STATUS OF ADVANCED TECHNOLOGIES FOR CANDU REACTORS

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INTRODUCTION

The future development of the CANDU reactor is a continuation of a successful series of reactors, the most recent of which are nine CANDU 6 Mk 1* units and four Darlington units. The genealogy of the CANDU reactors is given on Figure 1, which shows three projects underway that continue the development of the CANDU reactor. These new design projects flow from the original reactor designs and are a natural progression of the CANDU 6 Mk 1, two units of which are operating successfully in Canada, one each in Argentina and Korea, with five more being built in Rumania. These new design projects are known as:

- CANDU 6 Mk 2, an improved version of CANDU 6 Mk 1
- CANDU 3, a small, advanced version of the CANDU 6 Mk 1
- CANDU 6 Mk 3, a series of advanced CANDU reactors.

As a reminder, the CANDU reactor is a pressure tube reactor, natural uranium fuelled, heavy water moderated, and in these versions it is heavy water cooled. It also features on-power refuelling for resource efficiency and as the primary means of reactivity control.

CANDU 3

Looking first at the CANDU 3. This is a reduced-size version of the CANDU 6 Mk 1 which has been re-engineered to meet three main targets:

- to address a market in the mid-size reactor range (350 to 450 MW(e) gross output),
- at minimum capital cost, and
- with decreased construction time.

The CANDU 3 is essentially one half of a CANDU 6 Mk 1. The intention has been to retain the reliable components that were used successfully in the CANDU 6 Mk 1 without reduction in size, but to use only half of them. For example:

TABLE OF COMPONENTS

	CANDU 6 Mk 1	CANDU 3
FUELLING MACHINES	2	1
PUMPS	4	2
STEAM GENERATORS	4	2
FUEL CHANNELS	380	232

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*The reactor models have recently been redesignated and the 4 operating CANDU 600s and the 5 under construction have been renamed CANDU 6 Mk 1.

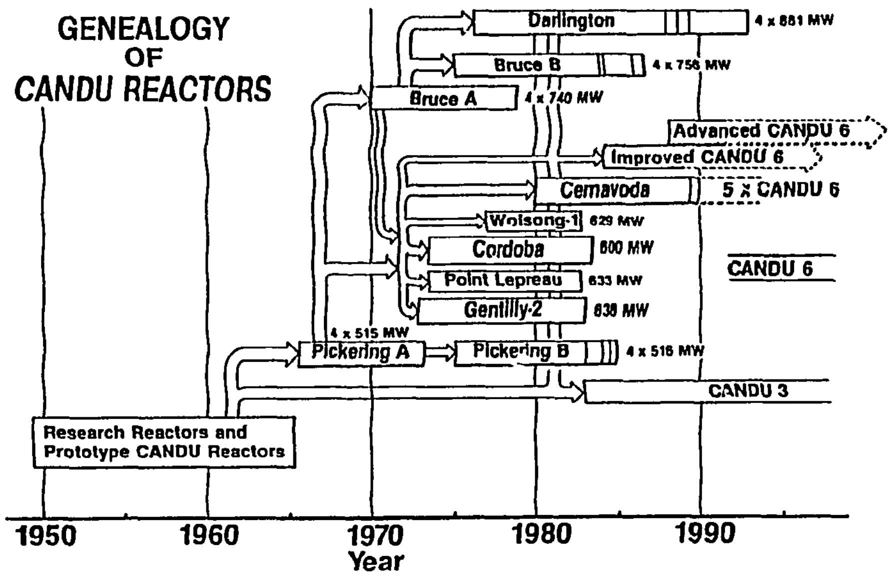

FIGURE 1: GENEALOGY OF CANDU REACTORS

The fundamental principle that is being used to reduce both construction cost and time is to divide the plant physically as well as functionally into different and separated buildings, see Figure 2. The function of this separation is to improve access and to allow construction to be carried on in parallel and by potentially different contractors. The five main buildings are the reactor building, the turbine hall, the reactor auxiliary building that includes the control centre, and the Group 1 and Group 2 service buildings.

