Report of the AECL Research & Development Advisory Panel for 1999

Report of the AECL R&D Advisory Panel for 1999

D.A. Armstrong

D.H. Lister

R.L. Armstrong

E.A. McCulloch

D.J. Burns

G.G. Patry

A.A. Driedger

J.T. Rogers

J.H.F. Jennekens

D. Rozon

J.J. Jonas

REPORT OF THE
AECL R&D ADVISORY PANEL FOR 1999

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Benefits to Society

Nuclear science and engineering have become so deeply embedded into the way of life in developed societies, that the average citizen is unaware of what the consequences of their withdrawal would be. Further research is still needed in order that society may continue to benefit from the possibilities that exist for the production of energy, while avoiding greenhouse gas emissions, and for new knowledge of the structure of materials.

Without inclusion of nuclear in the energy mix, in both developed and developing countries, it will not be possible to achieve the desired abatement of greenhouse gas emissions that Canada and other countries committed to in the Kyoto Protocol. Canada is a leader in the non-proliferative exploitation of nuclear technology, and a beneficiary of nuclear science through the international marketing of CANDU® and MAPLE reactors and related products, which also contributes significantly to economic development and job creation. It is in the interest of Canada that public funding of nuclear research and development should continue.

Safety

It is a primary concern of vendors, regulators, operators, and customers that all nuclear technology should be safe and, to this end, the Atomic Energy Control Board (AECB) issues licenses and inspects all nuclear facilities in Canada. It is also a requirement of international sales that the AECB have determined that the product would be licensable in Canada.

Since 1988, the AECB has identified a number of postulated modes of reactor failure that are considered to be generic to CANDU[†] stations, and has required the licensees to provide information about the margins of safety under those failure conditions. The responses necessary to satisfy these Generic Action Items have often required research and development for which AECL's facilities have been essential, even though the onus for the responses rested with the utilities. More recently, the AECB has moved to bring closure to a number of Generic Action Items which have been outstanding for some time.

Computer Codes

Much of AECL's intellectual property is formalized in computer codes for the design and safety analysis of CANDU systems. The codes are mathematical models that describe physical phenomena. They are tested in the laboratory and the levels of uncertainty attached with their use are established before they are deployed. At present, about one third of the safety-related R&D being done in AECL and under CANDU Owners Group programs is devoted to code development. AECL has developed and is implementing a

[†] CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL).

software quality assurance policy to guide its code development processes. Concurrently, the Atomic Energy Control Board has issued a Generic Action Item defining its requirements in this area and the criteria for closure of the item. This exercise is serving to define a body of professional skills that AECL must retain if it is to continue to develop, maintain and use this essential resource.

CANDU Reactors

The Zr-2.5% Nb fuel channel is at the heart of the CANDU reactor and its service life is determined by a tendency to undergo geometric distortion under operating conditions, as well as by a change in fracture toughness resulting from the pickup of deuterium. These behaviours have been taken into account through specification of materials, fuel channel design and protocols for inspection of fuel channels in operating reactors, for which latter purpose AECL has designed a new inspection machine.

The development of the CANFLEX fuel bundle was a significant advance, and the use of this fuel design will, in the short term, offset power derating that otherwise becomes necessary when aging fuel channels undergo geometric distortion. The CANFLEX fuel bundle also opens up the possibility of introducing slightly enriched uranium fuel and low void reactivity fuel as fueling options for existing or future reactors. These fueling possibilities offer advantages for the intermediate future. For the long term, the Direct Use of PWR Fuel in CANDU (DUPIC) option for the recycling of used pressurized water reactor (PWR) fuel through CANDU remains possible. The milestone achieved at the Chalk River Laboratories, in the past year when the first fuel pellets from used PWR fuel were produced by the proposed DUPIC process, makes this option more plausible for the long term.

A very positive feature of the CANDU design is that its performance is competitive with current PWR designs and it has much potential for further improvements in efficiency, for adaptation to fuels other than natural uranium, for the addition of passive safety features, and for reductions in capital and operating costs. AECL is conducting research on designs that would operate at higher temperatures and pressures up to those of supercritical water. The possibility of natural circulation, rather than pump-driven flow, is an example of an innovation that would simultaneously contribute to all the above goals. However, detailed studies are needed to determine the effects of sustained operation on materials and components under these conditions. The need for a different form of pressure tube may be met in the form of the CANTHERM composite fuel channel design. To address the requirement of on-power fueling, a new bore seal has been designed. Other requirements for the Advanced CANDU Reactor Concept (CANDU-X) include corrosion-resistant fuel cladding for the highest temperatures envisaged. Although CANDU-X is a concept rather than a tangible product, the products that evolve from this work can be progressively incorporated into the evolution of CANDU, thus ensuring that successive models will be ever more like CANDU-X.

Heavy Water

Heavy water is the moderator in CANDU reactors. It is essential that AECL has an assured supply of heavy water to service its projected reactor sales. An aggressive research program to develop efficient new ways to concentrate heavy water has culminated in the construction and commissioning of a prototype Combined Industrial Reformed Hydrogen Catalytic Exchange (CIRCE) plant at Air Liquide in Hamilton. If the prototype proves successful, a number of full- scale plants based on this principle will be required.

Collaboration with the Scientific Community

AECL's intellectual property can only be maintained and developed through the recognition of the national and international science community. Over the decades of its existence, AECL has often supported and benefited from collaborative scientific ventures. It is more important now than ever before that maximum benefits be realized from any expenditures for research infrastructure. The proposal to construct the Canadian Neutron Facility (CNF) as a partnership between AECL and the National Research Council exemplifies the point. The construction of this facility, in a timely fashion, remains the highest priority if AECL is to continue as an innovative reactor vendor with the ability to support its customers through post-sales R&D support. Radiation Biology and Health Physics, hitherto supported entirely as an in-house unit, similarly needs to be repositioned in order to give its scientists the independent public accountability and integration into the fabric of biological science in Canada that they need. Finally, the Panel has reviewed the value that accrues to AECL through its relationships with universities, through the funding of professorial chairs, research contracts and studentships and through the support of co-op programs. The underlying science that is eventually formalized into a product design only happens through the activity of creative and highly trained human minds supplied with the resources necessary for their enterprise. In an era of increasing specialization, the essential ferment can be maintained through partnerships that break down traditional barriers between industry and academe.

CHAPTER 1: INTRODUCTION

This is the eighth annual Report of the R&D Advisory Panel to the AECL Board of Directors, as required by the terms of the Panel's mandate. In preparation for the development of this report, the whole Panel, met on four occasions for a total of ten days to consider presentations by AECL's scientific, product engineering and marketing staff, concerning the development of the CANDU reactor. There were many additional Task Team meetings held throughout the year to develop the material presented in this report.

The Panel also met with representatives of Environment Canada, Industry Canada, the Climate Change Secretariat, the Atomic Energy Control Board (AECB), and Ontario Power Generation Inc. (formerly Ontario Hydro) in order to better understand issues relating to energy and environmental policy development, the regulatory environment, and the needs of AECL's largest customer for research and development support.

The Panel was invited by Natural Resources Canada (NRCan) to prepare a report entitled "A Rationale for Canadian Expenditure on Nuclear Research and Development in the 21st Century", a shortened version of which appears as Chapter 2. The central argument contained therein has been adapted into a version suitable for wider distribution under the title "Vision 2020 and Beyond: The Need for Nuclear Research and Development in Canada in the 21st Century".

The contents of this Report fall under the following inter-related themes:

1. Strategic issues (Chapters 2 and 3), in which nuclear research and development is reviewed in the context of AECL's historic and current issues and with respect to the increasing importance that the Panel attaches to avoidance of greenhouse gas (GHG) emissions in energy production.
2. CANDU R&D issues are reviewed briefly in Chapter 4. Safety, licensing and computer codes discuss licensing processes with the AECB and the closure of Generic Action Items (GAIs) is addressed. The section on computer codes follows directly out of the most recently issued GAI concerning standards and quality assurance. The Panel recognizes the importance of codes, which represent a form of intellectual property management, and intends to follow up in future reports on this introductory review. Plant life management and life extension follows on from previous Reports concerning the behaviour of materials and components in use. Advances in CANDU technology have been significant and the Panel has updated earlier reports concerning advanced fuel cycles, new means of heavy water production, and the CANDU-X concept.
3. Partnerships for research and development are covered in Chapters 5, 6 and 7. AECL and the Canadian research community interact in many arenas. The respective challenges facing the Canadian Neutron Facility (CNF) and the Radiobiology and Health Physics Program at Chalk River Laboratories (CRL) are reviewed. In both cases, the resolution of the challenges will depend heavily on AECL maintaining close relationships with the appropriate academic communities. Finally, the Panel has reviewed the importance of AECL's relationships with universities as requested by the Science and Technology Committee of AECL's Board of Directors.

The Panel's views are summarized at the end of each chapter or section (in the case of Chapter 4) in a total of 22 recommendations.

The Panel membership was strengthened in 1999 through the appointment of two new members, Dr. Robin Armstrong and Dr. Gilles Patry, who joined in May.

The Panel wishes to acknowledge the excellent cooperation it has enjoyed with the many AECL staff who presented their work on request, provided additional materials when asked, and who were always helpful in response to our questions. We especially thank Barbara Gray and Marilyn Lloyd who clarified policies, facilitated our requests, identified sources of information and assured the infrastructure that is required to prepare a report. The preparation of this Report would not have been possible without their whole-hearted collaboration.

CHAPTER 2: RATIONALE FOR NUCLEAR RESEARCH AND DEVELOPMENT

2.1 INTRODUCTION

Maintenance of a high living standard for Canadians requires, among other things, the assurance of a reliable, robust and competitive energy supply. An assured energy supply for the nation is, and will remain, a primary requisite for sustained wealth creation. A major purpose of national energy policy must be to safeguard energy sources through prudent planning, development and diversification. Events such as the 1973 oil embargo illustrate the importance of ensuring that Canada will continue to enjoy an adequate, diverse, reliable and competitive energy supply.

Energy policy must take into account the resources available for energy production in the country. Canada has an abundance of hydropower, natural gas, petroleum and coal, and is the world's leading uranium exporter. One result of this abundance is that Canada enjoys a diverse mix of electrical energy sources quite different from that of most developed countries, with significant reliance on hydro and nuclear power, and much less reliance on fossil fuel power. This has benefited Canada by providing economical and reliable electricity with much lower emissions of GHG and other air pollutants than almost all other industrialized countries.

Nuclear power plants account for 14% of Canada's electrical power output at this time, most of this electricity being produced in Ontario. Nuclear technology has also benefited Canada in many other fields, including medicine, industry, agriculture, the environment and the home.

To ensure that Canadians can continue to enjoy the benefits of reliable, low-cost and environmentally benign electrical energy, as well as the many other benefits of nuclear technology, the Panel strongly believes that nuclear science and engineering must be developed and sustained as an integral part of Canada's high technology profile. Because of the economic, health and environmental benefits of nuclear technology, we urge that the Canadian investment in R&D in nuclear science and engineering be continued and strengthened.

2.2 HISTORICAL ACCOMPLISHMENTS OF CANADIAN NUCLEAR SCIENCE AND ENGINEERING

The excellence of Canadian nuclear science throughout the last half century has been internationally acknowledged in a variety of ways including:

- development of the CANDU reactor, one of only three currently viable power reactor technologies;
- development of MAPLE research and isotope production reactors;
- development of products, such as medical radioisotopes, that improve the quality of human lives;
- representation on international nuclear science bodies;
- participation in the control of nuclear weapons proliferation; and

- the award of a Nobel Prize.

Several tens of thousands of Canadians derive their employment directly or indirectly from the investment in Canadian nuclear science and engineering research. About 150 Canadian firms and 3,000 subcontractors, scattered across the country, benefit from each international CANDU sale. The distribution of these firms is exemplified by the manufacture of pump seals by Sulzer Canada in British Columbia, the mining of uranium by Cameco in Saskatchewan, the manufacture of steam generators by Babcock & Wilcox in Ontario, the construction of calandria assemblies by GEC-Alsthom Energies in Quebec, and the manufacture of nuclear reactor control equipment by Adtech Manufacturing in New Brunswick.

In addition to providing employment opportunities, nuclear science and engineering contribute to improvements in the quality of life for Canadians at every turn through the innovative products they make possible. For example:

- In power generation, CANDU reactors have produced many thousands of terawatt-hours of economical and safe electricity in Canada and other countries.
- In biology, isotopes have made the molecular revolution possible. The design of highly effective new treatments, based on an accurate understanding of life at the molecular level, is a direct result of the application of nuclear sciences to biology.
- In cancer care, the Cobalt-60 cancer therapy unit, developed in Canada, is still widely used around the world and especially in developing countries. Canada supplies about 80% of the cobalt sources used in these units. Canada also supplies two thirds of the world's reactor-produced radioisotopes for nuclear medicine, with which 20 million diagnostic tests are performed each year world-wide.
- In materials science and engineering, the development of neutron scattering techniques at Chalk River's NRU (National Research Universal) Reactor, which led to the Nobel Prize in physics for Dr. Bertram Brockhouse in 1994, has enabled some of the metallurgical and mechanical properties of components such as turbine blades to be determined rapidly and non-destructively.
- In agriculture, the sterile insect technique, in which Canada played a leading developmental role, has controlled the Codling Moth in British Columbia apple orchards and the New World Screw-Worm Fly infestation of cattle in Libya, and has eliminated the Tsetse Fly cattle pest on the island of Zanzibar. Cobalt-60 irradiators are also used for such diverse agricultural applications as the sterilization of infected beekeeping equipment and destruction of parasites in wool.
- In the mining industry, neutron activation analysis is used to obtain inexpensive and rapid analysis of ore samples.
- In the oil industry, well-logging by radioisotopes and pipeline radiography are important tools.
- In many manufacturing industries, from fine paper to jet aircraft, nuclear technology is used for radiography, process control and quality assurance purposes.
- In environmental protection, nuclear technology is used to detect and measure a wide range of industrial pollutants.

- In the food industry, irradiation of meats and fruits to sterilize, prolong shelf lives and prevent potentially lethal poisoning, is being increasingly recognized as beneficial. This technology was pioneered at AECL. It is now being used on produce, poultry, and red meats in the USA to reduce the number of illnesses, recently estimated at 33 million per year, that are attributable to microbial contamination of food.
- In the sterilization of medical devices, such as specialized catheters, surgical tools, sutures and prostheses, Cobalt-60 sources are widely used. Almost two thirds of the irradiators for all medical and agricultural purposes and their Cobalt-60 sources come from Canada.
- In homes, smoke detectors incorporating radioactive sources save lives.

The question arises whether the benefits of nuclear science research are now safely in hand and whether anything more is to be gained by continuing government support in these areas. There is ample evidence to show that the benefits still to be realized will be as significant as those already achieved.

Critics of the nuclear industry argue that Canada's legacy of radioactive wastes and Ontario Power Generation's (OPG) management problems with its reactors constitute examples of problems with nuclear technology. In fact, these problems have been addressed. The management and disposal of wastes has been extensively researched and publicly reviewed; the Federal Government had announced its intention to present its preferred option for dealing with wastes by the end of 1999. Ontario Power Generation, which had management problems with its reactors, is actively refurbishing its nuclear establishment and has developed a plan, according to which all its laid-up units will be returned to service beginning with the first Pickering A unit in 2001.

