Chapter 8 Process Design and Optimization

8.1 Introduction

[Reference PON78]

The CANDU design had its beginnings in the early 1950's with preliminary engineering studies on a 20 MW(e) and a 200 MW(e) plant. These studies eventually culminated in commitments to the Construction of NPD and Douglas Point. The 1960's resulted in the operation of NPD in 1962 and Douglas Point in 1966. At the same time, commitments to construct Pickering were made in 1964 and for Bruce in 1969. The 1970's have witnessed the excellent operating performance of Pickering and Bruce and the commitments to construct Gentilly-2, Cordoba, Pt. Lepreau, Wolsung, Pickering B, Bruce B and Darlington.

In most cases, successive plants have meant an increase in plant output. Evolutionary developments have been made to fit the requirement of higher ratings and sizes, new regulations, better reliability and maintainability, and lower costs. These evolutionary changes have been introduced in the course of engineering parallel reactor projects with overlapping construction schedules - circumstances which provide close contact with the practical realities of economics, manufacturing functions, construction activities, and performance in commissioning. Features for one project furnished alternative concepts for other plants on the drawing board at that time, and the experience gained in first application yielded a sound basis for re-use in succeeding projects. Thus the experience gained in NPD, Douglas Point, Gentilly-1 and KANUPP have contributed to Pickering and Bruce. In turn, all of these plants have contributed to the design of Gentilly-2.[1] The evolutionary changes that have taken place are discussed below.

8.2 Primary Heat Transport System

There has been a continuing quest for higher reliability, better maintainability of equipment, and a reduction of radiation dose to operating staff. This is manifested in the dramatic reduction in the number of components. For example, NPD had approximately 100 valves per MW in the nuclear steam supply system. This has been reduced to less than 1 valve per MW in the Bruce, Gentilly-2 and Darlington designs. The number of steam generators have gone from 12 in Pickering to 8 in Bruce to 4 in Gentilly-2 and Darlington. Table 8.1 summarizes the evolution.

All materials in the heat transport circuit are now being specified for very low levels of cobalt in order to keep radiation fields to a minimum.

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[1] Gentilly-2 is the first of the CANDU designs, others are Lepreau, Cordoba and Wolsung

Table 8.1 PHT evolution

	NPD 1962	DOUGLAS POINT 1967	PICKERING 1971	BRUCE 1976	GENTILLY 1981	950 MW 1987
Output (MWe)	22	210	515	750	630	1030
No. of Fuel Channels	132	306	390	480	380	600
Heavy Water m^3/MW(t)	0.41	0.17	0.16	0.12	0.1	0.1
Power MW(t)/m	0.16	0.45	0.75	0.9	0.9	0.9
No. of Steam Generators/ MW(e)/SG		80/25	12/45	8/95	4/160	8/125
No. of Pumps/HP		10(8)/800	16(12)/1600	4(4)/12000	4(4)/9000	4(4)/16000
Non Welded Joints	4000	3000	1000	250	200	200
Valves - Packed/Bellows	1500/0	2000/0	175/570	75/500	90/300	90/300

8.3 Steam Generators

Steam generator size has been generally limited by the industrial capability to produce them. We are now down to 4 in the 600 MW(e) Gentilly-2 and Darlington designs. Monel was used as the tubing material for Douglas Point, RAPP, KANUPP and Pickering. This material has been proven to be quite satisfactory for the non-boiling coolant conditions of those plants. Inconel 600 has been used in NPD and in Bruce. This is a more costly material than Monel; however, its corrosion resistance in a boiling environment (as in Bruce) is much superior. We are using Incoloy 800 in all of the 600 MW reactors (Gentilly-2, Pt. Lepreau, Cordoba and Wolsung) as it is about equal in most respects to Inconel 600, has greater resistance to intergranular attack, and is somewhat lower in cost. Table 8.2 gives a more detailed comparison of the features of different steam generators.

8.4 Heat Transport Pumps

Pump-motor sets have remained essentially of the same configuration for all of the CANDU stations, i.e., vertical electric motor driven, centrifugal, volute type casing, one radial guide bearing in the pump with pumped fluid as lubricant, tilting pad type guide and double acting thrust bearing in the motor, and mechanical shaft seals.

Maintainability has been improved with the provision of interchangeable sub-assemblies. The appropriate placement of shielding has permitted the changing of a pump motor on Bruce while the reactor continues to operate at 60-70% power.

There has been a recent trend away from solid rotor flywheels (Douglas Point to Gentilly-2) to additional packages of rotor laminations located just outboard of the main rotor (Pt. Lepreau, Bruce 'B'). This manner of fabrication precludes the requirement for inservice inspection for that component as it is highly unlikely that a defect could grow from one lamination to another.

