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Developments in CANDU Reactor Operation and Design

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DEVELOPMENTS IN CANDU REACTOR OPERATION AND DESIGN

by

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SUMMARY

The first three 540 MW units at Pickering have provided solid evidence of the suitability of the CANDU reactor for commercial operation. Construction at the 3,000 MW Bruce station is well advanced. The duplication of both these stations is now the subject of a design study. Future development of this pressurized heavy water design is now concentrated on improved reliability and ease of maintenance for large (1200 MW) sizes.

Variants of CANDU, using alternative coolants, are being actively developed. The 250 MW boiling light water prototype reactor at Gentilly has performed well in early operation. Experience with organic coolant in a test reactor has been highly successful and has demonstrated the advantage of low activity in the primary circuit.

RESUME

Les trois premiers réacteurs de 540 MW de la centrale de Pickering ont démontré que le réacteur CANDU convenait bien à l'exploitation industrielle. La construction de la centrale de Bruce de 3000 MW est bien avancée. La duplication de ces deux centrales fait l'objet d'une étude de la conception. Le nouveau développement de la conception du réacteur à eau lourde pressurisée s'est concentré maintenant sur l'amélioration de la fiabilité et sur l'entretien d'unités de grandes dimensions (1200 MW).

Des alternatives du type CANDU utilisant d'autres caloporteurs sont en voie de développement. Le réacteur prototype à eau bouillante de Gentilly d'une puissance de 250 MW a eu un bon début de fonctionnement. Les expériences acquises dans un réacteur d'essai avec un caloporteur organique ont été pleines de succès et ont montré les avantages d'une faible activité dans le circuit primaire.

ZUSAMMENFASSUNG

Die ersten drei 540 MW-Einheiten von Pickering haben die Eignung der CANDU-Reaktoren fur den kommerziellen Betrieb bewiesen. Der Bau der 3000 MW-Kraftwerk Bruce ist weit fortgeschritten. Die doppelte Ausführung dieser Kraftwerke wird analysiert. Die weitere Entwicklung des Schwerwasser-Druckreaktors wird jetzt auf die Betriebsicherheit und Wartung von grossen Einheiten (1200 MW) konzentriert.

Variante der CANDU-Type mit anderen Kühlmitteln werden entwickelt. Der Siedeleichtwasser-Versuchsreaktor Gentilly von 250 MW hat einen guten Betriebsanfang gehabt. Erfahrungen mit organischem Kühlmittel in einem Versuchsreaktor waren erfolgreich und haben die Vorteile einer schwachen Aktivität im Primärkreis gezeigt.

1. INTRODUCTION

Within Canada, the nuclear power program, using the CANDU heavy-water natural uranium system, is moving rapidly ahead. At the present time, some 5500 megawatts of generating capacity are either in operation or being built, and the commitment of further large stations is imminent.

The achievement of full power in May 1971 by the first 500 MW unit of the 2000 MW Pickering Generating Station marked the arrival of the CANDU heavy water power reactor firmly on the commercial scene in Canada. During the first year of operation the capacity factor achieved was 79%.

The second unit, reaching full power in November 1971, set what may have been a world record of 7 weeks from reactor start-up to full power. This was broken when unit 3 reached full power from reactor start-up in 18 days in April 1972. More complete details of the performance of the first three Pickering units are given in a separate paper in this session by Mr. Horton.

In arriving at the present level of the design and of the operating performance, much valuable experience has been gained. Earlier experience was incorporated into the design of the Pickering station. More recent experience has been incorporated into the design of the four 750 MW reactors of the Bruce Generating Station, now under construction. This paper presents a discussion of this experience and solutions likely to be of general interest and indicates the direction in which future CANDU designs will move. It is to be noted that changes will be evolutionary, based on demonstrated performance rather than large departures from proven practice.

2. DOUGLAS POINT EXPERIENCE

The 20 MW NPD demonstration plant which went into service in 1962 and the 200 MW prototype Douglas Point Station, which began operation in 1967, provided the operational information which directly influenced the designs of the newer plants. The 500 MW units of the Pickering Generating Station and the 250 MW Gentilly unit are now also contributing to this pool of experience.