2.3 CURRENT AND FUTURE REQUIREMENTS OF NUCLEAR R&D

The perspective on nature that is provided by nuclear science will remain a vital benefit. The insights provided by nuclear science into the nature of matter will continue to open possibilities for and set limits on new technologies. The consequences of not supporting nuclear science research in Canada would be to create a dependency on other countries for this critical information and to reduce our industrial competitiveness, not only in areas that are overtly recognized as “nuclear”, but also in many other areas. Most Canadians are unaware of both the extent to which the products of nuclear science support their daily lives, and the extent to which nuclear science is still capable of contributing to the future development of our economy.

For the future, the importance of nuclear science and engineering to the nation must be considered in the context of a wide spectrum of academic, agricultural, industrial, medical, and fundamental science pursuits. The need for non-polluting energy sources and for continuation of scientific studies into the basic structure of matter are but two of the compelling examples of pursuits. The fact that the nuclear industry and the universities have some common needs, requires that there be a national policy in which resources are shared, as will be the case with the proposed Canadian Neutron Facility.

2.3.1 Economic Issues

Up to 1990, for each (US) dollar spent on nuclear power R&D in Canada, 254 kWh of electricity had been produced in nuclear power plants, while the comparable figure in the USA was only 140 kWh. The Canadian ratio of electricity produced per R&D dollar spent is better than that of any other country with a significant nuclear power program. Thus, Canadian nuclear R&D funding has been used effectively.

Nuclear generation currently provides 14% of Canada's electricity, and about 48% in the case of Ontario, the province that accounts for 40% of the country's Gross Domestic Product (GDP). The contribution of nuclear electricity to GDP over the period 1962 to 1992 was $23 billion compared to government support of $4.7 billion from 1952 to 1992. Historically, the total unit energy costs of OPG's reactors have been less than those for coal-fired plants, although this has not been true for the past two years because of the poor reactor performance in Ontario, and the falling cost of fossil fuels. However, a recent NRCan study shows that electricity from new CANDU reactors would be competitive with that from combined-cycle gas turbine plants and coal-fired plants in central Canada. At a real discount rate of 5%, the total levelized unit energy costs [1] projected for new plants are:

CANDU 9 (2 x 880 MWe)	3.42 cents (Cdn)/kWh
CANDU 6 (2 x 665 MWe)	3.98
Combined Cycle Gas Turbine (2 x 750 MWe)	4.44
Coal (4 x 750 MWe)	4.31

Ontario Power Generation's costs of nuclear generation are likely to go down again as the laid-up reactors are brought back on line and operated at high capacity factors. OPG is determined to achieve the same success as the Tennessee Valley Authority in the USA, which has now brought all of its laid-up reactors back on line. In short, the continuation of nuclear generation from the existing plants throughout their lifetimes and the construction of new plants will continue to be economical.

As the existing CANDU plants age, they continue to need R&D support so that the behavior of irradiated materials and components can be monitored to ensure safe and economic operation and to cope with unexpected events. An example of the close support provided by R&D and of the economic importance of that support is provided by the fuel bundle end-plate cracking encountered in the first two years of operation of the Darlington Nuclear Generating Station. Engineers and scientists from AECL and the utilities modeled and characterized the problem and initiated corrective action within a short time. At Darlington, failure to resolve the problem would have put the multi-billion dollar project in jeopardy. This pace of resolution would not have been possible without the involvement of skilled engineers and scientists at AECL and the utilities with a profound understanding of both the fundamental properties of materials and reactor operating principles backed up by AECL's research facilities.

Considerations of plant life maintenance, of plant life extension, and of the maintenance of an adequate margin of safety all require continued R&D support. The past strong emphasis by the utilities on the short-term economic performance of the stations seems to have been at the expense of this essential long-term perspective. It is not evident that the utilities have sufficient R&D resources to undertake problem solving at the basic level, and the onus now is on AECL to maintain sufficient R&D expertise to deal with issues as they arise. Ontario Power Generation's R&D resources are being rapidly eroded, while Hydro Quebec and New Brunswick Power have always been dependent on AECL. The Canadian investment in nuclear power will be at risk of being prematurely written off if the short-term view is allowed to persist.

In the USA, the 60-year reactor is becoming a competitive reality. In Sweden, a country that has publicly announced that it is exiting from nuclear electricity generation, Westinghouse has recently been awarded a five-year contract for the upgrading of the Ringhals reactors to permit their continued operation. For CANDU to achieve similar life-extension targets, additional R&D by AECL and the utilities will be necessary.

2.3.2 Environmental Issues

The importance of nuclear generation of electricity for minimizing or reducing the emission of GHG is discussed at length in Chapter 3. Here, we will only reiterate that Canada will not be able to meet its Kyoto targets for 2010 without greater reliance on nuclear generation, and that other nations will be assisted toward their targets if they can acquire nuclear generation in place of fossil-fueled plants. The CANDU product needs to evolve in response to the rapidly changing economic and geo-political environment if it is to continue to be an affordable option for Canada and AECL's international CANDU customers.

2.3.3 Regulatory Issues

Nuclear R&D capability is a requirement for the licensing and safe operation of nuclear plants throughout their lives. The AECB requires that licensees have the demonstrable capacity to perform the R&D essential to safe operation of nuclear plants in Canada. AECL's facilities have served as a shared resource for the utilities through which questions from the regulator can be addressed. The AECB has only a small budget for research, some of which is used to contract research at these facilities. In any proposed new arrangement, it will be essential that safety-related research continue to receive support. A great deal of the safety and licensing R&D has been done at the Whiteshell Laboratories. The closure of that facility necessitates that essential components be relocated to CRL and that the significant costs incurred in that transition be recognized.

2.3.4 Social and Political Issues

The Government of Canada has used its nuclear expertise to advantage in international diplomacy. Canada is a member of the G-7, a position from which it can contribute broadly to the development of the world community and, specifically, can contribute its expertise in nuclear science both to make the world safer and to improve the well-being of specific societies.

- Foreign policy initiatives, such as the proposal to destroy weapon-grade plutonium in CANDU reactors, are only possible because there is a nuclear program in Canada. It is highly improbable that Russia would hand over its plutonium inventory for destruction in the USA. It is, however, likely to agree to have it destroyed, along with American plutonium, in a third country such as Canada. There is a public misperception of the nature of the plutonium fuel, which will be a solid mixture of plutonium and uranium fabricated in Russia and in the USA.

- One of the major economic needs of developing nations is fresh water. CANDU reactors could provide desalination on a scale sufficient for the agricultural, industrial and personal needs of large populations. A reliable fresh water supply might well be the means of stabilizing strategically positioned developing societies through the resulting improvements in their agriculture and human well-being.
- The World Bank projects that the world's population will increase at 1.4% per year to reach seven billion by 2010. Both the additional one billion persons, plus the one billion who currently live in abject poverty, will require energy sources to meet their needs. The energy needs of these rapidly growing populations will be great as they develop their infrastructures. Nuclear energy will be one of the contributors to solutions for the development and stabilization of impoverished and rapidly growing societies. In 1997, the International Atomic Energy Agency (IAEA) forecast that electricity production from nuclear plants would reach over three times the current production rate by 2050 [2].
- In accordance with Canada's commitment to the Treaty on Non Proliferation of Nuclear Weapons, Canada contributes approximately $2 million a year in support of international safeguards R&D. Most of this work is done at CRL.

2.3.5 The Evolving CANDU Reactor

To ensure that CANDU reactors remain competitive, AECL is working to reduce capital and operating costs of future CANDU designs, through R&D on advanced fuel cycles and fuel bundle designs, improved fuel channels, new technologies for heavy water production, and new developments in information technology and plant constructability. Enhanced safety for these designs will result from R&D to resolve generic safety issues and from passive safety features. Necessary improvements in the performances of steam generators and other non-reactor components will also continue to require some R&D.

In the longer term, to remain competitive AECL must develop advanced CANDU designs incorporating features to lower unit capital and unit operating costs by 50%. To meet these challenging targets, AECL is investigating such features as direct thermodynamic cycles, thus avoiding the need for costly steam generators; new higher temperature coolants, to increase cycle efficiency as well as to reduce capital costs; and fuel channels to accommodate the higher temperature coolants. In the international market, new CANDU designs must compete against new light water reactor (LWR) designs, based on R&D done in the national laboratories of countries such as the USA, France, Germany and Japan. CANDU competitiveness in the international marketplace will be handicapped if it is evident that AECL does not have similar R&D support in Canada.

To ensure that Canada has adequate energy in the 21st Century will require approaches that not only recognize supply, technical, economic, and environmental realities, but that also develop new thinking about traditional ways of meeting the various demands for energy services. The concept of electricity and hydrogen as energy currencies that link energy sources, conversion technologies, and service technologies to the energy services needed by the population, can be the basis for this new thinking. Such an approach opens possibilities for nuclear energy to meet the needs of energy sectors such as transportation and desalination, to which it has not traditionally contributed. These are discussed at more length in Chapter 3.

2.3.6 A Vital Nuclear Facility

A vital element in the continued support of CANDU R&D is the replacement by 2005 of the NRU Reactor by a new research reactor, the CNF. This is discussed at length in Chapter 5.

2.4 HOW SHOULD CANADIAN NUCLEAR R&D BE STRENGTHENED?

In many countries the model for successful nuclear R&D programs is that of the National Laboratory, which serves as the developer and custodian of the nation's intellectual knowledge. In these countries the support given to the National Laboratories goes beyond simply supporting the laboratory infrastructure; it also ensures government funding for activities that are directly in the national interest, such as the health effects of radiation, dosimetry and health physics programs, safety, and environmental protection. It is particularly important that there should be support for such activities in Canada since the CANDU technology is unique. In the past, AECL served as a National Nuclear Laboratory. However, in recent years it had to give up those responsibilities and some of the associated funding in order to focus on its role as the CANDU vendor. Although its responsibilities for non-CANDU R&D have largely ended, AECL continues to carry the responsibility for decommissioning facilities that formerly served other purposes and for management of wastes that were generated in pursuit of missions that were not related to CANDU.

The funding, albeit reduced in amount, that AECL now receives from the Government is viewed in some quarters as an unfair subsidy of the CANDU business, a business that should flourish or fail on its own merits. That argument is not without merit when considering the business of selling and supporting the current CANDU product. However, it is the view of the Panel that subsidies, properly used, can be valuable tools of government to support public goals that have a time constant longer than can be sustained in the marketplace. In this sense, subsidies are long-term investments in future technology. The R&D required to support the design of the nuclear stations of the future, not unlike the aircraft and medical treatments of the future, needs decades to achieve results. In all such areas, when the time for development is long or the outcome, while desirable, is too uncertain to define the product for the marketplace, a form of subsidy is necessary to sustain the vision. Thus, there always will be aspects of nuclear science and technology in which public investment will continue to be necessary.

In view of all the present and anticipated future societal and economic benefits of nuclear technologies, the Panel, in the strongest possible terms, supports the continuation of nuclear science and engineering R&D funding. Some changes need to be made so as to factor future government support into specific categories with clarified lines of accountability. The current mechanism of funding AECL has become counter-productive in that it has isolated nuclear science in Canada from science in general.

The funding that AECL currently receives, nominally for R&D, actually includes responsibility for at least six different types of activities:

- management of obsolete nuclear facilities and of high-level radioactive waste resulting from former collaborations with American and British governments, as well as from the production of medical isotopes;
- some of the R&D required by the AECB for licensing of nuclear facilities and for the assurance of public safety;
- R&D concerning environmental and biological effects of low levels of ionizing radiation;
- some of the R&D that was formerly supported by the nuclear utilities under the CANDU Owners Group (COG) partnership for operational support;
- short-term R&D in support of immediate business objectives; and
- long-term R&D in support of future advanced reactor designs or of novel applications of CANDU technology.

The progressive reductions of both government and utility funding to AECL in recent years combined with AECL's largely fixed obligations for facility management have put its R&D functions under progressively greater limitations and strain. An improved mechanism of government funding would make distinctions between the CANDU business and historical issues, as well as among business-related, longer-term and public-interest R&D issues.

2.5 RECOMMENDATIONS

Recommendation 1

The Panel recommends to AECL that negotiations with the federal government and utilities for future R&D funding should continue to take cognizance of the following:

1. Responsibilities for managing wastes from historic obligations and the production of medical isotopes, as well as for obsolete nuclear facilities, should be funded separately from the CANDU business, whether these responsibilities continue with AECL or are given to a new site-management agency.
2. Funding of R&D that is required of licensees by the AECB for licensing and safety purposes, and which is largely performed at AECL's unique facilities, should be assured through mechanisms that do not burden the CANDU business beyond the extent to which they are required for that business. It is the Panel's opinion that AECL, the AECB, NRCan and the nuclear utilities have a shared interest in ensuring that this is done. Each party should accept a share of the associated costs and the utility partners should be encouraged to seek tax credits for their expenditures in this research.

3. Research concerning nuclear science that is in the public interest, such as environmental and health effects of low doses of ionizing radiation, should be reviewed and funded through processes that guarantee the independence of the researchers from the CANDU business and ensure their accountability through peer-reviewed processes such as those that apply to research funded by the Natural Sciences and Engineering Research Council (NSERC) and the Medical Research Council.

4. AECL and the nuclear utilities should develop their natural partnership in R&D for operational support, plant life maintenance and life extension issues. There will be some long-term issues that are difficult to address through a business plan. Governmental funding of such long-term work should continue with an appropriate mechanism of accountability for its development. Utilities should seek to obtain a tax credit for their participation.

5. AECL should fund its short-term R&D, as it relates to current products and immediate business prospects, from the revenues of the CANDU business.

6. Continued public funding of long-term and basic nuclear R&D should be structured within the framework of Canadian science funding in general. This has already been done for the Materials Science Program, formerly an AECL activity, which has been transferred to the National Research Council (NRC).

2.6 REFERENCES

1. B. Moore and S. Guindon, Natural Resources Canada, Comparative Costs of Electricity Generation: A Canadian Perspective, CNS Bulletin, Volume 19, No.2, pages 12to15, April-June 1998.

2. Global Energy Outlook, Key Issues Paper No. 1: International Symposium on Nuclear Fuel Cycle and Reactor Strategy: Adjusting to New Realities, International Atomic Energy Agency, IAEA SM-346, May 1997.

CHAPTER 3: CANDU REACTORS AND THE ENVIRONMENT

3.1 INTRODUCTION

There is much concern in the world today about global climate change and the role of GHG in this phenomenon. While there has been in the past considerable debate about this issue, the scientific consensus is now clear: increasing emissions of GHG, particularly carbon dioxide (CO_2) from the burning of fossil fuels, are causing increasing global temperatures which will, without mitigative actions, lead to global climate change with resulting severe social and economic consequences [1, 2].

Amongst the evidence for this conclusion is a very strong correlation between the growth of the consumption rate of fossil fuels, i.e., carbon-based fuels, and the increase in CO_2 concentration in the atmosphere from about 1850 to the present [3].

Growing concerns about global climate change have led to a number of international conferences, decisions and agreements over the last twenty years or so. These activities culminated in an international conference on global climate change in Kyoto, Japan, in 1997, at which developed countries pledged to reduce GHG emissions to levels below those of 1990. Under the Kyoto Protocol, Canada has undertaken to reduce GHG emissions in the period 2008 to 2012 to six percent below Canadian emissions in 1990.