Regulatory requirements for pumps have grown from very little in the beginning to the present time where the pump pressure boundary is considered in the same way as nuclear pressure vessels (ASME Section III Class I). Consequently, non-destructive examination (NDE) and quality assurance requirements have increased considerably.

A detailed comparison of pump characteristics is given in Tables 8.3 and 8.4.

Table 8.2 Steam generators

	DPNGS	PICKERING A	BRUCE A	GENTILLY-2
Power MW(e)/boiler	2.5	45	95	150
No. of Boilers	80	12	8	4
Tubesheet Diameter	10"/14"	5'-8 1/4"	8'-3 1/8"	9'-1"
Tubesheet Thickness	3 1/8"-4 1/2"	11 1/16"	14 1/4"	15 3/8"
Tube Size OD/Wall	0.496"/0.049"	0.496"/0.049"	0.51"/0.0455"	0.625"/0.0455"
Material	M-400	M-400	I-600	I-800
No. of Tubes	196	2600	4200	3550
Steam Drum Diameter	5' 6"	8'-2 3/8"	11'-8 1/4"	13'-1 3/4"
Shell Thickness	1/2"	1.625"	2.25"	1.943"
Overall Height	32'	46' 7"	50' 10 5/16"	63' 4 1/4"
Overall weight (dry)		185,000 lb	320,000 lb	420,000 lb
Heating Surface Area	11,190 ft^2	20,000 ft^2	26,000 ft^2	34,200 ft^2
Recirculation Ratios	3.71	5.5:1	5.4:1	5:1

Table 8.3 Heat transport pumps

STATION	DOUGLAS POINT	PICKERING	BRUCE A	GENTILLY-2
Pump Type	Vertical Centrifugal Single Stage	Vertical Centrifugal Single Stage	Vertical Centrifugal Single Stage	Vertical Centrifugal Single stage
Head m (ft)	143 (469)	146 (480)	213 (700)	215 (705)
Flow m^3/sec (Igpm)	0.43 (5670)	0.77 (10,100)	3.307 (43,600)	2.23 (29,400)
Power per Pump kw (hp)	600 (800)	1170 (1560)	8250 (11,000)	5250 (7000)
Discharge MPa Pressure (psia)	9.577 @ 249°C (1389 @ 480°F)	9.715 @ 249°C (1409 @ 480°F)	10.625 @ 265°C (1541 @ 509°F)	11.342 @ 266°C (1645 @ 512°F)
Number of Pumps operating per reactor	8	12	4	4
Speed (rpm)	1800	1800	1800	1800

Table 8.4 Heat transport pumps

	DOUGLAS POINT	PICKERING	BRUCE 'A'	GENTILLY-2	POINT LEPREAU	BRUCE 'B'
ASME CODE	Sect.VIII	Sect.VIII	Preliminary Sect.III Cl.1 1969	Sect.III Class 1	Sect.III Class 1	Sect.III Class 1
VOLUME MATERIAL	SA-216-WCB	SA-216-WCB	SA-216-WCB	SA-216-WCC	SA-216-WCC	SA-216-WCC
FLYWHEEL	Solid in Motor	Solid in Motor	Solid in Motor	Solid in Motor	Rotor Laminations	Rotor Laminations
ROTATIONAL INERTIA (lb-ft^2)	7,000	15,000	50,000	30,000	30,000	50,000
SEISMIC CLASSIFICATION	None	None	None	D.B.E. Cat.'A'	D.B.E Cat.'A'	D.B.E. Cat.'A'
PUMP BEARINGS	Hydro-dynamic Carbon	Hydro-dynamic Carbon	Hydro-static D2O Energized	Hydro-static D2O Energized	Hydro-static D2O Energized	Hydro-static D2O Energized
MOTOR BEARINGS	Oil Lubricated Tilting Pad Type	Oil Lubricated Tilting Pad Type	Oil Lubricated Tilting Pad Type	Oil Lubricated Tilting Pad Type	Oil Lubricated Tilting Pad Type	Oil Lubricated Tilting Pad Type

8.5 Reactor Core Design

In 1955, a detailed design of a demonstration natural uranium reactor was initiated. It was called NPD and was based on a vertical pressure vessel concept. In 1957, this was changed to a horizontal pressure tube configuration - a configuration which has remained in succeeding heavy water cooled reactors. The horizontal configuration aided the on-line fuelling scheme by making double-ended fuelling feasible. It also permitted the use of vertical safety control rods which do not interfere with the pressure tubes and feeders.