The secondary control room and all of the "hardened" safety related systems and services outside of the reactor building have been housed in the Group 2 building. This building has been seismically qualified and protected from tornado damage and aircraft impact. This localizes the special construction features needed and reduces the cost of the other buildings.

The reactor building has been surrounded by a single-storey ring section which acts as a distribution point for electrical and process systems that are located some distance from the nuclear steam supply section.

We are also reducing costs by taking maximum advantage of factory assembled modules which could be built off-site or, perhaps in a factory on-site, depending on the location of the plant. The advantages are:

- a reduction in the overall time required for construction;
- a reduction in the requirements for site facilities;

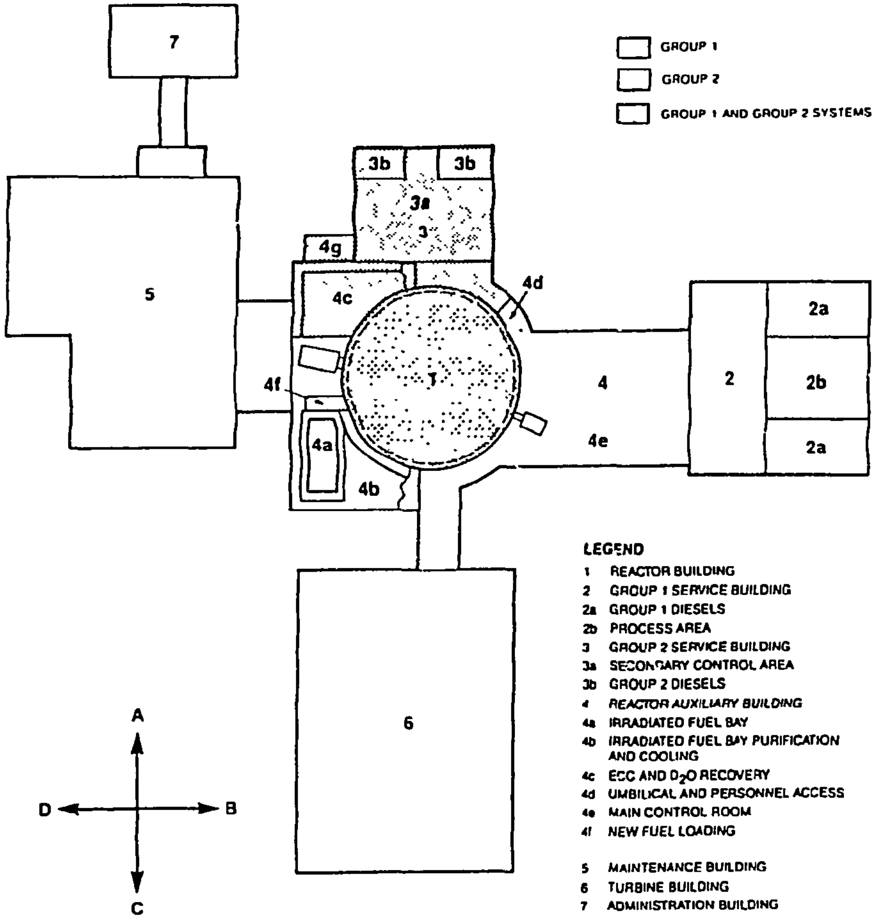

FIGURE 2: CANDU 3 STATION LAYOUT

- improved productivity since the working conditions can be more tightly controlled and the fabrication methods and assembly methods can be improved;
- a reduction in project management directly required at the site.

Quality assurance will also be improved because of the better controlled working conditions in a factory, and this should lead to a more secure schedule with fewer construction errors.

These factory manufactured modules are being designed for many systems and subsystems. For example, beginning with the Bruce A reactors, all of the CANDU reactor assemblies have been designed for factory assembly and been shipped by barge as a module. That principle has now been expanded to process piping systems and, for instance, the feeder banks and their headers will be fabricated in the factory and installed as a unit with field connections being made via mechanical joints to the fuel channel. Other modules being considered are:

- process packages such as the moderator heat transport system pumps, where pumps, coolers and basic piping would be assembled into a module,
- ion exchange and purification systems which would be modularized, and
- other subsystems and systems that can be identified and put together into framed units.