There are some who claim that the link between global warming and fossil-fuel consumption has not yet been scientifically demonstrated. This view is generally related to concerns that unwarranted restrictions on the use of fossil fuels, based on an unproven hypothesis, will themselves have disastrous economic and social consequences. However, prudence demands that the possible effects of CO_2 and other GHG emissions be taken into account because they are almost certain to be catastrophic should significant global climate change occur.

Since nuclear power plant operation does not produce GHG emissions, nuclear energy provides one means of meeting the energy needs of an industrialized society without adding to the atmospheric burden of GHG. Thus, the global climate-change issue presents an opportunity for extending the operating life of existing nuclear power plants and for promoting the future growth of nuclear energy to meet the increasing energy needs of the world.

Other environmental issues, i.e., the control of releases of radioactive substances, the management and disposal of discharged nuclear fuel and the decommissioning of nuclear facilities, have been covered in previous Panel Reports and are not considered here. However the Panel reiterates its previous conclusions that these matters are being managed appropriately.

3.2 GREENHOUSE GAS EMISSIONS AND CANDU

3.2.1 Greenhouse Gas Emissions in Canada and the Role of CANDU Reactors

The major contributors to GHG in Canada are carbon dioxide (CO_2, 77%), methane (CH_4, 12%) and nitrogen oxides (NO_x, 10%). Greenhouse Gas emissions are mainly caused by energy activities (78%), made up of energy end-use (59%, mostly from transportation), electricity production (17%) and fossil-fuel supply (12%) [4]. In Canada, electricity production is a considerably smaller contributor to GHG emissions than in most developed countries because about 80% of Canada's electricity is produced in hydro and nuclear power plants, which do not emit GHG. However, this does not mean that further reductions of GHG emissions from electricity production in Canada would be insignificant, as we will see.

The total emissions of GHG in Canada in 1990 are estimated to have been about 600 million tonnes (Mte) of which about 450 Mte was CO_2. Present trends indicate that CO_2 emissions will reach a level as high as 540 Mte/yr by about 2010, if no mitigative measures are taken. Under the Kyoto Protocol, Canada has committed to reduce GHG emissions to 6% below 1990 levels by 2010, equivalent to a reduction in CO_2 emissions of about 120 Mte/yr below the "business-as-usual" case in 2010.

A typical coal-fired power plant in eastern Canada would emit about 8 kilotonnes of CO_2 per megawatt-year. Therefore, a CANDU 6 operating at 80% capacity factor, as an alternative to a coal-fired plant of the same size and capacity factor, would avoid about 4.5 Mte/year of CO_2 emissions. Based on such an analysis, CANDU power plants in Canada have avoided emissions of over 1,000 Mte of CO_2 since the first plant came on line in the 1960s, because coal-fired plants would probably have been built if nuclear power had not been available. At present, even with the Pickering-A and Bruce-A plants laid up, nuclear power plants in Canada are avoiding about 70 Mte/yr of CO_2 emissions. It is obvious that Canada would have a much more difficult task in meeting its Kyoto commitments without the continuing contribution of nuclear power. Furthermore, it is essential for this purpose that the laid-up reactors be brought back on line as early as possible, since the replacement power is all fossil-fueled[1]. Up to an additional 30 Mte/yr of CO_2 emissions would then be avoided, a significant contribution to the total reduction needed.

It must be remembered that, in addition to CO_2 emissions, fossil-fueled power plants emit other atmospheric pollutants, particularly sulphur and nitrogen oxides, which contribute to acid rain and smog. The lay-up of Ontario's reactors and their replacement by fossil fuel-fired generation has caused a significant increase in emissions of these pollutants. In 1998, following the lay-up of the Pickering-A and Bruce-A nuclear power plants, sulphur oxide emissions increased 15% and nitrogen oxide emissions increased 30% over 1997 values.

[1] The GHG avoidance will be less for gas-and oil-fired power plants than for coal-fired plants, because of lower concentrations of carbon in those fuels compared to coal. The Panel has estimated that a CANDU-6 would avoid about 2.5 Mte/yr of CO_2 emissions compared to a conventional gas-fired steam power plant and about 1.7 Mte/yr compared to a higher-efficiency gas-fired, gas turbine combined-cycle plant, both of the same size and capacity factor. These estimates do not include the additional GHG emissions from the production and transmission of the natural gas fuel.

3.2.2 Kyoto Protocol Mechanisms and the Export of CANDU Reactors

Under the Kyoto Protocol mechanisms, Canada may obtain GHG credits for CANDU exports, to be shared with the customer country, although the details are yet to be worked out. Arrangements such as these would help Canada to meet its Kyoto commitments while gaining economic benefits.

International reactor sales since 1990 can be eligible for such benefits, so the recent sales of CANDU reactors to Korea and China will qualify. Assuming that coal-fired plants would have been the alternative if the CANDU plants had not been built, Wolsong units 2, 3, and 4 and the two units at Qinshan will be avoiding about 23 Mte/yr of CO_2 emissions by 2004; credit for a portion of this avoidance should be available to Canada to help offset its Kyoto commitments. Sales of CANDU reactors to Korea, Turkey and Romania, should they materialize, will also qualify for credits. Large populous countries such as China and India will continue to be the world's major atmospheric polluters; these and many other developing countries are still building coal-fired power plants on a large scale[2]. It is in Canada's environmental, as well as economic, self-interest to encourage these countries to include nuclear power in their energy mix.

3.2.3 Government Actions on Kyoto Commitments

The federal and provincial governments have agreed on procedures for developing policies to enable Canada to fulfil its Kyoto commitments. A Climate Change Action Fund was established in 1998 with a budget of $50 million per year for three years, under the joint responsibility of the federal Ministers of Environment and of Natural Resources. The main objectives of the fund are to lay the foundation for a national implementation strategy and to initiate early action to reduce GHG emissions. Activities began in April 1998 and are proceeding rapidly.

A key part of the activities so far has been evaluations, under “Issues Tables”, of the various issues involved on a sectoral basis, e.g., agriculture, electricity and transportation, and on a mechanism basis, e.g., analysis and modeling, science and application, and technology. These evaluations are being made by teams composed of various stakeholders. For each of these issues, a “Foundation Paper” is available which summarizes the current state of the issue and outlines challenges, opportunities and, where applicable, best practices. The Foundation Papers are to be followed in the fall of 1999 by “Options Reports”, summarizing options, emission-reduction potentials, risks, costs and benefits and other factors. In addition, NRCan is undertaking a program “Energy Technology Futures 2030”, to develop a set of visions of Canada's energy system in 2030 to 2050, and to identify long-term technological options that could fundamentally alter the relationship between economic growth and GHG emissions. Eventually, all these activities will lead to a National Implementation Strategy planned for release in 2000.

---

2 The installed electrical capacity in China is projected to increase from 210,000 MW in 1995 to 3,000,000 MW in 2000, with the great majority of the new plants being coal-fired. See Mechanical Engineering Power, American Society of Mechanical Engineers, November 1997.

In these activities, AECL and the nuclear industry, represented by the Canadian Nuclear Association, have been most involved in the Electricity Table, on which the utilities are represented, the Climate Change Technologies Table, on which AECL is represented, and in the Kyoto Mechanisms Table. *It is essential that the importance of nuclear power as a key option for the reduction of GHG emissions is recognized clearly in the appropriate Options Reports and in the Energy Technology Futures 2030 program.*

3.3 ELECTRICAL ENERGY PROJECTIONS AND IMPLICATIONS FOR CANADA

In 1997, NRCan published a "reference outlook" for Canadian energy supply and demand and for GHG emissions from 1995 to 2020 [5]. It is emphasized that the outlook is not a forecast; amongst other things the energy, environment and related policies of the federal and provincial governments are assumed to remain constant over this period, and the real costs of fossil fuels are also assumed to remain constant. The intention of the outlook is to provide a base against which to assess the need for, and form of, additional policy measures.

NRCan projects a growth rate of 1% per year in total electricity demand in Canada over this period, a significant reduction from the 2.6% per year experienced over the previous 15 years. It foresees that all existing reactors, except Bruce-2, will be re-tubed to ensure a total life of 40 years for each, that these reactors will not be replaced by nuclear units at the ends of their lives, and that no new nuclear capacity will be built. This scenario implies that the contribution of nuclear electricity in Canada will decline from about 19% in 1995 to 10% in 2020. The scenario is also based on no new large-scale hydro developments, except for the beginning of a project in Quebec in 2019, on most replacement and new capacity being provided by natural gas (combined cycle and co-generation) and coal-fired (using "clean coal" technology) plants, together with the refurbishment of existing fossil facilities and the re-development of some hydro facilities. Finally, it foresees that renewables will provide a total of about 3% of electricity demand in 2020.

The NRCan projection, with its increasing reliance on fossil fuels for electricity generation and its neglect of new nuclear and limited new hydro generation, coupled with increased use of fossil fuels for transportation and industry, inevitably results in significant increases in GHG emissions, rather than the desired decreases. *The total GHG emissions are projected to be 19% higher in 2010 than in 1990, rather than 6% lower, as committed to at Kyoto. In addition, GHG emissions would be 36% higher in 2020, with emissions from electricity generation projected rising significantly after 2010, when some of the nuclear generation is retired and replaced by fossil-fuel generation. It is evident that such a scenario is not environmentally acceptable.*

Recently, the National Energy Board (NEB) has developed energy scenarios for Canada which make assumptions similar to those of NRCan, e.g., no replacement or new nuclear power, but higher electricity growth rates of 1.2% to 1.6% per year, and reaches similar conclusions, that is, significant increases in GHG emissions by 2025 [6]. Again, this is not an acceptable scenario.

It is clear that the GHG emissions strategies being developed for Canada, must include a recognition that the currently laid-up reactors must be returned to service as soon as possible, and that new nuclear capacity must be planned if Canada is to meet its Kyoto commitments and to control GHG emissions beyond 2010. Other means of GHG avoidance, such as renewable energy sources, improvements in efficiency of energy production, and use and sequestration of CO_2 in underground reservoirs, will not together achieve the Kyoto target and ensure further reductions beyond 2010.

It is interesting to compare these NRCan and NEB scenarios with the views of the US Department of Energy (DOE), the US counterpart of NRCan. In a report on the potential economic impact of the Kyoto Protocol, the DOE states that the United States must extend the operating licenses of existing nuclear plants and build 40,000 MW of new nuclear capacity if it hopes to meet its Kyoto target of GHG emissions 7% below 1990 levels by 2012 [7].

3.4 EXTENDED APPLICATIONS OF CANDU REACTORS

3.4.1 Non-Electric Applications of CANDU

As pointed out in the 1997 Panel Report, the CANDU reactor up to now has been used mainly for electricity generation. The only exception was OPG's Bruce-A plant, which produced steam for heavy water production and for agricultural product heating purposes, in addition to generating electricity. In other countries, nuclear reactors have been used for district heating and for some industrial process heating. Nevertheless, on a world-wide basis, less than 1% of the heat generated in nuclear reactors is used for purposes other than electricity generation.

At present, about one-third of the world's energy consumption is used for electricity generation, 17% of which is produced by nuclear plants. Nuclear electricity has already contributed significantly to the reduction of GHG emissions in many countries, as discussed in Section 3.2.1 above for Canada. It has been estimated, as noted in Section 6.3 of the 1997 Panel Report, that the world's nuclear power plants are avoiding about 2,600 Mte/yr of CO_2, and also many megatonnes per year of associated sulphur and nitrogen oxides, assuming that coal-fired plants would have been built if nuclear plants had not been available.

However, if nuclear energy is to provide more than a relatively small fraction of the world's total energy requirements in the future, and is to contribute in more than a modest way to the reduction of GHG emissions, it is evident that non-electric, as well as electric, applications of nuclear reactors will have to be pursued.

Non-electric applications that can be considered for CANDU reactors include:

- district heating: studies by AECL and others have shown the feasibility of using CANDU reactors for this purpose;
- industrial and chemical process heating: CANDU reactors have already been used for process heating at the Bruce-A plant as noted above;

- de-salination of sea-water: a preliminary study by AECL has demonstrated the economic benefits of a combined-purpose CANDU providing electricity and potable water (obtained from sea-water by a reverse-osmosis process); and
- petroleum recovery from the Alberta Tar Sands: recent developments appear to make CANDU reactors feasible for petroleum recovery from tar sands.

In general, the most cost-effective approach to these uses would be by using combined-purpose plants, i.e., a plant combining electricity generation with another application. This is generally referred to as co-generation.

Such applications for CANDU reactors would contribute to the avoidance of GHG emissions in Canada, but are not considered in the NRCan and NEB reports discussed earlier. There are opportunities for exports of CANDU reactors for these other purposes, which could help meet Canada's Kyoto targets, and also produce economic benefits. For example, many developing countries that border on oceans or seas suffer from serious shortages of fresh water. It should be noted that the IAEA is actively promoting the use of nuclear energy for desalination in such countries [8]. Thus, there exists a potential market for CANDU reactors for desalination of sea-water as well as electricity generation.

A major potential opportunity for wider application of CANDU reactors and additional avoidance of GHG emissions is discussed in the following section.

3.4.2 Hydrogen and Nuclear Energy

In Canada, about 25% of end-use energy demand is for transportation purposes, almost all based on oil products. Nuclear energy makes practically no contribution to this sector, except for its contribution to the very small amount of electricity used in urban and suburban mass-transportation systems. However, an attractive new opportunity presents itself to AECL: the use of nuclear-generated electricity to produce hydrogen by electrolysis for use in fuel cells to power trains, buses, trucks and cars, as described by R.B. Duffey et al. [9]. The Panel considers this paper to be very important in providing a vision for the future and has reviewed it in detail. The Panel agrees with the main results obtained in the paper, which it has confirmed independently, and strongly supports its major conclusions.

Hydrogen used in fuel cells to propel vehicles is often touted as a major route to the reduction of GHG emissions. However, environmental problems associated with the production of hydrogen are generally ignored in such assessments. At present, hydrogen is almost always produced commercially by steam-methane reforming, in which natural gas from conventional gas wells is combined with steam generated in conventional fossil-fired boilers to produce the hydrogen. The recovery of natural gas from wells, its transportation in pipelines, the operation of the boilers and the reforming process itself are all accompanied by the emission of GHG, as well as other atmospheric pollutants. Therefore, while the end-use of hydrogen in the fuel cell may cause no significant GHG emissions[3], its production from natural gas certainly does. In

[3] Actually, water vapor, the only emission product from a fuel cell, is also a greenhouse gas. However, its saturation behavior prevents it from building up in the atmosphere.

fact, an analysis reported by Duffey et al. shows that the overall annual CO_2 emissions would be greater from a hybrid fuel-cell vehicle provided with hydrogen by this route than from a conventional gasoline-powered vehicle; there would not only be no advantage, but actually a disadvantage, in using hydrogen in fuel cells to reduce vehicle emissions, if this route were followed to produce the hydrogen.

