Nuclear Education and Manpower Development

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ABSTRACT

The successful applications of nuclear technology in areas as divers as research, health care, non-destructive examinations, agriculture and electrical power generation are all dependent on the expert human resources available to the country or region utilizing this technology. The expertise needed to understand and safely employ nuclear energy includes skilled craftsmen, operators, technicians and technologists, engineers and scientists, managers and executives. Nuclear technology is complex, has unique safety and resource requirements, and represents a significant financial investment. While international agreements govern or provide guidelines for managing the technology, local conditions must be considered in the acquisition and operation of nuclear facilities. To embark on a nuclear power program and to successfully manage it, the governing bodies of the locality where the nuclear installation is to be located, as well as the country's government, must be active supporters of the related facilities. Furthermore, the country's government must put in place a regulatory system that is independent of the designers, owners and operators of the nuclear facilities, as well as systems that meet such international agreements as the Nuclear Non-Proliferation Treaty. The paper reviews Canadian and other international experience in providing the education and training needed for a country or region to successfully initiate and maintain the expert human resources complement in order to benefit from the peaceful uses of nuclear technology.

1. INTRODUCTION

As the world's population continues to grow, as the demand for food, potable water, shelter, health care and all aspects of one's standard of living continue to increase, the demand for the many beneficial uses of nuclear technology will keep rising. Already, in much of the developed world, one in three hospital visits involves the use of nuclear medicines and radiation equipment, the world's supply of food could be much enhanced by the extensive use of food irradiation, and the dwindling fossil fuel supplies, along with the increased awareness of the harmful effects of climate change, point to the need for significant increases in nuclear electric generation.

At the end of 2007 there were 439 nuclear power reactors operating in 31 countries. 76% of these are in one of four large economic entities, namely the European Union (144), US (104), Japan (55), and Russia (31). Other countries with significant nuclear programs are the Republic of Korea (20), Canada (18), India (17), the Ukraine (15) and China (11) (UIC 2007).

To a significant extent the above named countries have developed the capability to address all the critical elements of the nuclear fuel cycle, including fuel production, research, design, construction, commissioning, operation and maintenance of the power plants, and management of radioactive by-products. Countries with large reactor programs (10 or more generating units) have typically developed the capability to be not only self-supporting in all aspects of nuclear technology, but to also export equipment and services to other countries. All the major nuclear reactor vendors have shown a willingness to transfer much of the nuclear technology to countries that are embarking on a significant nuclear power plant construction program. The Republic of Korea is an excellent example of a country with medium size population and economy that installed both PWR (Pressurized Water Reactor) and CANDU (CANada Deuterium Uranium) type nuclear electric generating units, became self-sufficient in operating and maintaining both types of reactors, and subsequently developed and constructed units of its own design.

An essential part of a transfer of technology is having the human resources developed to receive and make use of the technology. In practice, indigenous experts are typically developed in each country once the political decision is made to consider the nuclear option. This first generation of local experts are needed for the country to be able to make independent evaluation of available options, to establish the regulatory climate, and to ensure that the technical infrastructure and economic frameworks are ready for the introduction of nuclear electric power plants. The first generation of experts typically receive undergraduate and/or graduate education in countries other than their own, and will often bring back with them understandable preferences for the type of technology their host country is using. For this reason, as well as to achieve a level of language and cultural diversity, it is advisable to have the first generation of experts study in more than one country, as well as having expatriates and foreign consultants from a variety of jurisdictions.

Canada is a good example of a country that welcomed foreign experts to help develop and advance its use of nuclear technology. Canada has had a leading role in the development of nuclear irradiation equipment for medical and industrial uses, it developed the unique CANDU power plant technology, has established educational institutions to support the nuclear industry, has exported much of the key equipment and transferred the technology to a number of countries, and assisted in the development of highly qualified personnel around the world.

2. THE CANDU STORY

During World War II a number of European academics doing nuclear research and experimenting with the creation of a fission chain reaction came to Canada, along with a significant portion of the then available world supply of heavy water. Uranium production was already established in Canada and the achievement of the first nuclear chain reaction outside the US took place in 1945 at Canada's Chalk River Nuclear Laboratories, using heavy water and natural uranium.

