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CANDU Energy System Design and Safety - a Status Review

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1. Introduction

The CANDU nuclear-electric generating system, developed in Canada beginning in about 1950, has reached full maturity with 22 units operating in other countries, and 13 units under construction, as shown in Table 1. Production and enconomic performance of modern CANDU units is competitive with other nuclear generating stations in the world. The safety record of these plants is excellent; their level of safety protection against severe accidents is at least equal to that of other commercial designs.

Then what can be expected in the future? New plant design approaches are evolving in a very competitive market with other nuclear and fossil generating alternatives. Conservative customers tend to choose proven designs, but expect new stations to incorporate enhancements in performance, economics, and safety. Customers are sophisticated with regard to expectations for plants which they purchase; operability, long-term reliability, assured fuel cycle, and waste management systems are important factors in any decision to buy a plant. Safety regulations continue to add uncertainty to all projects.

Table 1. CANDU stations operating or under construction 1993.

Province/Country	Station	Reactors	In-Service date	MW
Ontario	Pickering A	4	71-73	2,060
	Bruce A	4	77-78	3,392
	Pickering B	4	82-86	2,064
	Bruce B	4	84-87	3,394
	Darlington	4	90-93	3,524
Quebec	Gentilly 2	1	82	640
New Brunswick	Pt.Lepreau	1	82	635
Argentina	Embalse	1	83	600
India	Rajasthan	2	73-81	440
	Kalpakkam	2	86-89	440
	Narora	1	91	220
	Naps-2	1	92-93	235
	Kakraper	2	92-93	470
	Kaiga	2	95	470
	Rapp	2	late 90's	470
Korea	Wolsong 1	1	82	630
	Wolsong 2	1	97	660
	Wolsong 3	1	98	660
	Wolsong 4	1	99	660
Pakistan	Kanupp	1	71	125
Romania	Cernavoda	5	95(unit 1)	3,025
	Total	45		24,814

Product acceptance in future markets will depend, therefore, not only on the record of past good performance but on the ability of the product to adapt to changing needs from the point of view of performance, economics, and safety as well as to meet requirements for local participation in manufacturing, design and construction. Products which can be adapted readily to specific customer requirements will have a competitive advantage in the marketplace.

The CANDU concept, which utilizes heavy water coolant and moderator in a channel geometry, has several advantages with regard to adaptability. CANDU does not have a large pressure vessel; thermal output can be increased simply by adding more standard fuel channels to the low-pressure calandria. On-power fuelling system, heat transport equipment and steam-cycle equipment are standardized. Control and safety rods are located outside the high-pressure boundary. The reactor can operate on a wide variety of fuel cycles from natural uranium to plutonium or thorium. Small, cheap, and simple fuel bundles can be adapted easily to new fuel cycles.

2. Design Development-CANDU3

The market for nuclear power plants is divided between very large units usually purchased by utilities with installed electrical capacity above about 10,000 MW, and small units required by small utilities around the world. Over the years, apparent economies of scale have led to larger and larger units being offered by vendor companies. Study of this market led AECL to the conclusion that a 'niche' exists for units in the output range around 300 net megawatts. To serve this small-utility market, in 1987 AECL undertook a full-scale design project for a new CANDU plant designated as CANDU3.

The second reason for undertaking this major "first-of-a-kind" engineering was to take advantage of operating experience accumulated by CANDU plants (over 150 unit-years at that time) as well as to incorporate new component and equipment designs which had become available since the completion of the very successful CANDU6 design about ten years earlier. New system designs such as fuel channels, fuel handling systems and control rooms would serve as "building blocks' for any proposed CANDU project, regardless of output power.

Another important reason for undertaking the CANDU3 development is because it has become possible to use, and to further develop, a comprehensive Drafting, Design, and Analysis package to make the process of design more efficient and the product more accurate. A new style of engineering has become possible which is expected to further improve the product.