The principal technical change to the CANDU 3 was the fuel channel, which has been changed from dual-ended refuelling to single-ended refuelling. Figure 3 shows the essence of this concept. During on-power refuelling the coolant flow assists the movement of the fuel into the fuelling machine. This is a cost reduction measure and, in addition, is expected to give substantial improvement in construction schedule since the complete channel can be fabricated in a factory and installed as a finished unit.

Integrated Design Engineering

AECL is introducing the use of integrated computerized design tools on the CANDU 3. Intergraph has been selected as the supplier of the CADDS work station and an active development program has been undertaken to integrate engineering application packages with computer aided design packages. This substantially reduces the design effort and time and allows the use of simulation techniques such as walkthroughs of the plant. It will also be possible to model construction activities by computer to simulate the installation of equipment, to ensure that routes for factory assembled modules are clear, and to avoid major surprises in construction.

CANDU 6 SERIES

CANDU 6 Mk 1

The initial CANDU 6 design, the CANDU 6 Mk 1, is operating in three different countries as mentioned earlier, and there are five units under construction at Cernavoda, Rumania. Their performance has been impressive. In 1987 all four reactors of this type operated with annual capacity factors in excess of 80% and the lifetime capacity factors are high by most standards. Point Lepreau NGS is one of the world leaders at 92% lifetime capacity factor. The two units below 70% have had their output limited by grid requirements.

In common with all of the CANDU plants built since the first Pickering units, radiation exposures in the CANDU 6 Mk 1 generating stations have been low. The target of less than 100 man-rem/reactor year has been consistently achieved and exposures have been as low as 60 man-rem/reactor year including both external exposure to gamma rays and internal exposure due to tritium.

Operational advantages have been shown in Korea, where the ability of the CANDU 6 Mk 1 to continue operation beyond scheduled shutdowns for

