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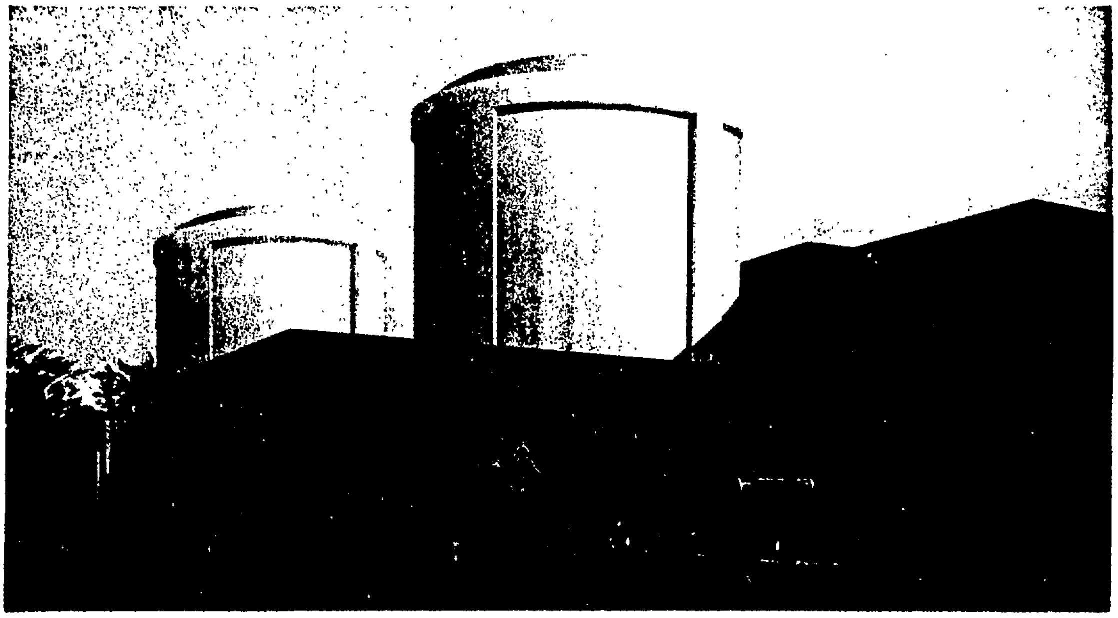
CANDU DEVELOPMENT

by G.L.BROOKS



Presented at the
Canadian Nuclear Association
21st Annual International
Conference, Ottawa, Canada

June 1981

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1. BACKGROUND

In developing the design of the 600 MWe CANDU plants now being constructed, both internationally (Argentina, Korea, Romania) and domestically (Gentilly-2 and Point Lepreau), it was natural that the initial design concepts evolved by Canadian General Electric and the final design evolved by AECL and private-sector consultants should draw heavily on the experience gained by Ontario Hydro and AECL in the design of the multi-unit Pickering-A station. In effect, the 600 MWe CANDU design represents an adaptation of the highly successful Pickering-A design to suit applications where only single or dual units are required, and where a wide variety of siting conditions prevail.

The nominal 600 MWe net unit output enabled the design to compete directly with contemporary 2 loop PWR designs having the same nominal output. Retention of the nominal 500 MWe unit output of the Pickering-A design would have placed the CANDU unit at a significant unit capital cost disadvantage as compared to its 2 loop PWR competitors.

As is well known, Pickering-A was followed in the Ontario Hydro system by the equally successful and somewhat larger Bruce-A station. In addition to its work for Ontario Hydro in designing the nuclear steam supply system for the larger Bruce-A units, AECL carried out a number of design studies and developed preliminary designs for larger CANDU units during the 1970's. These included a 900 MWe preliminary design which was bid to Italy in 1973, a major preliminary engineering program with Ontario Hydro for a 4 x 1250 MWe station from 1974 to the end of 1978, and a conceptual design study for a 2000 MWe CANDU unit from mid-1973 to the end of 1974. The latter study demonstrated that there are no substantial obstacles to extending the basic CANDU pressure tube concept to at least the 2000 MWe unit size range.

AECL has initiated a major program to develop a larger-sized CANDU design which would complement the 600 MWe design in the world marketplace. The remainder of this paper describes the design which has been evolved and the basic reasoning which led to the design.

2. MARKET CONSIDERATIONS AND THEIR INFLUENCE ON BASIC DESIGN APPROACH

2.1 General

It is, of course, obvious that a design intended for the world marketplace should be suitable, with minimum modification, to as many potential customer applications as is practicable. At the same time the design must be as "proven" as possible to minimize risks, both to the seller and to the buyer. Direct adoption of the latest Ontario Hydro station designs (Bruce-B/Darlington) would obviously well suit the latter consideration. Unfortunately, it would not well suit the former consideration since the designs of these stations have been carefully tailored to optimally suit the particular circumstances prevalent in Ontario.

It was therefore concluded that the correct approach was to develop a design which would have wide potential applicability in the world marketplace while at the same time drawing on the proven features of the CANDU stations in operation or under construction. Innovation was to be avoided except where necessary to ensure economic, reliable, safe operation and licensability.

The remainder of this Section outlines specific considerations which have led to the adopted basic design approach.

2.2 Unit Size

During recent years, there has been a substantial shift in the world market towards larger-sized nuclear units. This trend is shown in Table 1 by comparing the size range of operating (and hence earlier ordered) units with later ordered units. In the export market (excluding domestic sales by NSSS vendors), a study of the "World List of Nuclear Power Plants", Nuclear News, February 1981, clearly shows that recent export sales predominate in the 900-1000 MWe size range. This is, of course, not surprising as it is the general range of available output from 3 loop PWR's and their BWR direct competitors.

Even larger reactors (1200-1300 MWe) are under construction or in operation in certain technologically advanced countries but these are of domestic origin in almost all cases, i.e., a significant export market has not yet developed in this size range. It is considered likely that the export potential for such large units will remain limited for some time because of utility/electrical grid size limitations in most potential export market countries.

