CANDU REACTORS - EXPERIENCE AND INNOVATION

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by R.S. Hart and G.L. Brooks
Atomic Energy of Canada Limited

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Presented by G.L. Brooks
at the Symposium on "Achievement of
Good Performance in Nuclear Projects"

Tokyo, Japan
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Abstract

The title of this paper highlights two key considerations which must be properly balanced through good management in the evolution of any engineering product. Excessive reliance on experience will lead to product stagnation; excessive reliance on innovation will often lead to an unsatisfactory product, at least in the first generation of this product.

To illustrate this balancing process, the paper reviews CANDU evolution and experience and the balance between proveness and innovation achieved through management of the evolution process from early prototypes to today's large-scale commercial units.

A forecast of continuing evolutionary directions is included.

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Résumé

Le titre de la présente communication souligne les deux points-clés que l'on doit équilibrer par une saine gestion tout le long de l'évolution de n'importe quelle réalisation technique. Si l'on regarde trop à l'expérience, le produit deviendra stagnant; si l'on regarde trop à l'innovation, on obtiendra dans bien des cas un produit insatisfaisant, du moins pour ce qui est du produit de première génération.

En vue d'illustrer ce processus de tenue en équilibre, la présente communication passe en revue l'évolution du CANDU et l'expérience acquise avec cette filière, et l'équilibre démonstration-innovation qu'on a réussi à maintenir par la gestion du processus d'évolution, depuis les premiers prototypes jusqu'aux réacteurs de grande puissance qui sont actuellement en exploitation industrielle.

Des prévisions quant aux directions que l'on prévoit pour cette évolution continue sont comprises.

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1. INTRODUCTION

In the early stages of application of any fundamentally new technology, innovation will be unavoidably dominant since experience will be lacking. This was certainly the case with nuclear power in its early stages of development. Innovation ruled the day. Vocal proponents could be found for just about every conceivable combination of coolant, moderator, core geometry, etc., even though, in many cases little or no relevant experience existed.

The nuclear power systems which survived that early period were generally those which were most closely based on earlier research or military reactor designs or which could draw most readily on fossil-fuelled power plant technology, i.e. where relevant experience was most plentiful.

There are now several hundred commercial power reactors in operation in a sizeable number of countries around the world. What lessons can be learned from this now extensive program which can guide us in making the right management decisions regarding the balance between experience and innovation? To answer this question in the context of the CANDU program, the paper examines the progressive evolution of CANDU technology from the first commercial station, Pickering-A and its prototypical forbearers, through to the latest CANDU model, the CANDU-3 which is currently in the detailed design phase. Examples are included which illustrate the impact of both experience feedback and innovation at each major evolutionary step.

From this examination it will be clear that experience feedback has played a progressively greater role in shaping each succeeding evolutionary step. This is, of course, normal with a maturing technology.

Looking to the future, the paper then outlines a number of planned innovative changes in CANDU design and describes the experience base which has helped to shape these innovations. Approaches are described by which we are managing this process of change so as to achieve an appropriate balance between the need for innovation and the lessons of experience.

2. CANDU EVOLUTION

2.1 Overview

The CANDU reactor concept was formulated in the 1950s from an experience base centred on Canadian heavy water research reactors (NRX & NRU), Ontario Hydro fossil plant technology, and Canadian collaboration with other countries in the early development and testing of zirconium alloys and UO_2 fuel materials.

This technological and experience base facilitated the design and construction of the CANDU Nuclear Demonstration Plant (NPD), which entered service in 1962. Major innovations were necessary to coalesce these emerging technologies into a power plant configuration with commercial potential. These included, for example, on-power refuelling at high coolant pressures, the sealing technologies necessitated by the use of heavy water coolant, and the adoption of pressure tubes as the pressure retaining elements of the reactor core. Based on the design success of NPD and the growing experimental and technological base, NPD was followed quickly by Douglas Point, a unit of near commercial size (200 MW(e), an order of magnitude greater than NPD), which entered service in 1967.