Experience in reducing the escape and the loss of heavy water at NPD and Douglas Point has had a major influence on later designs. Examples of this are the current practice of keeping heavy water and light water systems separated as much as possible, the use of closed circulation and recovery systems, and a marked reduction in the number of mechanical and packed joints.

A major area in which Douglas Point experience is influencing later designs is the reduction in radioactivity in the primary system. Radioactivity, mainly of activated corrosion products, had increased at Douglas Point during the first two years of operation from its start-up in 1967 to the point where maintenance and improvement work became difficult and expensive. About 90% of the radiation fields came from ^{60}Co. The source of this was largely natural cobalt in the nickel of the monel boiler tubes and in hard facing materials in pumps and valves.

A large research and development effort was directed to this problem. It was found that "crud bursts" could be produced in the primary coolant system by temperature changes, particularly if the oxygen content of the system was raised beforehand. This crud, which contains the ^{60}cobalt, could then be removed by filtration and ion exchange provided that the flow through the purification system was high enough in relation to the volume of the primary coolant system. It appears that, by this process, not only is ^{60}cobalt removed, but the build-up in the system is interrupted.

In 1969 the decision had already been taken to install a purification system which was of sufficient capacity to take advantage of this discovery. This system became operational in November 1971. In the following four months, crud bursts were produced by short shutdowns together with oxygen addition and other chemical changes. Use of the purification system at maximum flow during these periods produced the results shown in Figure 1. The fall of radiation fields was so rapid that it is not yet clear how far the process can profitably be carried on, but the improvement obtained so far has been most valuable in every way, and there is every indication that this process can be profitably continued.

3. BRUCE

The 3000 MW, four-unit Bruce Generating Station was committed by Ontario Hydro in 1968. Figures 2 and 3 show the Bruce Generating Station. The first of its four 750 MW units will be in service in 1976.

The Bruce reactors have the same size channels as the Pickering reactors and both stations will use essentially the same fuel, although the power density in the Bruce reactors is 20 percent higher than that in the Pickering reactors. The Bruce reactors differ principally from those in Pickering in that they are fully steel and water shielded; it is possible to fabricate the shield as an integral part of the reactor vessel and thereby eliminate any construction of shutdown reactor shielding at the site. The reactor vessel as received at the site, Figure 4, is installed in a large room built to contain it and the primary heat transport system, Figure 5.

Another major difference between the Bruce station and the Pickering station is the use of a common fuel handling system to refuel all reactors rather than separate systems for each unit.

The final important difference is in the size and number of auxiliary components. The Pickering units were designed conservatively with little extrapolation in pump and heat exchanger sizes beyond those already in service when the station was committed in 1964. Besides conferring the assurance of components of proven design, this provided greater redundancy and avoided increases in piping sizes, thus easing containment requirements.

By 1968, when the Bruce station was committed, considerably larger auxiliaries were being built for water reactors. It was considered that components of these larger sizes could be adopted for Bruce and that as a result maintenance would be markedly reduced and plant availability enhanced despite less redundancy in the design. Consequently, in the primary heat transport system, where a Pickering unit has 16 pumps (12 operating) and 12 boilers, a Bruce unit has 4 pumps and 8 boilers. The resulting heat transport pumps in the Bruce plant are as large as any pumps being built for reactor coolant circulation. They have run successfully on test. This class of pump will probably be suitable for units of considerably larger size than the 750 MW Bruce units.

It is clear from even a cursory examination of the economics of nuclear power that reliability is a fundamentally important goal. Nuclear plants are more expensive than fossil-fuelled plants, and their economic viability depends on lower operating costs. When measured on a "per-kilowatt-hour produced" basis, virtually all operating costs,except the cost of fuel consumption, increase with increasing unreliability. A one percent gain in overall reliability is worth roughly as much as a six percent gain in fuel economy for a CANDU system, or as much as a two percent reduction in capital cost.

AECL's approach to the study of station reliability (or of unreliability) is to assess every component in the nuclear steam supply system. Its probability of failure, the consequences of its failure, and the time required to repair it are estimated using the best data available, including experience from operating plants where it exists. This has been done for Bruce. The result is a complete preview of the potential unreliability of the nuclear steam supply system, considered by systems and by individual major components. Those parts and those systems showing a disproportionately high contribution to outage are then re-examined to determine whether adequate redundancy exists, if access for maintenance can be improved, and if the consequences of failure can be eased.