We in AECL therefore concluded that a new export CANDU design should be aimed at the 900-1000 MWe unit size market and that we should aim for the upper end of this size range to minimize unit capital cost ($/MWe), thereby increasing the marketability of our design. This particular parameter is recognized to be of major significance to most potential customers.

Having established this unit size target, we reviewed the suitability of the largest existing CANDU reactor core design. This is the 480 fuel channel design utilized in Ontario Hydro's Bruce and Darlington reactors. While capable of providing net unit outputs of about 850 MWe in Ontario where condenser cooling water

TABLE 1

SIZE RANGES OF NUCLEAR STATIONS IN OPERATION UNDER CONSTRUCTION OR ON ORDER

North America

	U.S.A.			CANADA	
	LWR 400-800 Series	LWR 800-950 Series	LWR 950-1200 Series	Ontario Hydro	CANDU 600
Operating	34	20	15	9	
Under Construction	2	8	55	12	2
On Order	1	6	23		

Rest of World excluding North America and Eastern Block

	LWR 400-800 Series	LWR 800-950 Series	LWR 950-1200 Series	CANDU 600
Operating	26	24	7	
Under Construction	10	34	16	3
On Order	3	20	32	

temperatures are low, the unit output available from this reactor core would be reduced significantly in countries where available condenser cooling water temperatures are relatively high. The lower unit output would put this reactor at a serious unit capital cost disadvantage as compared to LWR's in the 900-1000 MWe size range. This results from the fact that the total capital cost of nuclear power plants does not vary in direct proportion to plant output since many cost factors are essentially independent of size over the range of interest.

We therefore concluded that a larger core would be essential. Studies showed that a 600 channel core could be accommodated within the basic Bruce/Darlington reactor configuration and without introducing feasibility questions. This core size will be capable of producing in excess of 950 MWe even with high condenser cooling water temperatures. As a result, the unit size will be at the upper end of the 900-1000 MWe size range, leading to the most favourable relative unit capital costs. This size also provides some margin to cover possible future "stretching" of unit output as a result of our continuing R and D program.

2.3 Cooling Water Sources

Whereas Ontario Hydro has been able to locate its nuclear plants where there is a plentiful supply of relatively low temperature, fresh cooling water, many potential international sites are located in coastal areas where seawater at relatively high temperatures is the only available cooling water source. In addition, significant tidal ranges must be accommodated. The Wolsung site in Korea, where we are building a 600 MWe unit, is fairly typical although even higher seawater temperatures will be encountered with tropical sites.

As a reference cooling water design basis for the Nuclear Steam Supply System (NSSS), we have assumed a seawater source at a maximum temperature of 32°C.

2.4 Codes and Standards

While, under the auspices of the International Atomic Energy Agency (IAEA) and the International Standards Organization (ISO), significant progress has been made towards the establishment of international nuclear power plant safety standards, much work remains to be done. In lieu of such complete standards, most customer countries rely substantially on the established standards in the NSSS supplier country to augment the IAEA and ISO standards. We have therefore adopted the basic approach that the design must satisfy both current AECB safety requirements as well as those of the IAEA and ISO. The latter represents additional requirements since these international standards are not currently applied to Canadian domestic plant designs.

2.5 Basic Plant Configuration

While the current Ontario Hydro stations are designed as integrated 4-unit plants, most international customers purchase either single or dual unit plants. The 600 MWe design caters for this established customer preference as will the new design.

2.6 Seismic Capability

Many potential international sites are located in regions of relatively high seismic activity as compared to those sites available to Ontario Hydro. For example, a reference horizontal ground motion acceleration of upwards to 0.3g is required to suit available sites in a number of potential customer countries, whereas the Ontario Hydro plant designs need only accommodate values in the range of 0.05 to 0.08g. A design spectrum based on 0.3g and relatively unfavourable site foundation conditions has been adopted to ensure suitability to a wide variety of potential sites.

2.7 Electrical Grid Considerations

In comparison to the large, well integrated Ontario Hydro electrical grid, the existing grids of many potential customer utilities are relatively small and hence insecure. As a result, the plant design must cater for a significantly higher probability of loss of grid connection during severe transients and postulated accident conditions.

2.8 Design Standardization

It is axiomatic that most, if not all, potential customers wish to purchase plants of fully proven design but which, at the same time, employ the latest in technology (particularly in safety features) and which are tailored to their specific needs. This is somewhat analogous to the case of a company which wishes to hire a 35 year old executive with 20 years of experience in the company's specific line of business. Some compromise is clearly essential since no existing CANDU plant design can meet all of the foregoing market considerations. We have adopted an approach of using proven "building blocks" as a basis for the new design. These building blocks have been drawn from both the Ontario Hydro plant designs and from the 600 MWe plant designs. In this way we have been able to benefit substantially from design standardization while at the same time catering for the basic world market requirements.

3. DESIGN DESCRIPTION

3.1 General

This Section describes the main features of the Nuclear Steam Plant design which has been evolved to satisfy the basic market requirements discussed in the previous Section. While we refer to the design as the 950 MWe CANDU, the actual net power output capability will be somewhat in excess of this, the exact value being dependent on cooling water source temperature and the choice of matching turbine-generator for a specific application. Major station parameters are summarized in Table 2.