On the other hand, hydrogen can be produced by the electrolysis of water, using electricity to break it down into its components. Not only does this process yield hydrogen without the emission of GHG or other atmospheric pollutants, but it also yields the valuable by-products, oxygen and heavy water. To ensure that the entire cycle for the production of hydrogen is GHG-free, the electricity must come from a non-GHG emitter, such as nuclear, hydro, wind or solar. Since this would be a new market requiring new electrical capacity, and since the opportunities for large new hydro developments are limited in Canada, nuclear reactors are the only practical electricity source that could produce electricity on a large scale for this purpose.[4]

Duffey et al. have calculated the hydrogen production from a centralized commercial-scale electrolysis plant provided with electricity from a dedicated CANDU 6 reactor. For an electrolysis plant operating at 70% efficiency and a CANDU 6 operating at 80% capacity factor, about 97 kilotonnes of hydrogen per year would be produced. In addition, the electrolysis process also produces, as valuable by-products, about 95 te/yr of heavy water and about 770 kte/yr of oxygen. Alternatively, hydrogen could be produced locally in small electrolysis units using off-peak power from general-purpose CANDU reactors or other non-GHG emitting sources.

Based on data for annual driving distances for cars and light trucks in Canada, and on calculations of the annual hydrogen requirements for such vehicles powered by fuel cells, Duffey et al. also show that one CANDU 6 operating at 80% capacity factor could supply the hydrogen needed for about 660,000 fuel-cell vehicles. Assuming a program of 20 new CANDU 6 reactors dedicated to this service, a total of about 13 million vehicles could be supplied; for comparison, the total number of cars and light trucks in Canada was about 15.5 million vehicles in 1995.[5] Assuming that the 20 new CANDU 6 reactors are introduced at a rate of one per year, beginning in about 2005, and that a fleet of 13 million fuel-cell vehicles is built up gradually, Duffey et al. show that CO_2 emissions from cars and light trucks would be reduced by about 45 Mte/yr by 2020, and by about 80 Mte/yr by 2030, compared to the emissions from vehicles powered by conventional gasoline engines.

Of course, many challenges remain, including the development of economical, reliable and safe fuel-cell vehicles, and the infrastructure to provide economic, convenient and safe fueling and servicing of these vehicles. There are many difficulties and uncertainties associated with the economics of such a fundamental change, including those associated with the significant capital investment required for vehicle

---

4 Renewable energies, such as wind and solar, suffer from two major inherent deficiencies for use as reliable large-scale suppliers of electricity - low intensity and intermittency. To use such sources on a reliable, large-scale basis in Canada would require large land areas, large quantities of materials and large storage capacities, all involving significantly high costs. The only potentially feasible use of such sources is to supplement nuclear and hydro for electricity generation for hydrogen production on a limited local, as-available basis.

5 Actually, more than 13 million vehicles could be supplied, since off-peak power from general-purpose CANDU® reactors could be used for electrolysis of water.

manufacturing, hydrogen production and distribution, and nuclear power plants. Nevertheless, preliminary analyses suggest that costs to the individual of fuel-cell vehicles and their operation would be reasonable.

As an enabling step in this direction, AECL has suggested that some of the difficulties associated with the conversion of the multi-owner private vehicle sector to fuel cells could be avoided by the conversion of railroads from diesel locomotives to fuel-cell powered locomotives [10]. Of course, further opportunities for the abatement of CO_2 emissions exist in other areas of commercial transportation, such as large trucks and buses.

We see that exciting opportunities exist for the potential conversion of Canada's transportation systems from a fossil-fuel base to an electrolytic-hydrogen base. Canada has all the essential elements to be a major participant in a world revolution in the development of non-polluting transportation. Canada has CANDU power plants to produce the electricity for the high-efficiency electrolyzers produced by Stuart Energy Systems (formerly Electrolyzer Corporation) to provide hydrogen for the world-leading fuel-cell technology of Ballard Power Systems to power cars, trucks, buses and trains. With the advantages resulting from pioneer roles in these leading-edge technologies, Canada would be in an excellent position to exploit world markets in these areas.

3.5 INTERNATIONAL VIEWS ON NUCLEAR ENERGY AND CLIMATE CHANGE

As noted in Section 6.3 of the 1997 Panel Report, it is estimated that the world's nuclear power plants are now avoiding about 2600 Mte/yr of CO_2 emissions, as well as millions of tonnes of sulphur and nitrogen oxides. Based on such observations, there is wide international recognition of the vital role of nuclear energy in coping with the global climate change issue. Some views are summarized here.

The Royal Society and the Royal Academy of Engineering have recently completed a study on the future of nuclear energy in the United Kingdom [11]. They concluded that it is vital to keep the nuclear option open as one of the approaches to mitigating the threat of drastic climate change, and that nuclear power plants must be included in electrical power planning for the UK. In addition, they considered a proposed UK energy tax as being deeply flawed, since it did not distinguish between energy sources with different levels of CO_2 emissions; they favoured a carbon tax instead. Finally, they recommended that an international body be formed, supported by individual nations on the basis of their gross domestic product and energy consumption, to fund research on energy in the context of global climate change.

The Atlantic Council of the United States, a non-partisan network of leaders in the policy, academic and corporate communities, has recently completed a major study on the global role of nuclear energy [12]. One conclusion of this study is that nuclear power facilities should be given credit for their contribution to the reduction of GHG, and that governments should ensure that the full external costs of all forms of electricity generation are incorporated in electricity rates. The Council also concluded that governments should take the lead in long-term R&D needs for all energy options.

Several other groups and bodies, including the Nuclear Energy Institute (USA), the US President's Council of Advisers on Science and Technology, the Club of Rome, and a Group of American Nobel Laureates in the Sciences, have expressed concern about GHG emissions and other environmental effects of fossil-fuel combustion, and have identified nuclear power as a key element in any strategy for reducing such emissions.

3.6 SOME CANADIAN VIEWS ON NUCLEAR ENERGY AND CLIMATE CHANGE

A Conference on the Future of Nuclear Energy in Canada, organized by the Carleton University Research Unit on Innovation, Science and the Environment (CRUISE) was held in Ottawa, September 30 to October 1, 1999. A consensus emerged from the Conference that the future of nuclear energy in Canada will be determined by the interplay of several interacting factors, including most prominently:

- the consequences of deregulating the electricity market, especially in Ontario, which will focus the industry on short-term returns on investment;
- the ability of AECL to reduce the capital costs and construction periods of new CANDU plants;
- political decisions taken in Canada to achieve GHG abatement to meet the Kyoto targets and long-term objectives;
- essential modifications of the nuclear regulatory processes to accommodate rapid change in the electricity market; and
- the degree of public acceptance of the nuclear option.

There was also general agreement that existing CANDU plants will continue to be competitive producers of electricity.

The conference and other meetings during 1999 indicate to the Panel that others also recognize that nuclear energy is a vital element in dealing with the problem of climate change and remains a viable technical option.

3.7 CONCLUSIONS

It is evident from the foregoing discussions that nuclear energy must play a significant role in Canada's efforts to meet its Kyoto commitment of a six percent reduction in GHG emissions below 1990 levels by about 2010. It is evident from the NRCan and NEB projections that Canada will not be able to meet its Kyoto target without the laid-up OPG reactors being returned to service, the lifetimes of existing reactors being extended and new nuclear capacity being built. The new nuclear capacity would be used to phase out coal- and oil-fired plants, to meet new electrical demands and to meet non-electric applications for nuclear energy.

In addition, the synergism of nuclear power and hydrogen opens up exciting opportunities for Canada to play a leading role in a revolution in world transportation in which fuel-cell powered vehicles replace gasoline- and diesel-powered vehicles, all based on Canadian-developed technologies: CANDU reactors, Stuart electrolyzers and Ballard fuel cells.

Several respected international bodies, including the Royal Society and the Royal Academy of Engineering of the UK and the Atlantic Council of the United States, have concluded that, to deal with the issue of global climate change, nuclear power must play a significant role in future energy plans.

In Canada, the climate change issue presents AECL with new opportunities for access to R&D funding relating to the role of nuclear energy in meeting Canada's Kyoto commitments, and in coping with GHG emissions beyond 2010.

The Panel strongly supports AECL's participation, in cooperation with the Canadian Nuclear Association, in the climate change activities of the Federal Government with the purpose of ensuring that nuclear energy is, and remains in the future, a key part of the Federal Government's implementation strategy for dealing with Canada's Kyoto commitments and ongoing climate change issues.

The Panel strongly supports AECL's cooperation with Canadian industry in the development of electrolyzers and its support of research and studies related to the electrolytic production of hydrogen for use in fuel cells.

3.8 RECOMMENDATIONS

Recommendation 1

The Panel recommends that AECL continue to co-operate with NRCan in the development of the Energy Futures 2030 program to ensure that nuclear energy is recognized as a key component of future energy supply in Canada, and that this recognition is reflected in future energy scenarios.

Recommendation 2

The Panel recommends that AECL give a high priority to investigating the possibilities of obtaining R&D funding from other agencies related to the role of nuclear energy in coping with the issues of global climate change, including the use of CANDU reactors for the electrolytic production of hydrogen.

Recommendation 3

The Panel recommends that AECL continue to assess the potential in Canada and abroad for non-electric application of CANDU reactors, particularly for sea-water desalination, and identify and support, as appropriate, the R&D necessary to pursue such applications.

Recommendation 4

The Panel recommends that AECL explore co-operation with other organizations in international efforts for R&D related to energy and global climate change, such as those proposed by the Royal Society and the Royal Academy of Engineering of the UK and the Atlantic Council of the United States.

3.9 REFERENCES

1. Intergovernmental Panel on Climate Change, Working Group III, Summary for Policy Makers, Second Assessment Report, August 1996.

2. R. van Berkel, A Primer on Climate-Relevant Technology Transfer, International Energy Agency, May 1997.

3. D. Pendergast, The Greenhouse Effect, AECL, January 1992.

4. Technology Innovation for Mitigating Greenhouse Gas Emissions, Technology Table Foundation Paper, Climate Change Secretariat, Ottawa, 1998 October 30.

5. Canada's Energy Outlook: 1996 - 2020, Natural Resources Canada, April 1997.

6. Canadian Energy Supply and Demand to 2025, National Energy Board, 1999.

7. Nuclear Energy Insight 98, Nuclear Energy Institute, December, 1998.

8. Plan for Producing Potable Water Economically, International Atomic Energy Agency, General Conference, Item 16, August 1999.

9. R.B. Duffey, W.T. Hancox, D.R. Pendergast and A.I. Miller, Hydrogen and Nuclear Energy: Building Non-Carbon Bridges to the Future, revised version of AECL Paper presented at 9th Canadian Hydrogen Conference, Vancouver, February 1999.

10. A.I. Miller, The Case for Rail Conversion to Hydrogen-Powered Fuel Cells in the Context of CO_2 Emission Abatement, CAN Conference on Energy and the Environment, November 1999.

11. Nuclear Energy - The Future Climate, The Royal Society and the Royal Academy of Engineering, June 1999.

12. An Appropriate Role for Nuclear Power in Meeting Global Energy Needs, Policy Paper, The Atlantic Council of the United States, February 1999.

CHAPTER 4: CANDU R&D

The Panel reviewed a number of areas of CANDU R&D this year. This is the first year that the Panel has reviewed the topics of Generic Action Items (GAIs) and Computer Code Management. The Panel also prepared updates of subjects covered in previous years, namely, Fuel Channels, Advanced Fuel Cycles, Heavy Water Production Technology and the CANDU-X concept. The following is a summary of the 1999 review. A detailed analysis of the review has been submitted separately to AECL.

4.1 GENERIC ACTION ITEMS

In 1962, the AECB established a requirement for analysis of the consequences of certain postulated failures in CANDU reactor systems (i.e., single process system failures) and of these same postulated process system failures coincident with the unavailability of special safety systems (known as dual failures). This requirement, and subsequent expansions of it, have served as an overriding determinant of the direction, scope, priorities and depth of AECL safety technology programs. It should be noted that this regulatory requirement was imposed upon AECB licensees (i.e., the three utilities in Canada that operate CANDU stations).

As the licensing of the Pickering, Bruce, Gentilly and Point Lepreau stations progressed through the 1970s, the AECB endeavoured to document its requirements in a Consultative Document entitled "Proposed Regulatory Guide - Requirements for the Safety Analysis of CANDU Nuclear Plants, C - 6, June 1980". Discussion among the AECB, the utilities and AECL on the conversion of the Consultative Document into a Regulatory Guide for application to new CANDU designs began in 1980 and continues today.

One outcome of the evolutionary development of regulatory requirements for the safety analysis of CANDU power reactors was the decision by AECB in 1988 to begin identifying and publicly reporting the significant issues that had arisen in the licensing of CANDU stations and were considered to be generic. These Generic Actions Items (GAI) were communicated to the utilities and to AECL with requests for plans and schedules for resolving them. The analysis of these unresolved safety issues is often complex and time-consuming and, in most instances, R&D programs are necessary to support and to validate the analytical methods employed and their results. In its Annual Report for 1995, the Panel discussed the status of GAIs being addressed in AECL's safety R&D programs at that time. Early resolution of the items has recently been declared by AECB to be of fundamental importance in licensing the continuing operation of CANDU stations. Equally, the importance to new CANDU 6 and CANDU 9 designs is self-evident. As a consequence, the Panel decided that its Annual Report for 1999 should include a more comprehensive discussion of GAIs and their status than previously reported.

In January 1999, the AECB began issuing a series of Position Statements on GAIs. These Statements identify the particular safety issues involved and the actions considered by AECB staff to be required for their satisfactory resolution. Eleven AECB Position Statements have now been issued and it is the staff's intention to issue similar statements on all outstanding GAIs, a total of fourteen as of 24 September 1999.

The Panel is confident that the actions currently underway and those to be initiated shortly by AECL and the utilities will successfully bring closure to all outstanding GAIs.

4.2 THE LICENSABILITY OF CANDU 9

In September 1994, AECL requested that the AECB undertake a regulatory review of the preliminary design of the CANDU 9 nuclear power plant, recognizing that prospective foreign customers of all reactor vendors require a statement of licensability in the country of origin for any new nuclear plant design as their first prerequisite. The purpose of the regulatory review was to identify any features of CANDU 9 and AECL's proposed licensing approach that would constitute a fundamental barrier to the licensing of a CANDU 9 in Canada. On 15 January 1997, the AECB staff issued a “Statement on CANDU 9 Licensability”, in which it concluded that there were no fundamental barriers to the licensing of the CANDU 9 design in Canada.

4.2.1 Additional Work Items

The AECB staff statement was based on documentation submitted by AECL on the preliminary design of CANDU 9 in what was agreed as the equivalent of the “pre-project” phase of an actual project. The statement was issued in anticipation that AECL would successfully complete the detailed design and assessment activities required for the preparation of the customary “Preliminary Safety Analysis Report” demanded by international customers of any power reactor vendor.

The AECB staff statement on CANDU 9 licensability lists Additional Work Items to be resolved. The AECB intends to issue an update of its licensability statement on CANDU 9 in mid 2000 to record its findings regarding AECL's actions on the Additional Work Items.

4.2.2 Conclusions

A regulatory review of the CANDU 9 preliminary design was requested by AECL in September 1994, to determine whether or not any significant barriers to licensing the design in Canada might exist. A co-operative approach to the accomplishment of their respective objectives and fulfilment of their respective responsibilities was developed by AECB and AECL staff members. The Panel commends the AECB and AECL staff members who developed this process.

It is essential that the momentum of the process developed by AECB and AECL staff be maintained. This will require continuing effort by both organizations.