A similar effort is required in the conventional part of the plant: in the turbine cycle, the electrical distribution systems, and in the peripheral equipment -- where the plant operators tend to be tolerant of failure because there is greater accessibility. Currently, in some nuclear stations, the reliability of nuclear steam supply exceeds the reliability of the conventional part of the plant. The effort required to upgrade the whole system undoubtedly will be made. It is a laborious and detailed task, beginning with the design concept and extending through the detailed design and procurement phases to quality control in the manufacturers' plants, to project management and to field construction and commissioning practices.

The question of exposure of operating and maintenance personnel to radiation has also received special attention and has influenced the selection of equipment and the layout of the Bruce station. Since water cooled reactors have the characteristic of transporting activated corrosion products to areas where the process systems must be approached for maintenance, appropriate steps have been taken, both to reduce the activity level in the coolant and to provide adequate shielding.

Examples of approaches which have been adopted for Bruce and which will exist in future CANDU plants are:

(1) Provision of local shielding. An example is the location of reactivity mechanism drives and the main coolant pump motors in fully shielded and accessible areas.

(2) Elimination of non-essential components such as isolation valves for coolant pumps and boilers.

(3) The use of valves which have been exhaustively tested and which are expected to require only the minimum of maintenance.

(4) The reduction of cobalt by, for instance, not using Stellite facings in valves.

(5) The provision of a suitably high capacity reactor coolant purification system.

4. DUPLICATE PICKERING(S) AND BRUCE(S)

Serious consideration is being given to the building of either duplicate or modified versions of the 2000 MW Pickering and the 3000 MW Bruce stations before progressing to substantially different designs. The objective in doing so would be, of course, to achieve the lowest capital cost and the highest reliability through the use of proven technology, known construction practices and components which have shown their reliability in previous service. Extensive studies on both the abovementioned projects are being undertaken. These are accompanied by a series of design reviews on specific features and components of the pressurized heavy water cooled (PHW) reactor. The duplicate or modified stations are expected to be in service by 1980.

5. 600 MW PHW REACTOR

Potential overseas customers have solicited proposals on 600 MW nuclear power units. In response to this interest a design of a 600 MW plant has been initiated. It is based on the Pickering and Bruce designs but incorporates a unit (as opposed to a station) containment system. Important features of this unit are the use of Bruce reactor channels, fuel, and fuelling machines, and the best assembly of components and design features from Pickering, Bruce and the five smaller stations which have been built to this date. For every critical component there is an existing precedent in actual operation which closely approximates it in size, materials and operating environment. The result is a unit design, capable of use as a one-unit or multi-unit station, with each unit being self-contained except for certain services like cooling water supply. While the design of the 600 MW reactor is more advanced than Pickering, its components are of proven design, and commercial reliability is assured. Figure 6 shows a cross-section of the reactor building.

6. 4 x 1200 MW CANDU-PHW

Based on a long-term assessment of its nuclear power needs, Ontario Hydro has asked AECL to undertake the design study of a four-unit station using reactor-turbine units of 1200 MW capacity.

It is expected that unit fuel cost for a 1200 MW plant will not be much less than that for a 500 MW plant; but construction cost, operating cost other than fuel, and project management all appear lower on a per kilowatt basis for the larger station. The 4 x 1200 MW plant for which the design study has been undertaken is intended for commitment in 1975 and is expected to be in service in 1982.

The pressurized heavy water cooled CANDU nuclear reactor and its systems which constitute the nuclear steam plant still contain great potential for further development.

Increases in fuel rating and steam temperature are under study. These reduce fuel cost, but this is already low - about one-sixth of the total energy cost. There are other benefits which may outweigh fuel savings. An obvious benefit is higher power density, resulting in smaller reactor systems and containment and a more efficient steam cycle. There are some penalties involved, and optimum conditions depend on reaching the best compromise current technology will permit.

Advances are being made in fuel technology, particularly in the direction of designing fuel capable of withstanding step changes in power generation which occur when a fuel bundle is moved along a fuel channel. These advances eventually will permit increases in fuel rating, at least insofar as the fuel itself is concerned.