TABLE 2

950 MW(e) N.G.S.

MAJOR NSSS PARAMETERS

Total Heat Transferred to Steam Generators = 3258 MW(th)

Total Number of Channels = 600

Number of Fuel Bundles per Channel = 12

Maximum Channel Power = 6.5 MW(th)

Radial Form Factor = 0.83

Maximum Channel Flow = 210,000 lb/hr

Outlet Header Temperature = 590°F

Outlet Header Pressure = 1450 psia

Outlet Header Quality = 1%

Number of Steam Generators = 8

Steam Generator Area = 33000 ft^2

Number of P.H.T. Pumps = 4

Steam Temperature = 735 (psig) saturated

Steam Flow = 12.6×10^6 lb/hr

3.2 Reactor Design

The design of the reactor proper, as shown in Figure 1, is based closely on the design employed for the Bruce/Darlington reactors of Ontario Hydro. It incorporates a horizontally-oriented austenitic stainless steel calandria located within a water-filled shield tank. Bruce/Darlington type water-cooled, ball filled calandria end shields are utilized. The calandria diameter has been increased to 9.3 m from 8.5 m to accommodate the 600 fuel channels (as compared to 480 fuel channels in the smaller Bruce/Darlington units). The calandria internal length of 6 m is retained.

The fuel channels, as shown in Figure 2, are of the Pickering/600MWe type which provides a lower coolant pressure drop than does the Bruce/Darlington fuel channel design. Bruce/Darlington type fuel channel closure plugs are utilized since Bruce-A experience has shown this design to be simpler to produce.

Reactivity control in the CANDU-950 reactor is achieved by the basic on-power refuelling program, and through use of dissolved moderator poison and reactivity control devices which have been thoroughly proven in previous CANDU stations. The number of these devices has been increased to provide effective regional power control in the somewhat larger reactor core.

Most of the in-core reactivity control devices are vertically oriented. These include all of the reactor regulating mechanisms (liquid zone controllers, solid adjuster rods and mechanical control absorbers) plus vertical in-core flux detector assemblies and the shut-off rods of shutdown system No. 1.

The remaining reactivity control devices enter the core from one side and are used exclusively for shutdown system No. 2. Thus the shutdown system No. 2 liquid poison injection nozzles and associated in-core flux detectors are spatially separated from regulating system devices and the in-core components of shutdown system No. 1.

Two reactivity mechanism decks support the reactivity control devices and their service and instrument connections. The main deck forms the top of the shield tank extension, set into the calandria vault roof and supports the vertical reactivity control devices. A second shielded deck is provided to form one side wall of the shield tank. This deck supports the horizontal reactivity control devices. The shielding of both decks is sufficient to permit on-power maintenance access to the reactivity control mechanisms.

