CANDU 9 - THE CANDU® PRODUCT TO MEET CUSTOMER AND REGULATOR REQUIREMENTS NOW AND IN THE FUTURE

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ABSTRACT

CANDU reactors developed under Canadian licensing regulations that placed the primary responsibility for safety on the licensee. The Atomic Energy Control Board (AECB), Canada's nuclear regulatory agency, state in their regulations what is expected in terms of safety performance so that designers are free to propose the best means of meeting this performance. This goal-oriented approach, besides encouraging innovation, allowed CANDU to be licensed in other jurisdictions. The latest design – the large, single unit, CANDU 9 – explicitly incorporates licensability in Canada through a formal AECB review of the design; lessons learned from licensing CANDU 6 in Asian countries, particularly with Wolsong 2, 3 & 4 in Korea, and more recently with Qinshan in China; utility requirements for modern evolutionary plants; and emerging international standards for safety, sponsored or issued by the IAEA. By combining the assurance of acceptability in Canada with compliance with foreign and international requirements, CANDU 9 becomes an internationally licensable product.

INTRODUCTION

PBNC 1998 highlights another year in a long history of Canadian collaboration in nuclear energy with Asian countries. Several major milestones marked the last twelve months: operation of the new CANDU 6 reactors at the Wolsong site in Korea; and commencement of construction of two new CANDU 6s at the Qinshan site in China. The CANDU PHWR design has become a good citizen of major Asian countries.

In the broader arena, 1998 marks further progress in the application of nuclear power for electricity generation. In the current reports of the International Atomic Energy Agency (IAEA)[1] we note that by the end of 1996, over 8100 reactor-years of operating plant experience had been accumulated by the current nuclear energy systems of the world. New generations of nuclear power plants have been or are being developed, building upon this background of success and applying lessons learned from the experience of operating plants.

The reasons normally adduced for commercial success are availability of financing, a proven design with good operating experience, and economic competitiveness. Although safety and licensing do not usually jump to the forefront of the decision to pursue a particular reactor type, these topics have become the focus of a number of international initiatives. Two examples are the preparation of Utility Requirements documents and regional plans for cooperation in areas of nuclear safety. Clearly inadequate public safety would be an insurmountable barrier, but it is taken for granted that modern Western designs, despite differences in degree and in safety characteristics, are adequately safe. Licensability is an aspect which is usually addressed in detail only after a purchase is made; and it is left to the utility, the designer, and the regulator to sort out.

It is the thesis of this paper that the CANDU approach to safety design and licensing is a particularly appropriate match to the needs of countries outside of Canada, and that the newest CANDU design, the

CANDU 9, has drawn on the experience with CANDU 6 in Asia, and has incorporated, from the beginning, both Canadian and international safety and licensing requirements .

EVOLUTION

Reactor Design

About 90% of the nuclear power reactors now in operation are water-cooled, mostly light water reactors (LWRs), with the remainder being pressurized heavy water reactors (PHWRs).

Advanced evolutionary designs presently under development comprise three basic types:

- water-cooled reactors, using water as coolant and moderator;
- fast reactors, using liquid metal, e.g. sodium, as coolant; and
- gas-cooled reactors, using gas, e.g. helium, as coolant, and graphite as moderator.

From its beginning the IAEA has provided a forum for the exchange of information and experience in the development and use of nuclear power. There are International Working Groups which focus on the different reactor types, with one of these groups dedicated to heavy water reactor technology. A newly created group focuses on the potential use of nuclear power for desalination. There is a plan to establish a group on fuel cycle options. These International Working Groups meet periodically and enable participating experts to exchange experience. The groups also advise the Agency on research subjects to be shared by interested Member States. Through its Coordinated Research Programmes, the IAEA assists researchers in developing countries and enables them to meet with their counterparts from developed countries on projects of common interest. The IAEA also publishes reports on the status of advanced reactor design development.

CANDU Reactor Design

To satisfy client and regulatory expectations, both now and in the future, AECL has adopted an evolutionary approach in which the proven designs of its operating products are improved incrementally and continually. This evolution is guided by the requirements of the utilities, who look for:

- improved economics, through the reduction of plant capital and operating costs and project implementation risks;
- enhanced safety, through more reliable operation, more effective safety systems and greater resistance to severe accidents, and
- improved operability, through design simplification and the appropriate introduction of new technologies.