Higher steam temperature has an appeal that is not wholly based on economics. While higher steam pressure should provide an unquestioned benefit, in the CANDU system as represented by Bruce a virtually constant cost of power exists with increasing steam pressure, at least up to 1000 psig. The savings in reduced equipment size and in fuel consumption brought about by the higher efficiency are balanced by the effect of the thicker pressure tubes required to withstand the coolant pressure and by the greater capital cost of higher pressure equipment. The best overall conditions must be selected.

In the CANDU reactor the steam can be produced over a range of pressures, to meet specific turbine needs. This can be done with little effect on the cost, as noted immediately above.

7. ALTERNATE COOLANTS

While the CANDU reactor cooled with pressurized heavy water is expected to remain competitive for many years, AECL has carried out studies of a variety of coolants other than heavy water. It was concluded that in the longer term improvements in the CANDU family could best be achieved through the use of boiling light water or organics as the coolant. The use of boiling light water is expected to reduce capital costs through a shorter construction schedule and some reduction in the number of systems and components. The use of organics is also expected to reduce capital costs: additionally it will reduce radiation fields in the region of the heat transport system, thereby improving maintainability and consequently availability. The use of either coolant will reduce heavy water upkeep costs.

7.1 Boiling Light Water Coolant

Work on this coolant has progressed to the stage of operation of a prototype plant at Gentilly.

Gentilly is the world's first power reactor to use natural uranium as fuel and natural water as coolant. This plant was approved in September 1966 and criticality was achieved in November 1970, fifty months later. Full power of 250 MW was reached in May 1972. As of September 1, the plant has operated for 119 effective full power days.

This type of plant has a positive power coefficient (0.1 mk/% power at 100% power) and this gives rise to two basic concerns: - safety and control. Chemistry, fuel, and fuel handling are also discussed in the sections to follow.

7.1.1 Safety

We are satisfied that this concept can be designed to operate safely. The first line of defence has been to design systems and components that are fail safe, i.e., insert negative reactivity on failure. However, there is a class of accidents which add reactivity if they should occur - these are the loss-of-coolant accidents*. A highly reliable and effective shutdown system is required to cope with this type of accident. Gentilly has two independent shutdown systems. One of the systems is heavy water moderator dump and the other system is injection of soluble neutron absorber into the moderator (70 mk in one second after signal received to initiate).

7.1.2 Control

To date, the control of the plant at 100% power has been quite satisfactory. Immediately upon reaching full power, a three-week demonstration run took place during which a capacity factor of 97% was achieved. No station outages occurred during the run. This performance was repeated in the month of August and a capacity factor of 97% was again achieved. Turbine trip tests and load rejection tests from 75% and 100% power have been completed routinely.

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* Coolant inventory in one circuit of Gentilly represents 23 mk.

A channel in the highest rated region of the core has been refuelled successfully at 95% power. This is a significant operation from the control point of view as a perturbation has been introduced in the core and the zonal control system has been able to cope with it. The maximum change in reactivity during the fuel change was about 1 mk. The response to perturbation of a zone control rod has been measured at various power levels up to 100%. Frequency response tests have also been completed and these will be reported at the IAEA Conference on "Nuclear Power Plant Control and Instrumentation" at Prague, Czechoslovakia in January 1973.

7.1.3 Chemistry

Great care was taken during the commissioning period to ensure that good chemical conditions were maintained in all process systems. A bypass purification system, in the reactor coolant system only, has been adequate to maintain the required chemistry of the coolant. This has proven beneficial in that corrosion and other adverse chemical effects have been minimal; also radiation levels throughout the station have been kept low. Exposures of personnel to radiation have been low, even during maintenance work on components of the coolant system. Operation as a direct cycle plant has been satisfactory. The separation of radio-iodine from the liquid phase and its appearance in the steam phase in the steam drums has been lower than predicted, hence activity release problems associated with failed fuel are not significant. Because of the clean coolant system and good separation of gaseous fission products in the steam drums, it is possible to detect very small fuel failures.

7.1.4 Fuel and Fuel Handling

The fuel in Gentilly is the most highly rated ($\int \lambda d\theta$ = 48 W/cm) of any fuel in operating CANDU stations. As of September 1, only six fuel bundles (out of 3080) have failed. These have all been small defects and the failed fuel bundles have been removed by the fuel handling system. Radiation levels in the coolant system and fuel handling system due to fuel defects have been low. The performance of the on-power fuelling machine has been excellent. Fuel removals and insertions were completed successfully under automatic control by the computer.