2-1. Conceptual Design Objectives

Every project aspires to the label "improved". In the case of CANDU3 the term has real meaning, not only due to the fresh approach taken to all aspects of the design but from design features resulting from discussions with CANDU station operating staff who made many specific recommendedations based on their knowledge of operating CANDU6 and multi-unit stations. Change recommendations were subject to review by a change Control Board composed of senior design staff; only those design changes which met several criteria including performance, economy and safety were accepted into the reference design.

Generally, unit capital cost as total output decreases; buyers' preferences are known to be sensitive to unit cost. The project's first target, therefore, was to reduce this cost to compete with alternative electricity sources; specifically, with coal-fired generation at the same net power output. This was impractical at the original power level of 300 megawatts: The break-even output was found to be 450 megawatts net. This objective led to minimization of construction time to reduce interest charges during construction. This led in turn to application of new techniques for plant construction, including large modules constructed separately and then lifted into place by a very-heavy-lift crane. Costs were reduced by simplifications such as single-end fuelling and a smaller number of components.

The objective of "pre-engineering" was derived from direct experience on other projects in which design changes introduced late in the design, and especially during construction, caused delays and cost increases beyond those justifiable in a well-organized project. This objective is closely coupled with the objective to "pre-licence" the design. Earlier projects suffered from changes in regulations during the project design and construction phase or from misunderstanding of. actual licensing requirements by designers. The goal was to reduce the "chop and change" pattern of design which previously had impacted construction schedules.

Since the plant location was unknown during the CANDU3 project, the objective of high safety standards was defined as a design which could meet current Canadian licensing requirements. Even this objective could not be met completely without knowing a site and an operating organization. The approach used was to seek agreement with the Atomic Energy Control Board that the design could be licensable if residual site-specific requirements were met. In addition, the CANDU3 design recently has been submitted to the US Nuclear Regulatory Commission to start the process of Design Certification.

2-2. Overall Design Philosophy

The major decisions affecting plant design were approved by senior management early in the project. The first of these was to specify a standard plant design which would be suitable for may different sites. The purpose of this specification was to minimize site-specific engineering in order to reduce repeat-plant incremental costs. Parameters such as seismic acceleration (0.3 g peak acceleration), tornado wind speed, and cooling water temperature were selected to "envelope" conditions at known nuclear plant sites around the world.

Short construction schedules were set; 38 months from first concrete to in-service, with three month contingency. Thirty-five months was specified for subsequent units. Maintenance times also were specified. Equivalent outage time of 180 days was allowed during a 40-year life, plus short maintenance outages of 11 and 18 days in alternate years. Provision was made for on-power maintenance. Systems and components were designed to operate without major service for a two-year period. These provisions allowed specification of a 94% capacity factor target.

Provisions for plant life extension with equipment replacement (as planned) permitted a design life specification of 100 years. Maximum annual station staff exposure to radiation was specified to be 0.75 man-Sv, about a factor of two less than that now experienced in CANDU6 stations, which are among the best in the world in this regard. Overall, CANDU3 requirements are consistent with international requirement documents; specifically, with those developed by the US Electric Power Research Institute for the advanced light water reactor.

2-3. Design Process Improvements

Throughout the development of the CANDU reactor type, plant systems have been completely specified as to function, design requirements, and interface requirements with other plant systems. A comprehensive system index is used to identify each component and structure in the plant. Design responsibilities are assigned according to this systems index, and documentation is referenced to the same index; the index is turned over to plant operations for use during the plant lifetime. This systematic approach to design was extended and refined during the design of CANDU3.

The first step in improvement of the design process was to set clear and comprehensive requirements at the beginning of the project. The basis for each decision was documented to show why the particular decision was made. These decision documents also provide clear guidance for what analyses were to be done at each step of the project. Regular peer reviews as well as formal design reviews were carried out for selected systems in the plant.