A fourth attraction, arising from and unique to the neutron economy of CANDU, is the flexible fuel cycle. In the long term, a thermal breeding cycle using thorium is possible with the same basic CANDU design. In the medium term, CANDU can make use of Slightly Enriched Uranium for better economics, and is synergistic with LWR fuel cycles since it can burn Recovered Uranium from LWR spent fuel. Even in the short term, the natural-uranium-fuelled CANDU offers energy independence and diversity for countries which do not have enrichment technology.

International Safety and Licensing

A fundamental component of the emerging global nuclear safety culture is a number of legally binding conventions concluded under IAEA auspices. The Vienna Convention on Civil Liability dates back to the 1960s. A new convention on liability has been under negotiation within the IAEA for several years and was adopted in 1997. The Convention on Physical Protection of Nuclear Material was developed in the late 1970s. In 1986, in the months after the Chernobyl accident, the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency were drawn up in record time. The Convention on Nuclear Safety, the latest addition to this basic nuclear legal infrastructure, has entered into force. The adoption of this Convention was an important event. It requires States to fulfill a number of obligations relating to regulation, management and operation of nuclear power. A central provision calls for peer review, at meetings held at least every three years, of national reports demonstrating fulfillment of the various obligations.

A Joint Convention on the Safety of Spent Fuel management and on the Safety of Radioactive Waste Management has now been adopted. As with the Convention on Nuclear Safety, basic requirements are laid down and it is envisaged that national reports will be submitted and be subject to international peer examination; countries would also report on their inventories of radioactive waste and undertake to deal with any existing unsatisfactory waste situations.

Even with several international conventions in operation, nuclear and radiation safety remains first and foremost a national responsibility. However, this does not preclude the international formulation of harmonized safety approaches. Safety standards, recommendatory in nature, have been a principal mechanism for achieving the desired harmonization and they form an important second component of the global nuclear safety culture. There are three examples within the IAEA system:

- At the end of 1994 the new International Basic Safety Standards (BSS) for Protection Against Ionizing Radiation and for the Safety of Radiation Sources were adopted after many years' work. They form the basis for many national regulations.
- The IAEA Nuclear Safety Standards (NUSS) programme has resulted in some 60 non-binding standards and supporting guides dealing with the principal aspects of nuclear power safety - from the siting to the operation of plants. The NUSS documents are the basis for a number of national laws and regulations and may be referenced in commercial contracts for Nuclear Power Plants.
- The first document in a comprehensive series of Radioactive Waste Safety Standards (RADWASS) was issued late in 1995. The series will address the important question of radioactive residues from past activities.

Thus, although the maintenance of radioactive protection and nuclear safety remains the responsibility of the host country, an international infrastructure of basic legal rules and standards aimed at ensuring adequate safety in all nuclear activities has emerged through the IAEA.

The sharing of safety relevant information is another component of a global nuclear safety culture. The correct understanding and assessment of nuclear accidents and incidents is an important result of experience-sharing.

CANDU Safety and Licensing

The basic philosophy of Canadian power reactor licensing has been sound and consistent since its beginnings in the 1960s. That is:

- The licensee has primary responsibility for the safe design, construction and operation of the plant.
- The Atomic Energy Control Board (AECB), Canada's regulatory agency, states what is expected in terms of safety goals, both numerical and non-numerical, and safety performance.
- The licensee is responsible for proposing a design that meets those goals.
- The AECB ensures, on behalf of the public, that the licensee meets his responsibilities, and takes corrective action where this is necessary.

This non-prescriptive approach has encouraged innovation and ensured public safety through an independent, enquiring attitude towards safety design and analysis.

The early Canadian export plants – first in India and Pakistan, then CANDU 6s in Korea, Argentina and Romania – were built to be licensable in Canada and generally accepted as such by the host country. At that time the foreign CANDU owners did not have a detailed set of regulatory requirements and practice that applied to CANDU; they accepted the licensing basis in Canada, and strengthened their knowledge by programmes of training and co-operation with the AECB. The AECB was also in a position to advise the host country on the acceptability of any changes made to the local plant, so that acceptability in the country of origin was preserved.