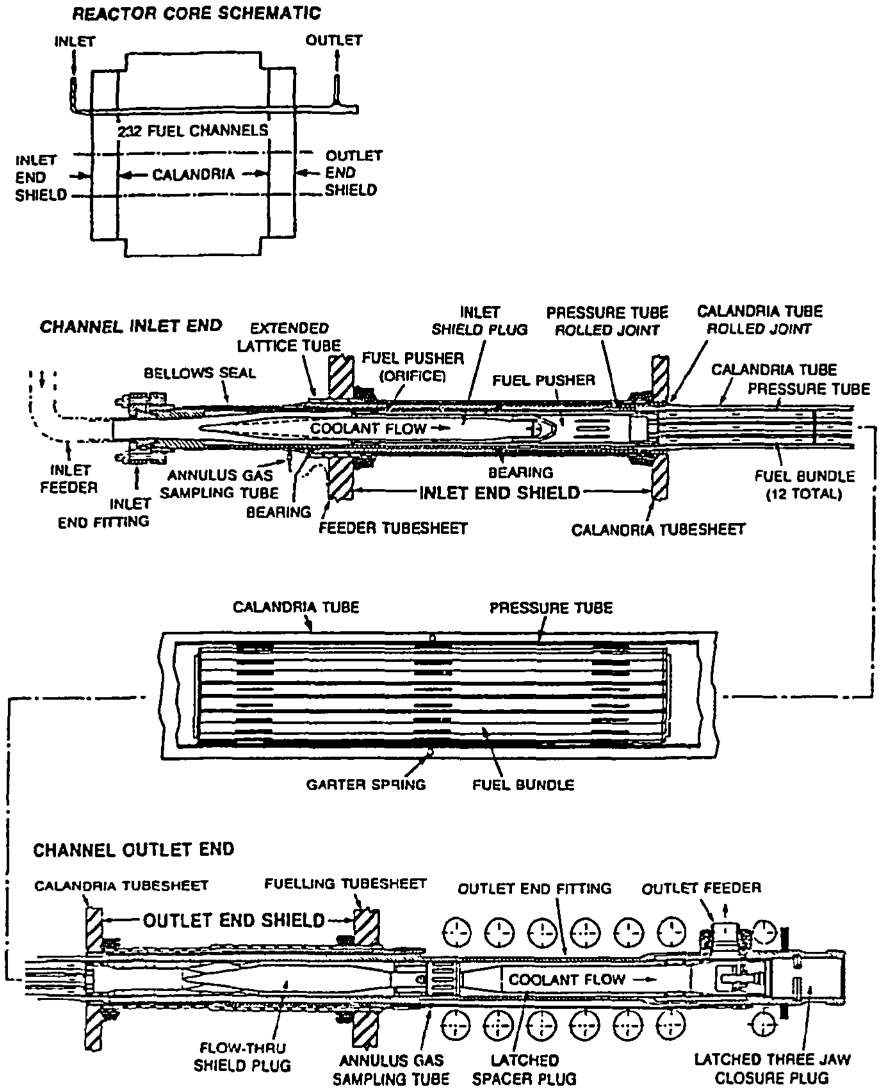

FIGURE 3: CANDU 3 FUEL CHANNEL

maintenance, because of on-power refuelling, provided flexibility for the utility to meet unexpected grid requirements.

Domestic fuel manufacture has been undertaken and accomplished successfully in Argentina and Korea, with fuel failure rates well within the standards expected for CANDU fuel.

CANDU 6 Mk 2

An improvement program for the CANDU 6 Mk 1, which began in January 1985, has recently been completed. This improved design, called the CANDU 6 Mk 2, includes increased use of computers for safety systems and an update to meet the requirements of recent codes and standards.

The principal objective of the improvement program has been cost reduction. Construction costs and schedule were targeted for reduction by using open-top construction, factory assembled modules, design simplification and schedule optimization. This will permit an 11 month reduction in the construction time to give a 49 month construction period from first concrete to commercial operation.

Open-top methods and the use of very heavy lift (VHL) cranes have now become established and were used in the Darlington reactor construction to install large pieces of equipment like the steam generators.

To use open-top construction and still retain a dousing tank, it was necessary to redesign the upper structure of the containment building. As has been done in the past, the perimeter wall will be poured using slip-forming techniques and a temporary top, which would be removable by the VHL crane, will provide weatherproofing during most of the construction period. When the building is to be finally sealed, a prefabricated liner framework will be installed to permit the pouring of a tank for the dousing system and the concrete dome.

The architectural layout of the plant is particularly important since it has been designed for rapid and easy assembly. Figure 4 shows the plan of the CANDU 6 Mk 3 and Figure 5 identifies the major changes that have been made and gives the reasons for them.

CANDU 6 Mk 3

AECL has undertaken the design and development of a series of advanced CANDU reactors with outputs in the range of 700 to 1150 MW(e). They are based on generic research and development programs and design studies. Specific designs are expected to be prepared for commitment in the early 1990s and, with ongoing development, to remain cost competitive into the 21st century.

These advanced CANDU designs will incorporate the design changes already developed for the CANDU 3. These include shop assembled fuel channels, single-ended refuelling, extensive modularization, as well as enhanced construction access by using separate buildings. Again, the principal objective is to reduce the specific capital cost. The target is to reduce it to less than 75% of the first generation of CANDU 6 Mk 1 plants. Additional targets are:

