The Future of CANDU: Vision and Realities

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Abstract

Present CANDU reactors are reliable, efficient, competitive power producers. Much has been learned about various aspects of CANDU reactors: the lifetime of their components, their management demands, and their operating characteristics and margins.
On reflection, we may identify three major forces from the CANDU reactor's past and three major factors that influence the future. Thus the design continuously and successfully evolves to meet the challenges presented by an ever-changing world energy market in respect to:

1. *Technical Innovation*
2. *Competitive Investment*
3. *External Forces*

We may also identify ten essential goals for the future evolution. By meeting these design goals, CANDU technology can effectively eliminate competition, and lower costs, construction times and fiscal risks, and ensure that social and environmental acceptability is high. CANDU reactor technology thus contributes to a sustainable energy future with reduced resource use and to stable energy and end use markets.

Currently, nuclear energy is projected to be reduced in the United States, Canada and Europe, and increased in Asia and the Pacific-Rim countries, as well as other economically growing countries. Consequently, environmental emissions are projected to increase, despite Herculean efforts to adopt alternate energy strategies without damaging the national or global economies or energy-intensive industries. CANDU reactors have a vital role in the potential for energy supply in these regions through their unique product line. CANDU reactors also have a long-term commitment to technical innovation, combined with evolutionary and competitive design enhancements.

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"We are such stuff as dreams are made of ... "
William Shakespeare, *The Tempest*

The future of CANDU reactors is reflected by their past. Present CANDU reactors are reliable, efficient, competitive power producers. Much has been learned about various aspects of CANDU reactors: the lifetime of their components, their management demands, and their operating characteristics and margins.

CANDU reactors have evolved in design and operation with time in an almost Darwinian fashion, adapting to the needs and markets of the day. Their natural evolution has led to the CANDU 6 and CANDU 9 designs that are based on the modular channel layout and the use of natural-uranium fuel.

As we look forward to new innovations and developments, we know we move into uncharted territories. Although we cannot predict the future, but we can anticipate what might happen and respond and plan effectively.

On reflection, we may identify three major forces from the CANDU reactor's past that might be said to have shaped its present position:

1. Technical Foresight

Historically, farsighted technical decisions, aimed at emphasizing economy and simplicity in design and providing fuel-cycle flexibility, have assisted CANDU reactor technology in retaining its competitive position.

2. Fiscal Investment

Major support—aimed at developing an independent Canadian nuclear business, from fuel supply to electricity generation—has provided for continuity of design and development in CANDU reactor technology.

3. External and Global

The world need for electric power and for economic development has meant an assured (but competitive) market for nuclear energy; this market has provided continued incentives to refine the CANDU design.

This development has succeeded, despite marked opposition to nuclear energy, its perceived relationship to nuclear weapons, the fear of radiation injury, and socio-political problems with waste disposal—all potent discussion topics by themselves.

Similarly, I envisage three major factors that will influence the future success of CANDU reactors and that parallel their past development. Thus the design continuously and successfully evolves to meet the challenges presented by an ever-changing world energy market.

1. *Technical Innovation*

The future success of the CANDU will depend on the design evolution, including the need to include additional passive safety features, avoid obsolescence, reduce construction and operating costs, increase efficiency, and extend the lifetimes of its components.

2. *Competitive Investment*

The increased use of natural gas, the stabilization of world energy supplies, and all the other nuclear reactor designs will bring increased competitive pressures to an already overcrowded energy generation market, as will the privatization, competition and divestiture of electrical generators.

3. *External Forces*

The need to reduce environmental emissions as world energy options dwindle and as environmental impacts increase gives increased public and political support for nuclear energy.

What CANDU technology has to do is to respond effectively to the above synergistic design and market factors, exploiting the opportunities created. Let us review how that might be accomplished.

2. THE FUTURE VISION

"The Future is not what it was"
B. Levin

The future successful development of world energy sources *requires* nuclear energy. This simple concept is apparently foreign to many and rejected or unpalatable to those who oppose advances in nuclear technology and its acceptance. This opposition, or denial, prevails despite the economic success of nuclear energy, the unparalleled safety record (as a completely new technology, it has injured far fewer people than any other power source for the equivalent energy output), and its extraordinary contribution to power generation and emissions reduction.