7.1.5 Enriched Version

An enriched version of the BLW concept is at present under study. The studies have included fuel cycles using recycled plutonium and U-235. The capital costs are expected to be reduced further; however, the fuelling cost will be higher than for the natural uranium variant.

7.2 Organic Coolant

For the past six years, the WR-1 reactor has been operating successfully at Whiteshell. This is a heavy water moderated, pressure tube, test facility of 40 MW thermal. The reactor uses a mixture of hydrogenated terphenyls (HB-40) as coolant and one of its two circuits has operated routinely at 400^{o}C outlet temperature for the past two years. Satisfactory performance of the coolant at 400^{o}C with regard to both decomposition (estimated to cost 0.1 mill/kWhr in a power station) and fouling has been successfully demonstrated.

For a natural uranium fuelled organic cooled CANDU reactor, there is a need for a fuel with uranium density higher than that of UO_2. Two such fuels, uranium carbide and uranium metal, are being investigated as possible choices for a power reactor system. Full size uranium carbide fuel bundles have been operated in the U-3 loop at Chalk River at 400^{o}C outlet temperature. The highest burnup achieved was 9800 MWd/TeU (bundle average). Because it has the highest possible uranium density, uranium metal is an attractive fuel. Since it is a metal, fabrication costs should be low. One major problem in its use is swelling under irradiation. Experimental fuel irradiations are continuing in WR-1 to develop this fuel.

Considerable work has been done in Canada on the development of zirconium base alloys for pressure tubes for an organic cooled power reactor. Whereas it had formerly appeared that zirconium base alloys could not be used with organics because of hydriding problems it now appears that a zirconium:$2\frac{1}{2}$% niobium alloy is feasible. Experience to date on zirconium base alloy pressure tubes has been the operation of 2 tubes in WR-1 for 5 years. In addition a further 30 tubes have been operating in WR-1 for periods varying from a few months to a few years.

At this time a coolant (HB-40), a fuel (UC), and a pressure tube (Zr:$2\frac{1}{2}$% Nb) can be specified for use under power reactor conditions. A design study is now nearing completion which puts all of this together into a design for a completed power station. If the results of the study are favourable, full consideration will be given to building a prototype.

8. CONCLUSION

The CANDU reactor system is fulfilling expectations. The major effort on the pressurized heavy water cooled version (PHW) has produced a commercial power plant which can be built in unit sizes up to 1200 MW.

The development potential of the CANDU system is already apparent from the experience with the first commercial units and with the boiling light water cooled and organic cooled variants. The versatility of the CANDU system in both unit size and, in particular, choice of fuel (natural or enriched uranium, recycled plutonium and in the longer term thorium) coupled with its high nuclear efficiency indicate a very significant role for this type of reactor for many years to come.

