ADVANCES IN COMMERCIAL HEAVY WATER REACTOR POWER STATIONS

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ABSTRACT

Generating stations employing heavy water reactors have now firmly established an enviable record for reliable, economic electricity generation. Their designers recognize, however, that further improvements are both possible and necessary to ensure that this reactor type remains attractively competitive with alternative nuclear power systems and with fossil-fuelled generation plants. This paper outlines planned development thrusts in a number of important areas, viz., capital cost reduction, advanced fuel cycles, safety, capacity factor, life extension, load following, operator aids, and personnel radiation exposure.

I. INTRODUCTION

In keeping with the Conference theme, this paper provides an overview of expected development directions for generating stations employing heavy water reactors through the 1990s. While the specific development directions described are those foreseen for the CANDU heavy water reactor system, it is considered likely that many of these same directions will be adopted for the pressure vessel heavy water reactor system.

Since the first commercial heavy water power reactors entered service in the early 1970s, this reactor type has established an outstanding performance record in utility operation. Despite this success, further developments are being aggressively pursued in order to improve the economic competitiveness of heavy water reactors relative to other reactor types and fossil-fired generation units. The primary focus of these developments is capital cost reduction. A number of specific approaches are described. In addition, a number of other developments related to overall competitiveness have been initiated or are foreseen. These are discussed in later sections of the paper.

II. CAPITAL COST REDUCTION

A traditional disadvantage of nuclear power plants, including the heavy water type, has been their relatively high capital cost in comparison to alternative fossil-fuelled plants. This disadvantage has become of greater significance in recent years because of the general world shortage of capital funds, coupled with relatively high interest rates. Since this situation is expected, by many economists, to persist for some years, capital cost reduction logically becomes a primary development target.

To this end, several development thrusts have been identified:

- power uprating
- improved constructability
- standardization
- simplification
- improved information systems.

These will now be discussed in turn. Considering, firstly, power uprating, it will be obvious that increasing the thermal output from a given size of reactor offers the potential of a lower specific capital cost ($/kWe). In the case of the CANDU-600 design, as typified by the Wolsung unit in the Republic of Korea, ongoing developments today offer a 17% uprating in output and good potential for further uprating to at least 130%, while retaining the same basic reactor size.

Turning next to improved constructability, this offers two potential gains, viz., a direct reduction in construction labour costs, and a reduction in interest during construction costs through schedule reduction. Several specific approaches are under development.

These include:

an "open" plant layout which provides much improved construction access to each of the plant buildings, thereby reducing construction sequence "bottlenecks";

- use of large, heavy lift cranes which can install much of the plant equipment and systems in the form of pre-packaged modular assemblies;

- factory construction of the pre-packaged modular assemblies which permits greater parallelling of activities, use of advanced factory equipment and methods, and facilitates quality assurance activities;

- use of multiplexed data highways for the transmission of plant monitoring and control signals, thereby greatly reducing wiring and cabling work.

At the current stage of development, we estimate that the foregoing offer a reduction in construction schedule of about 12 months for CANDU-600 with considerable scope for further improvement in new designs such as CANDU-300.

Turning now to standardization, the advantages have received much attention in nuclear power circles for several years so little need be added here. The CANDU program has already made extensive use of standardization in the Ontario Hydro four-unit plants (Pickering-A, Pickering-B, Bruce-A, Bruce-B, and Darlington-A) and in the CANDU-600 units (4 in operation and 5 under construction). For the future, the primary thrust will be toward maximizing component standardization. For example, in the new CANDU-300, most major components are the same as for CANDU-600, e.g., steam generators, reactor coolant pumps, fuelling machines, etc.

The next area is simplification. In this area, our objective is to reverse the past trend towards increasing plant complexity. This undesirable (in terms of capital cost) trend has been common to most, if not all, nuclear power systems and arose, primarily, because of escalating licensing requirements. While many of these could, in theory, have been satisfied without increasing complexity, given a brand new design, their introduction as effectively "back fits" during the design process led inevitably to patchwork solutions and consequent complexity. Provided the rate of proliferation of new requirements declines substantially as should reasonably be expected, there is a major opportunity for simplification through design rationalization. The design of the new CANDU-300 has already benefitted considerably through this process relative to the earlier CANDU-600 design. Considerable potential exists for further benefits to be realized.

Finally, we turn to improved information systems. This is a relatively new area in terms of recognized potential as a capital cost reduction approach. The potential becomes apparent if one considers the makeup of the total capital cost of a nuclear power plant. We have estimated that for a CANDU plant constructed in Canada, the following labour cost elements constitute almost 50% of the total plant cost - design engineering, equipment and material procurement, project management, construction labour, and construction management. Much of this aggregate labour cost is associated with information generation, transmission, and utilization.

