thermalhydraulics). The Nuclear Technology programs confer the Diploma on students who have successfully taken four university-based courses on specific topics. The Nuclear Technology Diploma programs are separate from the more intensive Master’s of Engineering offered by UNENE (see below).

The page at http://www.nuclearcanada.ca/nc-wiki/index.php?title=Universities collects links to universities and to professors active in nuclear science and engineering research and education in Canada.

4. Foreign Students

All Canadian universities readily accept foreign students – although the registration fees for foreign students are higher than for Canadian students. In the nuclear programs, foreign students currently represent a small number – perhaps 5% or at most 10% - of all students in the programs.

5. Research and Experimental Facilities

Canada has a large number of research and experimental facilities. The main ones are listed here:

- Research reactors at AECL’s Chalk River Laboratories:
  - ZED-2 for reactor-physics measurements
  - NRU for irradiation and testing of nuclear fuel and nuclear materials
- RD-14M, full-elevation thermalhydraulics loop at Whiteshell Laboratories, used for studying Loss of Coolant Accidents and Emergency Core Cooling phenomena, heat transport system stability, and natural-circulation
- Moderator Test Facility at Chalk River Laboratories, used to measure local moderator temperature and velocity distributions in 3 dimensions
- Large-Scale Vented Combustion Facility at Whiteshell laboratories, used to study hydrogen burning and explosions
- Large-Scale Containment Facility at Whiteshell Laboratories, used for gas-mixing tests and to simulate aerosol transport in containment
- Small-Scale Burst Test Facility at Chalk River Laboratories for research in fuel-channel performance
- Facility at Chalk River Laboratories to study molten-fuel-moderator interaction, as in a postulated fuel-channel rupture
- Hot Cells and other facilities at Chalk River Laboratories for research on materials and fuel performance
- Freon thermalhydraulics test loop at Stern Laboratories, used to measure critical heat flux
- 5-MW Nuclear Reactor at McMaster University, used for Neutron Activation Analysis (NAA), radionuclide production, research and teaching
- SLOWPOKE Nuclear Reactor at the Royal Military College, used for research and teaching
- SLOWPOKE Nuclear Reactor at École Polytechnique de Montréal, used for research and teaching
- SLOWPOKE Nuclear Reactor at University of Alberta, used for NAA and radionuclide production, research and teaching

6. National Links: UNENE Education and Research Network

To help increase the level of nuclear research in Canadian universities, and provide the nuclear manpower required by the Canadian nuclear industry in the future, the University Network of Excellence in Nuclear Engineering (UNENE) was established.

UNENE is an industry-driven alliance of universities, nuclear power utilities, research and regulatory agencies for the support and development of nuclear education, research and development capability in Canadian universities. UNENE was established as a not-for-profit corporation by the Government of Canada with Letters Patent issued July 22, 2002. Collectively supported by industry, governments and universities, UNENE, has started an integrated approach to address future workforce needs, create new or strengthen existing university expertise in nuclear technology and promote university-based nuclear research in Canada.

6.1 UNENE Objectives

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

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

6.2 UNENE Member organizations

Industrial Partners

Atomic Energy of Canada Limited (http://www.aecl.ca)
Bruce Power (http://www.brucepower.com)
Ontario Power Generation (http://www.opg.com)
Cameco Corporation (http://www.cameco.com)
Canadian Nuclear Safety Commission (http://www.nuclearsafety.gc.ca)
CANDU Owners' Group (http://www.candu.org)
AMEC-NSS (Nuclear Safety Solutions) (http://www.amecnss.com)

University Partners

McMaster University (http://www.mcmaster.ca)
Queen's University (http://www.queensu.ca)
University of Ontario Institute of Technology (http://www.uoit.ca)
University of Toronto (http://www.utoronto.ca)
University of Waterloo (http://www.uwaterloo.ca)

University of Western Ontario (http://www.uwo.ca)
École Polytechnique de Montréal (http://www.polymtl.ca)
University of New Brunswick (http://www.unb.ca)
Royal Military College (http://www.rmc.ca)
University of Guelph (http://www.uoguelph.ca)
University of Saskatchewan (http://www.usask.ca)

6.3 UNENE Educational Programs

UNENE educational programs consist of courses for professional development on one hand and full-time studies/research on the other hand. For professional development, there is a Master's of Engineering Degree in Nuclear Engineering which is accredited by the Ontario Council of Graduate Studies (OCGS). This is a course-based Master's of Engineering in Nuclear Engineering, offered by McMaster University, University of Waterloo, Western University and Queen's University. University of Toronto will join in the near future. Ten to twelve graduates are expected every year. This program is designed to provide practicing engineers with enhanced knowledge, tools, and technology, as well as business and management skills necessary to keep them at forefront of their profession. Uniquely it is offered outside working hours, in order to accommodate people who work in the nuclear industry.

