THE CANDU CONTRIBUTION TO ENVIRONMENTALLY FRIENDLY ENERGY PRODUCTION

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ABSTRACT

National prosperity is based on the availability of affordable, energy supply. However, this need is tempered by a complementary desire that the energy production and utilization will not have a major impact on the environment. The CANDU energy system, including a next generation of CANDU designs, is a major primary energy supply option that can be an important part of an energy mix to meet Canadian needs.

CANDU nuclear power plants produce energy in the form of medium pressure steam. The advanced version of the CANDU design can be delivered in unit modules ranging from 400 to 1200 MWe. This Next Generation of CANDU designs features lower cost, coupled with robust safety margins.

Normally this steam is used to drive a turbine and produce electricity. However, a fraction of this steam (large or small) may alternatively be used as process steam for industrial consumption. Options for such steam utilization include seawater desalination, oil sands extraction and heating. The electricity may be delivered to an electrical grid or alternatively used to produce quantities of hydrogen. Hydrogen is an ideal clean transportation fuel because its use only produces water. Thus, a combination of CANDU generated electricity and hydrogen distribution for vehicles is an available, cost-effective route to dramatically reduce emissions from the transportation sector.

The CANDU energy system contributes to environmental protection and the prevention of climate change because of its very low emission. The CANDU energy system does not produce any NO_x, SO_x or greenhouse gas (notably CO_2) emissions during operation. In addition, the CANDU system operates on a fully closed cycle with all wastes and emissions fully monitored, controlled and managed throughout the entire life cycle of the plant. The CANDU energy system is an environmentally friendly and flexible energy source. It can be an effective component of a total energy supply package, consistent with Canadian and global climate change mitigation objectives.

1. INTRODUCTION

Reliable, clean and affordable energy is key to human progress and to attaining a better quality of life for all people. It is needed to run our industry, our businesses and our homes, and it is critical for our transportation requirements. Around the world today, balancing society's needs for energy with the imperative to protect our air, water and climate is a key business and social challenge, and a significant opportunity.

In the last years of the 20^{th} century, and at the beginning of the 21^{st}, there have been tremendous changes in the energy marketplace. During the last twelve months, we have seen the continuing efforts to implement the Kyoto Protocol, price surges for oil and natural gas, and painful transitions to deregulation, leading to blackouts and near-bankrupt electrical utilities in California. Unpredictability has been the key characteristic of the emerging energy economy. However, through these complex signals, two needs are clearly and consistently expressed:

- The need for clean energy with zero, or minimal, emissions to support healthy communities, and
- The need for a reliable energy supply with stable prices, to support people's standard-of-living expectations.

The 21^{st} century will see affordable technologies emerge to change the ways in which energy is produced and delivered. At the same time, they will be required to reduce environmental impacts. A successful future would see these new and evolving technologies blending with existing technologies to provide a sound mix of energy systems that will ensure energy supply reliability, while making best use of our natural and technology resources and limiting environmental and health impacts.

Historically, increases in production and economic growth have been tied to increases in energy consumption and over the last fifty years to increases in electricity consumption. Traditionally, this growth in economic activity has also been accompanied by increases in the emissions of greenhouse gases (notably CO_2) and acid rain gases (NO_x and SO_x). However, when clean generating technologies are used, electricity can be produced in an environmentally responsible manner, without these emissions. Looking at Canada's Kyoto commitments and beyond, reduced emissions in the electricity sector are crucial. CANDU nuclear power plants, with essentially zero operating emissions of these compounds, can play a key role, along with other "zero-emission" technologies.

1.1 The Environmentally Friendly Energy Supply

Nuclear power is a proven technology for the production of large quantities of energy, which is also environmentally friendly. Nuclear power plants do not emit any carbon dioxide or other greenhouse gases, nor do they emit any acid rain gases during the production of electricity. Nuclear power plants require a smaller land area than any other comparably sized commercial energy source. They use a smaller quantity of fuel and generate a smaller amount of waste than fossil-fuelled generating stations. The relatively small amount of radioactive wastes that are produced are safely stored and monitored to ensure that there are no impacts on workers, the public or the environment.

The radioactive wastes decay naturally so that over time the radioactivity level and safety hazard naturally becomes lower and lower. After a period of 300 to 400 years, the level of radioactivity in spent fuel from a CANDU plant is about the same as the level in the uranium ore, which was extracted from the ground.

