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ATOMIC ENERGY OF CANADA LIMITED

ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

ADVANCED CANDU REACTORS

RÉACTEURS AVANÇÉS CANDU

J.T. DUNN, R.B. FINLAY and R.A. OLMSTEAD

Presented at the IAEA Technical Committee Meeting on
Progress in Heavy Water Reactor Design and Technology
Montreal, Quebec, Canada, 1988 December 6-9

CANDU Operations

Opérations CANDU

Mississauga, Ontario

December 1988 décembre

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RÉSUMÉ

L'EACL a entrepris la conception et la mise au point d'une série de réacteurs CANDU avançés dans l'intervalle de puissance 700-1150 MW(e). Ces réacteurs avançés sont le fruit de programmes de développement et recherche génériques en cours sur la technique CANDU et d'études de conception de réacteurs CANDU avançés.

L'objectif principal est de créer une série de réacteurs CANDU avançés qui sont concurrentiels, quant au prix, aux centrales au charbon sur le marché des grandes centrales productrices d'électricité.

On sera prêt à s'engager dans des projets d'unités particulières de la série avançée CANDU au début des années 1990 et on pourra les mettre davantage au point pour qu'elles restent concurrentielles bien avant dans le siècle prochain.

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ABSTRACT

AECL has undertaken the design and development of a series of advanced CANDU reactors in the 700-1150 MW(e) size range. These advanced reactor designs are the product of ongoing generic research and development programs on CANDU technology and design studies for advanced CANDU reactors.

The prime objective is to create a series of advanced CANDU reactors which are cost competitive with coal-fired plants in the market for large electricity generating stations.

Specific plant designs in the advanced CANDU series will be ready for project commitment in the early 1990s and will be capable of further development to remain competitive well into the next century.

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1. INTRODUCTION

AECL has undertaken the design and development of a series of advanced CANDU reactors in the 700-1150 MW(e) size range. These advanced reactor designs are the product of ongoing generic research and development programs on CANDU technology and design studies for advanced CANDU reactors. Specific designs will be ready for project commitment in the early 1990s and will be capable of further development to remain competitive in the next century.

The prime objective is to create a series of advanced CANDU reactors which are cost competitive in the market for large electricity generating stations, especially in relation to coal-fired generating stations. In addition, these reactors will be built to a fast construction schedule and achieve enhanced safety, high capacity factor, good load following and frequency control, long operating life and provision for plant life extension to 100 years. A key factor in achieving these objectives is the advanced control center which utilizes state-of-the-art technology and 17 years of operational experience with computerized control in CANDU reactors.

The well established CANDU approach to power station design has achieved very high operational performance in each of the variants represented by the eight units at the Pickering NGS, the eight units at the Bruce NGS and the four CANDU 6 NGS (Table 1). This demonstrates that the basic features of the CANDU concept are transferable over a range of detailed designs. Thus, there are significant degrees of freedom available in formulating an advanced CANDU design from existing and emerging technologies.

The advanced CANDU design and development program covers a broad range of considerations. The following sections provide an outline summary of topics and progress.

2. PLANT LAYOUT AND DESIGN

The advanced CANDU design incorporates a flexible plant layout for ease of plant siting and to facilitate various multi-unit configurations. This flexibility will be achieved without giving up the standardization program started on the CANDU 6 series of plants. This will be achieved through close specification of the interface between the nuclear steam plant and the balance of plant and with the extensive use of standard modules. All installations inside containment will be built as modules and, outside containment, station buildings and contents will be designed for assembly from very large modules. Where practical, modules will be factory built and shipped to a station site. At land-locked sites large modules will be assembled from smaller modules.

The advanced CANDU series will introduce a reoptimized nuclear steam supply configuration which will substantially increase the power output with a minimal increase in cost. This optimization ensures that all major components in the nuclear steam supply system are sized in such a way as to achieve the lowest overall cost. Maximum use will be made of proven components.

The reactor design will incorporate the single-ended fuel channels being developed for the CANDU 3 reactor (1). These fuel channels can be factory assembled, which significantly reduces the time required for installation into the reactor. In addition, this modular design also greatly reduces the time required for removal and replacement. This will make it possible to completely retube the reactor within a short maintenance outage to ensure that the target lifetime capacity factor of 94%, with a 3-year operating period between planned maintenance shutdowns, can be achieved.