Nuclear-electric unit	Country (Province)	In-service year	Rating (Gross MWe)
Pickering 1	Canada (Ontario)	1971	542
Pickering 2	Canada (Ontario)	1971	542
Pickering 3	Canada (Ontario)	1972	542
Pickering 4	Canada (Ontario)	1973	542
RAPS 1	India	1973	100
Bruce 1	Canada (Ontario)	1977	825
Bruce 2	Canada (Ontario)	1977	825
Bruce 3	Canada (Ontario)	1978	825
Bruce 4	Canada (Ontario)	1979	825
RAPS 2	India	1981	200
Point Lepreau	Canada (New Brunswick)	1983	680
Wolsong 1	Republic of Korea	1983	679
Pickering 5	Canada (Ontario)	1983	540
Gentilly 2	Canada (Quebec)	1983	675
Embalse	Argentina	1984	648
Pickering 6	Canada (Ontario)	1984	540
Bruce 6	Canada (Ontario)	1984	915
Pickering 7	Canada (Ontario)	1985	540
Bruce 5	Canada (Ontario)	1985	915
Pickering 8	Canada (Ontario)	1986	540
Bruce 7	Canada (Ontario)	1986	915
Bruce 8	Canada (Ontario)	1987	915
Darlington 2	Canada (Ontario)	1990	935
Darlington 1	Canada (Ontario)	1992	935
Darlington 3	Canada (Ontario)	1993	935
Darlington 4	Canada (Ontario)	1993	935
Cernavoda 1	Romania	1996	706
Wolsong 2	Republic of Korea	1997	715
Wolsong 3	Republic of Korea	1998	700
Wolsong 4	Republic of Korea	1999	700
Qinshan 4	China	2002	728
Qinshan 5	China	2003	728
Cernavoda 2	Romania	2007	706

Table 1: In-service dates and gross ratings of CANDU nuclear-electric units (STEED 2007)

The rapid post-war economic growth in Canada, and in particular in its most industrialized and populous province, Ontario, led to significant increases in electricity consumption that could no longer be supplied by Niagara Falls and the remaining sites suitable for hydro-electric generation. Coal had to be imported from the US and/or Alberta, which was contrary to Ontario's desire to maintain the economic advantages of cheap and plentiful electricity supply, as well as electrical energy independence. The early success with natural uranium fuelled and heavy water moderated technology led to the development of the CANDU reactor.

The proof of concept plant, NPD (Nuclear Power Demonstrator) had an output of 22 MWe, and operated from 1962 to 1987. The prototype CANDU unit Douglas Point generated 220 MWe, and operated from 1968 to 1984. Commercial units in the Canadian Provinces of Ontario, New Brunswick and Quebec followed in quick succession, as did the construction of CANDU power plants in India, South Korea, Argentina, Romania and China. The CANDU commercial units constructed in Canada and abroad are shown in Table 1. It should be noted that it has been possible to place in-service two or three units in a given year, both in the domestic and the export market.

3. HUMAN RESOURCE REQUIREMENTS

3.1 The early Canadian experience

How was it possible for a country such as Canada, with limited manufacturing capability and expertise, to develop the CANDU technology and to bring to commercial success such a major undertaking as the design, construction, operation and maintenance of so many nuclear power plants? Key aspects include the skill and dedication of the work force, and the support of federal, provincial and municipal governments. While getting started in the 1940s with nuclear research was a factor, the cooperation of electrical utilities (such as Ontario Hydro), multinational industry giant General Electric, several well-established Canadian companies (including Babcock-Wilcox, Montreal Engineering and Shawinigan Water and Power company) and the federally funded Atomic Energy of Canada Limited (AECL) were also essential to the successful deployment of nuclear power plant technology (HURST D.G., 1997).

The early nuclear physics and chemistry expertise came from Canadian universities and through immigration during and after World War II. Some of the expertise required to design, construct and operate conventional power plants already existed in Canada. Additional technical skills were available through consulting companies, and the uniquely nuclear capability was acquired by selective immigration, particularly from the UK. On an as-required basis nuclear-specific training was given to the engineers and other technical personnel required to bootstrap the knowledge and skills required for the demonstration and prototype units. The experience gained from operating these units, supplemented by the work done on the NRX and NRU research reactors at the Chalk River Nuclear Laboratories, created the knowledge base for the CANDU industry.