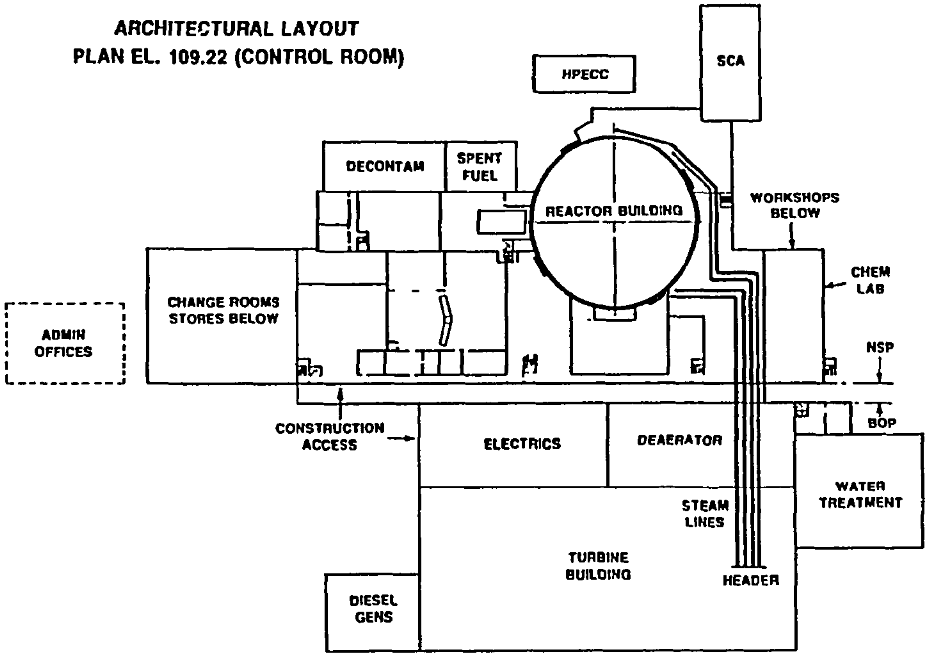

FIGURE 4: CANDU 6 MK 1 PLANT LAYOUT

- the construction schedule is to be shortened to 40 months from first concrete to inservice;
- the reactor is to be designed for operation with a 95% capacity factor;
- the load following capability of the plant is to be enhanced to fit a wider range of utility markets.

The last is seen as an enhancement of the demonstrated capability of load following that has occurred with the CANDU 6 Mk 1 units in Argentina, Quebec and Korea.

More extensive use of factory manufactured modules will be made and very large modules are planned for sites with ocean access.

Computer aided engineering will be expanded to include design, project management, manufacturing, construction, material control and procurement, operation and maintenance. The integration of these functions will be based on a three-dimensional plant model and database.

Greater use will be made of data highways by including them inside containment once the required hardening of equipment has been done to provide survival and continued operation under accident conditions so that the plant information base is secure.

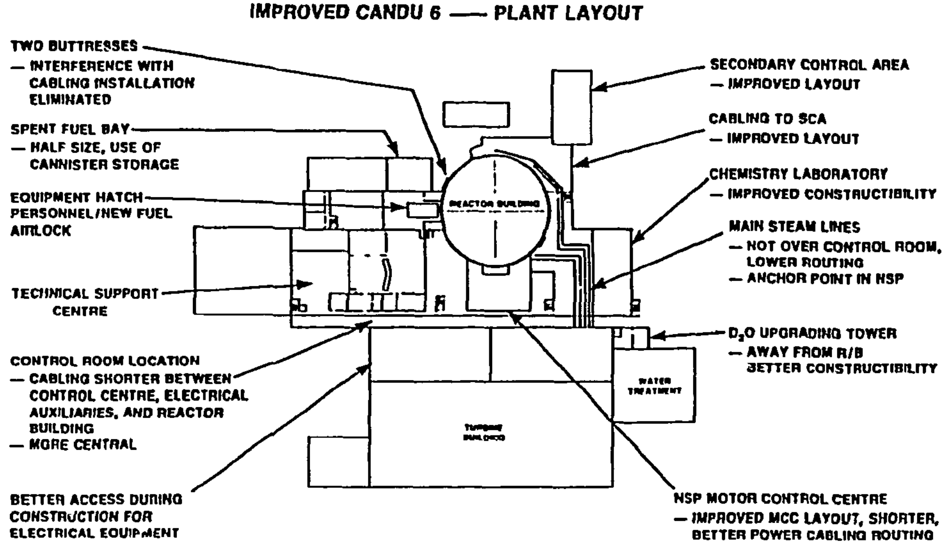

FIGURE 5: CANDU 6 MK 2 - IMPROVED PLANT LAYOUT

Additional objectives are:
- to review the process instrumentation with a view of reducing the dependence on process air systems to achieve what we call a "tubeless plant" where the process instrumentation would be largely electrified, and impulse tubes eliminated or minimized;
- to simplify the design by placing an emphasis on passive systems for heat rejection.