Integrated multi-disciplinary design teams were formed to produce 3-dimensional models of the plant. In essence, the plant was "built" progressively in the design office. Design interfaces and changes were controlled, and communicated to all designers via a computer network.

2-4. Integrated Design Methods

These methods were developed initially to meet the interrelated business objectives of low cost, short schedule, and high quality. This investment was returned quickly when designers naturally joined into the common venture and gave up the praticl of writing separate discipline-oriented documents before interaction with designers of other systems. Indentification with the plant model led to better communication and problem resolution.

Integrated productivity tools allowed automation of many repetitive tasks in a single computer ring. Geometry information was extracted automatically for use in the stress analysis of structures and piping, piping support design, and many other analysis tasks. Drawing production was automated in the same computer package. The greatest advantage was gained from the fact that all designers were using precisely the same information at any given time, thereby allowing resolution of problems in a number of disciplines at the same time if and when they occured.

A particularly significant improvement was gained throught the use of three-dimensional CADD graphics for the plant model. This model was linked directly to design databases so that designers could "see" the plant as it developed. Through this technique it was possible to eliminate many subtle interferences and to ensure that plant operations and maintenance were feasible. Operations required for replacement of major equipment were simulated, thus giving confidence that these operations could be done in the actual plant as and when required. Construction planning and sequencing of module emplacement during construction were developed on this 3-D model; it is expected that a CADD system will be located on-site for use by construction staff and for recording of as-built conditions. In general, the main payoff of this work is expected to come from smoother construction and reduction of interferences, particularly between components of different systems.

2-5. Current Status

Many small problems were found and overcome in process of designing the station. The largest problems arose from the need to simplify the plant for reasons of economy and ease of operation. Choice of single-ended refuelling required development of a new channel design. Early versions of this design utilized a small-diameter welded coolant inlet; operations staff who reviewed the design strongly preferred a capability for full-di-diameter access to channels for maintenance. The channel was redesigned to provide this capability.

The fuel channel, or more specifically the pressure tube, has been a key design problem since the beginning of the CANDU program. Major efforts have been made over the past several years toward understanding and correcting weaknesses revealed during plant opertion. Many improvements in metallurgy and design have been made so that new pressure tubes are expected to have an in-service life of at least 30 years. In addition, tube replacement methods have been developed which greatly reduce the time and radiation exposure for both single channel replacement and whole-reactor replacement.

The CANDU3 design[1] now is more than 75 percent complete, with remaining tasks involving details required only during the later stages of construction. The design will be substantially complete within the next two years.

3. Design Development-CANDU9

A new product design has been underway at AECL during the past year. This product, designated as CANDU9, will serve the large-utility market with net out-

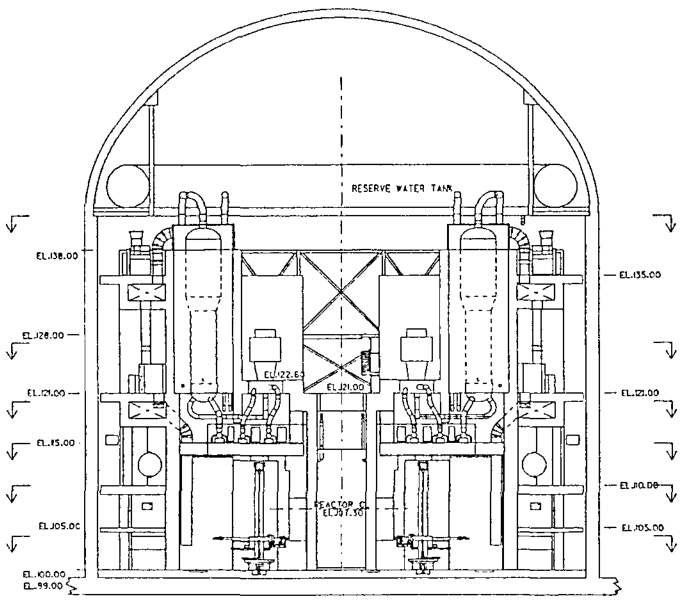

Fig. 1. Cross-section of CANDU9 reactor building.