Douglas Point was followed by the first commercial CANDU station, Pickering A, with four 515 MW(e) reactors, the first of which entered service in 1971.

In this era, as basic CANDU technology was established, innovation dominated each step. For example, in going from Douglas Point to Pickering, the fuel channel pressure tube diameter was increased from 75mm to 100mm, fuel was changed from 19-element to 28-element, and "light bulb" steam generators, now standard in CANDU plants, were adopted. Problems identified through operating experience and/or research were continually addressed and resolved. For example, the pressure tube alloy was changed during Pickering A construction from Zircaloy-2 in Pickering 1 and 2 to Zirconium 2 1/2% Niobium for Pickering 3 and 4 to obtain forecast benefits from this new material which was originally developed by Soviet scientists.

The fundamentally good performance of the Pickering A plant and the growing experimental data base enabled a much higher reliance on proveness in subsequent plants. However, innovation continued, with many new features introduced in next generation CANDU designs. Such features included the use of a pressurizer to assist in heat transport system pressure and inventory control, the development of the 37-element CANDU fuel, and the utilization of boiling in the core (time averaged quality of 4% or less at the reactor outlet) to improve overall station economics. Such changes were based on experience and research in Canada and other countries.

The following subsections discuss a few specific aspects of CANDU evolution in the context of managing innovation.

2.2 Unit and Component Size

When unit size (electrical output) is increased beyond that of operating plants, there are two options available to the designers - increase the number of components or increase the size of components. Both of these routes tend to increase the unreliability of the plant, although the first route is often more predictable than the latter.

CANDU evolution has followed a very conservative approach, increasing component size only after establishing a sound experimental and experience basis. In general, CANDU has utilized increased component size in prudent steps to reduce the number of components and thereby assure improved reliability.

Steam generators are an example (see Table 1). Steam generator size has evolved from 138 MW(th) in Pickering A to 685 MW(th) in CANDU 3, while the number of steam generators has reduced from 12 in Pickering A to 2 in CANDU 3 for a similar unit power output.

The reduction in the number of steam generators is, of course, accompanied by a reduction in auxiliary components, including steam lines, feedwater lines, feedwater control valves, level measurements and support structures.

TABLE 1: STEAM GENERATOR EVOLUTION

Station	Reactor Output MW(e)	MW(th) per SG	Area (m^2) per SG	No. of SG
Pickering	515	138	1850	12
Bruce	825	265	2415	8
CANDU 6	640	500	3200	4
Darlington	885	665	4760	4
CANDU 3	450	685	3900	2

A similar situation exists for reactor coolant pumps where, as indicated in Table 2, capacities have increased and redundancy has been eliminated as higher pump reliability was achieved. The recognized importance of reactor coolant pump performance resulted in substantial experimental effort and testing of pump and pump motor assemblies prior to reactor service. An area receiving particular attention was pump seals.

TABLE 2: REACTOR COOLANT PUMP EVOLUTION

Station	Reactor Output MW(e)	Total No. of Pumps	No. of Pumps Operating	Motor Rating kW
Pickering	515	16	12	1420
Bruce	825	4	4	8200
CANDU 6	640	4	4	6700
Darlington	885	4	4	9400
CANDU 3	450	2	2	9100

2.3 Station Control

A key requirement in the successful management of product evolution is to correctly assess the impact and potential of new and emerging technologies. An example was the newly emerging digital computer technology of the mid 1960s. Recognizing the future potential role of this technology, and based on earlier partial application in the prototype Douglas Point unit, the Pickering-A units were placed under the control of dual redundant digital computers. Projected advantages included reducing the potential of operator error and freeing the operator from routine control tasks so that he could focus on diagnostics, testing and other important functions.

Each subsequent CANDU plant has utilized **'state of the art'** computer control and electronic display systems to further reduce operator work load and to improve station performance, while maintaining the original dual-redundant computer approach. As a recent further development, both Darlington and CANDU 3 utilize computer-based logic for both reactor safety shutdown systems and have extensively automated computerized testing of all safety systems.