It became evident in the early 1970s that Ontario was committed to a strong reliance on nuclear-electric generation, and over the next 20 years a total of 20 CANDU units were placed into operation. Much of the design work for the reactor and for key equipment for these power plants, as well as for the units in New Brunswick and Quebec, took place in Ontario. At the same time there was a growing demand for engineers, technicians, operators and maintainers by the utilities that owned these units, as well as the need to provide training for the units being exported. Universities in Ontario, particularly McMaster University and the University of Toronto developed and offered undergraduate courses and graduate degrees in nuclear engineering. On a smaller scale, since there was only one CANDU plant in each of Quebec and New Brunswick, Ecole Polytechnique in Montreal and the University of New Brunswick in Fredericton also prepared nuclear courses and offered research, training and consulting services to the provincially owned utilities. The combination of locally developed experts, experienced immigrants and the new university graduates, supplemented by specific industry training courses, produced the required quality and quantity of experts.

3.2 Thai-Canadian Nuclear Human Resources Development Linkage Project

While Canada had a relatively long time, over 25 years from the first critical assembly to placing the first commercial CANDU unit into service, how can countries and regions that are making the decision more recently to add nuclear power plants to their electricity generation capacity, shorten the time from the initial decision to having nuclear units in operation? Given the current maturity of the nuclear power plant industry and the number of vendors offering a range of reactors with different technologies and capacities, most countries wanting to acquire nuclear power plants are almost certain to purchase their first few units from one of these vendors. Depending on the policies of the government and the electrical utility, the units may be purchased outright (often with attractive financial terms) or be acquired using the "build-operate-transfer" model. In most cases the purchasing country will also insist on significant levels of local content and technology transfer. Concomitant with this will be the need to train local personnel in the key support industries, including manufacturing and construction companies, and the owner/operator utility's operating, maintenance and technical staff.

An example of a human resources development (HRD) project that addressed many of the above issues took place between 1995 and 2001 under the Thai-Canadian Nuclear HRD Linkage Project (Table 2). The Thai government expressed and interest in 1994 to start preparation for a planned acquisition of nuclear power plants by 2010, and accepted an offer from AECL and CIDA (Canadian International Development Agency) to help develop some of the key human infrastructure (SUMITRA, 1998).

The Project was designed to develop the highly qualified personnel needed for utilities, regulators and government, as well as by engineering, manufacturing and construction companies. These people were identified as having a key role in evaluating the nuclear power option for Thailand, and if the decision to proceed was made, to ensure that its construction, operation and maintenance met international standards of safety and environmental impact. Within the overall project objective, the plan was to upgrade the academics and industry people who were already involved in nuclear technology, as well as to establish the framework for developing new technical personnel through university education and professional development training programs.

The Thai institutions and companies that had a particular interest in such a project included Chulalongkorn University, the Electricity Generating Authority of Thailand (EGAT) and the Office of Atomic Energy for Peace (OAEP). The training program consisted of 35 courses (Table 2), each delivered over a two week period of full time attendance. Present and future faculty, engineers and scientists working in industry, as well as graduate students were the main participants in these courses. A combination of Canadian university professors and industry experts delivered them in Thailand. Over 400 Thai participants attended one or more of these courses.

An important aspect of engineering education and training is the need for practical work. Without access to a power plant, this is difficult to realize for power plant engineering, and particularly so for nuclear generating station technology. The approach used by utilities and increasingly by universities is to use computer simulation to provide the hands-on aspect of power plant design, analysis and operation. The need for simulation was identified in the HRD Project proposal, and computers and simulation software were acquired to support the education and training courses.