AECL has done extensive research on the safe disposal of spent nuclear fuel in a geological repository and the technology exists to safely manage and dispose of wastes.

Operating CANDU plants in Canada are presently enabling avoided CO_2 emissions of close to 100 million tonnes per year. If the present fleet of CANDU's is refurbished to achieve its full life capability, estimated avoided emissions would be as shown below.

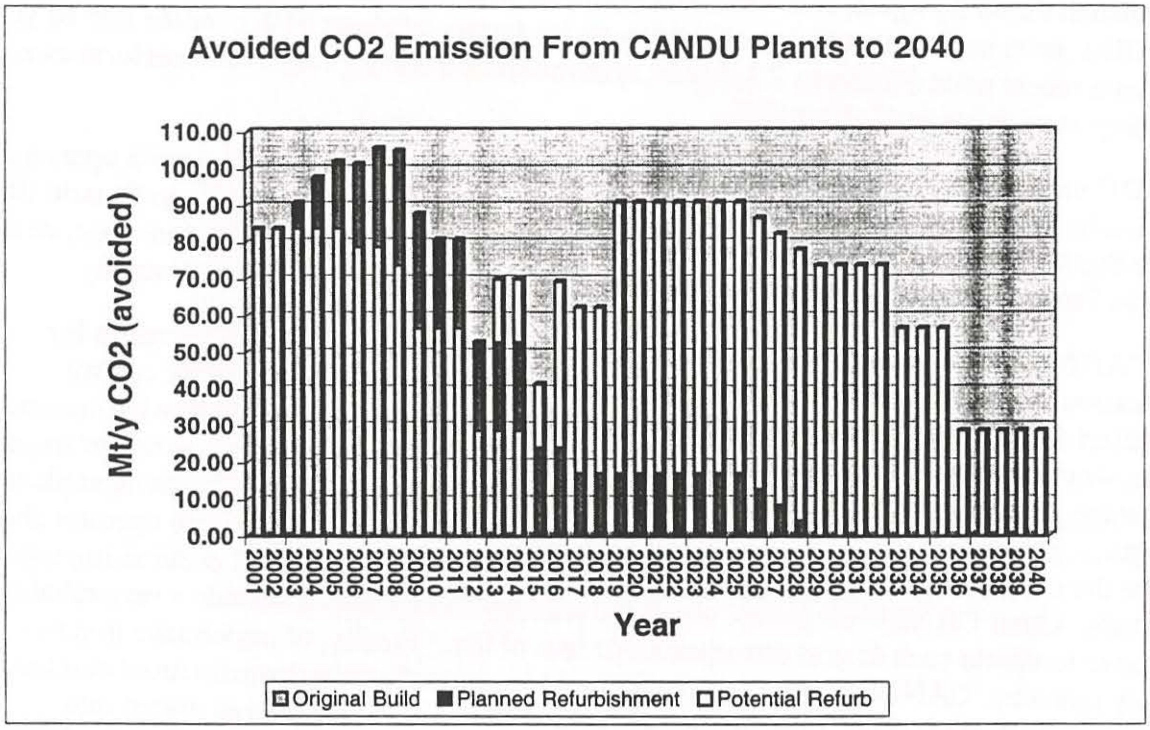

Figure 1. Avoided CO_2 Emissions from CANDU Plants in Canada

2. THE CANDU ENERGY SYSTEM

AECL has established the successful CANDU® line of pressurized heavy water reactors internationally, in particular the medium-sized CANDU 6 reactor design. The CANDU 6 design has evolved in both design and project delivery, so that the current CANDU 6 construction project at Qinshan Phase 3, in China, represents the state-of-the-art for the CANDU 6 design.

The 700 MWe class CANDU 6 nuclear power plant has earned an outstanding operating performance record since the startup of the first four CANDU 6 units in 1983. Cernavoda-1, the most recent European nuclear plant, started operation in 1996. The latest project to achieve startup is Wolsong-4, which achieved full power in 1999. Most recent of all are the two units of the Qinshan Phase 3 project, near Shanghai in China, which started construction in 1998. The CANDU 6 units have consistently achieved capacity factors of about 84% over the last 10 years. The more recent units (Wolsong 2,3,4 and Cernavoda) are showing even better performance, operating at an overage of about 88%.

CANDU units contribute significantly to Canadian energy supply. CANDU 6 units operate at Pt. Lepreau in New Brunswick and Gentilly-2 in Quebec. Importantly, CANDU's in Ontario (the Bruce Station, operated by Bruce Power and the Pickering and Darlington Stations, operated by Ontario Power Generation), provide approximately 50% of Ontario's electricity supply.