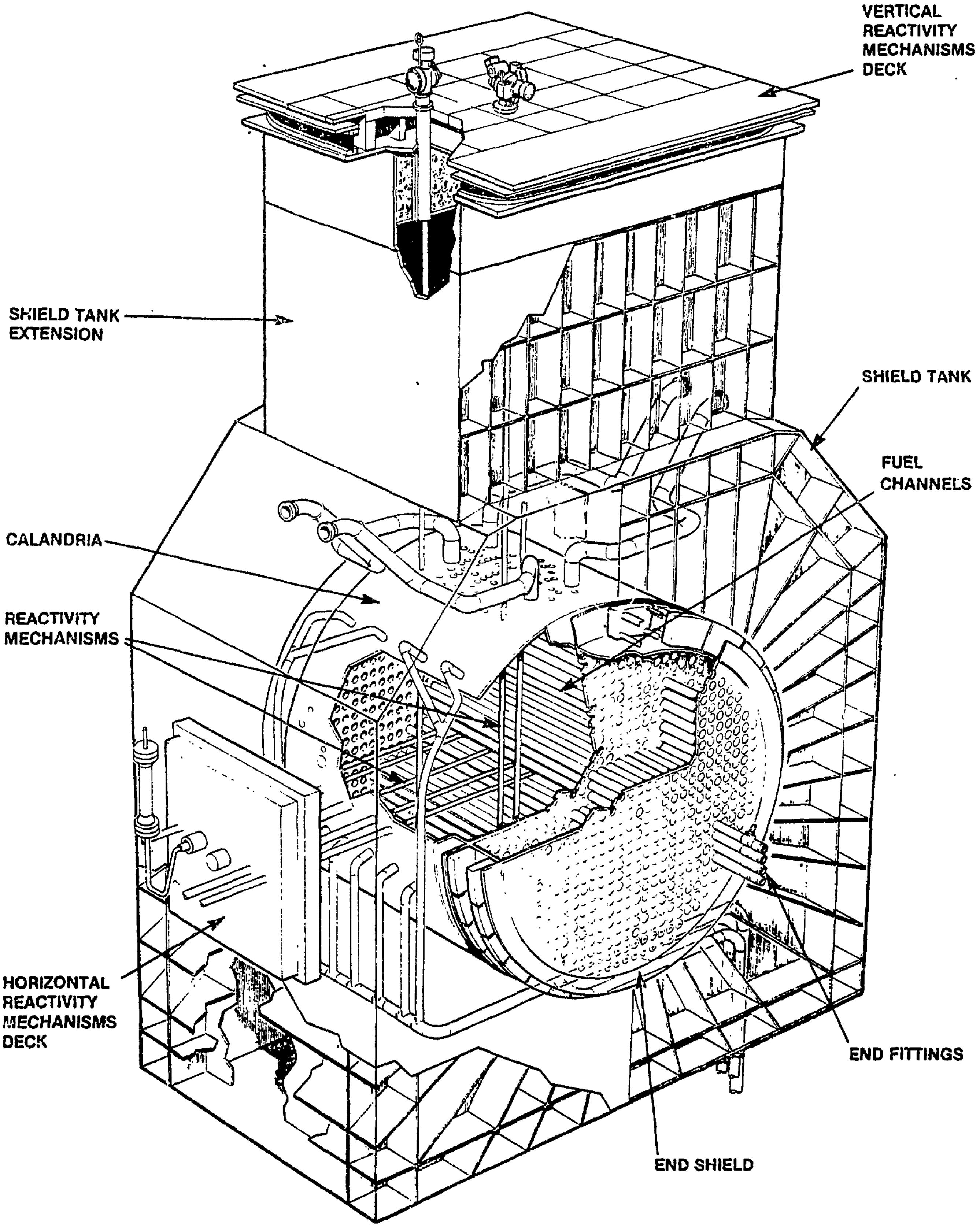

FIGURE 1 CALANDRIA AND SHIELD TANK ASSEMBLY

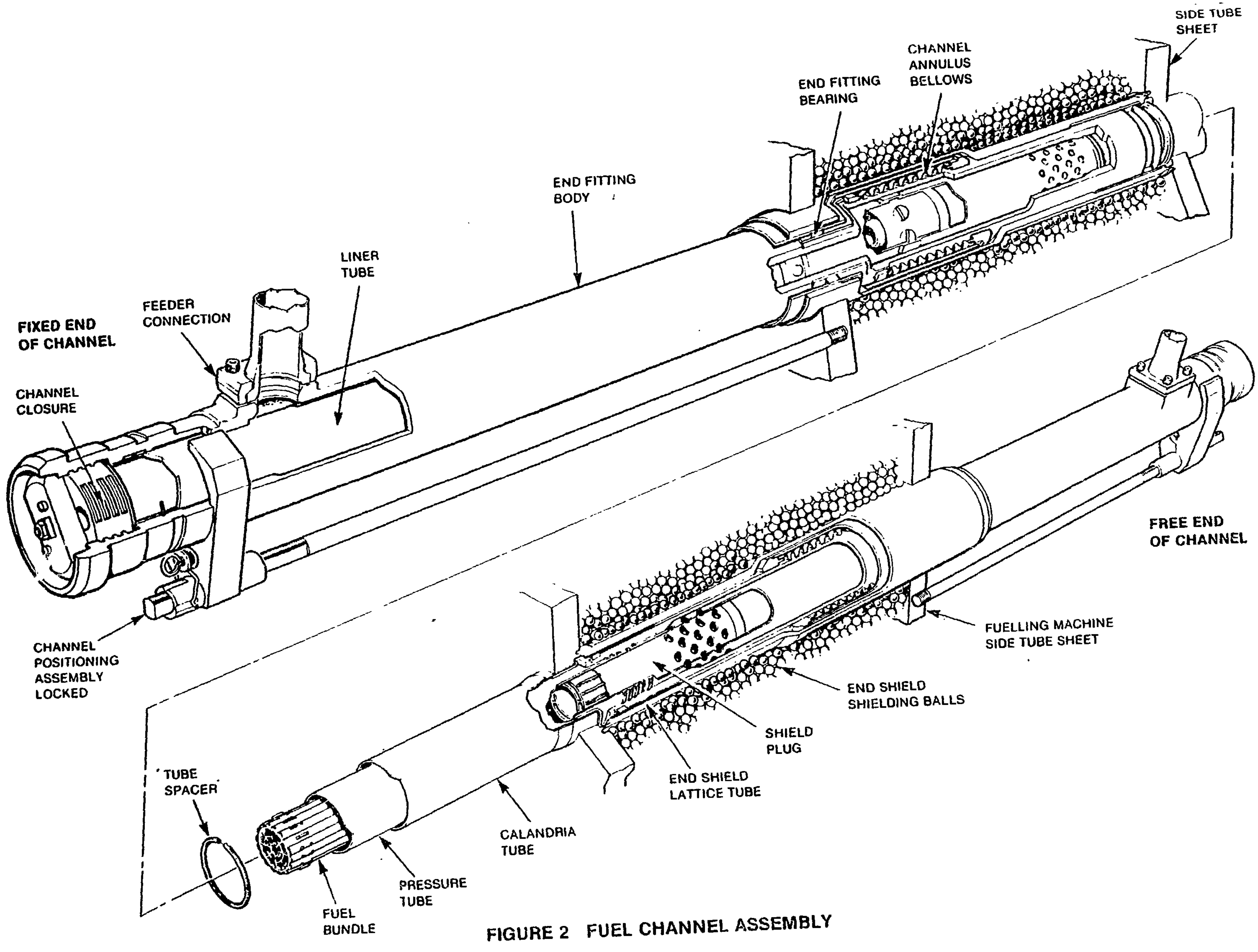

FIGURE 2 FUEL CHANNEL ASSEMBLY

3.3 Moderator System

The moderator system design is basically the same as that used for both the Bruce/Darlington reactors and the 600 MWe reactors, but with a proportionately increased capacity to suit the larger reactor size. The system also includes provision to allow moderator heat to be used for feedwater heating, thus improving station efficiency. The basic flowsheet is shown in Figure 3.

Heavy water is circulated through the calandria to remove heat induced in the moderator by neutron moderation and gamma absorption and heat transferred from the fuel channels. The moderator system also provides a backup heat sink in the very unlikely event of a loss of coolant accident coinciding with a failure of emergency core cooling. This inherent design feature is an important safety advantage of the CANDU system.