- Through UNENE, the student can take a variety of courses in areas that are fundamental to nuclear-power-plant design, operation and safety, as well as to the technologies of many industries which use nuclear techniques. The program provides an overview of the fundamentals in many nuclear areas.
- In order to take any of the UNENE courses the student must be registered as a graduate student at one of the UNENE universities.
- A graduate student registered in a UNENE university is eligible to take all the courses in the UNENE program and be credited for them at the university where the student is registered.
- The requirement for a Master's of Engineering degree is ten UNENE courses or eight such courses plus an industrial project.
- Course costs are normally covered by the student's employer, as long as the student has passed the course.

UNENE courses are listed below. Details of course expectations can be found under the web link http://www.unene.ca/courses/coursedescriptions.htm

- Nuclear reactor physics
- Nuclear plant systems and operations
- Reactor thermalhydraulics
- Nuclear reactor safety design
- Project management for nuclear engineering
- Nuclear materials
- Radiation health risks and benefits
- Power plant thermodynamics
- Engineering risk and reliability
- Control, instrumentation and electrical systems in CANDU nuclear power plants
- Reactor chemistry and corrosion
- Fuel management
- Nuclear fuel waste management

- Industrial research project

The student will be granted a Master's in Engineering Degree from the University where he/she is registered upon the completion of 10 term courses or 8 term courses and an industrial project (equivalent to 2 term courses) within a five-year period, with a minimum passing grade of B- or 70% for each course / project.

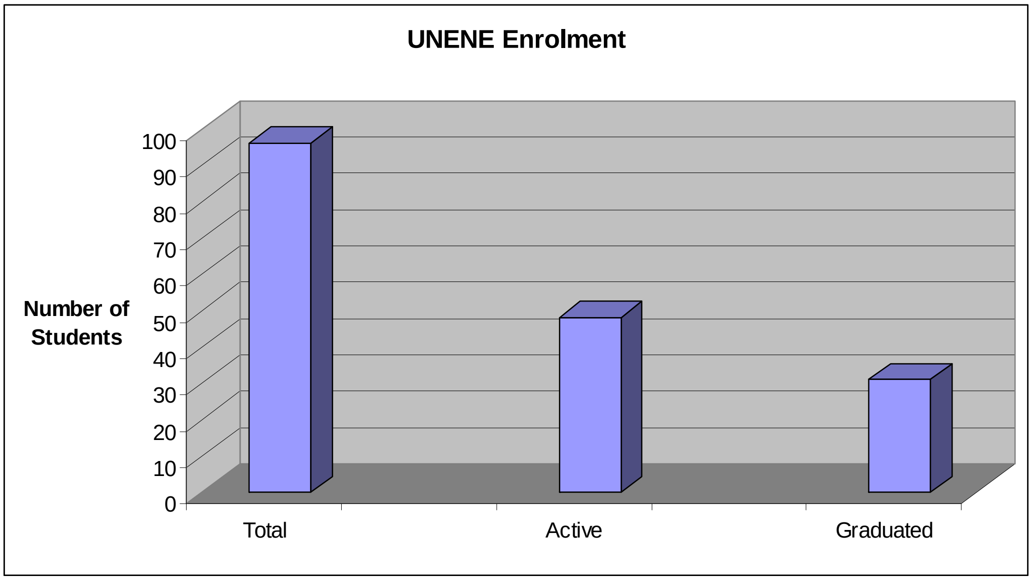
Eligibility

- Applicants must hold an honours baccalaureate (4-year) degree in the fields of engineering, science or mathematics, with an acceptable grade-point average, set by the university where admission is sought, for entry into a Master's degree programme in Engineering Physics (B or 75% minimum).

6.4 Enrolment in UNENE Courses

The total number of students, past and present, in the UNENE Master's of Engineering Program is now 96.

Of the 96, 31 have graduated from the Program, and 48 are currently active in it. See Figure below.



The new enrolment in the Program is growing, and this is expected to continue unabated.

Distance learning is being planned and is expected to bring in even more students from remote nuclear sites interested in registering in the Program.

6.5 UNENE Research Program

UNENE also enhances research and training of highly qualified personnel in CANDU technology by establishing Industrial Research Chairs (IRC) in Ontario universities and funding research at other Canadian universities. These research funds are complemented by matching funds provided by the National Science and Research Council of Canada (NSERC).

Since the creation of UNENE, seven IRCs, listed below, have been established. The Chairs were/are funded for 5 years in a first UNENE phase, and several of them are now being renewed for a second 5-year term. In addition, several Collaborative Research and Development (CRD) projects have been awarded to other researchers at Canadian universities.

The established IRCs and ongoing CRD projects allow the purchase of research equipment, the support of students, and the hiring of new faculty. UNENE facilitates research on a large number of industry issues, and many researchers have been and are being trained in specialized fields of CANDU technology to help replenish the eroding CANDU expertise in the industry.

The currently established UNENE/NSERC IRCs cover the critical areas of CANDU technology described below.

Nuclear Materials (Rick Holt and Mark Daymond, Queen's University): This chair program focuses its research on CANDU Fuel Channels (FC), basic mechanisms of Pressure Tube (PT) deformation and the effects of manufacturing variables, microstructure, and irradiation. The other focus of the Queen's chair program is the understanding of hydrogen effects on PT integrity and the behaviour of hydrides in zirconium to support research in Delayed Hydride Cracking and Fracture.