2.4 Reactor Safety Shutdown Systems

In some instances, the evolutionary process has followed a "full circle", returning to earlier concepts. Often, this results when designers do not look far enough forward in time or are overly influenced by past situations. The use of mechanical shutoff rods in Shutdown System 1 is an example.

Reliability shortcomings in the early application of mechanical shutoff rods in Canadian research reactors led to the moderator dump system, in which the D_2O moderator is rapidly dumped into a storage tank below the reactor to achieve shutdown, this approach being adopted for NPD and continued for Douglas Point.

However, at the time of the Pickering A design, moderator dump was determined to be too slow for some potential events due to the larger core size. Meanwhile, development work had resolved earlier shutoff rod problems. These were, therefore, incorporated in Pickering A as the principal shutdown means with moderator dump retained as an adjunct subsystem for greater shutdown depth capability.

In all subsequent CANDU plants, mechanical shutoff rods have been utilized as the primary shutdown system (SDS1) and moderator dump eliminated. At the same time, the injection of soluble poison into the moderator has been adopted for the full-capability second shutdown system (SDS2).

2.5 Simplification

Simplification has always been a focus of CANDU development. Simplification reduces capital cost, construction schedule, and operating costs while increasing availability. Simplification has generally been accompanied by system and/or component improvements. As an example, the earlier noted elimination of reactor coolant pump redundancy resulted from pump performance improvements, and also permitted the elimination of all pump isolation valves.

Valves, in general, are an example of simplification in the CANDU evolution. The number of valves in the Nuclear Steam Plant (NSP) has been reduced from 9.5/MW(e) in Douglas Point to about 0.4/MW(e) in Darlington. There has also been a substantial shift in valve technology to the reliable bellows-sealed type of valves utilized extensively for D_2O systems (See Table 3).

TABLE 3: Valve Evolution

Station	Reactor Output MW(e)	No. of Valves Packed	Bellow Sealed
NPD (1962)	22	1500	0
Douglas Point (1967)	220	2000	0
Pickering (1971)	515	175	570
Bruce (1976)	825	75	500
CANDU 6 (1982)	840	90	300
Darlington (1989)	885	90	300

3. REACTION TO EXPERIENCE

3.1 Pitfalls

We have identified two pitfalls which are not always readily recognized. One pitfall might be termed **"transient overreaction"** to problems. Such problems may be identified through operating experience or through R&D programs. Commonly, such experience may be very limited. It is, therefore, all too easy for designers to overreact and, through this overreaction, to incorporate design changes in the next generation of plants which are not optimum. The other pitfall could be termed **"success-induced conservatism"**. This occurs when the designer fails to innovate in an area where he perceives near perfection based on very positive, but limited, experience. The following sections provide examples of such pitfalls.

3.2 Transient Overreaction

The potential for "transient overreaction" to problems has been identified. This problem can be particularly evident when programs and commitments are advancing quickly without the time to accumulate and evaluate experience. The reaction to early shutoff rod problems has already been noted in Section 2.4.

In CANDU design evolution, a further example is the subdivision of the CANDU 6 reactor building interior. At the time of the conceptual design of CANDU 6, severe problems with piping system activation, activity transport, and heavy water leakage were being experienced at the prototype Douglas Point station and operating experience was not yet available from Pickering. The designers reacted, and possibly over-reacted, by subdividing the reactor building interior and creating many relatively small rooms in order to control ventilation flows and collect heavy water leakage.

However, the problems of Douglas Point were eliminated in subsequent stations through a variety of other means including improved material specification (low cobalt alloys for example), the development of bellows seals and live-load packings for valves, improved atmospheric dryer designs, enhanced purification system performance and a dramatic reduction in the number of active components.

Based on the operating experience of modern CANDU plants, the new CANDU 3 design has adopted a relatively open reactor building layout with simple robust concrete structures and the extensive use of structural steelwork while, at the same time, substantially reducing the forecast operating man-rem consumption relative to operating plants.