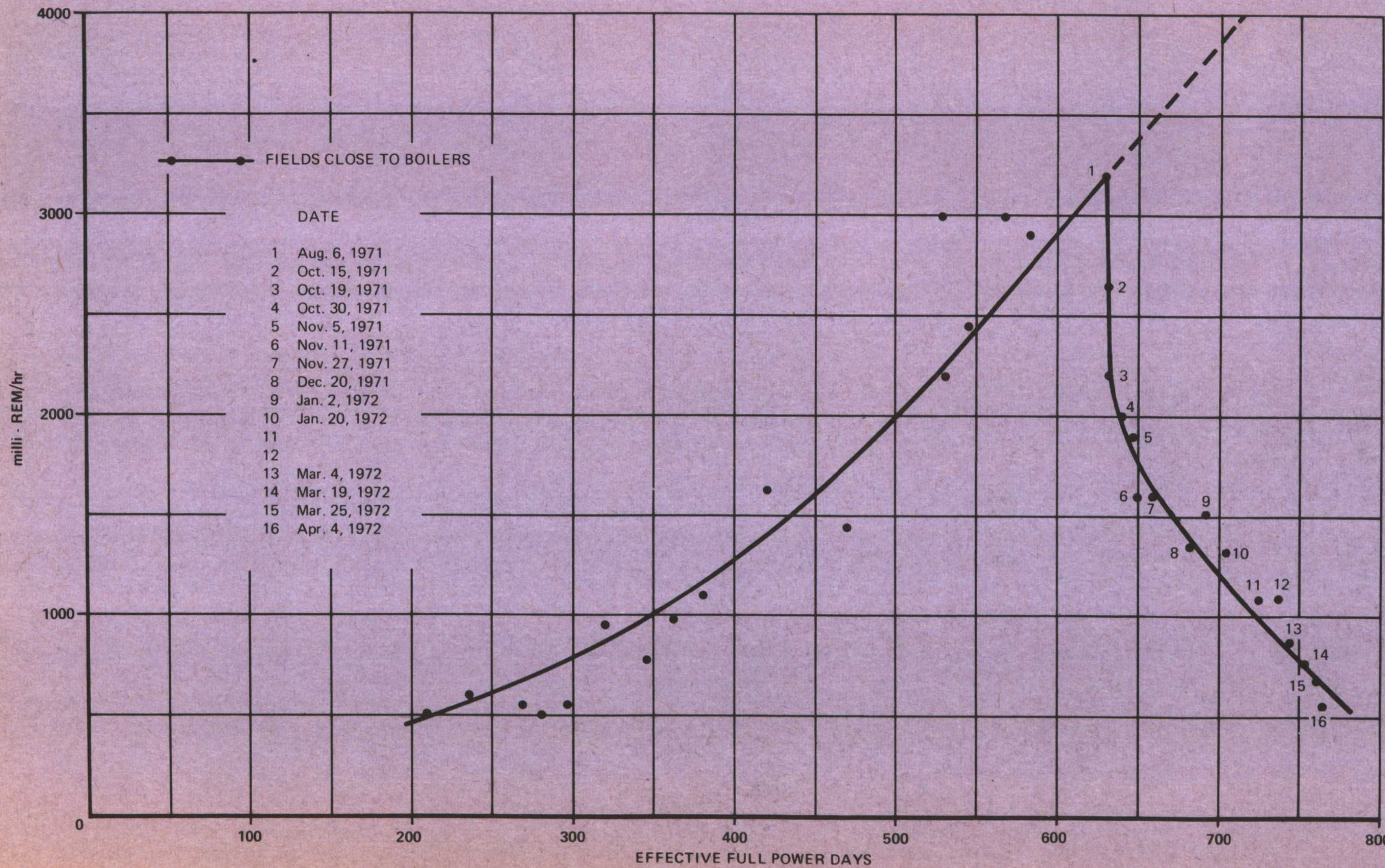

FIGURE 1 DOUGLAS POINT BOILER ROOM RADIATION FIELDS