The CANDU system, as deployed in the CANDU 6 design, has some distinct benefits for application in small and medium-sized grids. For example, the excellent reactor control characteristics of CANDU allow for efficient, reliable operation in reactor-following-turbine mode, where the reactor thermal output responds directly to the grid demand. Another important advantage stems from CANDU's use of on-power refuelling. This means that planned plant outages, e.g., for routine maintenance, can be timed at the plant operator or grid operator choice, unlike the case for other reactor designs, where outages for refuelling must occur at imposed intervals. Other CANDU attributes, which are attractive to operators, include a very reliable response to upsets such as grid disturbances or loss of line. Finally, of importance in power supply planning, CANDU 6 units can be delivered via manufacturing/construction/ commissioning in a very short time. For example, the recent Wolsong-3 project was placed into commercial operation on schedule in 1997, only 69 months after the project contract-effective date.

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3. THE NEXT GENERATION CANDU

AECL has consistently adopted the evolutionary approach to the development of nuclear power plant designs, since the CANDU system is ideally suited to this approach. The modular fuel channel reactor concept can be modified extensively, through a series of incremental changes, to improve economics, safety margins and performance. Building on its knowledge base, AECL is continuing to adapt the CANDU design and developing the Next Generation CANDU medium-sized fuel channel reactor. This advanced design features major improvement in economics, inherent safety characteristics and performance, while retaining the proven benefits of the CANDU family of nuclear power plants.

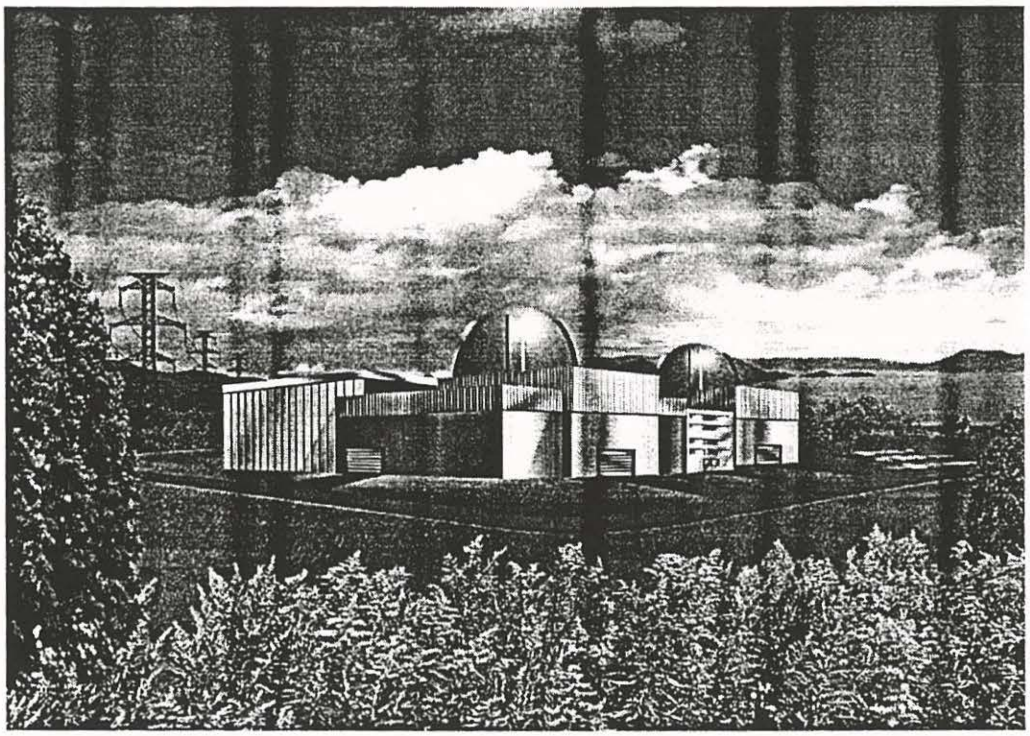

Figure 2. Pictorial View of a Two-Unit NG CANDU Plant Arrangement

3.1 Generation IV Reactor Design

The next generation CANDU is classed as a Generation IV nuclear power plant design. Following on the principles that have been established internationally for the evolution of power reactor designs, the next generation CANDU will include improvements to address the requirements for advanced power systems. In particular, Generation IV power systems are required to include significant advances in safety and reliability, sustainability and economics over the currently available power systems. These requirements are incorporated in the next generation CANDU power system.