Prompt resolution of a relevant GAI and successful completion by AECL (and subsequent formal closure by AECB) of the Additional Work Items described in the 15 January 1997 AECB staff statement on the licensability of CANDU 9 will ensure international acceptance of the design. Allocation of adequate resources and, in particular, appropriate human resources, by AECL is required to achieve this objective.

4.3 MANAGEMENT OF COMPUTER CODES FOR DESIGN AND SAFETY ANALYSIS

In the past year, the Panel had presentations from senior AECL personnel on the development, application and management of its computer codes. The Panel has not previously reported on this topic and intends to revisit it in the next annual Report. Also, the Panel deals here only with codes associated with nuclear reactor design and safety analysis. For the present purpose, a computer code may be defined as "a mathematical expression of the physical world which allows simulation of system design and performance".

Computer codes for design and safety analysis support key elements of AECL's business activities. AECL's continuing objective is to develop and maintain a qualified set of codes to support its business activities, including past and current projects as well as new designs and procedures.

4.3.1 AECL Computer Codes and Their Development

Although more than 600 computer codes have been used in CANDU and MAPLE reactor design and licensing processes, much fewer are key to its design and licensing processes in the areas of reactor physics, thermalhydraulics, fuel and fuel channels, fission-product behaviour and containment.

Key computer codes have evolved over many years. More sophisticated versions of the codes with better quality assurance and more comprehensive validation are certified for use as "frozen" versions from time to time. Continuing code development, led by technical experts in various fields, is needed to incorporate advances in understanding of the technology, and to permit product evolution. Computer code development often drives R&D programs. The basic approach taken by AECL, which has worked well over the years, is to perform experiments to provide insights and experimental data needed for its major computer programs. At present, about one-third of the work being done in AECL and COG safety-related R&D programs is on computer code development.

4.3.2 Software Quality Assurance

Since computer codes have vital roles in both design and safety analysis, designers and regulators must have high confidence in their accuracy and reliability. A key element in achieving this confidence is the application of quality assurance principles and procedures to computer codes. AECL has developed a specific policy for software quality assurance and issued the AECL Quality Assurance Manual for Analytical, Scientific and Design Computer Programs early in 1998.

4.3.3 Computer Code Validation

A major challenge in the validation of codes for safety analysis arises for accident scenarios that lead to severe consequences, such as large-scale core disassembly or fuel melting. Experimental programs to investigate such scenarios are very difficult and costly. Joint international programs are an appropriate means to ease the difficulties and costs in such cases. For example, AECL is participating in the international RASPLAV program, which is undertaking experiments on the melting of actual reactor core materials [1].

4.3.4 Uncertainty Analysis for Codes

It is important in the development of computer codes to establish the uncertainties in the predictions of key parameters. This is particularly important for safety analysis for licensing purposes, for which the AECB requires an uncertainty assessment and allowance. Together with others in the nuclear industry, AECL is now developing an approach to safety analysis that uses a best estimate, rather than a conservative approach, coupled with a more rigorous, statistically based uncertainty analysis that provides much more reliable knowledge of safety margins.

The present methodology represents an important step forward in the validation of computer programs and provides a more informative safety analysis, yielding reliable data on the true safety margins for key parameters in accident scenarios. Such information allows reduced conservatism in reactor design, with the potential to reduce capital costs and improve operating flexibility without jeopardizing safety. In addition, by identifying the uncertainties with the greatest impact, this methodology can focus R&D on the areas that really matter. The AECB has recently expressed support for the use of this methodology, while identifying certain issues that need further attention.

4.3.5 Industry Standard Toolset

Code development is very time consuming and costly. It has been recognized that the Canadian nuclear industry cannot afford to write, qualify and validate different computer codes to perform the same task. Agreement has been reached among AECL, OPG, New Brunswick Power and Hydro Quebec to use and maintain a single set of key computer codes, with one exception, for licensing and safety analysis. The one exception is for the basic thermalhydraulic codes; AECL, New Brunswick Power and Hydro Quebec will continue to use the CATHENA code while OPG will continue to use the TUF code.

AECL will have the responsibility for maintaining, ensuring software quality assurance, and validating six of the key industry standard toolset codes while, OPG will have the same responsibility for four industry standard toolset codes.

4.3.6 AECL Code Management Panel and Code Centre

AECL has established a Code Management Panel whose mandate is to provide advice and guidance on the development and application of AECL codes, to provide formal endorsement of quality-assured, validated codes (“frozen” codes), and to provide oversight and leadership.

Another responsibility of the Code Management Panel is to oversee the management of the AECL Code Centre. AECL intends that the Code Centre will make AECL technology more readily available to universities, institutes and clients under controlled terms and conditions. By this means, it seeks to open more business opportunities, to attract students to the nuclear field, and to make nuclear technology more familiar and more acceptable to those outside the industry. The Code Centre will keep track of AECL computer codes, facilitate and oversee the transfer of these codes to external organizations, facilitate operation of user groups for key codes, and serve as a point of contact for external bodies on AECL codes.

4.3.7 Conclusions

The development and maintenance of computer codes, which play a major role in the design and safety analysis of CANDU and MAPLE reactors, rely significantly on the knowledge, experience and judgement of experts in the various technical disciplines. In its 1998 Report, the Panel discussed a pilot project on succession planning for key personnel. Recognizing the importance of codes to AECL and the intense competition in the market place for people with computer skills, this approach should be used to analyze AECL's core expertise in computer codes.

The Panel endorses the effort that AECL is devoting to software quality assurance. The Panel is impressed with the approach being taken by AECL on uncertainty assessment for key output parameters of computer codes. It believes that this approach has the potential for reducing unnecessary reactor design conservatisms, improving reactor operating flexibility, and focusing R&D on the most significant areas.

The Panel also supports the establishment of the AECL Code Centre. It believes that promoting familiarity with CANDU and MAPLE technology will not only promote business opportunities, but will also help to attract young engineers and scientists to the nuclear industry.

4.3.8 Recommendations

Recommendation 1

The Panel recommends that AECL apply the methods developed in its pilot program on succession planning for the purpose of safeguarding and maintaining its core expertise.

Recommendation 2

Recognizing the difficulties involved in certain experiments needed for computer code validation, the Panel recommends that AECL continue to participate in appropriate generic international R&D programs.

Recommendation 3

To help achieve the objectives of the AECL Code Centre, the Panel recommends that AECL develop a program and mechanisms to inform potential users of the existence of the Centre, the services that will be provided and other relevant information.

4.3.9 References

1. Behaviour Of Corium Melt Under External Cooling, Final Report of First Phase of RASPLAV Project, Kurchatov Institute, Moscow, January 1998.

4.4 FUEL CHANNELS

The Zr-2.5% Nb alloy pressure tube, now used in all CANDU reactors, is the key component that determines the service life of a fuel channel. Irradiation and pick-up of deuterium, which is generated by corrosion and the dissociation of the heavy water coolant, can significantly change the strength and fracture toughness of this alloy at some locations along a pressure tube. Also, during normal operation of the reactor, there are changes in length, diameter and curvature (sag) of the pressure tube.

Research and development on the inspection of fuel channels by AECL spans three decades. During that period, AECL has provided equipment and conducted or supervised inspections of many pre-service and in-service channels. All pressure tubes are manufactured and inspected to AECL specifications prior to installation. Garter spring location is a key installation issue; AECL developed the eddy current method that is used by tube installers to confirm garter spring location. Since 1986, Ontario Hydro (now OPG) has provided most of the routine in-service volumetric inspection done on CANDU fuel channels, with R&D input from AECL.

Recent organizational changes at OPG have included cutting the inspection services that they offer to other utilities with CANDU power plants. To fill this gap, and to take advantage of R&D advances made by AECL and others in inspection techniques, AECL has designed and built a “wet” fuel channel inspection system that does not require feeder isolation or freeze plugs. The new system which is twice as fast as the old “dry” system, was used in the fall of 1999 to inspect a sample of fuel channel in Romania’s CANDU 6 reactor, Cernavoda-1.

Periodic inspection by non-destructive or destructive techniques, of selected pressure tubes, from operating reactors must be supported by an underlying research program on deformation, deuterium ingress, and fracture properties. Significant progress has been made in inspection techniques and in understanding the statistics of the material data and developing probabilistic approaches. The Panel is optimistic that this will lead to improvements in design equations, and that this program may eventually point the way to changes in material and manufacturing specifications that will reduce variability in deformation behaviour and/or deuterium pick-up.

4.4.1 Recommendations

Recommendation 1

Because of the growing importance of plant life extension and retubing methods and practices, the Panel recommends that AECL continue to have a research program in this area to support the enhanced inspection services that it will now offer CANDU owners in Canada and other countries.

Recommendation 2

Given the progress made in understanding and applying probabilistic approaches to the description of material and pressure tube behaviour, the Panel recommends that AECL continue its efforts to develop and improve the equations currently available to describe diametral expansion, longitudinal elongation and deuterium ingress.

4.5 ADVANCED NUCLEAR FUEL CYCLES

AECL has devoted considerable resources in the past to the development of advanced nuclear fuel cycles. Indeed, the Panel has noted in its past reports (1993 to 1996) that the demonstration of fuel cycle flexibility with CANDU will constitute a significant marketing advantage, even in countries already operating light water reactors.

Over the past year, various milestones have been reached, including:

- irradiation of 24 CANDU Flexible Fueling (CANFLEX) bundles in a CANDU 6 reactor for demonstration of behaviour under normal operating conditions in a power reactor; and
- fabrication of the first Direct Use of PWR Fuel in CANDU (DUPIC) fuel pellets from real spent fuel at CRL using the OREOX (Oxidation, Reduction of Enriched Oxide Fuel) process, for experimental irradiation in the NRU reactor.

4.5.1 The CANFLEX Fuel Development Program

The CANFLEX fuel development program has been one of AECL's major sustained efforts leading to the use of advanced fuel cycles. This program has now entered the critical stage of demonstration irradiation in an operating power reactor, leading to certification for full-core implementation in CANDU reactors. The 24-bundle demonstration irradiation started in September 1998 in Point Lepreau and will extend to April 2000, when the final irradiated CANFLEX natural uranium bundles will be subjected to post-irradiation examination at CRL.

Relative to the current 37-element fuel bundle design used in most operating CANDU reactors, the new CANFLEX bundle design offers a significantly higher critical channel power, lower peak element power ratings and the ability to maintain integrity to extended burnups at high power.

In addition to opening up the way to advanced fuel cycles, the CANFLEX fuel bundles with natural uranium can be introduced economically in operating CANDU reactors, because they provide enhanced reactor operating margins. These margins could avoid or postpone derating due to aging. Although the fabrication costs of CANFLEX (with natural uranium) may initially be 10 to 15% higher than the standard 37-element fuel bundles, the additional revenues arising from the increase in reactor power make a strong business case.

Another short-term benefit arising from the CANFLEX program is the opportunity of marketing a low-void-reactivity fuel. Such fuel could conveniently be introduced when the existing reactors are shut down for retubing. For new reactors, it could be offered as an option.

4.5.2 The DUPIC Option

For the DUPIC fuel cycle to become a reality, the feasibility of recycling spent PWR fuel directly in a CANDU reactor must also be demonstrated from a reactor physics point of view. In particular:

- achievable burn-up in CANDU with spent PWR fuel must be sufficient to justify the cost of remote fabrication and disposal of the DUPIC fuel;
- performance parameters for DUPIC fuel must fall within the standard (natural uranium) CANDU operating envelope; and
- reactivity coefficients may differ, but the existing reactivity devices must be adequate for control and safety.

Development of the DUPIC cycle is being carried out in collaboration with the Korean Atomic Energy Research Institute (KAERI) and the US Department of State. Over the past five years, KAERI has done detailed reactor physics analyses of a CANDU 6 reactor with DUPIC fuel. The KAERI study is based on the heterogeneous inventory of fuel from different reactors at different times. One of the major difficulties with the direct use of this spent fuel is the heterogeneous composition of the assemblies, and the fact that as many as 23 CANDU bundles can be fabricated from each assembly.

It is clear that variations in spent PWR fuel composition could lead to a large uncertainty in DUPIC fuel bundle properties and result in a significant reduction in operating margin. The proposed solution to this heterogeneity problem is a blending strategy for the powder coming out of the OREOX process. In the Panel’s view, the feasibility of DUPIC in a CANDU 6 has been demonstrated for Korea, but would require a significant degree (20%) of blending with fresh fuel to reduce the heterogeneity of the DUPIC fuel bundles.

The Panel considers that the heterogeneity problem with DUPIC could possibly be resolved without resorting to blending with fresh uranium, with a more judicious inter-assembly mixing of DUPIC powders.

4.5.3 Conclusions

The Panel concurs with AECL that R&D in advanced fuel cycles must continue to be supported. In the short term, the slightly enriched uranium (SEU) option offers the most potential for improving the performance of CANDU reactors. This option also includes the use of recovered uranium from commercial reprocessing of light water reactor fuels. Use of SEU fuel not only leads to significant savings in operating costs (as much as 30% of the fueling costs), but it will also provide an additional degree of freedom to design low-void-reactivity-fuel and to reduce the size of the core.

As a long-term option, the DUPIC fuel cycle appears to be most promising.

4.5.4 Recommendations

Recommendation 1

The Panel recommends that AECL investigate the proposed powder mixing strategy for DUPIC in greater detail, in view of the negative impact of using fresh fuel in the current approach.

4.6 HEAVY WATER PRODUCTION TECHNOLOGY

The use of heavy water as a moderator is undoubtedly the key characteristic of the CANDU reactor. The heavy water moderator underlies the excellent neutron economy of the CANDU, exceeding that of all other power reactor types. The excellent neutron economy leads to efficient utilization of mined uranium, and permits the use of advanced fuel cycles without major changes to the CANDU design.

The Panel reviewed in detail heavy water production technology, supply and demand, economics and R&D requirements in its 1996 report, and up-dated this review in its 1997 report. In these reports, the Panel recommended ongoing and increased support for R&D on new production technologies. Since then, the Panel has been updated on recent developments in this area and has visited the Prototype CIRCE Plant being constructed at Air Liquide in Hamilton. This section provides a progress report and assessment of current AECL activities in this field.

In order to meet the demand for projected sales of CANDU reactors, AECL has an existing inventory of heavy water. Some of this heavy water is on loan to the Sudbury Neutrino Observatory project. AECL is inventing new technologies to meet future demand based on the patented wet proof catalyst system. AECL also has an inventory of tritiated heavy water which it acquired during the development of its prototype reactor programs. Some R&D activity is directed toward the removal of tritium from this inventory.

4.6.1 New Technology Initiatives

In Section 6.2.1 of its 1997 Report, the Panel noted that AECL was working on the final details of an agreement with Air Liquide Canada to deploy a prototype 1 Mg per year by-product heavy water plant from Air Liquide hydrogen production in Hamilton. Construction of this plant, the Prototype CIRCE Plant was almost complete and commissioning was beginning when the Panel visited the site in September 1999.

The plant utilizes the Combined Industrial Reformed Hydrogen and Catalytic Exchange (CIRCE) process as the first stage. Hydrogen is produced in a modified steam-methane reformer owned by Air Liquide Canada in which a methane feed reacts with steam at high temperature to produce hydrogen and other gases. After removal of the other gases, hydrogen passes through a catalytic-exchange bed in which the deuterium content of counterflowing water is increased. The water then goes to a second stage which uses the Bithermal Hydrogen Water process to further enrich the water in deuterium. In the third and final stage, the

Combined Electrolysis and Catalytic Exchange (CECE) process is used to produce the product heavy water.