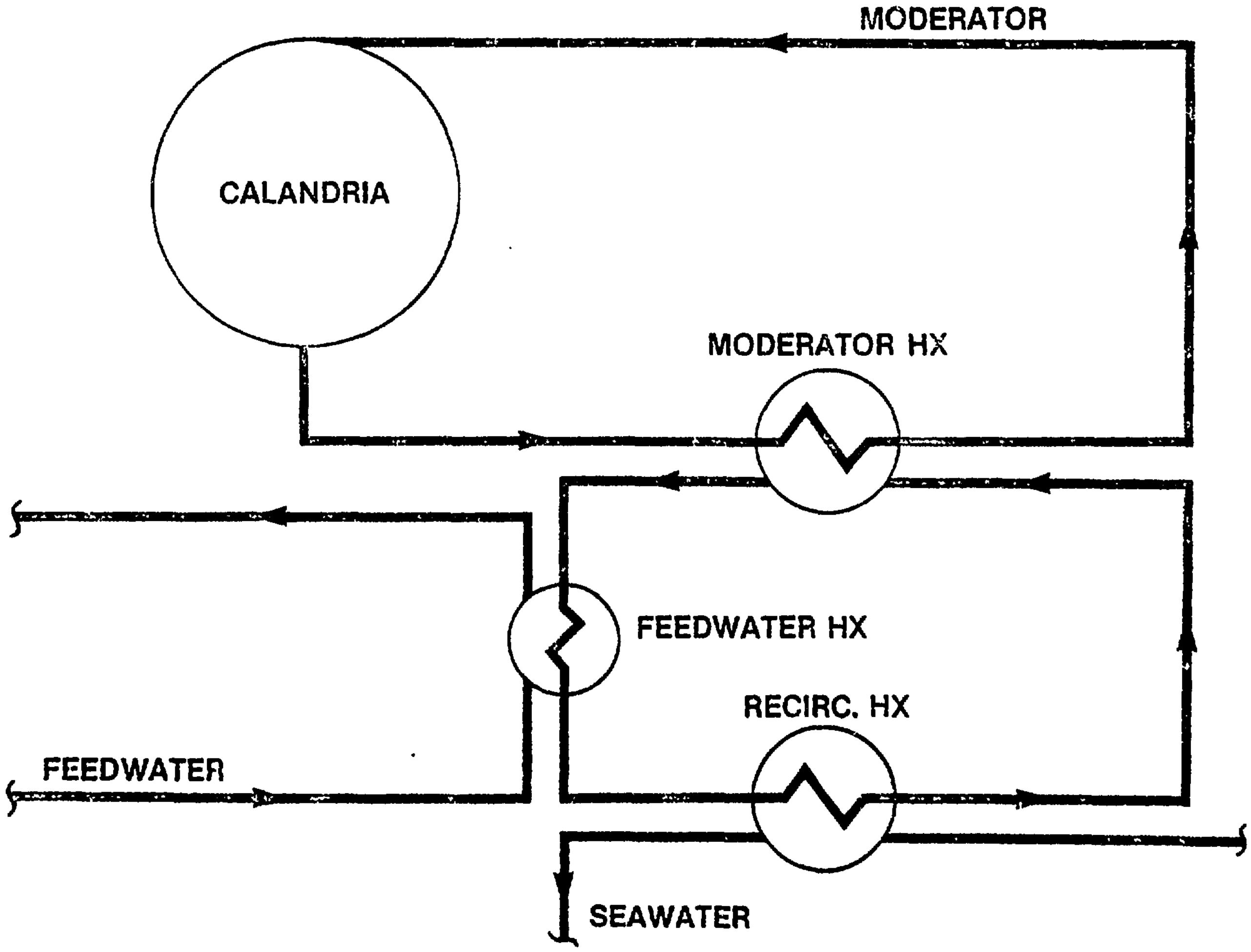

FIGURE 3 MODERATOR HEAT RECOVERY

Two 100 per cent capacity pump/motor sets, connected in parallel, circulate the moderator through two 50 per cent capacity heat exchangers, also connected in parallel. This arrangement allows either pump to be operated with both of the heat exchangers at full reactor power.

The moderator pumps are driven by induction motors from the main station service (Class IV) power supply. Each pump set also has a pony motor capable of driving the pump at one-third speed; these motors are connected to the diesel-backed standby (Class III) electrical power supply. In the event of a failure of the normal (Class IV) supply, one of the pony motors starts automatically to drive its pump at one-third speed and thus ensures that adequate moderator circulation is continued with the reactor shut down.

The moderator is also circulated through a purification system, containing six ion exchange columns, a heat exchanger, a filter and a strainer. This system maintains the purity of the heavy water moderator to minimize radiolysis, which could result in a buildup of deuterium and oxygen in the helium cover gas. Soluble reactivity poisons which are added to the moderator under certain circumstances (boron and gadolinium) are also removed as required by the ion exchange columns.

3.4 Fuel Handling System

The basic dedicated on-power fuel handling system developed for the Pickering and 600 MWe reactors has been adopted (as compared to the shared system developed for the multi-unit Bruce/Darlington stations) since the design must be suitable for single-unit stations.

t the outset, a detailed study of the throughput capability of xisting fuelling machine head designs was carried out, based on he extensive operating experience gained with the Pickering and ruce designs. This study showed that neither existing design ad sufficient capability to handle the larger 600 channel reactor ore. It was therefore decided that a new head design was ssential but that this new design could be closely based on roven components to minimize development time and risks. The uelling machine head is shown in Figure 4.

e ancestry of the various major fuelling machine head components s as follows:

snout - Bruce/Darlington
separators - Pickering/600 MWe
magazine - Bruce/Darlington
ram - Douglas Point
drives - electric as in Bruce/Darlington