Nuclear Safety (John Luxat and David Novog, McMaster University): This chair program focuses on Nuclear Safety Analysis Methodology, primarily on "best estimate" models of physical processes, plant conditions and failure events. The program objective is to define the ranges of key plant parameters that ensure safety limits are met at a prescribed confidence level.

Nuclear Fuel (Brent Lewis, Royal Military College of Canada): The purpose of the Chair is to provide a better understanding of nuclear fuel chemistry, behaviour and performance in order to improve operating margins and safety in nuclear reactors.

Nano-Engineering of Alloys (Roger Newman, University of Toronto): The primary focus of research in this chair program is corrosion and protection of metals used in CANDU NPPs.

NPP Instrumentation and Control (Jin Jiang, University of Western Ontario): The objectives of this chair are to: (1) investigate new control concepts and systems in refurbishing the existing plants, (2) develop new techniques to increase the reliability of neutron flux detectors, and (3) develop new techniques to relate probabilistic-based risk-analysis techniques to plant maintenance and outage planning.

Risk-Based Life Cycle Management (Mahesh Pandey, University of Waterloo): The primary objective of this chair is to advance the life-cycle management of critical components of CANDU reactors, namely, Fuel Channels, Steam Generators and Feeder Pipes.

Health Physics and Environmental Safety (Anthony Waker and Ed Waller): The primary objective of this chair is to perform research on characterization of radiation sources, techniques to minimize radiation fields, the development of specialized radiation-detection devices, and the monitoring and modelling of the environmental impact of ionizing radiation.

6.6 Research-Based UNENE Graduates

As mentioned earlier, the research performed by the Industrial Research Chairs and also within the Collaborative Research and Development projects is not performed by Professors alone. Graduate Students participate in the research and thereby become Highly Qualified Personnel in the nuclear field.

The level of research being performed suggests that approximately 90 Master's and 30 Doctoral students will be participating in the short term, along with 15 Post-Doctoral researchers. Currently, there are 16 Master's, 10 Doctoral, and 10 Post-Doctoral candidates registered in the research programs.

7. Other University Research Chairs

In addition to the above UNENE IRCs, there are also other University Chairs established outside UNENE. For example:

- NSERC, NB Power and Atomic Energy of Canada Ltd. established the Chair in Nuclear Engineering in the Department of Chemical Engineering of University of New Brunswick. Since 1984 the Chair has taken a leading role in the training of personnel and the development of nuclear technology (www.unb.ca/che/Research/Research.html).

- Hydro-Québec has established the Industrial Chair in Nuclear Engineering affiliated to the Mechanical Engineering Department of École Polytechnique de Montréal. It supports a Nuclear Analysis Group (NAG) which is specialized in neutron transport, including the development of new numerical methods in transport theory and diffusion theory (www.polymtl.ca/recherche/rc/en/unites/details.php?Langue=A&NoUnite=29).

8. Other National and International Links

Canadian nuclear companies and Canadian universities enjoy many links to similar organizations and educational institutions worldwide, too many to list.

The Canadian Nuclear Association (CNA, http://www.cna.ca) is the trade association representing the interests of companies active in the Canadian nuclear industry. The CANDU Owners' Group (COG, http://www.candu.org) is a partnership of AECL and Canadian and offshore owners of CANDU reactors; it manages research projects for its members.

The Canadian Nuclear Society (CNS, http://www.cns-snc.ca) is the Canadian technical and learned society for individuals interested in the nuclear industry. It is dedicated to the exchange of information in the field of applied nuclear science and technology, and it organises national and international nuclear conferences. In order to help broaden the knowledge of the working professional, the CNS also organizes continuing-education (non-university-accredited) courses on CANDU Reactor Safety, CANDU Fuel, CANDU Plant Configuration, CANDU Chemistry, Eddy Currents, Regional Overpower Protection, etc. The CNS also has collaboration agreements with a large number of sister nuclear societies worldwide.

CANTEACH and NUCENG are other elements contributing to nuclear education in Canada. The CANTEACH site (canteach.candu.org) provides educational and training material, useful to nuclear professionals and students alike. It currently contains over 1500 CANDU-related technical documents. The Canadian regulator, the Canadian Nuclear Safety Commission, has kindly donated much of its training material for CANTEACH to use [I put this in as it is the only mention of CNSC anywhere!!]. NUCENG (http://www.nuceng.ca) is a site for students and others interested in Nuclear Engineering as it relates to the program in the Department of Engineering Physics, McMaster University.

UNENE serves as an additional link to organisations in the national and international nuclear field. UNENE actively participates in World Nuclear University (WNU) affairs. The role of UNENE in WNU is significant, as its officers and members serve on the WNU Academic Council Resource Committee and provide chair and membership of several Working Groups of WNU. In 2005/6, UNENE hosted visits from representatives of the Asian Network of Education in Nuclear Technology (ANENT) and the Nuclear Technology Education Consortium (NTEC) of the UK. Mutual web links have been created and collaborative discussions continue. UNENE participated in a UK-Canada nuclear workshop and UNENE is leading the Canadian half of the working group established at that workshop. The World Nuclear University's very successful 2008 Summer Institute was held in Ottawa, Canada.