As a new and demanding technology, "teething" problems have existed, as evidenced by management and fiscal issues at some large and small utilities, the emergence of potentially life-limiting factors such as in (non-nuclear) steam generators, and two unfortunate but not unforeseeable accidents in the United States and Russia.

Yet despite considerable uncertainties, the future is clear. Is it all business as usual? Projections beyond 2000 show or assume continued growth in world population and energy demand, with concomitant increases in living standards and environmental emissions. Specifically, the use of electrical energy will increase, and projected supplies will be mostly met by increased natural gas, oil and coal generation, with nuclear energy growing in the emerging industrial nations. Options being considered to meet the reductions in emissions, agreed to or proposed at the Kyoto Accord, include hypothetical increases in efficiency, increased use of "renewable" energy sources (excluding nuclear reactors with renewable fuel cycles), and the adoption of incentives (taxes—no matter what they may be called to obscure their real nature) to reduce emissions and transportation energy demands.

Given the combination of and focus on competitive and environmental factors, the CANDU reactor of the future must produce power at relatively less cost than other sources. With a level environmental playing field, the CANDU reactor must also have these 10 essential goals:

1. continued evolutionary design acceptance;
2. capital and generating costs that are significantly below today's values, and a reliability and availability that is second to none;
3. all components must have at least a 60-year lifetime;
4. passive safety features that require little or no active intervention;
5. flexible licensing with a modular and repeatable design;
6. thermal efficiencies that exceed 40%, thereby reducing thermal pollution, increasing efficiency and enhancing resource utilization;
7. nuclear electric market penetration of the electrical energy sector of at least 50%, with complete public and political acceptance of nuclear energy;
8. unparalleled technical support for the projected life of the plant (to 2060 and beyond);
9. flexibility in design, to fit with both developing and developed electricity markets and national infrastructures; and
10. last and not least—a proven system to generate the energy we need without having a significant impact on the environment.

By meeting these goals, CANDU technology can effectively dominate the competition, lower costs, construction times and fiscal risks, and ensure that social and environmental acceptability is high.

Specific design developments, aimed at attaining these goals, must be visionary in nature and in execution; if achievable, there should be no national constraints. We now consider the specific innovations needed in CANDU technology.

3. TECHNICAL INNOVATION

"That all our knowledge begins with experience, there is no doubt ..."
Imanuel Kant

3.1 Fuel Cycle

The CANDU design has been predicated on exploiting the advantages of efficient moderation and discrete channels. But fuel remains a small component of overall cost.

CANDU fuel costs are relatively low, and their reliability is high. Incentives to enhance the fuel are based on fuel-cycle flexibility, efficient fuel utilization and proliferation (real or imaginary) concerns. Political forces and conservative utilities will resist innovations in the fuel cycle, particularly those utilizing plutonium, until the increased economic and social costs of on-site storage and fuel make fuel reuse a viable alternative again. Moreover, the CANDU fuel cycle is adaptable to a thorium cycle, which also is proliferation-resistant. The disposal of spent fuel has already been technically solved, and it is a resolvable social problem.

CANDU fuel and its latest development, the CANFLEX bundle design, use less uranium, cost less to manufacture, are readily disposable, and increase operating margins. Light-water reactors (LWRs) use the relatively energy-wasteful once-through fuel cycles, and the use of mixed-oxide (MOX) fuel in France and Japan will lead the way to ultimate social and political acceptance of plutonium recycling.

The potential synergism of CANDU reactors with LWRs, with liquid-metal fast-breeder reactors (LMFBRs),the potential use of thorium fuel cycles, plus the ability to burn MOX fuel efficiently are unique to CANDU. The CANFLEX DUPIC cycle offers such a Utopian future because it is completely synergistic with its competitors (LWR and MOX reactors). The cycle reduces projected uranium resource requirements to the year 2050 by about 50% relative to the once through LWR cycle. DUPIC fuel is proliferation-resistant in the sense that transuranic isotopic separation is not needed or undertaken.