3. SAFETY AND AVAILABILITY

Recent studies have indicated that an operating CANDU 6 power plant has a lower core melt frequency and more benign core melt consequences than light water reactors of the same vintage (2). This study also identified a number of easy-to-implement improvements which will be included into the design of the advanced CANDU reactors. The target is to reduce the predicted core melt frequency to less than 10^{-6} events per year. This will ensure that very severe events, which might lead to exposure to the public or economic damage to the plant, will be very unlikely.

The goal is to achieve the required level of performance with the simplest, most passive design possible. To help achieve the target, the advanced CANDU will be designed in parallel with reliability and unavailability analyses to ensure that any weaknesses are eliminated at the beginning of design. Service and support systems will receive attention from the inception of design to ensure that the same criteria are applied to them also.

Rapid advances in computer technology combined with low-cost computing power provide opportunities to substantially improve the man-machine interface, simplify plant control operations and provide advanced decision support facilities for the operator. The automatic, computerized testing of safety systems is another area which will be expanded. These improvements will lead to a practical improvement in safe, economical plant operation.

4. SIMPLIFICATION AND COST REDUCTION

The use of passive systems and components will be expanded in the advanced CANDU to decrease complexity and cost.

For example, the capacity of the pressurizer will be increased to accommodate reactor coolant volume changes from cold shutdown to full power conditions. This will permit a substantial reduction in coolant feed and bleed requirements and a less complex coolant recovery system. This change will not increase the amount of heavy water; it will merely be relocated. The pressurizer heater installation and shielding will also be simplified.

Heavy-water inventory requirements for the moderator and reactor coolant functions have been evaluated carefully, and development requirements have been identified for new design features which will result in substantial reduction in heavy-water requirements.

Tubeless process instrumentation is an emerging technology which will be applied inside the containment of advanced CANDU plants to simplify the plant and reduce design and construction cost. Current CANDU practice is to locate instrumentation in rooms inside containment which are accessible during operation. Installation of tubing to connect process instruments to systems is a significant analytical and construction activity which will be reduced or eliminated when electronic transmission meeting the necessary requirements is available.

The instrument air and pneumatic systems are another source of small-size piping and tubing that reach into every area of the plant. Development work is underway to find electrical alternatives for all these applications so that these systems can be eliminated.

5. ADVANCED TECHNOLOGY

Introduction of new proven technology, consistent with achieving long-term capability for a high level of performance and economy, is a principal goal for the advanced CANDU series of reactors.

Starting with the CANDU 3, AECL has undertaken an integrated computer-aided approach to the design of CANDU reactors. The advanced CANDU series of reactors will extend the use of this technique to all phases of a project including computer-aided manufacture of components and modules. This will improve the schedule and quality while reducing the cost. In addition, the electronic plant model and database created during design will form the basis for an extensive plant-status monitoring system to assist with station operation.

Data highways have already been applied outside containment in the CANDU 6 Mark 2 and CANDU 3 designs since CANDU requirements outside containment are similar to industrial requirements. To achieve significant improvements in noise reduction and higher data transmission rates, fibre-optic data highway technology is being investigated for incorporation into the advanced CANDU series of plants. Further developments will enable the use of data highways within containment. This will provide a major simplification in construction with attendant schedule improvements.

6. ADVANCED PLANT CONTROL CENTER

Conceptual work is well underway on the design of an advanced CANDU control center incorporating maximum use of advanced computing technology (3). This new design is based on the lessons learned by operators of CANDU and other nuclear plants and on the principles of cognitive engineering. The latter is a new interdisciplinary field which integrates the characteristics of human beings into the design requirements of an information processing system.

Computerized plant control has been operational in CANDU plants since the 1960s, but the advanced display/control system will provide a substantial improvement. The design objectives are to:

- reduce capital cost and schedule,
- reduce potential for operator error thus reducing the potential for serious accidents that threaten the owner's investment,

- reduce staff complement on the site, and
- improve the plant capacity factor.