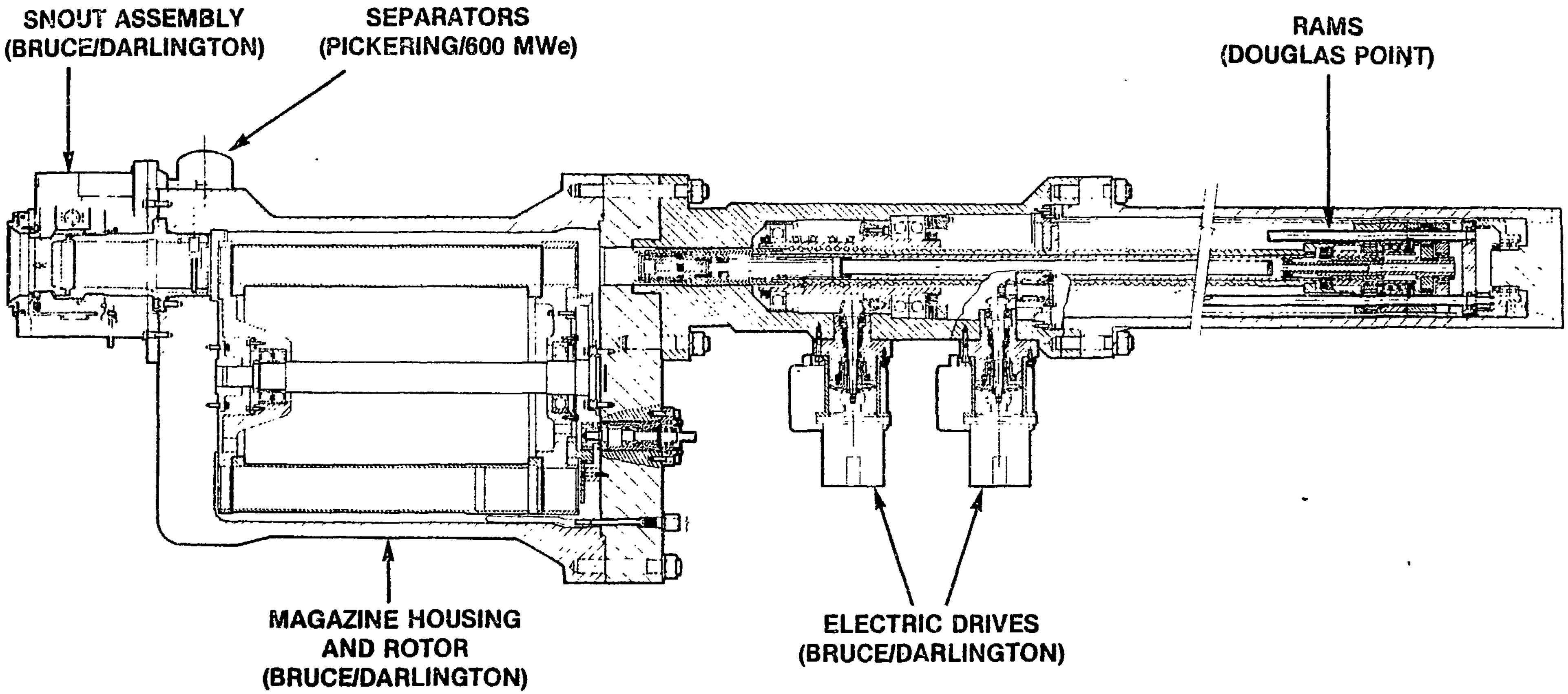

FIGURE 4 FUELLING MACHINE HEAD

The fuelling machine carriage and bridge design is based on the Pickering model, modified to suit the larger diameter reactor and higher seismic design requirements.

3.5 Primary Heat Transport System

The main heat transport system circulates the pressurized heavy water coolant through the 600 reactor fuel channels and transfers the heat to eight steam generators. The system, as shown in Figure 5, is arranged in two circuits, each containing two pumps, four steam generators, and two reactor inlet and two reactor outlet headers. Each circuit has 300 inlet and 300 outlet feeders connecting to the fuel channels.