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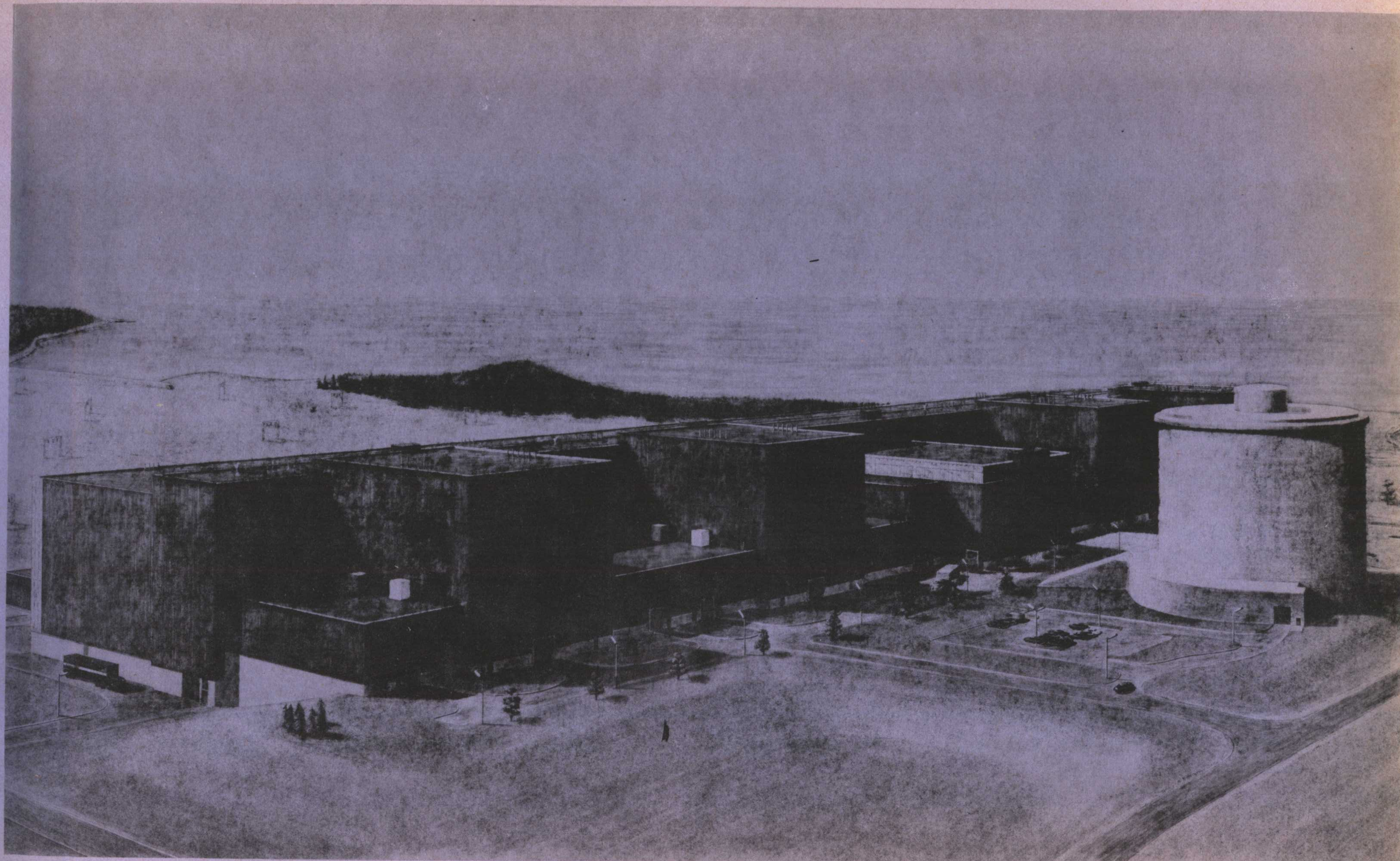