Utility personnel are being included in the conceptual design team to help with the definition of the integrated objectives, tasks and activities required for all aspects of plant operation. This joint design-utility participation will be continued during the detail design stage through the development of detailed operating procedures in parallel with the detail design of the plant and the control center, to ensure that the operational objectives are met.

The most apparent difference will be a complete redesign of the main control room. The traditional vertical control panels will be replaced by a few desk-type consoles with a number of interactive CRT displays. Centrally positioned in the room will be a large, computer-controlled dynamic plant mimic that provides a plant status overview and a consistent plant mental model for all control center staff. To ensure continuous control under all circumstances, a critical function backup facility, with an identical operator interface, will be provided in case of total failure of the main display/control system.

The advanced display/control system will provide information to the operator which has been processed to reflect the context of his specific objectives in each particular situation. Also available to the operator will be a complete plant equipment status and interactive computerized flowsheets for all systems. To ensure that the plant equipment status is always current, means will also be provided to tie the operational database into a computerized work control system.

The universal problem of alarm overload will be addressed by defining a small number of meaningful alarm messages backed up by a decision support system. In addition, the following features of the annunciation system are designed to reduce alarm overload:

- categorization by system and/or function
- categorization by time
- separation on the basis of significance with respect to maintenance of plant operational states
- a simple means to allow authorized station staff to apply conditioning logic to any alarm.

All procedures required in the control center will be computerized to allow the operator to rapidly find what is required. These will be much more than the computerization of the printed operations manuals and will include voice annunciation for critical prompts and animation for enhanced understanding of complex processes.

To provide additional assistance to the operator, advanced CANDU control centers will also have an on-line knowledge-based decision support system utilizing several expert systems. This system will provide the operator with diagnostic assistance to help locate root-cause events. The output will be in the form of recommendations, with the rationale for each recommendation provided upon request.

This decision support system will be backed up by a set of symptom-oriented emergency procedures and a display of critical safety parameters. When the root cause of an incident or upset cannot be determined quickly, these symptom-oriented emergency procedures will ensure safe shutdown of the plant.

7. OPERATOR TRAINING

Since the plant display/control system and the operating procedures are being designed in parallel with the plant, it will be possible to provide a full-scope plant simulator early in the project schedule. This will ensure that there is adequate time available for proper staff training. This will be especially important on the advanced CANDU series of plants because of the very short construction schedule.

8. FUEL CYCLE OPTIONS

The basic CANDU concept allows the use of a wide range of fuels (4). The optimal fuel cycle for any utility depends on political, economic, and strategic considerations. With current and projected uranium and enrichment prices, the use of slightly enriched uranium is economically attractive in CANDU reactors. The optimal enrichment is around 1.2%, which would result in improvements in fuel cycle costs and uranium utilization of about 25%, compared to the use of natural uranium fuel. In addition, the burnup is about three times greater than with natural uranium fuel, and therefore the volume of spent fuel produced would be reduced by a factor of three.

The CANDU reactor is also synergistic with other reactor types, allowing efficient utilization of the uranium and/or plutonium recovered from LWR spent fuel. For example, plutonium from LWR fuel can be used to produce electricity in a CANDU reactor without significantly degrading the quality of the plutonium. Thus, the plutonium can be effectively "stored" in CANDU, before use in a fast breeder reactor. The thorium fuel cycle is the CANDU answer to long-term energy sufficiency, with near-breeding being possible.

The advanced CANFLEX fuel bundle being developed by AECL would facilitate the achievement of the higher burnups resulting from enrichment, by lowering the linear element rating, and by changes to the fuel pellet design. The CANFLEX bundle would also permit deep daily load-following cycles, and could be operated at up to 20% greater power per bundle without exceeding linear element ratings already proven in CANDU reactors.

9. UTILITY PARTICIPATION

From the inception of CANDU, utility participation in the design activity has ensured that CANDUs are practical electrical power stations. In the early stages of concept development of the advanced CANDU series, utility participation has been indirect. However, as the basic concept is defined further, utility representatives will be invited to work as members of the concept development team. This will ensure that sound, modern power station principles are applied.

Utility participation will expand with the scope of design work to provide guidance through to completion of the detailed design.