Evolutionary changes have been in the direction of achieving

a) large increases in core rating with the minimum increase in reactor size (the higher the power density, the lower the capital cost);

b) reduction in shop fabrication costs through simplification.

c) reduction in field assembly through more shop fabrication.

The major impact of higher power densities on capital costs is in the reduction of heavy water inventory. The amount of heavy water in the reactor core per MW produced in the reactor is listed in table 8.5.

Table 8.5 Heavy Water in Core per MW Thermal

	M^3/MWt
NPD	.410
Douglas Point	.169
KANUPP	.182
Pickering A	.157
Bruce A & B	.112
Gentilly-2	.105

Higher power densities require more MW's produced per meter length of fuel channels. Table 8.6 below indicates the achievements to date.

Table 8.6 MW Thermal per Meter Length of Fuel Channel (total MW thermal / total fuel channel length)

	MWt/m
NPD	.163
Douglas Point	.453
KANUPP	.443
Pickering A	.752
Bruce A & B	.881
Gentilly-2	.931

The above increase in rating has been achieved by:

a) increasing the pressure tube diameter from 3 1/4" (NPD, Douglas Point and KANUPP) to 4" (Pickering, Bruce, Gentilly-2);

b) increasing the number of fuel pencils per bundle from 19 in NPD to 37 in Bruce and Gentilly-2;

c) increasing the fuel rating from 24.9 kW/m in NPD to 50.9 kW/m in Gentilly-2 (possible with an accompanying increase in PHT pressure).

8.6 Reduction in Radiation Exposure

Recommendations have been made by the International Commission on Radiological Protection (ICRP) on maximum permitted doses for occupationally exposed persons. Continued exposure at these limits is expected to have a risk of fatality comparable to, or less than, conventional fatality risks facing occupational groups in industry in general. Canada has accepted the recommended limits of the ICRP which are 5 rem/year whole body exposure for Atomic Energy workers. In practice, we have taken a design target of 2.5 rem/year per man as the average.

The major factors which affect the radiation dose incurred by a worker are:

1) Amount of equipment.
2) Frequency of failure.
3) Time required to repair, service, inspect.
4) Radiation conditions (fields and airborne concentrations).

Since radiation dose is proportional to the product of these four factors, a reduction in any factor will reduce the dose received.

It became quite evident in the late 1960's with the operation of Douglas Point that a formal program of radiation dose reduction was required to prevent future problems. For Douglas Point, the major emphasis was on the reduction of radiation fields by chemistry control and the removal of high activity materials (item 4 above). For new stations not yet operated, the emphasis was on all four items listed above. This has taken the form of detailed design reviews. From these design reviews a general classification of solutions in the design stage have emerged:

1) Stop adding equipment.
2) Eliminate equipment.
3) Simplify equipment.
4) Provide necessary equipment of high reliability.
5) Relocate equipment to lower radiation fields
6) Eliminate materials such as cobalt which could become highly radioactive.

7) Provide better chemical control and purification.
8) Extend interval between maintenance periods.
9) Arrange for quick removal for shop maintenance.
10) Reduce in-situ maintenance times.
11) Provide adequate space around equipment.
12) Provide adequate shielding in order that maintenance can take place in low fields.

8.7 Nuclear Power Demonstration Station, NPD

Figure 8.1 shows the simplified HTS schematic for NPD. The circuit contained inline isolating valves for maintenance purposes. Pump reliability was enhanced by using 3-50% pumps with check valves to prevent reverse flow through the non-operating pump. The check valves were placed at the pump discharge, of course, rather than at the suction to meet net positive suction head (NPSH) requirements. The 66 inlet and 66 outlet feeders at each end of the core terminated in a reactor inlet and a reactor outlet header, respectively. Thus, bidirectional channel flow was used to limit spatial reactivity feedback. The channel flow was trimmed to match the radial power distribution by inserting an orifice plate in the inlet endfitting. All feeders were of the same diameter. Pump flywheels were used to match the power rundown during a Class IV power failure to ensure adequate fuel cooling as in all CANDU stations. Boilers were placed above the core to enhance thermosyphoning. Feed and bleed provided pressure and inventory control.

The NPD nuclear station has some significant design features that are quite different from other CANDU stations. There is only one set of inlet and outlet headers. The end fittings of the reactor channels do not have shield plugs, so that there is a large holdup of heavy water in this region. The core itself, consists of two fuel bundle types. The central region as 19 element bundles and the outer region has 7 elements bundles.

The major difference is that the steam generator is a horizontal 'U' tube vessel with the steam drum situated above and connected to the steam generator by a series of 4" risers and downcomers.