Since the first foreign sales, the amount and depth of detailed regulatory review has increased. In Canada, the regulatory audit of plants being designed today includes:

- a more rigorous application of the basic philosophy;
- operating experience of CANDU gained over the last 20 years;
- the steady development of knowledge about the behaviour of CANDU plants;
- more sophisticated models of accident behaviour;
- resolution of outstanding safety and licensing issues;
- introduction of human factors considerations during design and operation of the plant;
- continued increase in computerized plant control, safety system operation, and monitoring in new designs;
- simplification of the design, operation and maintenance of the plant; and,
- improvements in severe core accident mitigation and management.

Similarly, at the time of the next CANDU 6 order in Korea, and the first order in China, both countries had developed strong regulatory regimes, and were operating light water reactors (LWRs). In the case of Korea, the regulations were written largely from a LWR point of view. Although the safety objectives were similar, most of the LWR regulations, which were highly prescriptive, did not apply to CANDU. Licensability in the country of origin therefore still played a large part in the initial acceptability of Wolsong 2, 3 & 4. However the Korean regulatory agency (the Korea Institute of Nuclear Safety, or KINS) performed a very detailed review, against the AECB written regulations (the "Regulatory" or R-series documents, and the "Consultative" or C-series documents); and against those Korean regulations which were felt to be applicable to CANDU. Generally the latter consisted of regulations which were not design-specific. The product, when licensed, therefore met both Canadian and applicable Korean requirements and, inasmuch as Korea was (and still is) the only country operating both LWRs and CANDUs, the end of the process marked the first reactor design which had been successfully licensed under two very different jurisdictions and practices.

The challenges were both philosophical – combining the prescriptive Korean approach with the goal-oriented Canadian approach – and technical: in areas such as containment design practices, siting practices, and civil design requirements, the Canadian and Korean models were markedly different, and a lot of effort was spent trying to combine and rationalize the two approaches.

EVOLUTION TO AN INTERNATIONALLY LICENSABLE PRODUCT DESIGN

Wolsong 2/3/4

The interaction of the LWR-influenced Korean requirements, and the AECB requirements for the reference CANDU 6 plant, caused a number of changes to Wolsong 2, 3 & 4 which made it more of an international product:

- The organization of the Safety Report was revamped. The original domestic CANDU 6 plants had a Safety Report divided into two portions: a design description and a safety analysis. This would have been difficult for KINS to review, as it was not consistent with LWR practice (along which lines KINS was organized) nor with evolving IAEA guides. AECL therefore developed a Safety Report format for its products consistent with international practice, and applied it to CANDU 3, CANDU 3U (a version of CANDU 3 designed for the U.S. market) and Wolsong 2, 3 & 4. Previous practice had been to put design details in subsidiary documents such as Design Guides, Design Requirements, and Design Descriptions; much of this was now moved into the Safety Report. The accident analysis was moved into Chapter 15 but not otherwise changed: it remains more extensive than LWR accident analysis.[1]
- Both Canadian and Korean practices were used for siting, as discussed in the section below describing CANDU 9.
- KINS instituted[2] a number of technical requirements in addition to AECB requirements. These included:
  - operating guidelines for the pressure tubes, for normal operation and in case of a leak;
  - improvement of the procedure for leak detection using the Annulus Gas System;
  - three dimensional analysis of hydrogen distribution and combustion in severe accidents;
  - submission of a Level 2 PSA, including external events;
  - application of AECB Consultative document C-6. This document specifies a requirement for the designer to identify and analyze a set of "design basis" accidents for the plant, and compare them to acceptance criteria. While C-6 had been used on the Darlington station in Canada on a trial basis, previous CANDU 6 plants had used the "single/dual" failure approach. KINS was the first regulatory agency to apply Consultative document C-6 to a CANDU 6 plant.

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[1] The reason is that the AECB does not prescribe in detail what accident analysis is to be done, but places the onus on the CANDU designer to systematically identify all accident sequences with a frequency above about 10^{-6} per year, and analyze them. Thus the "design basis" set in CANDU is larger than in LWRs and includes a number of severe accidents, such as LOCA+LOECC, and LOCA with impaired containment.

- application of AECB Regulatory Documents R-8 and R-10 to trip coverage, resulting in more comprehensive dual-parameter trip coverage than in the reference plant;
- improvements in the containment liner material to enhance leaktightness;
- intensive review of the design changes and improvements;
- applicability of PWR safety issues in a practical manner to achieve a safety enhancement equal to or above the international level.