As the start-up of the Prototype CIRCE Plant approaches, there is increasing urgency to develop a computer simulation of the plant as-built. The as-built simulation is needed to analyze the performance of the operating plant to demonstrate that it meets expectations, to provide a means of resolving operating problems, and to serve as the basis for the design of commercial CIRCE plants.

To remove tritium and up-grade the used heavy water, AECL is proposing the construction of the Heavy Water Production System at CRL, with a capacity of about 300 Mg per year. The technology to be used is a modification of the CECE process. The CECE process makes use of the water-hydrogen exchange process in which counterflowing streams of water and electrolytically produced hydrogen are passed over the AECL-developed wet-proof catalyst to increase the concentration of the deuterium isotope in the water stream.

The CECE technology to be used in the Heavy Water Production System is also being considered for small units for de-tritiating heavy water at reactor sites. AECL is collaborating with Stuart Energy Systems (formerly part of the Electrolyzer Corporation) on the development of electrolyzers for these applications. Large centralized electrolyzers, as well as small local units, would also be needed for the hydrogen economy discussed in Section 3.4.2 of this report. Development of electrolysis cells for all these purposes is partly funded by the federal government, and testing of improved electrolysis cells is in progress at l'Université du Quebec à Trois Rivières.

Recent R&D on the wet-proof catalyst has yielded some important results:

- Evidence is growing that catalyst activity has a lifetime greater than originally anticipated. The longer the lifetime, the less frequently the catalyst will have to be reactivated or replaced, thus lowering operating costs.
- A method for spraying catalyst onto the supporting screen has been developed, which will reduce the costs of producing catalyst beds.
- Effective reactivation of catalyst beds has been achieved with a flowing mixture of oxygen in nitrogen.

4.6.2 Conclusions

AECL has now obtained experience in catalyst operation under industrial conditions and has brought the technologies to the brink of commercial demonstration.

The Panel agrees with the view, as expressed by senior AECL personnel, that there are still large benefits to be achieved from improvements in catalyst performance. Therefore, the Panel is convinced that continuing support for further R&D on wet-proof catalyst performance, reactivation and fabrication is essential.

4.6.3 Recommendations

Recommendation 1

Because of the importance of a computer simulation of the as-built Prototype CIRCE Plant to the analysis of its performance, the Panel recommends that the development of this simulation be given a high priority.

Recommendation 2

The Panel strongly recommends that AECL continue its collaboration with Canadian industry in the development of improved and larger electrolyzers.

Recommendation 3

Recognizing that there are still large benefits to be achieved from improvements in wet-proof catalyst performance, such as maximizing catalyst activity, minimizing fabrication cost, increasing lifetime, and scaling up for industrial process conditions, the Panel strongly recommends that support continue to be provided for research and development in this area.

4.7 THE CANDU-X CONCEPT

The Panel reviewed the objective and implementation of AECL's strategy for the evolution of the CANDU reactor design and the long-term Advanced CANDU Reactor Concept (CANDU-X) in its 1996 Report. The Panel revisited the CANDU-X concept in its 1997 Report following a change in the proposed coolant.

The long-term objective is to achieve reductions in both capital and operating unit energy costs below those of present CANDU designs while retaining the essential features of the design that underlie its successes and have made it attractive to customers, namely:

- heavy water moderator, separate from the coolant;
- horizontal fuel channels in pressure tubes; and
- on-power fueling with short fuel bundles.

The CANDU-X concept represents AECL's long-term vision of a revolutionary reactor design that, while retaining the essential CANDU features, incorporates "quantum" changes designed to meet the Company's ambitious unit energy cost targets. The purpose of the concept is to challenge AECL engineers and scientists to develop such a design, and to focus long-term R&D efforts to support this development. While the CANDU-X design may never be built as such, spin-offs from the supporting R&D should benefit the evolutionary development of the CANDU. This approach has already yielded potential benefits.

The current CANDU-X design concept is based on the use of supercritical water (SCW) coolant. There are a number of modern fossil-fueled power plants operating with SCW coolant, and recent studies in Japan and Russia indicate that SCW-cooled light water reactors are feasible with some extrapolation of current pressure vessel technology. The CANDU-X modular design, with pressure tubes rather than a pressure vessel, should provide an advantage in this respect.

4.7.1 Current CANDU-X Conceptual Design

The latest conceptual design for the CANDU-X, as described by Bushby et al. [1], is based on an arrangement that utilizes natural circulation of the primary coolant, rather than a pump-driven flow[6]. The advantages of this design are the absence of pumps in the primary circuit, reducing both capital and operating costs, and the enhancement of passive safety.

4.7.2 Analytical Studies of Natural-Circulation SCW Cooling of CANDU-X

AECL has developed an analytical model for predicting the thermalhydraulic behaviour of a natural-circulation SCW-cooled CANDU-X [1]. Preliminary results from analysis with this model show that, while channel powers similar to those in current CANDU reactors should be achievable with natural-convection SCW cooling, some modifications in fuel bundle design may be needed and some constraints on operating conditions may exist.

As discussed in the 1997 Panel Report, the high temperatures and pressure of the SCW coolant require a new composite fuel-channel design, the CANTHERM channel. In this design, there is no calandria tube and the pressure tube is maintained at a temperature close to that of the moderator by internal insulation.

Also in its 1997 Report, the Panel emphasized the necessity of developing successful designs for ensuring adequate sealing between the fuel channel and its end-fitting, and between the fuel channel and the fueling machine under the more onerous pressure and temperature conditions of the SCW-cooled CANDU-X design. AECL has developed a new "bore seal" design concept for fuel channel sealing, which should reduce the probability of leakage, simplify the fueling machine and increase fueling rates. A working model has been produced to demonstrate the principle of the bore seal.

[6] Natural circulation flow was used in some small boiling-water reactors in the USA in the 1950s by taking advantage of the large difference in densities between the water at the core inlet and the water-steam mixture at the core exit. Natural circulation flow is also used in AECL's low-power SLOWPOKE research reactors.

4.7.3 Plant Engineering

Considerable R&D, as well as design effort, will be needed to ensure that the target for unit capital cost reduction is achieved, particularly considering the significant increase in pressure from current levels. Continuing efforts to improve plant constructability will be needed. In addition to development of the horizontal steam-generator design and of fueling machines suitable for the CANDU-X conditions, questions of plant control under supercritical pressure conditions, including start-up and shut-down procedures, must be addressed. Also, work will be needed to adapt or extend existing computer codes for the safety analysis of these designs, and to undertake studies on accident scenarios under supercritical water conditions.

4.7.4 Conclusions

The Panel is very impressed by the progress made by AECL on the SCW-cooled CANDU-X and is pleased to note that a key function of the CANDU-X concept, to generate spin-offs that can be incorporated in to evolutionary CANDU designs, is already beginning to produce benefits. The bore-seal design, which could reduce costs and improve performance in conventional CANDU designs, is already the focus of an engineering project.

4.7.5 Recommendations

Recommendation 1

Considering the potential for spin-off benefits from the CANDU-X program, as well as its continuing challenge to researchers and engineers, the Panel recommends that AECL consider a significant increase in the budget for the CANDU-X concept.

4.7.6 References

1. S.J. Bushby, G.R. Dimmick, R.B. Duffey, N. Spinks and D.J. Wren, Conceptual Design for a Supercritical-Water-Cooled CANDU, June 1999.

CHAPTER 5: THE CANADIAN NEUTRON FACILITY

5.1 INTRODUCTION

Since its inception, the Panel has been a strong advocate of a new research reactor for AECL to replace the aging NRU Reactor. In 1998, the Panel devoted considerable efforts to help make the case for the Canadian Neutron Facility (CNF), based on a variation of AECL's MAPLE reactor technology, to meet the needs of:

- AECL, as a reactor vendor, for a research reactor for the support and future development of the CANDU reactor; and
- Canada, as an advanced industrial economy, for a neutron beam facility for basic and applied materials research.

The Panel presented a detailed review of issues relating to the CNF in its 1998 Report, and issued a special report in October 1998: "The Importance of the Canadian Neutron Facility to the Support and Future Development of CANDU Reactors". Members of the Panel also attended a National Workshop on Neutron Scattering in Ottawa in November 1998, which emphasized the importance of the CNF as a materials research tool.

These activities were a small part of those leading up to the completion of the CNF Proposal and Executive Summary. Now that these documents have been completed, submitted to the federal government and distributed to other interested parties, the Panel has very little to add to its already strongly expressed views on this matter. Therefore, only a brief progress report and assessment is provided here.

5.2 CURRENT STATUS

5.2.1 Recent Activities

As already noted, the major event of the year was the completion of the CNF Proposal and its Executive Summary by the NRC and AECL, which occurred in May 1999. The Panel is pleased to note that its above-mentioned October 1998 report on the importance of the CNF for support of CANDU technology was included as an appendix in the Proposal. The Panel contributed to the Proposal by providing AECL with a detailed editorial review. Members of the Panel have also written letters in support of the CNF to the federal Ministers of Natural Resources and of Industry.

As noted in the 1998 Report of the Panel, NRC and AECL have formed a high-level Steering Committee to provide direction and leadership to the campaign to secure financing for the CNF. The Steering Committee, composed of senior representatives of NRC, AECL, NSERC, and the independent Advisory Group has developed the CNF Communications Plan to raise the profile of the CNF to a broad audience in Canada.

Since the 1998 Panel Report was issued, actions based on the Communications Plan have emphasized the need for the CNF to federal and provincial ministers and departments, universities, industries and local politicians. The importance of the CNF as a materials research tool has been publicized in feature articles and editorials in newspapers. Presentations on the CNF have been made at scientific and industrial conferences.

These activities have elicited strong statements of support from universities, business leaders and local federal, provincial and municipal politicians.

5.2.2 Federal Government Policy Issues

The federal government perspective towards science and technology has become much more positive recently. Based on statements by the Prime Minister and senior cabinet members, as well as certain concrete actions, the government recognizes that the future of the Canadian economy and social structure depends greatly on Canada's success in adapting to a global economy that is becoming more and more knowledge-based, rather than resource-based. Evidence of this recognition includes an allocation of over $1.8 billion in the February 1999 budget, in the area of science and technology, and the announcement of funding for the Canadian Light Source at the University of Saskatchewan, the largest single R&D infrastructure investment in the last 30 years.

In addition, the important role of nuclear power in avoiding GHG emissions and assisting Canada into meeting its Kyoto Protocol commitments, as discussed in detail in Chapter 3 of this Report, is becoming recognized more fully by federal government departments involved in such questions. This should lead to a growing recognition of the need to ensure that AECL continues the commercial success of the CANDU reactor, which will not be possible without the replacement of the NRU Reactor by the CNF.

A recent book by Lester Thurow, a well-known professor of management and economics at the Massachusetts Institute of Technology, sets out new rules for success in the knowledge-based world [1]. Rule seven is: “A successful knowledge-based economy requires large public investments in education, infrastructure and research and development”. Federal government financing of the CNF would be an important investment in R&D infrastructure to help ensure the ongoing success of the Canadian economy.

Therefore, the climate appears to be favourable for funding of the CNF. However, the Panel recognizes that there are many competing demands on the federal government for funding, and that considerable efforts will be needed to develop an understanding of the benefits to Canada of the CNF, and to ensure the federal government’s commitment as soon as possible.

5.2.3 Design and Operational Issues

Experience gained in the design and construction of the MAPLE reactors, Hanaro in Korea and the MDS-NordionMedical Isotope Reactors (MMIR) at CRL, and in the preparation of the proposal for a

MAPLE research reactor for the Australian Nuclear Science and Technology Organization (ANSTO), have led to beneficial modifications to the CNF design.

Experience with the MMIRs has suggested that construction costs may be reduced by moving the CNF from a site within the active area at CRL to a new site, adjacent to the present site but outside the active area. Before the reactor would go critical, the active area would be extended to enclose the CNF. The new location may also have the benefit of facilitating access for researchers using the neutron beam facilities. The costs and benefits of such a step are now being evaluated.

From experience with the ANSTO proposal, AECL has developed improved specifications for the cold source in the CNF, has optimized the plant layout and has identified more competitive sources for certain components.

The Panel has assessed the operating costs for the neutron beam facilities, as given in the proposal, and has found them to be reasonable, particularly considering the inclusion of a cold neutron source. Experience at a Japanese research reactor showed a ten-fold increase in users and associated costs after a cold source was installed.

5.2.4 Governance Issues

The Proposal does not go into detail on the governance of the CNF other than suggesting a possible management structure consisting of a Management Authority with separate directorates for the reactor, the CANDU facilities and the Neutron Beam Laboratory.

A key challenge to AECL and NRC is to work out a viable method of governance that satisfies the federal government's strategic concerns, AECL's needs for CANDU R&D, and the needs of individual researchers using neutron beam facilities. Also, the AECB must be satisfied that the design and operation of the CNF is managed appropriately to ensure that licensing requirements are met and that safety is assured.

Two of the issues that must be addressed in the governance model are:

- a means to manage the complex experimental scheduling requirements, and
- arrangements for funding neutron-beam research.

NRCan has been requested to develop a governance model for the CNF that will meet these needs. One possibility being considered is setting up a separate legal entity from AECL and NRC to receive and administer the funding. An acceptable governance model may be key to gaining federal government approval of the CNF proposal.

5.2.5 The Neutron Gap

In its previous reports, the Panel has expressed concerns about a "neutron gap", a period between the shutdown of the NRU Reactor and the start up of the CNF in which Canada, and the CANDU program in particular, would not have access to an indigenous research reactor.

5.3 CONCLUSIONS

As stated by Nobel Laureate Bertram Brockhouse in the Executive Summary of the CNF Proposal "The Canadian Neutron Facility offers unprecedented potential for the advancement of materials research in Canada and is indispensable for the continued success of Canada's nuclear program". The Panel strongly endorses this statement, which is essentially the same message expressed many times in the past by the Panel.

In addition, the Panel emphasizes the urgency of a firm commitment by the federal government to the CNF. The Panel believes it is important to make this strategic investment in a timely manner in order to maintain scientific talent and continue with leading edge research.

5.4 RECOMMENDATIONS

Recommendation 1

The Panel recommends that AECL continue to press for the earliest possible commitment of the CNF by the federal government to minimize the neutron gap.

Recommendation 2

Since a governance model acceptable to all stakeholders will be required, the Panel recommends that AECL give high priority to working closely with NRCan, NRC and other bodies to develop, as soon as possible, a governance plan that meets the key needs of those involved.

5.5 REFERENCES

1. L.C. Thurow, Building Wealth: New Rules for Individuals, Companies and Nations in a Knowledge-Based Economy, Harper Business, 1999.

CHAPTER 6: THE RADIATION BIOLOGY AND HEALTH PHYSICS PROGRAM

6.1 INTRODUCTION

In its previous reports, the Panel emphasized the importance of research concerning the effects of ionizing radiation on biological systems and the environment. The insights gained from such investigations support the industry, both directly and indirectly. Biologically-derived constraints are directly used by AECL, the nuclear utilities, and by the AECB to define the limits of acceptable engineering and design of safe operating conditions for the protection of workers, the public, and the environment from adverse effects of ionizing radiation. The costs associated with the design and operation of power plants within these limits impact on the economic viability of the long-term nuclear option. While nuclear energy continues to be an economically competitive option, under the current conservative regulatory framework, design and regulation in excess of biological necessity increase costs, which must ultimately be borne by the consumer. Thus, AECL, as the CANDU vendor, needs a continuing source of radiobiological information, and the in-house ability to critically analyze these data. The AECB and other government agencies need evidence and radiobiological advice in order to set workable regulatory standards.