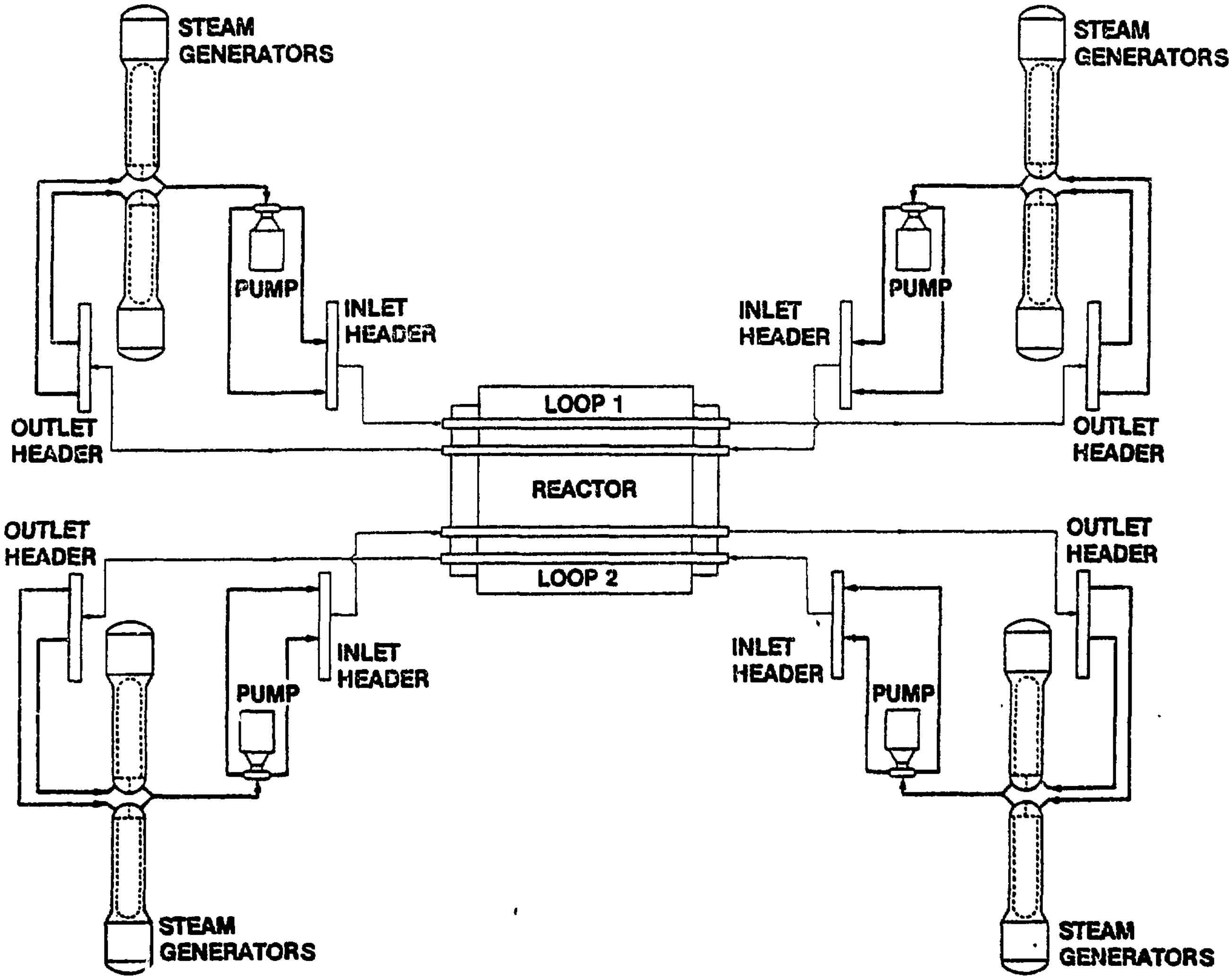

FIGURE 5 PRIMARY HEAT TRANSPORT SYSTEM

As in the case of the Pickering and 600 MWe designs, each of the two circuits forms a "figure of 8" which provides a two-directional flow through the core, so that flow is in opposite directions in adjacent channels. The maximum coolant flow in the channels at full power is at 26.5 kg/s. Heavy water enters each reactor outlet header at 310°C and exits at a quality of 1 per cent D_2O steam by weight.

The steam generators for the CANDU 950 have an overall height of 20 m and an approximate weight (empty) of 180 Mg. The 2500 inverted U-tubes in each generator are made of Incoloy 800.

The use of eight steam generators parallels basic Bruce practice (although the common cross-drums are not used). Consideration was given to the use of four generators as in the Darlington case. This would have necessitated each generator being even larger than those for Darlington. The decision to adopt eight generators was based on conservatism, in terms of manufacturing, and on consideration of potential transport limitation with inland sites.

The four heat transport pumps are rated at 266°C for a flow of 3400 kg/s with a nominal pump head of 245 m. The vertical, totally enclosed, air-water cooled induction motors have a rated capacity of 11.8 MW for a normal operating load of 9 MW.

While these pump/motor units are somewhat larger than those employed in the Bruce/Darlington design, the decision to retain a 4 pump configuration as compared to the alternative of 4 sets of 2 parallelled pumps was taken to avoid inherent complexities with the latter. These complexities would arise in starting parallelled pump pairs and in operation with one of the two pumps in a pair shut down.

3.6 Station Control

In common with recent CANDU station designs, all major control loops are implemented by direct digital computer control, utilizing two computer systems in a redundant configuration that achieves an availability of better than 99.8%.

For the CANDU-950, this basic configuration is retained for the major station control loops. These major control loops cover overall plant control, including boiler pressure control and unit power regulation, the reactor regulating system, primary heat transport pressure and inventory control, moderator temperature control, boiler level control, on-power fuelling machine control, and turbine runup.

To provide for greater flexibility in computer usage, three additional computers have been added to relieve the main control computers of peripheral functions such as information display control. This expanded capacity is used to enhance the already advanced colour graphics and alarm annunciation systems. It also increases the system's flexibility to deal with the larger plant and apply digital techniques to systems formerly using analog controllers.

The annunciation and display systems use the computers to log all alarms on printers and indicate only a priority-sequenced subset of faulted or abnormal conditions to the operator. This is done via colour CRT displays, by annunciation windows (for major conditions only), and by audible alarms that cease when acknowledged.

The various plant systems are segregated, each with its own CRT and standardized console for operator-computer communication. The CRT graphics options include graphical trends, bar charts, and alphanumeric or pictorial display.

The success of this approach to annunciation and data display in earlier stations has now led to its introduction in safety systems. The first such system is presently being installed at the Bruce Station, and an enhanced version is being designed for the CANDU-950.

3.7 Shutdown Systems

As in the case of Bruce-A and all later CANDU units, each of the two shutdown systems is designed to be fully effective in terms of trip parameter sensing ability and reactivity insertion rate and depth. Since both systems are highly reliable (unavailability better than 10^{-3} yr/yr), and since their reactivity mechanisms are diverse, complete failure to shut down when needed can be considered as incredible.

The shutdown systems each monitor seven process variables and two neutronic variables. The fast in-core flux detectors permit high-resolution protection of the fuel for both normal and abnormal flux shapes. Loss of heat sink type accidents are detected by the shutdown systems in time to provide at least 30 minutes of operator action time to bring in an alternate heat sink. In the case of a loss of coolant, the shutdown system action is automatically followed by high-pressure coolant injection by the emergency core cooling system.

3.8 Emergency Core Cooling System

The ECC system design follows that developed for the single-unit 600 MWe stations. In the unlikely event of a loss of coolant accident, emergency core cooling is triggered when the heat transport system pressure drops to 5.5 MPa(g). Valves operate between the two heat transport circuits to isolate them from each other. Emergency coolant is supplied to the heat transport system in three successive stages. At first, high pressure gas is used to inject water into the core from water tanks located outside the reactor building. The intermediate stage uses water from a reserved portion of the reactor building dousing tank, using emergency core cooling pumps which feed the water at intermediate pressure to the heat transport system. In the final, long-term stage, the same pumps recirculate the water which has accumulated in the reactor building sump, passing the water through three 50 per cent capacity dedicated heat exchangers back into the reactor. The two 100 per cent capacity emergency core cooling pumps are supplied from the Class III electrical system.

3.9 Containment System

The containment system is designed to limit radioactive releases to acceptable levels if a release should occur from the nuclear steam supply system. The containment system includes the following elements which are based on the design of the 600 MWe units:

- a pre-stressed, post-tensioned concrete building with an epoxy liner;
- extensions to the building including piping, isolating valves, etc.;
- two independent gravity-fed dousing systems;
- two independent containment isolating systems.

3.10 Electrical Systems

Two separate groups of Class III standby power supplies are provided. One supply is for process loads, the other one is for safety-related loads. The latter group is seismically qualified. A 100 per cent supply redundancy is maintained for motor driven auxiliaries. In each group non-interruptible a.c. (Class II) and d.c. (Class I) power supplies are also provided via solid state inverters and batteries to assure essential supply continuity during the startup period of the standby generators. Control and instrumentation power supplies from Class II and I sources are triplicated. These include supplies for reactor safety and regulation instrumentation.