Passive systems are seen mainly for economic advantage and we anticipate benefits from improved reliability in safety systems, however, we await design and confirmation of the reliability before making any claims for improved safety. For example, a larger pressurizer will be provided to accommodate reactor coolant volume changes from cold shutdown to full power conditions, thereby simplifying the feed and bleed system. The emergency core cooling system and the service water systems will also be simplified.

OTHER ACTIVITIES

The specific power costs of a power station can be improved if the power output can be increased without major changes to the capital investment. Three programs are underway to investigate aspects of increasing the power output of the standard plant.

CANFLEX fuel is a new design which will feature greater subdivision and improved boundary layer thermalhydraulic conditions by the use of turbulence enhancement devices. This will result in lower fuel temperatures for the same powers. This fuel can be used either to operate at the same fuel bundle powers but with reduced linear heat rating of the fuel elements, or can be used to increase bundle powers without exceeding the fuel element linear heat ratings that have been used successfully in the current plants. This allows more power to be extracted from the channel without increasing the demands on the fuel.

The use of low levels of uranium enrichment is being considered to improve the burnup of the fuel. Natural uranium has been used in all CANDU designs to date, but it can be shown that the isotopic concentration of U-235 in natural uranium is not optimum for a heavy-water moderated pressure tube reactor. Now that the cost of enrichment is reducing rapidly, and since there are several reliable sources of supply, it is possible to consider the use of enrichment up to 1.2 wt% U-235 in uranium. This gives us some improvements in the core performance as well as burnup improvement by a factor of three. Significant but secondary advantages are the reduction in the back-end fuel handling and storage requirements due to the three-fold reduction in fuel required.

Improvements to instrumentation and control are continuing. The new technologies that are becoming available, such as artificial intelligence, bigger and faster computers, parallel processing and many others, are well suited to the digital control methods that AECL pioneered in the 1960s with the Douglas Point reactor and which have been steadily expanded. On the newer operating reactors these now include reactor startup and regulation, fuelling machine control, control of pressure and inventory of the high temperature heat transfer system, boiler pressure, boiler level, hot turbine runup, unit power and shut down systems. We anticipate using the new technologies to improve the man-machine interface and to provide significant operator aids for both normal and off-normal conditions.

The worldwide awareness of the stress on operators and the potential for operator error in complex plants is a serious problem, and a number of ways are being investigated for improving the operator's working conditions. For example, improvements in graphic displays have been significant over the last decade and these can be used to effectively display features for the operator in ways that have not been available in the past allowing greater advantage to be taken of the visualization and diagnostic abilities of the human operator.

A major initiative is an improvement in the information handling systems for the overall plant control including the human operator and procedure based controls, which has been termed the "Operator Companion". The basic principle is that expert systems or other new technologies can be used to act as advisors to the operator or could be watchdogs on individual systems. It is possible, eventually, that microsimulations or other techniques might be incorporated to advise the operator in advance of the consequences of various actions.

The principle that we have adopted is that the technologies should be particularly well suited for operation and be well tested before being added to the control room. Many operations aids can be anticipated that would be centred around an extensive database of plant design data, knowledge of operations, and domain expertise developed from the operating experience of previous plants. Specific targets for early development are improved alarm annunciation, automated fault diagnosis, on-line plant configuration and status display, safety vital signs display, and so-called smart operating procedures.

The first work on smart operating procedures will be to bring the emergency operating procedures for obscure events forward to the operator via computer but under h's direct and continuing control. Initially, these computerized procedures will be simply on-line page turning of existing procedures presently on paper. However, we anticipate adding data display so that the operator can move more quickly and expeditiously through these established procedures and that control functions may be added.

The development program for the CANDU 6 Mk 3 began in June 1987 and concepts are expected to have sufficient definition by 1990 to firmly define costs and performance factors. Specific designs are expected to be prepared for committment in the early 1990s and, with ongoing development, to remain cost competitive into the 21st century.