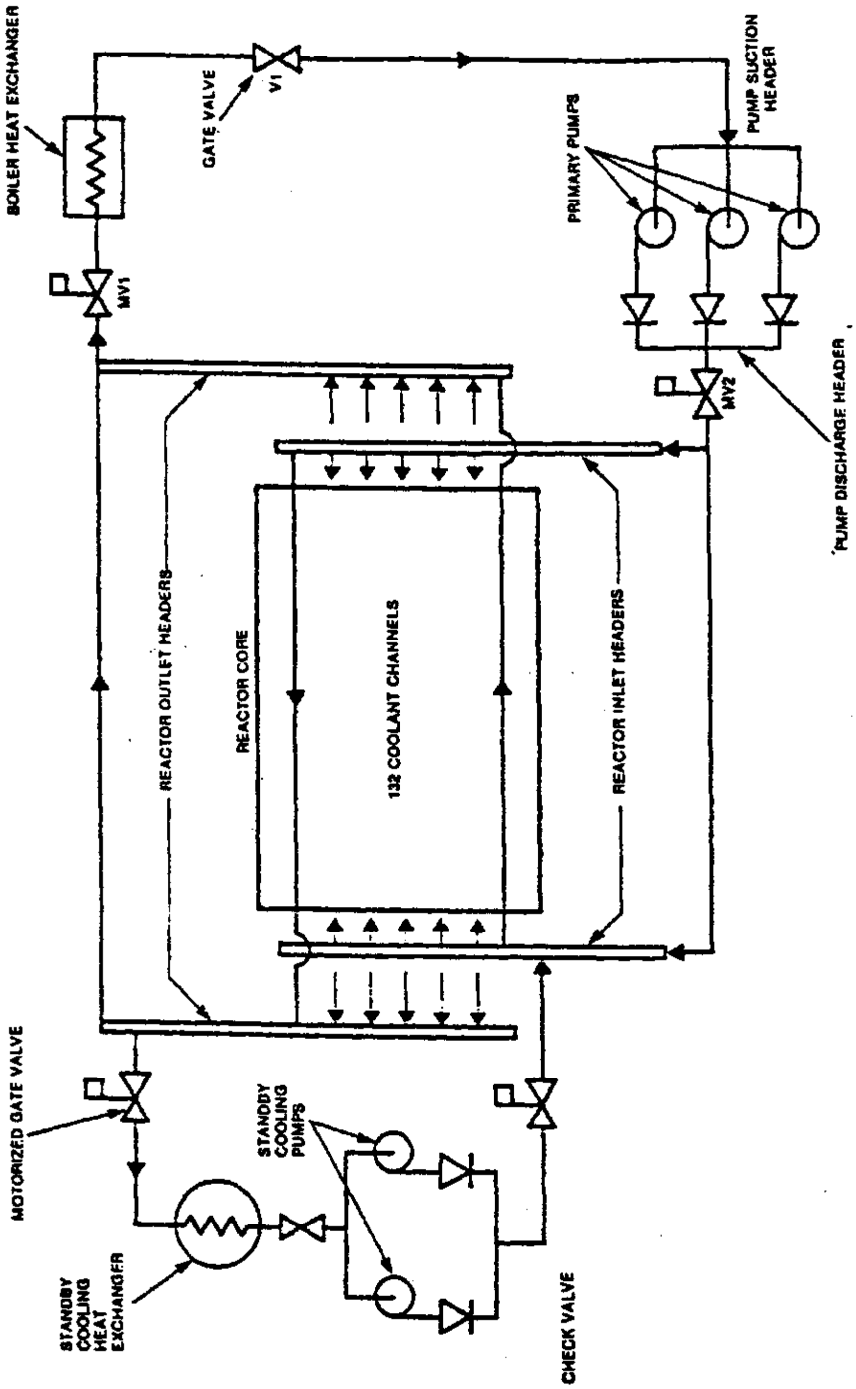

Figure 8.1 NPD main PHT circulating system

8.8 Douglas Point

Figure 8.2 show the simplified HTS schematic for Douglas Point. This station utilized the "figure of eight" loop layout (so coined because of the loop crossover to form an "8" when drawn on paper). This configuration has the advantage of reducing D_2O holdup and pressure drop by eliminating the long piping runs to the far end of the core inherent in the NPD design. This introduces the possibility of east-west (loop end to end) imbalances. The configuration is thus, more susceptible to overloading (of fuel heat transfer) upon the loss of one pump set. Redundancy in pumps were required to get adequate reliability. As in NPD, bidirectional channel flow, check valves at the pump discharges and isolation valves were employed. Trimmed channel flow to match the radial power distribution was obtained by different feeder sizes or orifice plates in inlet feeders and shield plugs.