Demonstration of the DUPIC fuel cycle requires a demonstration irradiation, which means that it will be fifteen to twnety years, or so, to full commercial adoption of this fuel.

Ultimately, CANDU-type bundle designs will be extended to very high-temperature conditions (450°C to 600°C), exploiting the enhanced thermal efficiency offered by reactor designs operating at supercritical temperatures. Thus the CANDU fuel design is evolutionary, offers resource conservation and is adaptable to both developing and developed markets, and enables the achievement of higher thermal efficiencies.

3.2 Fuel Channel

The pressure tube is, in principle, a replaceable item and, in fact, has been changed at operating plants. Lifetime determinations are based on the bounding limits of the data, so that worst-case conditions are used to define pressure tube and channel life (i.e., elongation maximum growth and hydriding). Pressure tube lifetimes can be up to ~40 years, based on available data and recent materials and manufacturing experience. Channel powers are determined by factors such as the worst diametrically-crept tube, void reactivity assumptions, and the increase in inlet temperatures from aging of the heat transport systems. Critical power ratio calculations (CPRs) have to be derived from data obtained in full-scale steam-water testing. Margins to EOL are not limiting for any normal power transients if other components do not degrade.

It is possible to exploit further the simple and robust channel layout. An interchangeable channel that meets or exceeds a 60-a lifetime for the pressure tube can be developed, based on the insulated channel concept. This pressure tube would not require inspection, would not significantly hydride or creep, and would easily be replaceable. The pressure tube would be cheaper than its alternates and would show little variability in properties with manufacturing process.

In the advanced concepts, the calandria tube is removed so that the pressure tube itself is effectively at moderator temperature, and hence it undergoes less thermal creep. The channel also provides a full decay-heat-removal capability, without active safety systems through moderator convective cooling.

The channel is interchangeable from plant to plant, and from design to design. Single-channel blockage becomes a hypothetical event with consequences mitigated by the available calandria heat sink. Pressure drop of the channel and fuel should be such that natural circulation is both stable and predictable. Ideally, the CPR would be a known function of channel and fuel geometry, predictable at a given confidence level without testing.

3.3 Primary and Secondary Circuit

The remaining components are related to the heat-transport system (HTS), and the item of interest is the material behavior in a lifetime chemical, thermal, mechanical and hydraulic environment.

All practical and neutronically acceptable materials creep and corrode—the life-limiting factors tend to be governed by the limiting erosion and corrosion of tubing. Feeders, headers and steam generator tubing all have to be periodically examined. To achieve high efficiencies, higher temperatures and pressures are needed, which lead to increased stresses. Therefore, high-temperature materials that have reduced corrosion and creep rates are always being sought. The time scale for the development of new materials is long because of the intensive qualification testing.

It is well known that operating margins are reduced by progressive steam generator tube secondary- and primary-side fouling, despite extensive materials selection and defined chemical regimes. Replacement is possible but costly, mainly because of the outage time. Steam generators, piping and valves should exhibit minimal corrosion or erosion, and hence not transport significant material to the generators. Fouling on the primary and secondary side should be reduced so that a 60-year life is achievable.

With regard to the fluid flow, the evolution to passive safety concepts leads to natural circulation in the emergency cooling systems (ECSs) and steam generator. Generally, passive safety system designs have low driving heads, so there is a need to test the stability and functioning of the systems.

The evolution of the design is being examined, based on supercritical fossil boiler concepts to take advantage of the >40% thermal efficiency and the existing utility international operating experience.In addition, considerable simplification would be achievable by a natural circulation of the HTS primary side, and this process is in principle achievable for supercritical conditions.

In summary, if CANDU technology addresses the goals of continuous development to improve performance and to extend lifetime, then all the circuit components would then have a 60-a lifetime, without the need to replace components. Steam generators can be improved so that thermal performance is independent of lifetime, and inspections are only needed at infrequent intervals. Passive safety features can allow three or more days of cooling without operator intervention. Secondary-side and overall thermal efficiency are predicted to be >40% or greater when supercritical water at ~600°C is adopted as the working fluid.