6.2 PUBLIC CONCERNS

Public concerns about the safety of nuclear power plants can only be addressed responsibly through recourse to an evidence-based understanding of radiation effects. While science alone will not be sufficient to counter all the negative public opinions of nuclear energy, it is essential that proponents of the technology base their contributions on accurate information about biological and environmental effects, inter alia, of the nuclear plant life cycle. This need is not so much driven by AECL's internal requirements, as it is by the needs of public policy and long-term planning.

As an aside, it is noted that radiation biology has many fertile interconnections with other fields of health science as varied as oncology, toxicology, molecular biology and aerospace medicine. Thus, the continuation of a strong Canadian radiation biology program will be beneficial to areas of development that extend well beyond the immediate needs of a nuclear power program. Since the benefits of radiobiological research are far-reaching, it is reasonable to expect that all the beneficiaries should collectively contribute to its support, and that AECL alone should not be expected to continue to fund the entire program in Radiation Biology and Health Physics.

Public concerns and the needs of the nuclear industry centre around the same issue, namely, what are the effects of low radiation doses. The conservative assumption underlying the internationally accepted basis for the regulation of radiation safety is that all exposures are harmful in proportion to the dose received, an assumption that has been received as a fact by the public. This dose effect holds in the high dose range in which it is possible to perform statistically sound experiments. However, at the very low doses, which can realistically occur with some frequency to nuclear energy workers or to the public, the effect, if any, is less certain. This is so because it has not been possible to perform statistically valid epidemiological analyses to detect the low frequency of birth defects or cancers caused by radiation against the high background of spontaneous events.

The evidence that the cellular basis of radiation effects is due to DNA damage came from radiobiological research, as did the observations that much of the damage, even at high doses, is quickly repaired. The magnitude of the damage from large doses swamps the repair mechanisms preventing complete repair. The residual damage leads to altered cell behavior and, in some cases, to the initiation of a cancer. It is not known whether this also happens with a proportional frequency at low doses since the extent of repair may be greater or even complete. New techniques in molecular biology allow consideration of experiments to determine whether cells, in fact, do reliably repair all the damage following low doses. Thus, the hypothesis that there is a threshold dose below which no significant effects occur has become testable. Should the hypothesis be proven to be true, then relaxation of current dose limits would permit major changes to be made throughout the industry, which would enhance the economic competitiveness of the nuclear energy option and could significantly improve public acceptance of nuclear power. The US DOE is proposing to fund a large research program to test the threshold hypothesis and Congressional approval of the funding is currently awaited.

6.3 FUNDING FOR RADIATION BIOLOGY

The dilemma faced by AECL regarding the Radiation Biology and Health Physics Branch was reviewed in the Panel's report in 1998. Briefly, reduced R&D funding by government together with the Corporation's mandate to become the CANDU reactor vendor, rather than remain the National Nuclear Laboratory, have constrained priority setting such that the minimum financial support required to maintain a vital stake in an independent biology program is no longer available. Although AECL continues to need dosimetry services and some radiation biology and health physics studies for its own purposes, the volume and scope of internal work in radiobiology are not adequate to sustain the interest of scientists and technologists, or to fully utilize the value of the CANDU Life Sciences Centre.

Radiation Biology and Health Physics is not a solitary outlier in AECL's R&D programs: it is an example of aspects of nuclear research that are required to support national policy development, nuclear industry regulation, public safety, and environmental protection. As such, it should logically be funded independently of AECL and held accountable through channels that are also independent of AECL. Thus, with the exception of the Dosimetry Services component, Radiation Biology and Health Physics is a program in transition. There needs to be a clear vision of what it is to become in the future. The program will need transitional support until the vision is accepted and implemented.

Through 1999, AECL's biologists and staff have led an initiative to sensitize the, hitherto, silent beneficiaries of the Radiation Biology and Health Physics Program to the need for change. There have been discussions with the AECB and the Radiation Protection Bureau of Health Canada. Perhaps fortuitously, the government announcement in the 1999 Budget of the restructuring of health research under the Canadian Institutes for Health Research presents an opportunity for a resolution in which radiobiology could become integrated within one of the envisaged virtual institutes. Were this to occur, it would help to integrate this important aspect of AECL's R&D with the mainstream of biomedical research at the universities.

The situation now concerning Radiation Biology and Health Physics is somewhat comparable to that which formerly existed in the Material Science Program, and which has now been successfully transferred to the NRC after a three-year transitional period. The concern with Radiation Biology and Health Physics is that the mode and means of transition are not yet fully clarified, and that interim funding has not been identified.

6.4 NATIONAL CENTRE FOR RADIOLOGICAL SCIENCES

The AECL vision for the Radiation Biology and Health Physics Program is that it will be restructured as a "National Centre for Radiological Sciences", an independent institute attached to a university, or AECL, or another government department, and funded by its customers and beneficiaries. The National Centre for Radiological Sciences would be primarily based at CRL so as to take advantage of the facilities and to service AECL's requirements, but it would network nationally and internationally. Its scientific direction would be overseen by a board representing the shareholders, and its main function would be to:

- conduct R&D in radiation biology and health physics,
- provide dosimetry services to AECL and other customers,
- offer R&D and commercial services to clients,
- inform and advise government and industry, and
- participate in national and international standard-setting bodies.

It is projected that AECL will continue to support the Dosimetry Services component and the Radiation Biology and Health Physics R&D for CANDU-related needs.

The view from outside AECL is that Canada, for several reasons, very much needs to maintain a radiobiological capability.

6.5 CONCLUSIONS

There is a broad consensus that the radiobiological expertise that AECL has nurtured for so many years is a national resource and should continue with future financial support from its customers and beneficiaries.

The Panel commends AECL's scientific and technical staff for their creativity during this difficult period. The biologists have had success in several external funding competitions to support ongoing research. This demonstrates that the group has external credibility and that the focus of its work is seen to have national and international significance. It is the Panel's view that the success of these initiatives should be seen as evidence of the importance and credibility of the program, and should not blind government and other potential beneficiaries of the program to the importance of ensuring the existence of a stable transitional funding platform for Radiation Biology and Health Physics over the next five years.

6.6 RECOMMENDATIONS

Recommendation 1

The Panel recommends that AECL continue to support the transition of the Radiation Biology and Health Physics Program toward a stable configuration. In the short-term, future customers and beneficiaries should be sensitized to the value of a National Centre for Radiological Sciences concept, and the necessity of sustaining the program through the transitional period. All reasonable possibilities for external funding should be pursued.

Recommendation 2

The Panel recommends that AECL closely follow developments related to the Canadian Institutes for Health Research and participate, where possible, in the development of the virtual institutes to ensure that no opportunity is lost to link the Radiation Biology and Health Physics Program into related national health research interests.

CHAPTER 7: UNIVERSITY RELATIONSHIPS

7.1 INTRODUCTION

Over the eight years during which the Panel has had an overview of AECL's R&D activities it has recognised the importance of links with universities. Probably the prime example of how successful such links can be is the strong interaction between the high-tech industries and the universities, in which industry promotion and support of teaching and academic research has given rise to extensive benefits for both sides.

Four major advantages are seen to accrue from AECL's university links:

- AECL has kept in touch with young people, who are the pool of developing talent needed for recruitment and who also play an important public relations role.
- Researchers at Chalk River keep abreast of developments elsewhere in the fundamental aspects of science and engineering; this helps AECL to maintain its position as a leading R&D organisation in Canada and abroad - a status that may be important to potential customers.
- University researchers in nuclear-related subjects are able to bring different but complementary perspectives to technical problems.
- University laboratories can be contracted to study problems which AECL cannot tackle itself because it lacks the resources.

These benefits - particularly the last two - have changed in significance in the last few years. This has been brought about by several factors, all of which have had the effect of placing more emphasis on "engineering" and "development" as opposed to "science" and "research". The single most important factor has been the approximate halving of the parliamentary grant to AECL. This necessitated the closure of the Tandem Accelerator Superconducting Collider (TASCC) facility and the decrease in importance of the "National Laboratory" aspect of AECL's activities. A second important factor has involved the restructuring of the CANDU Owners' Group (COG), which has reduced its R&D funding considerably to concentrate on improving CANDU plant performance. This has led to a reduction in the amount of COG R&D being carried out at AECL.

An indirect effect of all these reductions and changes has been that the numbers of undergraduate and graduate students, as well as post-doctoral fellows and professors, working at AECL have diminished over time. It therefore seems appropriate for the Panel to take stock of the situation in 1999, and to consider what can and should be done to improve AECL's relations with Canadian universities to take advantage of the potential benefits.

7.2 UNIVERSITY CHAIRS

AECL has a long-standing tradition of supporting senior research positions at Canadian universities, early examples being the appointments in materials science at the University of Western Ontario in the mid 1980s when AECL's materials science activities were curtailed and Chalk River staff moved there. More recently, the Bertram Brockhouse Chair was established at McMaster University in 1998 after AECL had made a one-time endowment in 1996.

Such appointments provide AECL with the links to the fundamental sciences mentioned earlier and enhance its reputation with the academic community. For example, at its 1999 December meeting, the Panel heard a presentation by the Brockhouse Chair incumbent, Professor Bruce Gaulin, who described his research activities in advanced materials. It is clear that these activities are at the forefront of research into condensed matter physics and provide an excellent example of the synergy between the NRC group operating the neutron beam facilities at Chalk River and the universities. The provision of the CNF will be vital for these and other activities in the future. Similarly, AECL is seen as giving considerable support to the fundamental science community by its loan of a large quantity of heavy water to the Sudbury Neutrino Observatory Project.

7.2.1 NSERC Industrial Research Chairs

One important aspect of supporting university chairs is that matching funds can often be obtained from industrial partners and, through NSERC, the federal government. In general, a financial contribution to an NSERC Industrial Research Chair by AECL is matched by one industrial partner or more, and their total is matched by NSERC. By providing seed money and other appropriate support, therefore, AECL is able to favour the development of certain topics of research and specializations; in this way, types of expertise that would otherwise be lacking can be fostered. The initial commitment to an Industrial Research Chair is made for five years, and during this period the chairholder's salary is gradually taken over by the university. This means that the university commits a tenure-track position to the chair. Once the incumbent is appointed to an Industrial Research Chair and the infrastructure and equipment put in place, graduate students, post-doctoral fellows, visiting professors, etc. arrive to participate in the research of the group.

An Industrial Research Chair may be renewed for another five years, but the NSERC rules for funding the second term are different since only the incumbent's salary, again on a sliding scale with the university, may be funded through this grant. The research activities are then supported by some other NSERC mechanism such as an Industrially Orientated Research grant, for which the incumbent must apply in competition with all other applicants for these grants.

AECL's experience with NSERC Industrial Research Chairs (IRC) is briefly summarized here:

IRC in Nuclear Engineering, University of New Brunswick

This was established in partnership with New Brunswick Power in 1984, renewed in 1989, and ended in 1991.

This was NSERC's first Industrial Research Chair. The appointee, Dr. D. Meneley from Ontario Hydro, established a low-level radiation laboratory for radiation tomography studies at the University of New Brunswick and developed techniques of analysis and modeling for nuclear reactors. Undergraduate and graduate courses in a nuclear option program were established to meet the recruiting needs of New Brunswick Power, and university faculty became involved in the operator training program at the Point Lepreau Station. Dr. Meneley resigned in 1991 to become AECL's Chief Engineer at Sheridan Park.

IRC in Nuclear Engineering, University of New Brunswick

This was established in partnership with New Brunswick Power in 1992, and renewed in 1997.

This succeeded the first Industrial Research Chair, but was established, under NSERC rules, as a completely new venture. The appointee, Dr. D. H. Lister from Chalk River, built a medium-level radiation laboratory where high-temperature loops and autoclaves have been installed for studying corrosion and mass transport problems in reactor coolant systems. Low-temperature systems have also been built to study the mass transport aspects of heat exchanger fouling. Undergraduate and graduate courses in the nuclear option have been developed, and contributions to the training of operators at Point Lepreau and the other Canadian nuclear stations are made.

IRC in Nuclear Engineering, University of Toronto

This was established in partnership with Ontario Hydro in 1989, renewed in 1994, and ended in 1999.

Dr. B. Cox from Chalk River brought expertise in the corrosion and hydriding of zirconium and its alloys to the University of Toronto where the Centre for Nuclear Engineering was established. Further elucidation of the mechanisms of zirconium alloy corrosion was accomplished in the research program using high-temperature autoclave facilities and surface analysis techniques. An important aspect of the program involved interaction with the University of Toronto SLOWPOKE reactor, where radiation damage phenomena could be studied. In fact, as Chair of the Centre for Nuclear Engineering, Dr. Cox led the application to NSERC for funding for a replacement core for the SLOWPOKE in 1996. Both the Centre for Nuclear Engineering and the SLOWPOKE reactor were key elements in an undergraduate option program in nuclear engineering and in training graduate students and post-doctoral researchers. By 1998, however, support for the reactor refurbishment had waned and by1999 the undergraduate option program had been discontinued. Dr. Cox retired and became Professor Emeritus in 1999 but remains as Chair of the Centre for Nuclear Engineering; he also has a position at Chalk River as Researcher Emeritus. While his research activities at the University are continuing, it is only until his remaining research students graduate.

IRC in Advanced Engineering Design, University of Saskatchewan

This was proposed by AECL in 1995.

This Industrial Research Chair was conceived as a complement to AECL's existing and planned design activities in Saskatchewan, and was aimed at developing more efficient schemes for the construction of major CANDU components with the added benefits of reducing costs and improving scheduling. The AECL activities in Saskatchewan have now been curtailed, however, and the Industrial Research Chair never materialised.

IRC in Applied Mechanics, École Polytechnique

This was under negotiation in 1999 with B&W Canada as AECL's industrial partner; and was approved by NSERC in 1999 December.

When this Industrial Research Chair is established, a scientist from Chalk River will be appointed as the Chairholder. The expertise that will be developed will be in the area of flow-induced vibration, which can be a life-limiting phenomenon in CANDU components such as heat exchangers and steam generators. The research should provide underlying scientific support for the more applied work being pursued at AECL. The appointment is expected to strengthen the nuclear component of the undergraduate engineering programs at École Polytechnique and to lead to further training of graduate students and post-doctoral researchers in an area of nuclear engineering. A strong link with the Nuclear Engineering program and the SLOWPOKE reactor operation at École Polytechnique is expected to develop.

7.2.2 Nuclear Engineering Chairs

Interactions with foreign universities, including the provision of Nuclear Engineering Chairs, has been and continues to be an important activity for AECL.

Currently, two chairs come into this category:

Chair in Nuclear Engineering, Institute for Advanced Engineering, Yongin, Korea

This was established in 1993 with the Institute for Advanced Engineering as partner. AECL's commitment is negotiated annually.

The objective of the incumbent, Dr. M. J. MacBeth, is to facilitate technology transfer between AECL and appropriate Korean organisations in aspects of CANDU, such as Computer Assisted Design and Drafting System (CADDS), controls, construction and safety analysis. Another objective is to forge strong collaborative links with important Korean industrial organizations.