New approaches related to these information processes are developing at a rapid pace, as permitted by the spectacular advances in computer and communications technologies. When one considers the enormous quantity of information which must be generated, transmitted, and utilized in the design and construction of a nuclear power plant, it is not difficult to conclude that very major cost savings can be made. While this potential is, of course, not unique to heavy water power reactors, it does offer a relative advantage to nuclear plants in general as compared to fossil-fired plants simply because the totality of relevant information needed for the former greatly outweighs that needed for the latter.

III. ADVANCED FUEL CYCLES

The fundamental fuel cycle advantage offered by heavy water power reactors arises from their outstanding neutron economy. The currently employed once-through natural uranium fuel cycle is excellent, both in terms of overall fuelling costs and in terms of utilization of uranium. Furthermore, it offers long-term independence of fuel supply to countries which do not possess uranium enrichment facilities.

However, as has long been recognized, heavy water power reactors can operate on a wide variety of fuel cycles in addition to the once-through natural uranium cycle. For example, relatively low levels of enrichment of fissile elements, e.g., U-235 or Pu-239, can greatly extend the burnup of the fuel in simple once-through cycles. This can be accomplished by direct enrichment of natural uranium or, as a variant, by utilizing uranium produced as a byproduct from the reprocessing of Light Water Reactor (LWR) fuel since this uranium commonly is slightly enriched in U-235 as compared to natural uranium. More advanced fuel cycles are also possible based on thorium as a fertile feed material with recycling of the fissile U-233 produced by neutron capture in the thorium. A near-breeder cycle can be obtained in this way.

All of these cycles can be utilized without necessitating major changes from current heavy water power reactor designs. In fact, the simple once-through low enrichment cycles can be utilized with no reactor design changes other than in control software, certain trip settings, and the like.

The timing of the introduction of these cycles will be determined on the basis of economics. In the case of the low enrichment, once-through cycles, two economic factors are of importance, viz., the cost of natural uranium and the cost of enrichment. If the cost of the former is low and the latter high, then the current natural uranium cycle is favoured. If the converse is true, then the low enrichment cycle is favoured. At the present time, the economic balance would seem to slightly favour the low enrichment cycle. Assuming current forecasts of markedly lower enrichment costs in the 1990s prove true, then it is likely that at least some utilities operating heavy water power reactors will convert to the low enrichment cycle within that time frame. The alternative use of uranium from LWR fuel reprocessing is less certain since a variety of factors come into play, notably the availability of such uranium and its market price.

The use of plutonium enrichment is much less certain, primarily because of uncertainties in reprocessing costs. The thorium-based cycles are not expected to come into commercial use until there is a major increase in uranium price which is not anticipated until well into the next century. Nevertheless, their potential ensures that heavy water reactors have a long-term future.

IV. SAFETY

We can anticipate that reactor safety development will remain a thrust of major importance for many years to come, even assuming that there are no further significant accidents beyond Three Mile Island (TMI)-2 and Chernobyl. Given that the basic safety characteristics of current heavy water power reactors are excellent, as are those of light water power reactors, what directions will these developments take?

A first direction we see is to wider use of Probabilistic Risk Assessment (PRA) techniques in safety analysis. This will direct additional attention to the reliability of what we term safety support functions, particularly those which must operate reliably for extended periods in potentially hostile environments following a serious accident in order to mitigate the consequences. Turning to PRA techniques themselves, it is probably fair to say that their greatest current weakness is in the treatment of operator action (both correct and wrongful). We can anticipate major world-wide thrusts to overcome this weakness. Related to the foregoing, we can also anticipate a greater emphasis on passive safety features which place lesser demands on equipment reliability and operator actions. We see this as a progressively staged trend rather than a quantum step as represented by concepts such as the Swedish PIUS reactor.

With current CANDU reactors, the most frequent cause of spurious reactor trips is the routine testing of safety systems. While not directly a safety issue, such trips are clearly undesirable in terms of both lost generation and stress placed on plant systems. To overcome this problem and, in fact, to enhance the protection provided by the safety systems, we are moving towards making these systems more "intelligent". Instead of simplistic single-parameter, series chain, "go no-go" logic, we will employ dedicated small computers (with appropriate redundancy) to assess a wide range of relevant plant parameters in determining appropriate safety system response. A major step in this direction is already being taken for Ontario Hydro's newest station (Darlington-A). Further evolutions will be incorporated in future CANDU units.