3.3 Success-Induced Conservatism

When actual experience with a particular design or design feature is very positive, designers are often reluctant to contemplate major innovative changes in these areas; sub-consciously, past success is associated with perfection. Opportunities for product improvement (cost or schedule reduction, operability improvements, etc.) can, therefore, be lost. For example, the success of the early CANDU computer control systems temporarily restrained designers from fully incorporating the benefits of rapid advances in this technology, developed for other applications. This is now being corrected for the new CANDU 3 design.

Past success can also generate over-confidence. An example is the computerization of shutdown system logic and testing in the latest CANDU models. Confidence generated by the success of previous computer systems led to retention of a software verification approach that did not fully satisfy modern software development requirements; although corrected late in the design process, significant additional work and cost have been incurred.

4. NEXT GENERATION DESIGNS

As an example of next-generation designs being developed in several countries, CANDU 3, being developed by AECL, relies, to an unprecedented degree, on proveness and experience. One of the principal design requirements embodied in CANDU 3 is, in fact, to utilize **only** proven components, concepts and technologies (not necessarily CANDU). We observe that this approach is being generally followed in the power reactor design field worldwide.

At the same time, several new and demanding requirements have been adopted for the CANDU 3 design, including:

- 100 year plant design life through provision for component replacement
- 94% lifetime capacity factor capability
- 3 year operation between major outages
- Any major rehabilitation within a 90 day outage
- 50% reduction in man-rem/MW relative to CANDU 6
- 30 month construction schedule
- Adaptable to site and client requirements without substantial design or documentation changes
- Energy competitive with coal at $45 US/tonne

The result is the integration and application of fully proven technologies to provide a new product responding to current market demands.

All key NSP components, including steam generators, reactor coolant pumps, fuelling machine, and pressure tubes are effectively identical to those proven in service in CANDU 6 or larger Ontario Hydro stations and, because of the output selected for CANDU 3 (450 MW(e)), only half as many of these components are required.

In CANDU 3, there has been an emphasis on optimizing the plant design to achieve cost, schedule, construction and operability targets. To this end, all interests are being represented in the design process including safety and licensing, construction, commissioning and utility operations personnel. As an example, the subject of the first formal CANDU 3 design review was "Maintainability" with strong operations representation. This differs from past practice, in which much of the design was complete at the time of such reviews, thereby precluding significant changes to layout to accommodate maintenance requirements.

Operations personnel also have a substantial input to man/machine interface considerations, including the main control room and the secondary control room for CANDU 3. A team of designers and operators is developing first-stage operating procedures before finalizing the man/machine interface. As a result, the control room is being designed to accomplish the tasks required in an efficient and error free manner. This approach extends to abnormal and accident events, with particular attention being given to the presentation of alarms on a functional requirement basis.

The effective integration of various aspects of the station design is frequently utilized to meet design objectives, without any need for technological advancement. For example, a reduction of the fuel channel inlet end-fitting diameter facilitates complete modularization (pre-assembly) of the fuel channel. This feature, when integrated with tooling design, reactor design and reactor building layout, permits complete fuel channel replacement (232 channels) within the target 90-day outage time.

In some cases, the technologies employed in several past designs have been integrated. CANDU 3 refuelling is an example. A CANDU 6/Pickering fuelling machine is utilized; the fuelling machine is located on a floor-mounted trolley similar to Douglas point but with the addition of top seismic restraints. Upon leaving the fuel channel, the fuelling machine rotates 90° on the trolley as in Pickering; the trolley then moves to the containment wall and irradiated fuel is discharged directly from the fuelling machine into the irradiated fuel bay and new fuel is loaded via a nearby new fuel port as in the Bruce and Darlington designs.