1. Reactor Physics
   - 1.1. Nuclear Theory I (Statics)
   - 1.2. Nuclear Theory II (Kinetics)
   - 1.3. CANDU Reactor Kinetics
   - 1.4. Reactor Physics & Fuelling Strategies
   - 1.5. Reactor Core Analysis
   - 1.6. Monte Carlo Method for Particle Transport Simulation
   - 1.7. Reactor Analysis Computational Methods
2. Reactor Thermalhydraulics
   - 2.1. Introduction to Reactor Thermalhydraulics
   - 2.2. Thermal Study of Nuclear Reactors
   - 2.3. Reactor Thermalhydraulics Design
3. Nuclear Power Plant Engineering
   - 3.1. Introduction to Nuclear Power Engineering
   - 3.2. CANDU Overview
   - 3.3. Reactor Simulation and Control
   - 3.4. Nuclear Plant Control Design
   - 3.5. Nuclear Reactor Containment Design
   - 3.6. Reactor Mechanical Design
   - 3.7. Nuclear Reactor Safety Analysis
4. Nuclear Power Plant Management
   - 4.1. Radiation Protection
   - 4.2. Operational Reactor Safety
   - 4.3. Nuclear Plant Operation & Maintenance
   - 4.4. Peer Evaluation Techniques
5. Nuclear Fuel Cycle
   - 5.1. Reactor Siting & Licensing
   - 5.2. Introduction to Radiation Waste Management
   - 5.3. Radiation Waste Management Engineering
   - 5.4. Radiation Waste Management Assessment
   - 5.5. Radiation Waste Management Field Study
6. Other Nuclear Applications
   - 6.1. Radiation Processing
   - 6.2. Neutron Activation Analysis
7. General Industry
   - 7.1. Quality Management
   - 7.2. Non-Destructive Testing
   - 7.3. Corrosion for Engineers
   - 7.4. Instrumentation and Control
   - 7.5. Welding Engineering
   - 7.6. Public Education
   - 7.7. Managing for Results

Table 2: Training courses delivered under the Thai-Canadian Nuclear HRD Linkage Project

As a result of the Asian economic downturn in 1997 and the availability of inexpensive natural gas from Myanmar, Thailand had postponed the acquisition of its first nuclear power plant from the early years of the new millennium to some time after 2010. However, much of the individual expertise, the education and training infrastructure created under the HRD Linkage Project remained in place and are expected to have a significant role in establishing nuclear-electric generation in Thailand.

3.3 University Network of Excellence in Nuclear Engineering (UNENE)

While Canada succeeded, as described in section 3.1, in acquiring and developing the highly qualified personnel to design, construct and operate nuclear power plants using CANDU reactors, it became apparent in the late 1990s that not only were many of the older units in need of life-extension, but the nuclear expert were also reaching retirement age. Following the large hiring efforts to staff the nuclear industry in the 1970s and 1980s, demand for new hires decreased and was virtually eliminated by 1990. With no additional new nuclear units planned in Ontario beyond Darlington, there were layoffs of design and construction staff, as well as giving early retirement incentives to operating and maintenance personnel. Collective agreements favoured workers with 25 or more years of experience, resulting in a major loss of experienced staff. Although some of the people taking early retirements subsequently rejoined the industry as consultants or contract workers, there was a significant loss of knowledge and experience that resulted in units being shut down for extended periods.

In recognition of the impending shortage of engineers in the nuclear industry, the two largest nuclear operating utilities, Ontario Power Generation (a successor company of the former Ontario Hydro) and Bruce Power, and the principal CANDU design company Atomic Energy of Canada Limited decided in 2002 to establish a fund of $8M to create in Canada the University Network of Excellence in Nuclear Engineering (UNENE) with the following objectives:

- enhance the supply of highly qualified graduates in nuclear engineering and technology;
- reinvigorate university-based research and development in nuclear engineering and science, with the focusing on mid to longer term research;
- create a group of university-based nuclear experts for public and industry consultation.

Currently six universities are funded under this initiative, allowing each of them to appoint an industrial research chair professor, hire post-doctoral researchers, fund doctoral and masters students, and to conduct research of particular interest to the industrial partners. The six universities are Queen's University, McMaster University, University of Toronto, University of Waterloo, University of Western Ontario, and the Royal Military College. The seventh chair, at the University of Ontario Institute of Technology, is expected to be approved in 2008. A significant benefit of Canadian industry funded research chairs is that they receive matching funds ($1M per chair) from the National Science and Engineering Research Council (NSERC). Smaller amounts (typically in the order of $100k per project) are awarded to university researchers not working directly in the chair programs, and these also receive matching NSERC funds.