Sustainability

Nuclear plants provide significant benefits in terms of air quality and climate change. Nuclear power plants generate zero emissions of sulphur dioxide (SO_2), nitrogen oxides (NOx), heavy metals and particulates. Each year, a 700 MWe nuclear power plant avoids emissions of about five million tonnes of CO_2, the amount that would be generated by an equivalent coal-fired power plant of the same size. Between 1971 and 1999, nuclear power plants in Ontario avoided 11 million tonnes of SO_2, 2.5 million tonnes of NO_x and 1.2 billion tonnes of CO_2.

Nuclear plants, such as the next generation CANDU plant will build on the sustainability of the current designs and will incorporate features to significantly reduce the level of emissions

Safety and Reliability

The CANDU plants have a well-established record for safety and reliability that is backed by the vigilant oversight of the Canadian Nuclear Safety Commission. The next generation CANDU will build on this performance by including features to increase the robustness of the safety systems and safety margins (such as stronger materials, greater thermal margins and improved component reliabilities).

The CANDU system incorporates a number of inherent safety advantages, which are retained in the next generation design: Special Safety Systems are rigorously designed to be completely independent of all power production systems, and of each other. This minimizes the potential for common mode failures, and ensures that the day-to-day routines of operation have no impact on safety functions.

Two separate, independent and functionally diverse shutdown systems are retained in the nominal design for Next Generation CANDU. Each shutdown system and all other reactivity mechanisms are located in the low pressure and temperature moderator, eliminating the possibility of accidents such as rod ejection.

The CANDU reactor type also features the inherent ability of the cool, low-pressure moderator to act as an emergency heat sink, in the event of a loss of coolant coincident with postulated complete failure of the emergency core cooling system.

As a further step, AECL has been carrying out enabling research to incorporate passive heat removal systems. Coupled with inherent safety of a fuel channel core, long-term passive containment heat removal reduces the probability of large radioactive release from containment, even after severe, beyond-design-basis accidents, to the point where credible scenarios can be all but eliminated.

The designers of the next generation CANDU will make use of lesson learned from operating CANDU plants and other plants around the world plus an assessment of the plant safety using probabilistic risk assessment techniques, to ensure that the plant can meet the highest safety standards.

Economics

Advanced nuclear power plants must be able to provide electricity at economically competitive rates. A primary focus of the next generation CANDU design has been cost reduction and particularly capital cost reduction. This has been achieved through the advanced design features discussed below, plus careful attention throughout the design to opportunities for simplification and ease of manufacture and installation of equipment and components. As a result, the projected capital cost for the next generation CANDU is targeted at 40% lower than current CANDU plants. This leads to electricity unit energy costs competitive with other large sources of electricity.

CANDU plants have a proven record for delivering electricity with a low operating cost, in part because of the very low cost of the CANDU fuel. The next generation CANDU is expected to meet equivalent operating cost targets.

3.2 Advanced NG CANDU Design Features

In developing the next generation CANDU, AECL has adopted the evolutionary approach, accommodating significant changes to design while retaining traditional CANDU strengths:

- A modular horizontal fuel channel core (economic to build),
- A simple, economical fuel bundle design,
- On-power fuelling (to provide high availability),
- A low-temperature, low-pressure moderator to provide passive safety and high fuel efficiency, and
- Relatively low neutron absorption for good fuel utilization.

Based on these principles, AECL has developed a number of enabling technologies at the component level, which together are adopted in the next step in CANDU design. The design offers the opportunity for reduction in capital cost, reduction in schedule, and enhancements in inherent safety. At the same time, the design is firmly rooted in the principles and characteristics of the CANDU system, and takes full benefit from the extensive knowledge base in CANDU technology, built up over many decades.

The following key features are incorporated into the design concept for the next generation CANDU:

- A slight enrichment of the uranium fuel to increase burnup (and decrease waste quantities),
- Replacement of heavy water with light water in the reactor coolant system, to lower costs and increase safety,
- A more compact core design, to reduce costs and improve safety and ease of operation, and
- A high steam supply temperature, to increase thermal efficiency and the range of plant applications.