4. COMPETITIVE MARKETS

Economic studies all show that CANDU reactors are competitive with alternate generating concepts, provided interest rates are reasonable. Electricity consumption is expected to rise, and the historical link between the economy and electricity use is likely to remain.

4.1 Horizons on Competitive Alternatives

The "rush" to burn natural gas has lead to a bonanza in gas pipelines and exploration. Gas usage is predicted to rise, and hence price stability and supply integrity are the national and market place issues. Nuclear reactor designs showing a trend to larger plant sizes (>1500Mw(e)) have emerged, to take advantage of the economies of scale and to compete with gas, including combined cycle (electricity and heat) plants.

However, developing economies often cannot integrate plants of sizes larger than 600 to 1000Mw(e); therefore, an optimum design is one that spans the size range, as CANDU reactors can and do. By replication of components (fuel, channel and circuit) costs are lowered, and construction times are reduced.

Thus CANDU designs will evolve to include a span of products from the proven CANDU 6 design for introductory conditions, the evolved CANDU 9 design for larger grids, and eventually a larger design for the countries and markets that need larger units because of population density or end use demand.

For energy-intensive countries such as the United States and Canada itself, the issues of sustained economic growth and overall energy usage will come to the fore. To that end, a replicated design that can be built at a fast pace will be important, to meet the rapid changes in economic conditions in world markets.

Existing LWRs, based on past standard designs, are predicted to be phased out or hopefully to have their licenses renewed until the year 2020 or beyond, thus stultifying innovations in design. The US and Canadian nuclear capacity is projected to decline until at least 2020. Therefore, the development of LWRs will be in the hands of Europe and Japan, and that of heavy-water reactors (HWRs) in Canada into the far future, with significant enhancements supported by the emerging nuclear nations of China and Korea.

4.2 Realities of Resource Use

The world needs increased energy resources. The competing theories of resources (of unlimited supply but at a market governed price and of limited supply subjected to periodic development crises) are used by conservationists and energy suppliers as tools to promote particular agendas. By 2020, efficiency gains of 50% or more in fuel efficiency, reductions of 25% or more in energy intensity, and enhancements in supply lines and gas fields in the order of 100% are all projected. Global increases in OPEC oil supply of 100%, in oil imports by 300%, and in natural gas consumption by 300% are estimated; these projections and estimates are being made without considering supply-side scarcities, economic crises, or political uncertainties and instability. Plainly, these estimates do not represent sustainable numbers.

Resources for energy production will become subject to greater market forces and scarcities will and must develop, either on a regional or also on a global basis. The US preoccupation with the Middle East is presaged on protecting the continued and increasing reliance on imported gas and oil. The curve relating oil use to reserves will pass its peak in about 2005; significant market uncertainties will exist thereafter. Therefore, diversity of fuel supply—as advocated by France and Japan—will become more necessary.

CANDU reactor technology offers unparalleled resource diversification and uranium utilization potential. The adoption of CANDU reactor technology reduces uranium resource requirements and needs beyond the year 2020 by 50% or more. Adoption of CANDU X technology reduces the resource needs even more because of the increase in thermal efficiency.

The introduction and attainment of a full DUPIC fuel cycle at its optimum of 2:1 LWR: CANDU ratio will not be achieved because of previous national commitments to LWRs and the MOX fuel cycle. In addition, the United States will want to go its own way and NOT reuse the spent LWR fuel, which is a waste of resources.

Countries with developing nuclear programs want fuel independence, so demonstration of the DUPIC and thorium fuel cycles will be on a prototype basis, to tiptoe around objections of entrenched positions.

5. EXTERNAL FORCES

"It is no use arguing with a prophet; you can only disbelieve him."
Winston Churchill

Technical innovation in reactor design is desirable, simply because other technological advances—in computers, software, manufacturing efficiency, and in materials—make unforeseen things possible. Thus, for advanced concepts such as CANDU X, we can easily envisage a mass-produced design that is totally passive in the containment systems and an insulated channel that has passive (e.g., natural circulation) primary flow, with an indirect cycle of at least 42% efficiency. The time scale for all these developments to be implemented is seen as 20 or more years.