Table 2. Once-through fuel cycles in LWR and CANDU.

Reactor fuel utilization startegy (One pass in each Reactor Type)	Mass of uranium arising kilograms per Gigawatt-Year of electricity poduced	
	Natural fuel to system	used fuel from system
1. Enriched uranium (Once-Through) in LWR-Reference	217	33.2
2. Plutonium recycled in LWR	185	29.2
3. Plutonium and recovered (re-enriched) uranium recycled in LWR	157	24.7
4. Natural uranium in CANDU	161	161.0
5. Slightly-enriched uranium in CANDU	114	49.8
6. LWR plutonium recycled in LWR and recovered LWR uranium in CANDU	151	23.8
7. LWR plutonium and recovered uranium recycled in CANDU	119	18.8
8. LWR fuel (DUPIC) cycle in CAND	125	19.7
9. "Perfect cycle"-best possible	1	1.0 (fission products)

put ranging from 900 megawatts to 1000 megawatts in the short term, and with output capability up to about 1400 megawatts in the longer term. The CANDU9 reference design designated 480/SEU has more than twice the electrical output of CANDU3. However, it uses the same steam generators (four instead of two), fuel channel (modified to permit double-ended fuelling), fuelling machine (with longer ram stroke) and fuel handling system. Use of slightly enriched uranium fuel allows an increase of electrical output from 860 to 1038 megawatts with a reactor design identical to those operating in the twelve units at Bruce and Darlington sites.

Using the Bruce, Darlington, and CANDU3 design files as the starting point, a group of senior designers met to establish the groundrules for the large CANDU design and to produce the conceptual design. The first detailed 3-dimensional CADD layout of CANDU9 was produced in less than six months. A reference design was established and a Change Control Board was convened. Documentation of the conceptual design description was completed in less than one year. Fig. 1 shows a cross-section of the reactor building, which is a 57 meter diameter reinforced concrete structure with a steel liner. Two fuelling machines are installed but the capability for single-end fuelling is retained. Four steam generators are used, of the same design as Darlington but slightly larger. Accumulators for emergency coolant injection are located inside the building; the reserve water storage tank provides a number of long-term cooling functions in case of a severe accident.

It is expected that the detailed design phase of CANDU9[2]
will be shortened and simplified substantially through the use of the systematic design process and CADD software developed on the CANDU3 project.

4. Advanced Large Scale CANDU Study

Atomic Energy of Canada and Japan's Electric Power Development Corporation have collaborated on heavy water reactor development for the past fifteen years. The concept currently under study is a Highly Advanced Core with output of about 1200 megawatts utilizing enriched fuels with discharge burnup of approximately 40 GWd/Mg. The design will meet the high seismic loads and all regulatory requirements of the Japanese safety authority.

5. Fuel Cycles

From early days it has been recognized that the PHWR reactor is well-suited to a variety of fuel cycles. Table 2 presents a brief summary of the results of recent work on once-through combined fuel cycles[3]. The first figure of merit is the mass of uranium which must be mined to produce a given amount of energy.

This indicates the degree to which the chosen cycle conserves fuel resources. The second figure of merit indicates the volume of used fuel arising per unit of energy produced. These CANDU fuel cycles can achieve significant savings in both fuel resources and used fuel arisings, relative to LWR cycles. These are once-through cycles: it is possible to increase performance further by reprocessing used fuels.

Note the last line in Table 2. It shows the same figures-of-merit for an ideal cycle which utilizes all of the energy in mined uranium. Since nearly all heavy metals are fissioned, the used fuel to be disposed of is near-zero. Only fission products remain in the waste stream. It is obvious that even the best once-through thermal reactor cycles leave considerable room for improvement in fuel utilization.