Development of the conceptual design of a next generation CANDU plant was initiated at the beginning of 2000, after feasibility studies had demonstrated the powerful benefits from applying the enabling technologies described above. The design approach has been to exploit the cost reductions inherently available from the choice of light water coolant and higher steam pressure, while maintaining a high degree of proveness in design features, and maintaining or enhancing safety margins. This has meant applying key enabling technologies above, in a way that retains ample design margin. It also means adopting a conservative approach to any uncertainties arising from innovation; to ensure that key design parameters will be well supported throughout the complete design process through to first plant construction.

Advances in fuel channel, end fitting and fuelling machine design have been applied to establish the compact fuel channel lattice required to achieve the required core geometry for the next generation design. The next step was to develop a reactor coolant system and steam/turbine system design to achieve the higher efficiency targeted. Based on these and many other supporting studies, a nominal configuration for a 600 MW class design has been established. The configuration has the following characteristics:

- Nominal output of approximately 600 MW(e) net, dependent on site conditions,
- Light water coolant hot-leg pressure of approximately 13 MPa,
- Steam outlet pressure of 7 MPa, allowing turbine cycle efficiency of approximately 37%,
- Reactor core configuration consisting of 256 fuel channel locations in a square lattice,
- Average channel power increased from 5.8 MW (th) (CANDU 6) to 6.8 MW (th), primarily from an increased core radial form factor of 0.93,
- Thanks to inherently even core flux shape (reflector-driven thermal flux), estimated peak bundle power is 850 kW compared to 875 kW for CANDU 6, while peak fuel element ratings are 14% lower than CANDU 6, due to CANFLEX fuel design,
- UO_2 fuel in CANFLEX fuel bundles enrichment nominally 1.65% ^{235}U, with burnup of 20,000 MWd/tU,
- Reactor coolant system in a single-loop, figure of eight configuration with two steam generators,
- Double-ended refuelling employing two fuelling machines and a 2-bundle shift.

A comparison of the next generation CANDU core end view versus previous AECL CANDU designs is shown in Figure 3. A view of the CADDS model of the reactor and coolant system main components is shown in Figure 4.