The above universities also cooperate in delivering a course-based Master of Nuclear Engineering program. The usual graduate studies standards are applied for admission into the program. A total of 10 courses must be completed to meet the graduation requirements. In 2007 UNENE funding enabled 16 masters, 10 doctoral and 10 post-doctoral candidates to conduct research in nuclear science and engineering. 30 part-time students are enrolled in the course-based M.Eng. program, 10 graduated earlier in the year, and approximately the same number is expected to graduate in each of the next several years.

3.4 The University of Ontario Institute of Technology (UOIT)

The UNENE initiative has principally been aimed at university research and graduate programs. However, the majority of the engineers working in the nuclear industry are graduates of bachelor degree programs, which UNENE only addresses indirectly, via the chair professors offering some undergraduate courses. Given the history of Canada's nuclear industry, namely the rapid build-up in the 1970s and 1980s of nuclear engineers, as well as engineers from such traditional disciplines as mechanical, electrical and chemical engineering who received nuclear specific training after joining the industry, universities did not develop undergraduate nuclear engineering programs. McMaster University and the University of Toronto have offered nuclear options in engineering physics and mechanical engineering respectively, but the graduates of these programs still required much the same industry-specific training as the graduates of the previously mentioned programs.

The combination of the aging nuclear work force, the need for additional engineers to work on life-extension projects, and the recent decision by the Government of Ontario to have new nuclear units built in the Province, created a level of demand for nuclear engineering graduates that justified the creation of an undergraduate nuclear engineering program. The Government also recognized that the established government funded universities were not meeting the demands by students for access to university education, nor the needs of certain industries for graduates in short supply. These considerations led to the establishment of a new university east of Toronto in the City of Oshawa in 2002. Nuclear Engineering, Health Physics and Radiation Science are two programs offered at UOIT, in response to specific demand from the nuclear industry for such graduates.

The first cohort of 40 students graduated from these programs in June 2007, and similar numbers are expected to complete these programs in subsequent years. Although the universities receiving UNENE funds are producing graduates at the masters and PhD levels in nuclear engineering, given the location of UOIT within 25 kms of the Darlington and Pickering nuclear plants and in close proximity to several nuclear design and consulting companies, UOIT is also planning to offer graduate programs in nuclear engineering. The masters program is expected to commence in September 2008.

The combination of undergraduate and graduate level courses offered by UOIT is expected to make a significant contribution to meeting the industry's demand for nuclear engineering education in Ontario. In particular, many of the graduates of the traditional engineering degree programs who find employment in the nuclear industry are expected to take several of the nuclear courses offered by UOIT. The list of courses currently offered or under development is given in Table 3.

3.5 Training of skilled craftsmen

The previous sections concentrated on university programs, but the largest group of workers with special skills belong to the trades, principally the constructions, operation and maintenance trades. In terms of specialized skills, large numbers of civil maintainers, mechanical maintainers (welders, fitters and turners) and electricians are required. Once the nuclear plant is ready for commissioning and to be placed in-service, additional specialists such as chemical, instrumentation and control technicians, non-destructive examination technologists are needed. Because of the radiation risk that is unique to nuclear facilities, significant numbers of health physicists are employed, and various levels of radiation protection training is given to all workers, the extent of the training being determined by the potential radiation risk.

Different countries and jurisdictions have various approaches to the training of skilled craftsmen and the type of specialists indicated above. Some form of post-secondary education is usually combined with on-the-job training, often in the form of an apprenticeship. Technical colleges, both state and privately funded, are available to educate and train the technicians and technologists. Health physics specialists come from both college and university programs. In all cases plant-specific training needs to supplement the post-secondary formal education. Since not all parts of the plant are accessible or suitable for hands-on training, equipment similar to what is used at the plant is installed at local training centres, and often presented in an environment that closely replicates the system configurations found inside the power plant.