3.11 General Plant Layout

The only substantial layout deviation from past practice for single unit CANDU stations involves the service building configuration. As is shown in Figure 6, the basically square service building surrounds the reactor containment building and is located on a common foundation mat with the latter. This large-area foundation mat reduces the magnitude of the building response spectra to earthquake vibrational inputs, permitting the unit to be located on high seismic activity sites having relatively poor underlying soil or rock conditions.

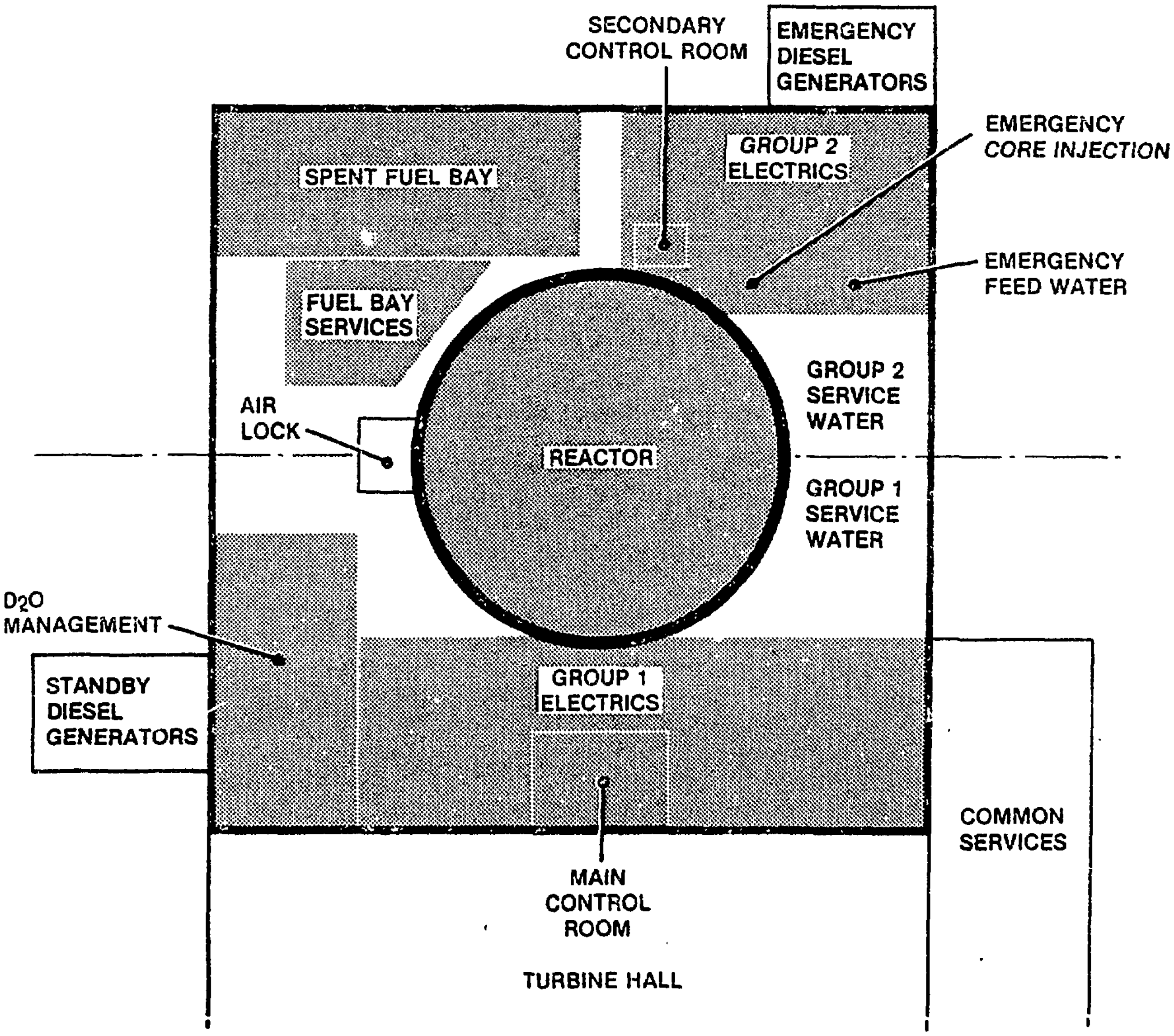

FIGURE 6 SERVICE BUILDING LAYOUT

Advantage has been taken of this change in service building configuration to improve internal layout in terms of separation between process and safety-related systems and components.

4. COSTS

In order to provide a benchmark for comparative purposes, AECL commissioned studies by two large American architect engineering firms of current capital costs of PWR stations in the 900 MWe size range. Based on these studies and on estimates for the CANDU-950, we have concluded that the CANDU-950 will, indeed, prove to be very competitive in terms of total power generation cost.

5. CONSTRUCTION

In evolving the design of the CANDU-950, close attention has been paid to plant construction considerations in order to minimize both field construction costs and schedule. AECL has commissioned Nuclear Construction Managers (NCM) to review the design from these aspects. This company is providing construction management for the Wolsung-I and Cernavoda projects. Ontario Hydro is participating in a separate review of the layout and constructability of the CANDU-950 design to ensure that experience gained in the construction of the Pickering A and B and the Bruce A and B plants is fully utilized.

6. SUMMARY

With the development of the new CANDU-950 design, the Canadian nuclear industry is now able to compete in the international marketplace in this larger unit size range. The design retains the outstanding proven advantages of the CANDU system, in particular its lower fuelling costs through use of natural uranium fuel, and its high plant availability through use of on-power refuelling and other superior features. While the design offers international customers the economic advantages of a larger-sized unit, well proven basic component and system designs have been retained to ensure that the CANDU-950 will prove to be a highly reliable source of electrical energy in the tradition of its predecessor CANDU plants. As in the case of the 600 MWe design, the CANDU-950 utilizes components which are well suited to eventual manufacture in industrially developing countries.