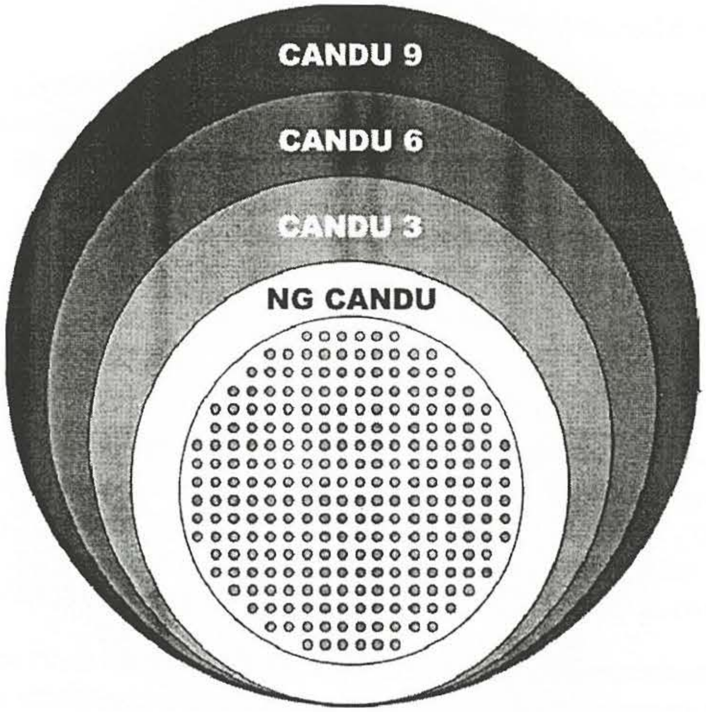

Figure 3. End-View of Reactor Calandrias Comparing Reactor Core Size

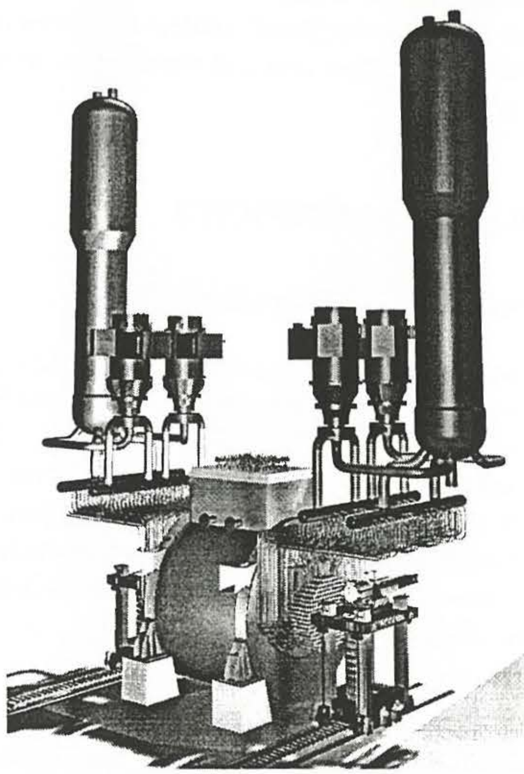

Figure 4. 3D-CADDs Model of the Next Generation CANDU Reactor Concept

3.3 A Market Driven Energy Source

Nuclear power plant designs for the future must respond to increasingly demanding market requirements. This means that value can be gained from substantial product development directed at these requirements. The primary requirements of the energy market today are:

- Low capital cost,
- Low operating cost,
- High reliability/availability,
- Short project construction schedule.

As discussed above, the next generation CANDU is being designed to meet the market needs for low cost, highly reliable electricity. The energy market also requires that generating plants be available as quickly as possible, in order to adjust to changing market energy demand levels without the possible penalty of installing too much generating capacity. This requirement is met by the next generation CANDU through the adoption of a short project construction schedule.

Many of the construction project improvements required for the short schedule have already been successfully demonstrated in AECL's recent CANDU construction projects in Korea (Wolsong 2, 3 and 4—completed 1997-99) and in China (Qinshan Phase 3—completion date 2003). Improved modularization techniques, where power plant systems are pre-fabricated and lifted into place ready-built, are saving money and improving the quality of the finished product. AECL has also been a pioneer in the application of 3D-CADD computer aided design techniques to nuclear projects. These help to integrate all project activities including equipment specification and procurement, construction and installation, inventory management, plant commissioning, and operation.

4. MORE THAN ELECTRICITY

4.1 Reducing Transportation Emissions

The importance of improving transportation efficiency and lowering associated emissions is gaining ever-increasing recognition. Transportation represents 35 per cent of total energy use in Canada and about 4 per cent of total Gross Domestic Product. Since most transportation fuels are hydrocarbon-based, emissions of by-products that affect air quality are an issue in high-use, high-population areas. Sixty per cent of smog-causing compounds are generated from Canadians' use of transportation. Contribution to greenhouse gas emissions, which cause climate change, is high, too—about 150 million tonnes of CO_2 per year. This is about 25 per cent of Canada's climate–change gas emissions.

Hydrogen: A Clean Transportation Fuel

Hydrogen can be readily stored, distributed, and used as a transportation fuel—and it could provide a solution in reducing Canada's environmental emissions. Conversion of hydrogen into energy, whether by combustion or by fuel cell, is an exceptionally clean process. If pure hydrogen is used, the only by-product is water. Hydrogen thus offers the potential of a transportation fuel completely free of all airborne emissions, whether NO_x, particulates, or greenhouse gases. A complete emissions-free fuel cycle, however, depends on emissions-free generation of hydrogen. Electrolytic hydrogen production is one potentially emissions-free route.

Large amounts of electricity, however, are required to operate the industrial plants that use electrolytic methods to produce the hydrogen. This means that, in order to achieve the objective of reducing emissions from all sources, the electricity required to power hydrogen production plants must be produced using technology that does not emit such gases itself. Hydrogen, when produced by plants powered by nuclear or renewable energy sources, offers us, and future generations, an important "sustainable" fuel. An extensive U.S. study states that: *As the ultimate fuel, hydrogen, once established, will provide a single alternative fuel, which......would last for the foreseeable future.* (Berry, 1996)

The use of CANDU-generated electricity to run hydrogen-producing plants would ensure that the full cycle of hydrogen production was emission-free. Current electrolysis technology delivers pure hydrogen, thus eliminating even trace by-product emissions when used for transportation. Hydroelectric power, along with more intermittent renewable energy sources—such as solar and wind farms—could supplement reliable, baseload CANDU electricity for this purpose.

Recent improvements in electrolysis technology mean that hydrogen production using electricity, as a power source is increasingly cost-effective. As well, hydrogen distribution can be handled from one large centre or, alternatively, distribution corridors with many smaller distribution centres can be established. Production scale can be tailored to the size of the application, because the modular nature of electrolysis equipment means that cost is not significantly affected by size.