Chair in Nuclear Engineering, Chulalongkorn University, Bangkok, Thailand

This was established in 1995 with partners Chulalongkorn University, Electricity Generating Authority of Thailand and the Canadian International Development Agency.

The chair is a key element of AECL's support for the Thai initiative in the extension and upgrading of university education in nuclear engineering, the planning and implementation of professional development programs for industry, and the education of the public with respect to nuclear energy. The incumbent, Dr. G. Bereznai, is also active in forging collaborative relationships with universities throughout Southeast Asia.

7.2.3 Summary

In summary, AECL's Canadian university chairs at present comprise one on-going Industrial Research Chair at the University of New Brunswick and one about to be launched at École Polytechnique. The collaborative links between AECL and universities are mutually beneficial and strengthen the science that is of interest to both parties.

7.3 RESEARCH CONTRACTS WITH UNIVERSITIES

AECL issues substantial research contracts to universities.

Of the 28 contracts issued in 1997 to 1998, 5 were performed abroad: 3 at Keele University (UK), and 1 each at the University of Minnesota (USA) and the University of Liverpool (UK). The Canadian contracts were distributed as follows: Carleton University (4), École Polytechnique (4), University of Manitoba (1), McMaster University (3), University of Montreal (1), University of New Brunswick (3), University of Ottawa (2), Sherbrooke University (1), University of Toronto (2), and University of Western Ontario (2).

Numerous graduate students have also prepared Masters' and PhD theses on nuclear-related subjects; many of these students took up employment subsequently in firms or agencies that deal with nuclear power.

Contracts are not only a cost-effective way of doing research and of providing important information to AECL, they also play key roles in improving the general understanding both of CANDU technology and of the importance of nuclear power in electricity generation and other applications. Accordingly, university contractors should be seen as partners, and not as competitors, in the achievement of specific scientific and engineering goals.

The Panel approves of university research contracts and finds that, given the many benefits to AECL that accrue from the issue of these contracts, the current policy of seeking the assistance of appropriate university experts be continued.

7.4 STUDENTS AT AECL LABORATORIES

AECL has a long tradition of hosting undergraduate and graduate students at both the Whiteshell and Chalk River Laboratories. In addition to the useful work they provided (and training they received), their involvement in AECL's programs has also served as an important public relations function, since it led to an increased understanding of the science and engineering aspects of nuclear power. Students have thus played a role in promoting public acceptance of nuclear power generation as a policy option.

In recent years, however, there has been a decline in the employment of students by AECL. For example, in the summer of 1991 (the year when the Panel began its deliberations) 79 summer students were employed at CRL, while in 1999 there were only 45 students and interns.

Because of the public relations importance of maintaining links with the university community, as well as the significant recruitment benefits that accrue by providing summer and other (e.g., co-op) jobs at AECL, the Panel recommends that these activities be maintained at least at their present levels.

7.5 THE CANADIAN SITUATION IN NUCLEAR ENGINEERING EDUCATION AND TRAINING

While no department offering first degrees in nuclear engineering has ever been set up in Canada, conventional engineering schools offering degrees in chemical, mechanical, etc., engineering have provided courses or option programs based on nuclear subjects. A few of these programs have emphasized the traditional nuclear engineering subjects such as reactor and neutron physics, reactor core design, thermalhydraulics and coolant technology, and have therefore offered quite intensive training in nuclear engineering. Others have merely added a smattering of nuclear-related subjects such as radiochemistry to give a flavour to conventional core subjects. At the graduate level, many graduate students have pursued research related to nuclear energy in various engineering departments in Canada.

Some universities and colleges have contracted their services to industry for training nuclear personnel and for preparing training material. It should be remembered here that the AECB imposes strict training requirements on personnel running nuclear facilities. To fulfill these requirements, the utilities Hydro-Québec and New Brunswick Power, with limited nuclear training facilities of their own, have used appropriate university services to fill in the gaps, which are often in the underlying science and engineering areas. Moreover, staff members employed by the AECB have used universities or colleges, which are independent of direct industry influence, to fulfill some of their own training needs.

It is interesting to note that at the five Canadian universities that provided data on their nuclear engineering programs to a survey-administered by the Canadian Nuclear Association [1], the numbers of undergraduates and the awarded bachelor degrees with nuclear content remained about the same from 1990 to 1998. By contrast, master's and doctoral students and the numbers of degrees awarded at those levels declined somewhat over the period, but probably not outside the expected statistical variation for such small numbers. The numbers of teaching staff also remained fairly constant.

In terms of research facilities at the universities, the recent shutdown of the SLOWPOKE reactor at the University of Toronto will have an impact on programs, in particular in Ontario. Elsewhere, however, there remain five university reactors. The SLOWPOKE reactor at École Polytechnique in Montreal has just received a new core, and the SLOWPOKE at Dalhousie University in Halifax is in the process of being refurbished. The SLOWPOKE reactors at the Royal Military College in Ontario and the University of Alberta also operate steadily as required, and the larger 5 MW pool-type reactor at McMaster University in Ontario is now operating successfully with a new management scheme. Although not all of these reactors are involved in nuclear-engineering programs per se (neutron activation analysis being the major role of the Dalhousie SLOWPOKE, for example), they all involve important aspects of nuclear technology in their operation, research and teaching functions.

It should be noted, too, that there are several facilities for nuclear engineering research at universities besides those ancillary to the SLOWPOKE reactors. In particular, the Nuclear Chair at the University of New Brunswick operates the intermediate-level radiation laboratory with high-temperature loops and autoclaves for reactor coolant studies, while a proposed new Chair at École Polytechnique will establish a laboratory with rigs for studying flow-induced vibration in reactor components. There are also engineering departments at universities across Canada with facilities capable of carrying out, or even devoted to, nuclear-related research. As a general example, thermalhydraulic rigs are available in many departments, while as a particular example, a containment simulation facility in the department of Mechanical and Aerospace Engineering at Carleton University, built to simulate SLOWPOKE accident conditions, has been adapted for general containment studies.

One issue of which the Panel is becoming increasingly aware in connection with nuclear engineering education and training is the advantage of writing a comprehensive text book on CANDU technology. While CANDU is mentioned in several texts as one example of a water-cooled nuclear reactor, no work offers a complete description of all the major CANDU aspects (by contrast, we refer to the recent publication by Dr. D. Rozon "Introduction to Nuclear Reactor Kinetics", Polytechnic-International Press, 1998, which concentrates on the core physics of CANDU). If such a comprehensive text were available to universities, institutes, clients and potential clients, the task of teaching the principles of CANDU and of transferring CANDU technology would be much easier. The provision of a CANDU text would also help an AECL Code Centre to achieve its objective of managing AECL's intellectual property, as invested in computer codes, and disseminating it appropriately.

7.6 THE CHANGING NATIONAL LABORATORY ROLE OF THE CHALK RIVER LABORATORIES

The change in AECL's mandate from a national nuclear laboratory to the nuclear vendor has caused a shift in the direction of research at AECL. The National Research Council now operates the Neutron Program for Materials Research (NPMR), formerly run by AECL. The NPMR includes five neutron-beam experimental facilities at the NRU Reactor, plus support services and equipment (as well as about 20 staff members). The existence of the NPMR within the Chalk River technical community provides an important, continuing link between AECL and the more fundamental science conducted by university researchers.

It is significant that the neutron beam facilities at the NPMR (especially the powder diffraction component of the DUALSPEC equipment and the surface analysis capability of the reflection technique) have brought a new breed of researcher to Chalk River - one that is far less versed in neutron diffraction techniques (they are not all physicists!) and less willing to spend lengthy periods at the facility. A new management scheme has been put in place to deal with the modified operating arrangements, which involve more users and much more data to be analyzed. The success of this venture should provide valuable lessons for the use of the proposed CNF by an even wider and much more numerous group of scientists.

The NPMR program currently involves about 100 scientists and engineers, who collectively carry out about 180 projects per year. Universities from across Canada (including ten from Ontario in 1997) have ongoing projects at NPMR. Many industrial customers in addition to the numerous AECL users have made use of the facilities. While the pattern of usage involving universities and industry is likely to continue, the numbers are likely to change.

7.7 RECOMMENDATIONS

Recommendation 1

The Panel recommends that AECL continue to support the establishment of University Chairs to complement specific aspects of CANDU development and to help its marketing activities; in this regard, AECL should move quickly to take advantage of the new federal government funding of 1,200 chairs promoting research excellence. The Panel further recommends that in order to do this effectively, AECL should institute a policy to consider the strategic placing of such chairs, to expedite their establishment and to monitor their progress when in place.

Recommendation 2

The Panel recommends that the employment of students be continued at the current level as a minimum.

Recommendation 3

The Panel recommends that AECL work with the universities and the Canadian Nuclear Society to support the writing and publication of one or more university-level text books to cover all the major features of CANDU technology.

7.8 REFERENCES

1. D.H. Lister, Country Report for Canada; The Survey and Analysis of Education in the Nuclear Field, OECD/NEA Report, 2000.

APPENDIX A: PANEL MEMBERSHIP

Dr. D.A. (David) Armstrong
Faculty Professor, Department of Chemistry
University of Calgary

Dr. R.L. (Robin) Armstrong
Department of Physics
University of Toronto

Dr. D.J. (David) Burns
Professor of Mechanical Engineering
University of Waterloo
(1999 Vice-Chairman)

Dr. A.A. (Albert) Driedger
Professor, Faculty of Medicine
University of Western Ontario
(1999 Chairman)

Mr. J.H.F. (Jon) Jennekens
Jonor & Associates

Dr. J.J. (John) Jonas
Birks Professor of Metallurgy and
Co-Director, McGill Metals Processing Centre
Department of Mining & Metallurgical Engineering
McGill University

Dr. D.H. (Derek) Lister
Chair, Nuclear Engineering
University of New Brunswick

Dr. E.A. (Ernest) McCulloch
Senior Scientist Emeritus
The Ontario Cancer Institute
Princess Margaret Hospital

Dr. G.G. (Gilles) Patry
Vice-Rector (Academic)
University of Ottawa

Dr. J.T. (Terry) Rogers, Professor Emeritus
Mechanical and Aerospace Engineering
Carleton University

Dr. D. (Daniel) Rozon, Directeur
Institut de génie nucléaire
École Polytechnique de Montreal

APPENDIX B: TERMS OF REFERENCE OF THE RESEARCH AND DEVELOPMENT ADVISORY PANEL TO THE BOARD OF DIRECTORS ATOMIC ENERGY OF CANADA LIMITED

B-1 MANDATE

The Research and Development Advisory Panel shall advise the Board of Directors of Atomic Energy of Canada Limited (AECL) respecting the strategic needs, alliances, and direction of the research and development activities of AECL. The Panel shall provide advice to the Board as to whether or not these programs have the appropriate scope, composition, and balance between short- and long-term activities, to sustain AECL's nuclear program, nationally and internationally.

B-2 DUTIES/RESPONSIBILITIES

To perform its Mandate, the R&D Advisory Panel shall undertake the following duties and specific responsibilities:

- The Panel shall meet not less frequently than three times during each AECL fiscal year to review all the R&D activities of AECL, and the operation of its major research facilities. The Panel shall report regularly to AECL's Board of Directors, including submission of an annual report, respecting the quality, appropriateness and relative size, and the need for any redirection of the scope, resources and priorities of the R&D programs.
- Panel representatives shall participate in the meetings of the Science and Technology Committee of the Board, and provide advice and confidential reports, as appropriate.
- The Panel shall meet regularly with AECL's product engineering and marketing staff to obtain their views on the R&D programs.
- The Panel shall meet periodically with representatives of Canadian utilities to discuss their needs and requirements so as to reflect these in the Panel's advice to the Board of Directors.
- In examining and advising on existing and proposed national and international scientific collaboration, the Panel shall also evaluate AECL's current and potential relationships with Canadian universities, and other post-secondary educational institutions, and organizations in the public and private sector conducting Canadian nuclear-related research.
- Members of the Panel may, after appropriate consultation with AECL, appear before properly constituted boards, commissions or committees of the federal or provincial governments in order to comment on all matters relevant to its Mandate.

APPENDIX C: PANEL PUBLICATIONS AND SUBMISSIONS

REPORTS

- Report of the AECL Research & Development Advisory Panel for 1998
- Report of the AECL Research & Development Advisory Panel for 1997
- Report of the AECL Research & Development Advisory Panel for 1996
- Report of the AECL Research & Development Advisory Panel for 1995
- Report of the AECL Research & Development Advisory Panel for 1994
- Report of the AECL Research & Development Advisory Panel for 1993
- Report of the AECL Research & Development Advisory Panel for 1992

SUBMISSIONS/PAPERS

- Science and Technology Review Submission, 1994 September
- Submission to the Environmental Review Panel for the Nuclear Fuel Waste Disposal Concept, 1995 August
- Submission to the Parliamentary Sub-Committee on Natural Resources on Bill to Review Nuclear Safety Act, 1996 October
- *The Importance of the Canadian Neutron Facility to the Support and Future Development of CANDU Reactors*, 1998 November
- Presentation to Natural Resources Canada on Consultation on Options for Federal Oversight of Nuclear Fuel Waste Management and Disposal, 1999 February 17
- Submission prepared at the request of Natural Resources Canada, *A Rationale for Canadian Expenditure on Nuclear Research and Development in the 21st Century*, 1999 May 14
- A report for Senior Levels of Government, *Vision 2020 and Beyond - The Need for Nuclear Research and Development in the 21st Century*, 1999 September

APPENDIX D: FREQUENTLY USED ABBREVIATIONS/ACRONYMS

Abbreviation/Acronym	Definition
AECB	Atomic Energy Control Board
AECL	Atomic Energy of Canada Limited
CANDU-X	Advanced CANDU Reactor Concept
CANDU®	CANadian Deuterium Uranium Reactor
CANFLEX® fuel bundle	CANDU Flexible Fueling
CATHENA	Canadian Algorithm for Thermalhydraulic Network Analysis
CANTHERM	A new composite fuel channel design for CANDU-X
CECE	Combined Electrolysis and Catalytic Exchange
CIRCE	Combined Industrial Reformed Hydrogen and Catalytic Exchange
CNF	Canadian Neutron Facility
COG	CANDU Owners Group
CRL	Chalk River Laboratories
DOE	US Department of Energy
DUPIC	Direct Use of PWR Fuel in CANDU
GAI	Generic Action Items
GHG	Greenhouse Gases
IAEA	International Atomic Energy Agency
IRC	Industrial Reseach Chair
LWR	Light Water Reactor
MAPLE	Multipurpose Applied Physics Lattice Experiment
MMIR	MDS-Nordion Medical Isotopes Reactor
NEB	National Energy Board
NPMR	Neutron Program for Materials Research
NRC	National Research Council

Abbreviation/Acronym	**Definition**
NRCan	Natural Resources Canada
NRU	National Research Universal Reactor
NSERC	Natural Sciences and Engineering Research Council
OPG	Ontario Power Generation (Before April 1999 – Ontario Hydro)
OREOX	Oxidation, Reduction Of Enriched Oxide Fuel
PWR	Pressurized Water Reactors
SCW	Supercritical Water
SEU	Slightly Enriched Uranium

Time-frame Definition as used in this Report	
Short-Term	0-5 years
Medium-Term	6-9 years
Long-Term	10-15 years