3.6 Training of operators and shift supervisors

In Canada, as in many other countries with nuclear power plants, the control room operators and their supervisors, including the shift supervisor or manager, must be authorized (or "licensed") by the country's nuclear regulator. These key operating personnel undergo extensive training and must have had several years of operating experience at the nuclear plant at which they are authorized to perform these roles. In the past, a high school diploma was the entry-level educational requirement for the operator training program in Canada, but more recently this has been replaced by two or three year college diplomas. These diplomas are typically at the technician or technologist level, in either mechanical, chemical, electrical, instrumentation or control specialties. At least five years of on-the-job experience and training are required for such a person to become an authorized control room operator, including having to pass examinations specified by the nuclear regulator. A critical feature of getting the necessary qualifications is extensive training and testing on full-scope simulators that replicate the physical and functional characteristics of the plant's control room and systems.

Undergraduate courses	**Graduate courses**
Problem Solving, Modeling & Simulation	Project Management for Nuclear Engineers
Introduction to Nuclear Physics	Mathematical Methods in Nuclear Applications
Radiation Protection	Transport Theory
Health Physics Laboratory	Monte Carlo Methods
Nuclear Reactor Kinetics	Applied Risk Analysis
Safety and Quality Management	Nuclear Concepts for Engineers and Scientists
Environmental Effects of Radiation	Environmental Modelling
Scientific Instrumentation	Advanced Topics in Environmental Degradation of Materials
Nuclear Plant Chemistry	Occupational Health and Safety
Nuclear Plant Safety Design	Reactor Physics
Corrosion for Engineers	Advanced Reactor Physics
Radioactive Waste Management Design	Advanced Reactor Engineering
Nuclear Plant Operation	Fuel Management in Nuclear Reactors
Risk Analysis Methods	Advanced Nuclear Thermalhydraulics
Heat Transfer and Thermodynamic Cycles	Heat Transfer in Nuclear Reactor Applications
Shielding Design	Power Plant Thermodynamics
Nuclear Materials	Reactor Containment Systems
Nuclear Plant Design and Simulation	Control, Instrumentation and Electrical Systems in CANDU based Nuclear Power Plants
Reactor Control	Advanced Reactor Control
Nuclear Reactor Design	Advances in Nuclear Power Plant Systems
Nuclear Fuel Cycles	Advanced Topics in Radioactive Waste Management
Principles of Fusion Energy	Advanced Radiation Science
Medical Imaging	Physics of Radiation Therapy
Introduction to Radiological and Health Physics	Aerosol Mechanics
Radiation Biophysics and Dosimetry	Advanced Dosimetry
Therapeutic Applications of Radiation Techniques	Advanced Radiation Biophysics and Microdosimetry
Industrial Applications of Radiation Techniques	Non-destructive Analysis
Radioisotopes and Radiation Machines	Industrial Radiography
Radiation Detection and Measurement	Nuclear Forensic Analysis

Table 3: Undergraduate and graduate courses that are unique to the nuclear programs at UOIT

Shift supervisors/managers typically have a university degree, mostly in engineering, although some operators have been able to achieve promotion to this level without a university degree. Additional operating experience, training, testing and supervisory ability must be demonstrated by the people who aim to become shift supervisors. Operators and shift supervisors must undergo frequent re-training and re-qualification, including many hours on the simulator under normal as well as abnormal and emergency conditions. The ability to work as a team member and team leader are critical aspects of the evaluation process.

In many jurisdictions an appropriate university degree is required for the shift supervisor position, and often also for the control room operator position. This trend is expected to grow in recognition of the continuously increasing complexity of the power plants, the operating procedures, and the regulatory requirements.

4. CONCLUSION

The safe and reliable operation of a nuclear power plant or related facility depends as much on the selection of the technology and hardware as on the qualification and experience of the human resources employed by the facility's owner. A company negotiating the purchase of a nuclear generating station needs to ensure that the expert manpower needed to construct, operate and maintain the facility will be made available by the vendor, as well as ensuring that the owner's staff complement receives the necessary plant-specific training to operate and maintain the plant with its own employees.

The acquisition and development of the human resources will come from a combination of well educated recent graduates, people with experience in related industries such as process and energy production companies, and a core of senior staff with experience in the particular type of power plant to be operated.

To ensure the on-going additions to and replacements of expert staff, the operating units need to establish strong partnerships with the owners of similar units in the region, and with the key educational institutions that produce graduates with the desired technical knowledge and personal attributes. Partnerships with universities are particularly important, not only to produce graduate engineers, scientists, managers and IT professionals, but to conduct research and provide expert consulting services when needed.

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