At the same time, recent developments in fuel cell technology are beginning to allow efficient, cost-effective conversion of hydrogen into electricity as an on-board power source for transportation. Fuel cell conversion efficiency of 50 per cent for hydrogen fuel is well established, as are commercially competitive reliability and cell life. Prototype demonstrations of fuel-cell-powered vehicles are building an experience base to launch this technology. For example, fuel-cell-powered buses are successfully operating in Vancouver and elsewhere. A recent prototype (100-kilowatt) fuel cell, sponsored by the U.S. Department of Energy, passed its two-year operating test with flying colours. In this way, the clean electricity-hydrogen-fuel-cell cycle powers emissions-free transportation, with substantially greater end-use efficiency than traditional internal combustion power sources.

A final strength of this unique energy system is the synergy between hydrogen production and the generation of heavy water, which is needed to sustain the required chain reaction in CANDU reactors. While producing an industrial stream of hydrogen from electrolysis would be the main objective of a hydrogen plant, a side-stream generation of heavy water could also be produced, with virtually no additional energy expenditure. This can be achieved by using AECL's CECE (Combined Electrolysis and Catalytic Exchange) technology. In a production setting, this would earn additional revenue for the hydrogen production process, thus improving the economics of hydrogen supply while, at the same time, producing essential heavy water for CANDU reactors.

4.2 Industrial Steam Production and Oil-Sands

Nuclear power plants generate electricity by heating water to produce steam and passing this steam through turbines. Alternatively, this steam could be used directly by other large-scale industries. The Bruce industrial park linked to the Bruce CANDU nuclear power plants in Ontario has proven the value of this economic and environmentally attractive use of steam energy. The alternative method of producing steam through the use of fossil-fired boilers would result in the emission of greenhouse gases.

In Canada, one of the largest potential uses of industrial steam is in the extraction of oil from the oil-sands in northern Alberta. Large quantities of steam are needed in order to extract the oil out of the ground and to process it. Studies of the steam requirements have found that the steam production from an advanced CANDU plant could meet the needs of the oil-sands industry economically.

There are a number of different ways in which a CANDU plant could be integrated into the oil extraction process. In addition to a requirement for large quantities of process steam, the oil-sands industry requires large quantities of hydrogen for the purpose of upgrading the heavy oil extract to a more marketable oil product. The next generation CANDU plant is well suited to meet this need, because it generates high temperature steam. This steam could be passed through a high-pressure turbine to produce electricity, and the low-pressure steam that emerges from the turbine will meet the needs of the oil extraction process. The electricity generated by the turbine could then produce hydrogen for use in the upgrading process.

Integration of a nuclear plant into the oil sands process is an environmentally attractive option because the nuclear plant has a small land requirement and it would allow the production of oil with minimal additional emissions of greenhouse gases.

4.3 Desalination

Canada is blessed with an abundance of fresh water, but the situation is very different in other parts of the globe. The availability of fresh water is a serious concern in many countries and is the alternatives are limited. Desalination of seawater is one of the answers to the shortages. The conventional desalination technologies require either high-temperature steam (for thermal processes) or electricity (to drive the pumps required for reverse osmosis processes). Nuclear power plants provide an environmentally friendly option for the production of either steam or electricity without burning fossil fuels. Hydroelectric power is not normally an option in a country where there is a severe fresh water shortage.

CANDU power plants are particularly well suited for integration into a system that employs a reverse osmosis process. The efficiency of this process is optimized with the use of warm water and the temperatures required match well with the availability of low-grade waste heat that must be rejected from a CANDU plant. At the same time, the CANDU plant can provide the electricity required by the desalination process.

5. SUMMARY

Nuclear power plants are an environmentally responsible option to meet energy needs. They can supply base-load energy in large quantities, reliably and at competitive costs. In the USA, Canada and many other countries, utilities recognize the environmental and economic benefits of nuclear generation and are refurbishing existing plants, to extend their operating life for these reasons. This approach to energy supply, with a significant nuclear power component, will help to avoid large potential emissions in the future.

AECL is working to maintain the attractiveness of the nuclear energy component in an overall energy supply strategy by advancing the design of its proven reactor product line. Development of the next generation CANDU plant will provide a more economic and environmentally product for the future for traditional electricity generation customers and other emerging energy users.

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