Safety-related R&D programs continue in many countries with primary focus on severe accident phenomena associated with water-cooled reactors. As a result, most of the new knowledge derived from these programs will be relevant to heavy water power reactors. Canadian safety-related R&D complements these multi-national programs with particular focus on specific aspects related to CANDU. While we would not expect this R&D work to lead to major changes in the design of CANDU reactors, we can expect that the results will permit our designs to be improved in terms of meeting safety objectives with minimum uncertainties and, hopefully, lower costs.

V. CAPACITY FACTOR

As is now widely recognized, heavy water power reactors have established a world-leading position among commercial reactor types in terms of capacity factor achievement. There are several reasons for this including the use of on-power refuelling, high quality engineering, manufacturing and construction necessary to minimize heavy water losses, and the ability of the fuel and plant systems to permit rapid plant startups and loading rates. Despite this excellent performance record, further improvements are possible and will be actively pursued.

We have now adopted, as a design target, a 36 month operating cycle between major maintenance outages. While this represents a major challenge, its achievement is necessary to maintain the competitive edge over light water reactors as the latter move towards longer operating cycles between refuelling outages. Fortunately, the reliability already achieved with most CANDU components puts us within reasonable striking distance of this new target. This thrust will also provide a major challenge to the suppliers of turbine generators and other balance of plant equipment.

In addition to improved component reliability, certain other steps will be taken to aid in the achievement of the 36 month target.

These include:

developing in-service inspection techniques to provide a capability to monitor the "state of health" of components, piping, etc. while the plant is operating and to minimize the time needed for such inspections during maintenance outages;

further development of component life-cycle data banks and predictive techniques which will aid in the optimization of preventative maintenance programs.

Turning to the major maintenance outages themselves, it is obvious that their impact on capacity factor is not only a function of their frequency, but also of their duration. The latter is commonly determined by the time needed for a major component repair or replacement, i.e., the critical path item. In terms of design, CANDU plants have traditionally catered for component replaceability. However, improvement is clearly possible and will be pursued. For the new CANDU-300, we have adopted, as a target, a requirement that any nuclear steam plant component be replaceable within a 90 day plant outage. This includes replacement of all of the reactor fuel channels. Once again, this is an ambitious target but one which we believe is achievable.

VI. LIFE EXTENSION

Traditionally, and for financial accounting purposes, nuclear power plants have had a "book" life of between 15 and 30 years, depending on the practices of particular utilities and countries. Designers have adopted a target design life of 25 or 30 years although this has been a relatively "soft" number because long-term operating data has been unavailable with respect to key "nuclear" components. This picture in now changing with early nuclear power plants reaching operating lifetimes of 25 years or more. The earliest heavy water power reactor still in operation is the small (22 MWe) CANDU prototype Nuclear Power Demonstration (NPD) which has been in service for 25 years.

We can now have reasonable confidence in service lives exceeding 30 years. Ontario Hydro has recently adopted a 40 year "book" service life for their existing CANDU units. We note that some LWR designers are now targeting for a service life of 60 years for their projected new designs. In order to achieve this, the designers are planning major modifications to reduce the fast neutron fluence seen by the large steel reactor pressure vessels. Fortunately, in the case of CANDU, the equivalent to the pressure vessel (the pressure tubes) can be replaced. Based on current pressure tube technology, this replacement may be necessary to extend plant life beyond about 30 years. Improvements in design and pressure tube technology should increase this to at least 40 years. Hence, with only one retubing, service lives of 60 to 80 years are available.

Turning to other plant components for future CANDU units, these will either be periodically replaceable or will have a service life of at least the foregoing 60 year target. Where the design basis calls for periodic replacement, provisions will be incorporated to facilitate such replacement including considerations of accessibility, shielding, contamination control, and transport.

VII. LOAD FOLLOWING

As in the case of other power reactor types, heavy water reactors have, to date, been basically designed as base-load units. However, once nuclear units represent a major proportion of a utility's total generation capability, the need for them to accept some load following duty arises. In general, of course, utilities will prefer to use fossil-fired units for load following because of their much higher fuelling costs (compared to nuclear plants). Nevertheless, once this capability is exceeded, the nuclear units will have to accept load following.

This situation will become increasingly prevalent in future. It is already arising to a substantial degree in countries such as France.