In addition, Korea engaged several domestic and foreign experts, and an IAEA Design Review Mission in the design review. The satisfactory conclusion of the review demonstrated the practicality of harmonizing the Korean Atomic Energy laws, with supplementary provisions from the Canadian regulatory policy, Canadian Codes and Standards, and the use of US NRC Regulations and IAEA Codes and Standards as reference material.

Qinshan

The reference plant for Qinshan is Wolsong 3 & 4. As noted earlier, the Chinese regulations use "HAF" guides which are partly based on IAEA guides and partly reflect Chinese-specific requirements. CANDU complies with IAEA guides, although demonstrating detailed compliance with HAF guides to the Chinese regulator's satisfaction is the major focus of the activity prior to the Construction License. There were a number of changes from the reference plant to meet Chinese requirements. These include:

- To reflect site conditions, the design includes tornado protection of systems which carry out the essential safety functions. This is the first application of tornado protection to CANDU 6, and allows more flexibility in siting.
- The fire protection system was seismically qualified – this is not required in Canada[2].
- Interface equipment was provided for a remotely-located Emergency Response Centre.
- A Technical Support Centre was provided on-site.
- A Critical Safety Parameter Monitoring System was provided (in Canada, this function is performed by the Post Accident Management System).

CANDU 9

The CANDU 9 design incorporated lessons from Asian experience. From the beginning, a number of fundamental design requirements were set for safety and licensing, requirements that have moved CANDU 9 toward an internationally licensable product[3].

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[2] This is because of the provision of two separated, independent groups of systems, either of which can carry out the essential safety functions of: shutting down the reactor, removing decay heat, preventing release of radioactivity and monitoring the state of the plant. Equipment required for safety in each group is protected by fire barriers or distance so that a fire cannot easily spread from one group to another. This philosophy goes well beyond fire protection and gives a design which is robust with respect to common-cause failures, sabotage, local external events, etc. For example CANDUs have *two* sets of emergency diesel-generators, widely separated for protection against a common cause event; each set, consisting of two or more diesels-generators, can supply essential safety loads.

- The design had to be licensable in Canada. There were two reasons for this. First, it would make the product attractive to Canadian utilities when they began to build nuclear generating stations again. Second, although CANDU 9 is an evolutionary design, and all major components have been proven in service in operating CANDUs, it was felt that utilities would still want an independent assurance of licensability, particularly focused on any changes, even if these changes were improvements. Thus the AECB was asked to perform a formal licensability review to ensure that there were no "fundamental barriers" to licensing the CANDU 9 design in Canada. This conclusion would form the basis for the regulatory review done when a CANDU 9 was ordered, whether in Canada or overseas, and would assure the purchaser that the risk of significant design changes due to licensing was small.
- In terms of the licensing process, the AECB recognizes and supports the concept of "up-front licensing". The AECB believe that an agreement with designers and licensees on the basis for licensing and the safety-related design requirements, at a very early stage in the licensing process, will reduce the licensing risk for the owner; and the cost of modifications, should they be needed, will be much less. The "up-front" licensing approach is not new in Canada, although the CANDU 9 assessment is the most extensive application of it to date.
- The design had to meet licensing requirements in the host country. A Licensing Basis Document (LBD), described below, was written explicitly incorporating both AECB and KINS requirements, using KINS as a model since it was an experienced regulator that had licensed both LWRs and CANDUs. Host country licensing requirements had the biggest impact in containment design. CANDU 9 had to accommodate Korean siting practice and demonstrate a small Exclusion Area Boundary (EAB) of less than 500m. Canadian practice on siting is to calculate the consequences of accidents, up to and including public doses, using mechanistic physically-based models of reactor and containment behaviour with conservative input parameters. In particular the predicted (not a stylized) containment source term and pressure transient is used. Korean practice uses a fixed source term of radionuclides inside containment, which is assumed to be held at design pressure for a fixed period of time. There is therefore no credit for active containment pressure suppression, but leaktightness is extremely important. Thus in CANDU 9, the pressure-suppression high-flowrate dousing spray used in CANDU 6 was removed, the epoxy liner was replaced by a steel liner for greater leaktightness, the design pressure was increased, and the design leakrate reduced by a factor of 2.5.
- The design had to meet International licensing requirements, as embodied by the International Atomic Energy Agency (IAEA). There is, of course, no formal international licensing agency. However IAEA Standards and Guides are accepted as a starting point by increasingly more countries, and, when written into a bid specification, become *de facto* licensing requirements for the project. In China, IAEA guides have been used extensively to formulate the HAF guides. IAEA requirements tend not to be particular to a specific design, although they do reflect LWR practice to some extent.
- The design had to meet utility requirements for a modern evolutionary plant. In the U.S., EPRI has published a summary of utility requirements; in Korea, utilities have done likewise, using a similar framework. Although the specific requirements are tied to LWR designs, the general requirements are applicable to all water-cooled reactors, and were incorporated into CANDU 9.
- The design had to possess enhanced safety, especially in the area of severe accidents. Both the NRC and the IAEA had defined numerical targets for the frequency of core melt and large releases, and these were adopted for CANDU 9. Severe accidents were a particular focus of the LBD and