Thus the vision and challenge set by the 10 goals can be met by ensuring that :

1. continued evolutionary design acceptance is achieved by retaining the channel concept and D_2O moderation;
2. capital and generating costs are significantly below today's values, and a reliability and an availability that are second to none are achieved by using a simplified system layout, passive design concepts and increased thermal efficiency, together with reduced inspection requirements;
3. a components achieve at least a 60-a lifetime, by adopting advanced steam generators and the insulated channel concept.
4. passive safety features that require little or no active human intervention are included both in the containment design and in the insulated fuel channel;
5. flexible licensing is obtained and a modular and repeatable design is achieved through modularization and the use of a standard channel and circuit layout;
6. thermal efficiencies that exceed 40% are achieved, thereby reducing thermal pollution, increasing efficiency and enhancing resource utilization by using supercritical conditions;

7. nuclear electric market penetration of the electrical energy sector of at least 50% is attained, with complete public and political acceptance and with the excellent environmental advantage and cost competitiveness;
8. unparalleled technical support for the projected life of the plant (to 2060 and beyond) is achieved by continued technical innovation and design evolution;
9. flexibility in design, to fit with both developing and developed electricity markets and national infrastructures, is due to the predictable scale up of CANDU units in power and size, and the ready localization of much of the technology; and
10. last and not least—a proven system that will generate the energy we need without significant impact on the environment is now self-evident.

Reductions in emissions have now become more than talk; they are now global social and political targets. The Kyoto Accord requires, for example, Canada and the United States to reduce emissions appreciably. This goal is not readily or easily achievable. The problem is how to reduce emissions without harming the economic growth of individual countries (because energy use and economic growth are tied together). Conservationists argue that this paradigm can be broken by a move to 'renewable' sources of energy, but this paradigm also requires intervention in energy use markets. The risk is of unpalatable social and political effects, increased prices, reduced growth, reduced convenience, carbon taxes, etc.

For natural and human resource-rich Canada, the United States is a vast market also, but as a result the Canadian energy and economic scene is tied to global developments. We may show that building between 12 and 24 CANDU reactors between 2003 and 2020 (a modest build rate of 1 to 2 plants per year) will meet between 25% and 50% of the Kyoto Accord reductions in emissions for Canada, thereby avoiding the need for additional coal and gas plants. With planned hydropower additions, these additions meet all projected electricity energy needs based on either historical or projected economic scenarios. They, of course, also provide jobs and investments, as well as significant export potential. This rosy picture is opposed by Greenpeace and others, who also oppose all forms of energy generation, except "renewable," which is also unexplored in the *Energy Outlooks* published by Natural Resources Canada.

6. CONCLUSIONS

"The time has come," the Walrus said ...
Lewis Carroll

CANDU reactor technology can continue to successfully evolve in design to meet anticipated technical goals, economic challenges and environmental needs. The achievable vision is of a 60-a life CANDU reactor, with advanced passive safety features, improved efficiency, and reduced fuel resource needs. Performance is characterized by proven capacity factors in excess of 85%. All major components are replaceable, if needed. With negligible environmental emissions, CANDU reactors—in combination with planned hydropower increases—help Canada in meeting all renewable electrical generation energy needs for Canada to 2020 and beyond. The CANDU reactor also makes a significant contribution to meeting projected increases in global energy demand.

The significant export potential in assisting with the Kyoto Accord and with other emission stabilization initiatives (without increased taxes or economic stagnation) is also inherent in this concept.

CANDU reactor technology thus contributes to a sustainable energy future with reduced resource use and to stable energy and end use markets.

Currently, nuclear energy is projected by the US DOE to be reduced in the United States, Canada and Europe, and increased in Asia and the Pacific-Rim countries, as well as other economically growing countries. Consequently, environmental emissions are projected to increase, despite Herculean efforts to adopt alternate energy strategies without damaging the national or global economies or energy-intensive industries. CANDU reactors have a vital role in the potential for energy supply in these regions through their unique product line. CANDU reactors also have a long-term commitment to technical innovation, combined with evolutionary and competitive design enhancements.

The real question is Do energy production, demand, and use fuel the economy or vice versa? We cannot wait until the year 2020 to find out.