In the case of heavy water power reactors, it has now arisen with the Ontario Hydro system because of regulatory approval delays in constructing additional transmission facilities. As Ontario Hydro's new Darlington-A units come on line, it will become more prevalent. The CANDU-600 unit in Cordoba, Argentina, has been regularly load-cycled over a range of powers from 50% to 100% depending on grid demand. Its performance in this regard has been fully satisfactory.

The above, admittedly limited, experience has been gained with CANDU units which were not designed explicitly for load following. Nevertheless, certain basic characteristics of CANDU units have proven very beneficial. For example, CANDU fuel has been developed to have a high tolerance to step changes in power level. This has been necessitated by the on-power refuelling programs but is beneficial in terms of the fuel's ability to withstand varying reactor power levels. Reactor control during power changing is facilitated by the fact that the power coefficient of reactivity is essentially zero. The use of on-line computer control of both the reactor and turbine generator also facilitates changing power levels.

For the future, this load following capability will be further developed to meet a broad spectrum of desired load-change patterns. Areas of interest will include further life-cycle thermal fatigue analysis of equipment and piping affected by load following, optimization of control system designs (particularly control software), and further investigation of power cycling limitations imposed by the fuel. Experience to date suggests that no substantial changes will be required to either plant or fuel designs.

VIII. OPERATOR AIDS

As has been widely reported, both the TMI-2 and Chernobyl accidents resulted, in large part, from a lack of understanding, on the part of the plant operators, of the true state of the plants and of the consequences of actions which they took. In addition to these two highly publicized events, it is well recognized that lesser mishaps have resulted from basic deficiencies in the "man-machine interface".

From a historical perspective, man-machine interface practices in the design of nuclear power plants started from utility standards established for fossil-fired plants. Progress from these early standards has, in some cases, been relatively slow, partially at least because of basic conservatism on the part of many utilities. In other cases, progress has been much more apparent with modern digital computer technology being adopted, firstly, to plant monitoring, and then, in some cases, to on-line computer control of most plant systems. The latter has permitted, at low additional cost, the provision of extensive displays of plant parameter information via CRT monitors. The great flexibility provided by the computers permits this information to be presented in a wide variety of formats to suit specific operator needs. Keyboards provided at the CRT monitor locations permit the operators to directly input control commands while monitoring the variables of interest.

Current CANDU plants typify this advanced approach which provides an excellent starting point for further improvement. What directions will this further improvement take?

We envisage several stages as follows:

a) The first stage will involve further refinements in providing clear, comprehensive, unambiguous, and easily digestible information regarding current plant status at any point in time. This stage is under active implementation for CANDU-300.

b) The second stage will add a predictive capability. Unsafe or undesirable trends in important parameter values will be identified and extrapolated forward in time to provide the operator with advanced warning of developing problems and information regarding available time frames for corrective action.

c) The third stage will provide an additional capability to "test" the consequences of actions which the operator may propose to take in handling abnormal situations. This will present a challenge to system designers since the program will have to execute quickly and the interface with the operator will have to be particularly "friendly" to cope with operator stress levels under such circumstances.

d) The fourth stage represents a further development of the second and third in that the system would recommend to the operator the "best" set of actions which he should take in dealing with an abnormal situation.

e) As a final evolution, the fourth stage would be "closed-looped", i.e., the system would automatically take the recommended actions with the operator providing only a surveillance function.

It will be obvious that a great deal of care and attention will have to be paid during the development of the foregoing stages to prevent plant operators from being misled by software errors or omissions. Nevertheless, we believe that the approach is both practical and potentially of great benefit in reducing the probability of operator error. During this development, experienced operating staff will be closely involved to ensure that the system responds to real operator needs. At each stage, the system will be exhaustively checked against plant simulators as a final stage in quality assurance.

IX. PERSONNEL RADIATION EXPOSURE

Relative to other water-cooled reactors, CANDU units have already achieved an excellent record in terms of radiation exposure to operating staff. For example, during 1985, the average occupational dose for CANDU units was about 1.7 millisieverts per MWe year. Further improvements are being actively pursued in both plant design and operating practices based on our now extensive operating experience.

X. CONCLUDING REMARKS

Obviously, many of the foregoing development thrusts are not uniquely applicable to heavy water power reactors but have broad application to all power reactor types. Nevertheless, we believe that their aggressive development will ensure that heavy water power reactors remain at the forefront of technology and economic attractiveness for utility application. Looking back to the early stages of power reactor development, there were many who claimed that the theoretical advantages of heavy water reactors could never be realized in practice. These doubters have clearly been proven wrong. Equally, and through the improvements outlined in this paper, we are convinced that those who claim that heavy water power reactors will be superseded by other types will also be proven wrong.