Since this new series of CANDUs will be built for different utilities, representation by several utilities will be sought for the generic design phase. This diversity of participation will provide assurance that the design can satisfy requirements representative of the best international utility practices.

10. PROJECT SCHEDULE REDUCTION

All of the schedule reduction means used for CANDU 6 Mark 2 and the CANDU 3, such as open top construction, modules, design simplification, data highways and schedule analysis, are applicable to this new series of CANDU reactors. In addition, the advanced CANDU will make provision for the largest practical scale of modules so that most station buildings can be built as completely equipped factory-assembled modules when project and site conditions permit. Exploitation of modules on this large scale will minimize site construction activities, construction manpower requirements, and construction infrastructure requirements. There will be substantial project cost and schedule benefits.

In parallel with the design activities, two reference project schedules will be produced. One will be representative of conditions at a site accessible by ocean shipping and the other representative of conditions at a land-locked site. Thus, flexibility will be built in by design so that the full spectrum of project activities can be accommodated.

11. SUMMARY

Good progress has been made towards the prime objective of designing a series of advanced CANDU reactors which are cost competitive in the market for large electrical generating stations. Conceptual designs already show the potential for a specific capital cost at least 25% lower and a unit energy cost 15% lower than could be achieved by a replication of one of the operating CANDU 6 reactors. Definition of the advanced CANDU reactor design will continue as additional concept options are evaluated and incorporated.

The concept will have sufficient definition by 1990 to firmly define costs and other performance factors. Once the concept is frozen, work will focus on completing a specific detail design to permit first project commitment at the earliest opportunity.

It is already evident that the advanced CANDU program will identify significant generic improvements. AECL is confident that this new series of CANDU reactors will be capable of superior performance and economics. This will attract major interest from a broad range of world utilities beginning in the 1990s, and continued improvements will sustain this interest well into the next century.

12. REFERENCES

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(2) CANDU 6 PROBABILISTIC SAFETY STUDY SUMMARY, Atomic Energy of Canada Limited Report, AECL-9607, 1988 July.

(3) Olmstead, R.A., Atomic Energy of Canada Limited, and Fenton, E.F., Ontario Hydro, THE ADVANCED CANDU SINGLE UNIT CONTROL ROOM, to be presented at the International Conference on Availability Improvements in Nuclear Power Plants, Madrid, Spain, 1989 April 10-14.

(4) Green, R.E., Boczar, P.G., and Hastings, I.J., ADVANCED FUEL CYCLES FOR CANDU REACTORS, presented at the 28th Annual Conference, Canadian Nuclear Association, Winnipeg, Manitoba, 1988 June; Atomic Energy of Canada Limited Report, AECL-9755.

TABLE 1

TOP 20 CUMULATIVE (LIFETIME) CAPACITY FACTORS*
TO END 1988 MARCH FOR
POWER REACTORS OF 150 MWe GROSS AND ABOVE
(except for Hungary, Comecon countries are excluded)

Rank	Reactor Name	Country	Load Factor %	Type
1	Pickering 7	Canada	90.3	CANDU
2	Bruce 7	Canada	89.0	CANDU
3	Pickering 8	Canada	88.2	CANDU
4	Point Lepreau	Canada	87.9	CANDU
5	Philippsburg 2	West Germany	87.8	PWR
6	Paks 1	Hungary	87.6	PWR
7	Bruce 3	Canada	86.8	CANDU
8	Paks 2	Hungary	86.6	PWR
9	Grohnde	West Germany	85.7	PWR
10	Beznau 2	Switzerland	85.4	PWR
11	Bruce 5	Canada	85.1	CANDU
12	Lovisa 2	Finland	85.1	PWR
13	Bruce 6	Canada	84.9	CANDU
14	Hunterston A2	UK	84.9	Magnox
15	Tihange 3	Belgium	84.8	PWR
16	Paks 3	Hungary	84.2	PWR
17	Genkai 2	Japan	83.2	PWR
18	Kori 4	South Korea	83.2	PWR
19	Grafenrheinfeld	West Germany	83.0	PWR
20	Bruce 4	Canada	82.9	CANDU

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