CANDU 3 also continues the simplification theme of earlier CANDU evolution. Simplifications, in addition to those noted earlier, include the elimination of the dousing system for post LOCA containment pressure suppression and the use of simple mechanical zone controllers, utilizing the same components as the adjuster rod system, in place of the complex and costly liquid zone control system of previous plants.

Just as early nuclear power plants drew heavily on the experience and technology bases of other industries (fossil fuelled power plant technology, for example) new nuclear power plant designs must take full advantage of currently available technologies.

As an example, CANDU 3 is being designed utilizing CANDID Engineering (an acronym for CANDU Integrated Design Engineering) which utilizes 'state of the art' computer aided design and drafting (CADDS) and electronic data control and transmission systems developed for other industries to substantially reduce design costs and to improve the quality of the product. Advanced data highway/multiplexing/remote controller technology, again developed and proven by other industries, is being incorporated in CANDU 3, as are modern construction methods, including complete modularization and the use of a Very Heavy Lift (VHL) crane, now common to many major construction projects. These and other technologies developed and proven by other industries complement the unique nuclear technologies, allowing risk-free nuclear power plant advances in the areas of cost and schedule reduction and reliability.

An essential first step in any undertaking is to comprehensively establish the design requirements and the criteria for the assessment of the design relative to these requirements. In no area is this more important than in licensing, due to the adverse impact changes in these requirements, made during the construction phase, can have on project cost and schedule. This adverse impact can be largely avoided through reaching detailed agreement with the regulatory authorities regarding licensing requirements, analytical techniques and assumptions, and design features prior to construction start. Therefore, as the conceptual design of CANDU 3 progressed, a dialogue was maintained with the Atomic Energy Control Board in Canada. The Board is strongly supportive of this new approach, which is termed "up front" licensing. This, of course, requires that the design and analysis work be substantially complete prior to construction start.

5. FUTURE DEVELOPMENT

5.1 Overview

As typical of today's proven commercial reactor types, the current CANDU experience base will be extended to meet emerging market demands and to enhance the economics and performance of the CANDU system through ongoing research and development. Several examples are briefly noted in the following subsections to illustrate overall directions.

5.2 Fuel Channels

Present fuel channel technology supports a pressure tube life of 25 years or more under CANDU 3 operating conditions (and 94% capacity factor) while CANDU 3 provides the capability for fast and economical replacement of fuel channels. The continuing fuel channel development programs will result in pressure tubes immune from hydriding problems that exhibit reduced creep and improved structural properties.

5.3 Fuel Design

The development of an advanced fuel design featuring 43 elements is well in hand. This bundle design, a modest extension of the proven 37 element design, will facilitate a combination of higher bundle power and increased operating margins in future reactors.

5.4 Fuel Cycle

Fuel cycle development continues with the demonstration of several potential fuel cycles. These include the use of low level enrichment (LEU) fuel in which the uranium is enriched to the order of 1.2%, and the use of reprocessed uranium from LWR spent fuels.

5.5 Safety Systems

The CANDU indepth approach to safety will continue with development focussing on simplification and the greater utilization of passive systems. Such approaches may include passive containment cooling following a loss of coolant event and/or passive cooling of the existing moderator heat sink.

5.6 Man/Machine Interface

In future stations, CANDU computer automation will be extended to eliminate the remaining repetitive, distracting procedural tasks that are susceptible to human error. Also under development are a number of decision support systems that permit the operator to function on a higher level (planning, diagnosing and providing a strategic overview) during plant upsets and accidents.

6.0 SUMMARY

The need for innovation in power reactor design has, by no means, disappeared. Utility requirements are changing, regulatory requirements are changing, construction and manufacturing technologies are advancing and computation technologies are advancing. In the CANDU program, the emphasis in the application of innovation has shifted from the technical innovation of the early years of the program to innovative ways to utilize and integrate the appropriate and proven technologies available from all sources to meet the shifting market demands. As briefly described, CANDU 3 is an illustrative example. This approach is, of course, being broadly followed in the evolution of all power reactor systems and will enable them to more competitively meet utility requirements throughout the world.

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