Other synergistic cycles are possible in principle[4]. The high fuel conversion ratio which is characteristic of CANDU suits the system well for combined cycles with fast breeder reactors. In a balanced CANDU-breeder system, the number of breeders needed to sustain the system is small (about one in eight) so that the additional capital cost incurred is low in return for the ability to utilize essentially all of the mined uranium and/or thorium.

5-1. CANDU Design Improvement Using Advanced Fuels

One limitation which has an adverse effect on CANDU economics is the steam pressure, which is limited by increasing fuel cycle costs as the pressure tube thickness increases. This constraint can be removed by using slight additional enrichment to allow thicker pressure tubes. Steam pressure can be raised to approximately the same level as used in pressurized water reactors; the capital cost advantage arises from higher output for a given plant size. References 5 and 6 indicate some of the possibilities of this type of reoptimization. Further work is necessary find optimum values for future advanced CANDU designs.

Some jurisdictions have placed restrictions on coolant void reactivity. Even though the current CANDU designs have adequately addressed coolant voiding as a safety issue, it might become an impediment to marketing in some countries. Reference 7 describes techniques for reducing the coolant void reactivity in CANDU. A theoretical and experimental program is underway with the objective of verifying these results and developing a low-void fuel.

5-2. Actinide Burning

Reference 8 describes the concept of actinide burning by recycle from reprocessing to CANDU reactors. Discharge from light water reactors also could be processed in the same way; fast reactors or heavy water reactors are inherently more useful for burning actinides because of their high ratio of flux to power or, put in another way, because of the large number of extra neutrons available for parasitic absorption. At the end of one two-year cycle, over 99% of the long-lived actinide burning is either necessary or efficient as par of the waste management system, it may lead

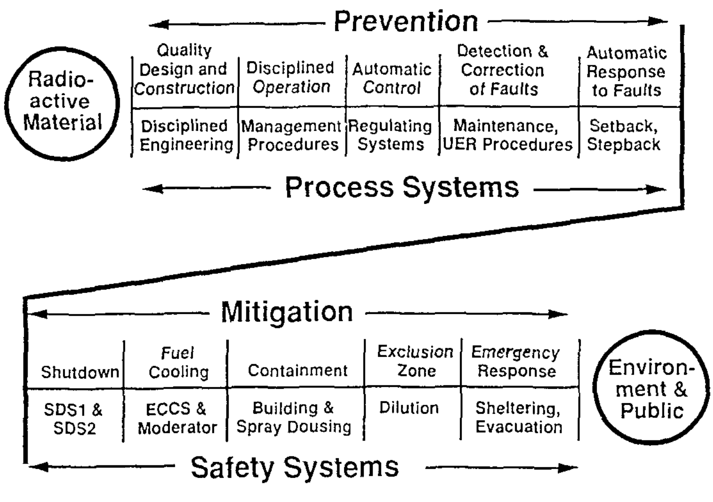

Fig. 2. Defence in Depth systems in CANDU stations.

to advantages in the area of waste facility siting.

5-3. Safety Issues

All modern nuclear power plants provide a high level of protection against accidental release of radioactive materials. Defence in depth is used for both accident prevention and for mitigation, as shown in Fig. 2 for the CANDU system. The remaining issues fall under the heading of "severe accidents" which, though they contribute only slightly to public health risks, have become dominant in recent years. References 9 and 10 discuss the severe accident issue in some detail.

5-4. Existing Designs

The world has come full circle in its interest in severe accidents. People knew from the beginning of nuclear power that it had the potential for destructive accidents. Early U. S. studies looked at the consequences of a "maximum credible accident" (generally driven by a reactivity increase without shutdown) in which most of the core inventory of radioactivity was released energetically to the environment, and usually predicted large numbers of casualties. The design had to make sure that this was a very rare event. The U. S. adopted deterministic design rules. The Canadian regulatory agency set an upper limit on the frequency of such disasters through requirements for reliable process systems and independent, testable safety systems, each of which had to meet specified reliability target as measured in-service. A severe accident might occur only if a process system and more than one special safety system failed simultaneously. Prudent choice of reliability targets along with a number of subsidiary deterministic regure ments ensure that the combined frequency is very low.