FIGURE 2 BRUCE GENERATING STATION ARTIST'S IMPRESSION

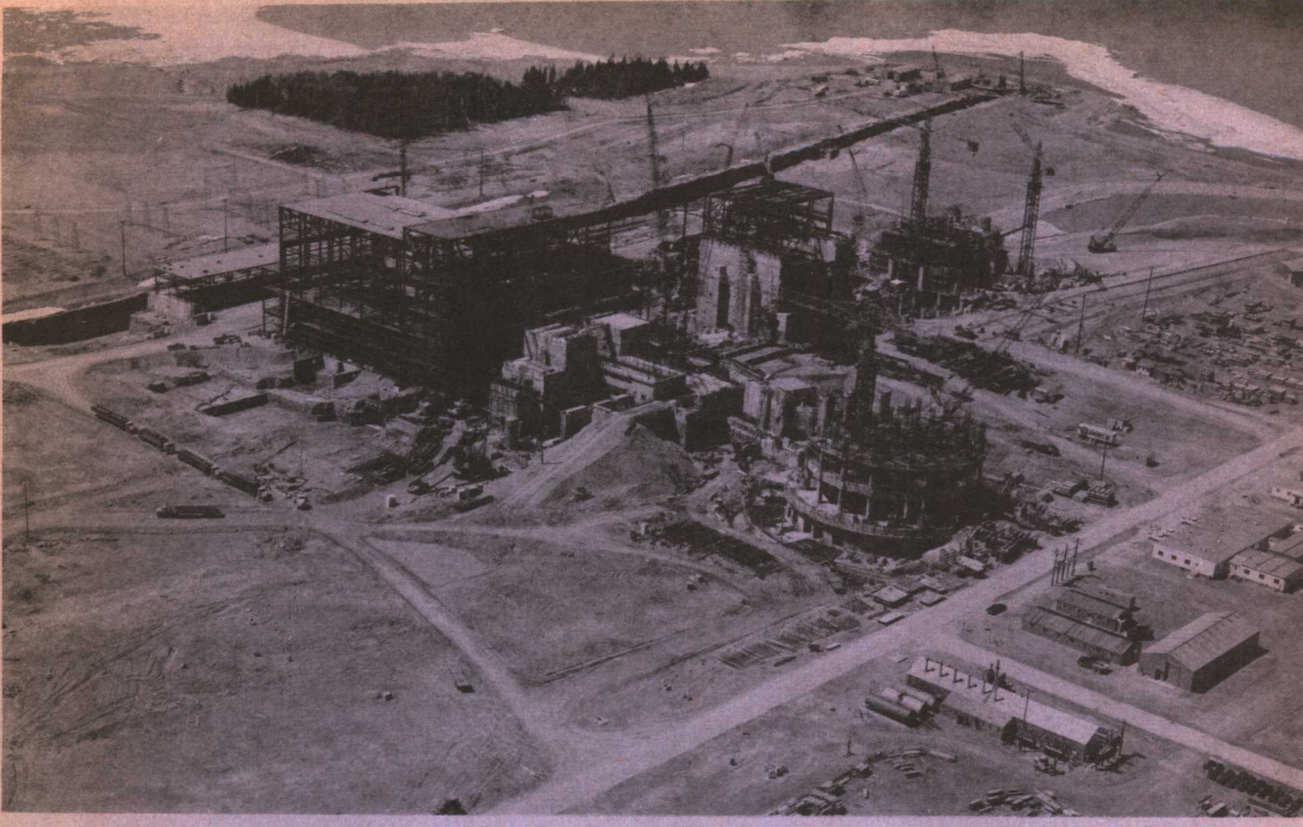

FIGURE 3 BRUCE GENERATING STATION UNDER CONSTRUCTION

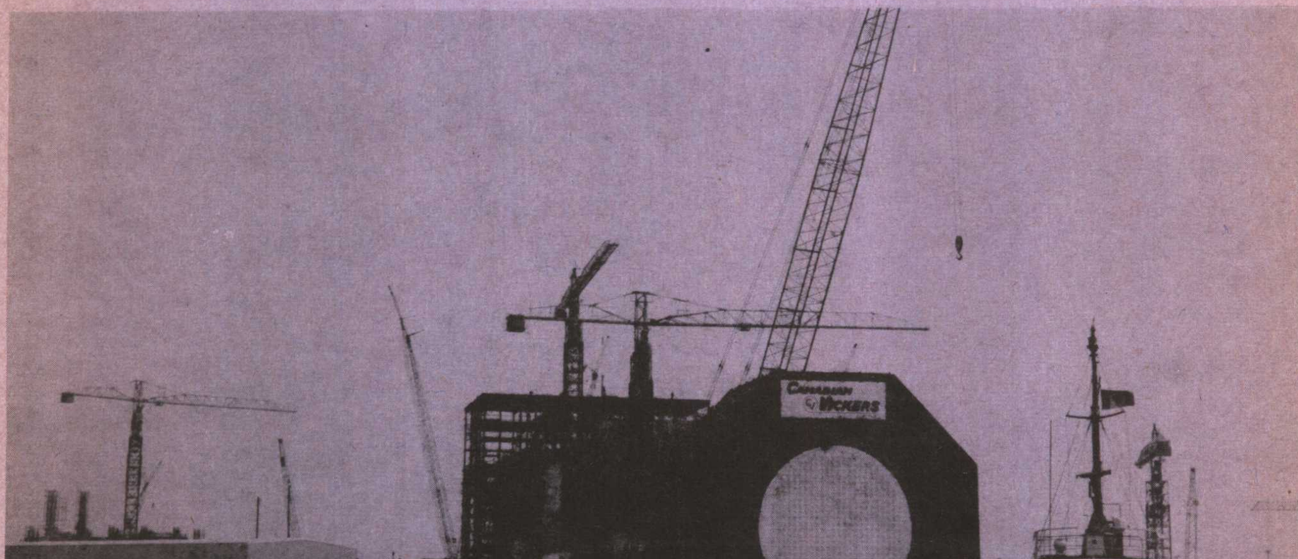

FIGURE 4 BRUCE REACTOR AT SITE