subsequent requirements documents, and the high level requirements on the summed frequency of severe core damage were:

- 10^{-4}/year for 'moderator as a heat sink'[3]
- 10^{-5}/year for severe core damage
- 10^{-6}/year for large release.

- In order to have confidence in that these requirements were met, a number of passive safety characteristics, already present in CANDU 6, were enhanced. For example, in current CANDUs, if a Loss of Coolant occurs, followed by failure of the Emergency Core Cooling System to inject, a combination which in LWRs leads to a core melt, the moderator can remove the decay heat, preserve channel integrity, and prevent fuel melting[4]. Further severe accident defenses were added to CANDU 9[5]. Improvements to the containment have already been discussed. In addition a large Reserve Water Tank (RWT) was located high in the reactor building. This tank provides severe accident prevention (backup emergency water supplies to the secondary side of the steam generators and to the heat transport system). It also provides severe accident mitigation (makeup water to the moderator and/or the shield tank). The ability to add makeup water to the moderator allows it to remove decay heat after a LOCA + LOECC for some time even if electrical power or service water to the moderator is lost or the calandria has a leak (Fig. 1)

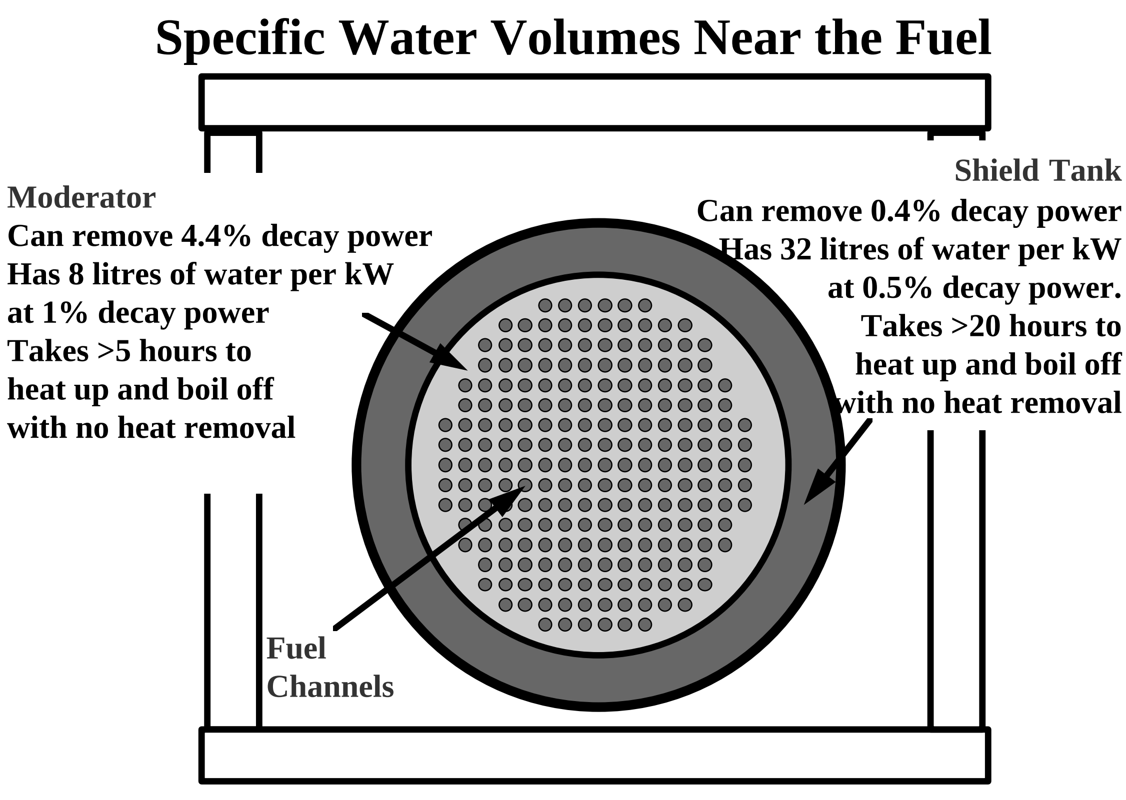

Figure 1

[3] This is a severe accident without fuel melting in CANDU, because of the presence of the moderator around the outside of the fuel channels