The first Canadian nuclear power plants (NPD, Douglas Point) were designed based on numerical limits on severe accident frequency. These limits were used to set reliability requirements for safety systems. The single/dual failure approach retained severe accidents in the design basis. Because the Gentilly-1 reactor had only one fast shutdown system, the consequences of the dual failure "loss of coolant plus loss of (fast) shutdown" had to be analyzed. This severe accident would result in severe core damage early in the transient. The results were later scaled to Douglas Point and Pickering-A. The Pickering-A analsis was redone recently by Ontario Hydro[11] using more modern tools, but the conclusions were similar: the runaway does not cause gross, early containment failure. All CANDU plants after Pickering-A have two diverse, independent shutdown systems and do not dump the moderator; thus those severe accidents within the design basis do not lead to severe core damage.

Work by Prof. T. Rogers[12] suggested that a severely damaged or molten CANDU core could be contained inside the calandria by conductive and convective heat transfer to the shield tank water on the outside. This is a line of defence beyond the moderator. This was noted in the first CANDU-6 overall assessment of severe core damage accident, done for the Dutch scientific organization, KEMA. Severe core damage frequencies were calculated to be about 5×10^{6} per year; the overall frequency of severe accidents, that is those which require the moderator as a heat sink, was about 5×10^{4} per year. The Ontario Hydro Probabilistic Safety Evaluation on Darlington, a more detailed assessment of frequencies, gave similar frequency values, but did not include the consequences of severe core damage. Ontario Hydro has developed a CANDU version of the U.S. MAAP code to look at these consequences.

5-5. New Designs

For nuclear energy to grow internationally, the industry must show that a severe accident does not lead to a public health or environmental disaster. Specifically, severe accidents should neither require prolonged evacuation nor lead to significant, permanent damage to the environment. While such consequences can never be mathematically ruled out, they must be ruled out for all practical purposes--precisely the balance between science and public acceptance achieved in other industries.

The advanced CANDU designs (CANDU-3 and CANDU-9) follow and evolutionary approach[13]. They adopt three defense-in-depth procedures for severe accidents:

1. Define frequency and consequence targets. These are similar to the EPRI requirements. Additional upper limits are placed on the frequency of calling on the moderator as a heat sink, for economic reasons.

2. Meet these targets in a way which takes advantage of CANDU characteristics.

－first, reduce the frequency of severe accidents where practical.

－second, if a severe accident occurs, design so that the moderator reduces the probability of progression to severe core damage.

—third, if severe core damages starts, design so that the shield thank contains it.

3. Develop accident management procedures to control the consequences of severe core damage accidents if they occur.

The severe accident approach for future designs is expected to follow parallel paths:

1. The primary focus will be on reducing the number and frequency of accident initiators. The classical accident defences (safety systems) are well-developed; further design enhancements will have a modest effect on safety while increasing the potential for complexity [13]. Strict rules for separation of process systems from safety systems are essential for new designs. Reducing accident initiators not only reduces risk of severe accidents, also assists the plant to be a "good neighbor".

2. Where design changes at modest cost can mitigate a severe accident--e.g. use of the refuelling water for LWR or the shield tank water for CANDU as emergency heat sinks--they will be implemented. These measures will be supplemented in operation by well-developed plans for severe accident management so that a severe accident can be controlled short of a disaster. A hybrid concept--with passive systems added on to a conventional design--has the advantages of retaining proven capability in operation while simplifying the safety case.

5-6. Concluding Remarks

The CANDU electrical energy system has passed the tests which qualify it as world-class technology. Planned developments will make the system even more competitive and useful in meeting future energy requirements in the world. The system is adaptable to diverse needs of operating utilities.

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