The combination of the calandria around the core, the shield tank around the calandria, and makeup from the Reserve Water Tank to both, provides an inherent core debris spreading and cooling area. Engineered features performing this function (outside the pressure vessel) are being proposed for new LWR designs.

Should the moderator makeup and heat removal nevertheless be lost, the moderator water will boil off over several hours, and the core will start to collapse, but the debris will be arrested by the calandria vessel and cooled by the shield tank water[6]. The capability of adding water to the shield tank from the RWT prevents failure of the calandria vessel and avoids an attack on the containment basemat. Steam relief pipes, sized to remove decay heat, have been added to the shield tank to effect this performance.

Recall that the first requirement for the CANDU 9 design was licensability in Canada. To demonstrate licensability in Canada, and to assure overseas customers that the design had independent regulatory review in the country of origin, the Basic Engineering Program included an extensive two year formal review[7] by the Canadian regulatory authority, the Atomic Energy Control Board (AECB). Documentation submitted for this licensing review included the Licensing Basis, safety requirements, and safety analyses necessary to demonstrate compliance with regulations as well as to assess system design and performance. The first submissions were the Technical Description and the Licensing Basis Document (LBD). The LBD is the high-level listing of the major licensing requirements. It calls up the appropriate regulatory documents and codes and standards, and interprets, in case of ambiguity, how the licensing requirements will be applied. It included not only requirements for licensability in Canada but also in the international market. The LBD, when accepted by the AECB, provides important guidance to a foreign regulatory authority on how licensability in Canada is implemented on CANDU 9, and AECL's interpretation of additional requirements from the foreign authority .These two submissions were followed by more detailed design requirements documentation, design methods (e.g., for safety critical software), safety analyses, probabilistic safety analysis, and other programme documents such as quality assurance, decommissioning, safeguards, and security requirements. In selected cases, AECB inspected details of the design implementation. In total, over 200 formal documents were submitted. AECB review of the detailed submissions, while comprehensive, focused particularly on:

- new or unique features in the CANDU 9 design;
- new or revised AECB Regulatory or Consultative documents;
- Generic Action Items applying to all CANDU plants;
- known operational safety issues;
- importance to reactor safety.

Midway through the review, the AECB staff identified thirteen key issues requiring a more detailed assessment. Intensive discussion took place for almost a year on these issues, resulting in many further submissions and analyses by AECL, and in some cases design changes, so that the issues could be closed at the end of the licensing review. At the end of the two years, AECB issued a final detailed report summarizing the disposition of all issues raised, and any further commitments made by AECL. The summary of this report stated that:

> "AECB staff conclude that there are no fundamental barriers to CANDU 9 licensability in Canada."

This statement results from the review of the information provided to the AECB, and is based on three general conclusions: that the CANDU 9 design complies, or can be made to comply with licensing requirements in effect, in Canada, on January 1, 1995; that the proposals to address AECB Generic Action

Items on the CANDU 9 design are acceptable; and that the major issues identified during the course of the licensing review have been adequately addressed.

CONCLUSIONS

The development of CANDU reactors under a goal-oriented licensing regime has allowed CANDU to be licensed in other jurisdictions. The latest design - the large single unit CANDU 9 - explicitly incorporates licensability in Canada through a formal AECB review of the design; lessons learned from licensing CANDU 6 in Asian countries, particularly with Wolsong 2, 3 & 4 in Korea, and more recently with Qinshan in China; utility requirements for modern evolutionary plants; and emerging international standards for safety, sponsored or issued by the IAEA. By combining the assurance of acceptability in Canada with compliance with foreign and international requirements, CANDU 9 becomes an internationally licensable product.

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KEY WORDS

CANDU, safety, licensing, PHWR, CANDU 9, Qinshan, Wolsong, AECB, international, IAEA