8.9 Pickering A and B

The Pickering stations are similar in loop-configuration to Douglas Point, as shown in Figure 8.3. Power output was increased to 540 MW(e) and two loops were used to reduce the rate of blowdown in the event of a loss of coolant accident (LOCA). A loop interconnect was provided to reduce loop to loop imbalance. Manufacturing limits on steam generators and pumps led to 12 operating steam generators and 12 operating pumps with 4 reserve pumps. Component isolation was still possible but check valves were eliminated because of the leakage and poor reliability experienced at Douglas Point. Trimmed channel flow was achieved by different feeder sizes and inlet feeder orifice plates. Reference [MORR74] provides an excellent overview of the philosophy behind the Pickering A station.

8.10 Bruce A and B

Figure 8.4 shows the simplified schematic of the Bruce HTS system. It shows a marked layout difference from the Pickering station. For Bruce (and later stations, CANDU 6, Darlington), the reliability experience gained from previous plants justified the elimination of standby pumps. For man-rem and maintenance reasons, valves were eliminated. Manufacturing now permitted larger components. Thus 8 steam generators and 4 pumps were adopted. Figure 8.5 illustrates the growth in steam generator size. Channel flow was <u>not</u> trimmed as in <u>all</u> other CANDU's. A constant radial distribution of flow was maintained by different feeder sizes to account for geometry and feeder length differences. As in all CANDU designs, channel velocity was limited to 10 m/s due to fretting considerations of the fuel bundle and pressure tube.

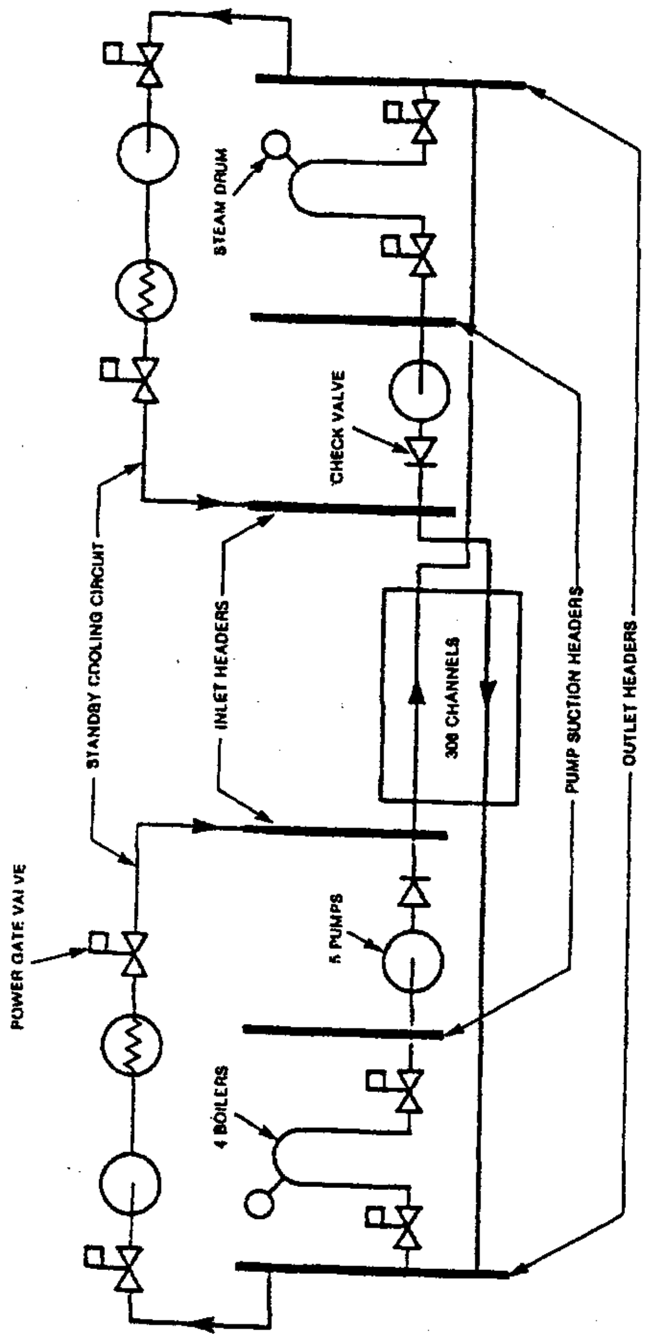

Figure 8.2 Douglas Point PHT main circulating system

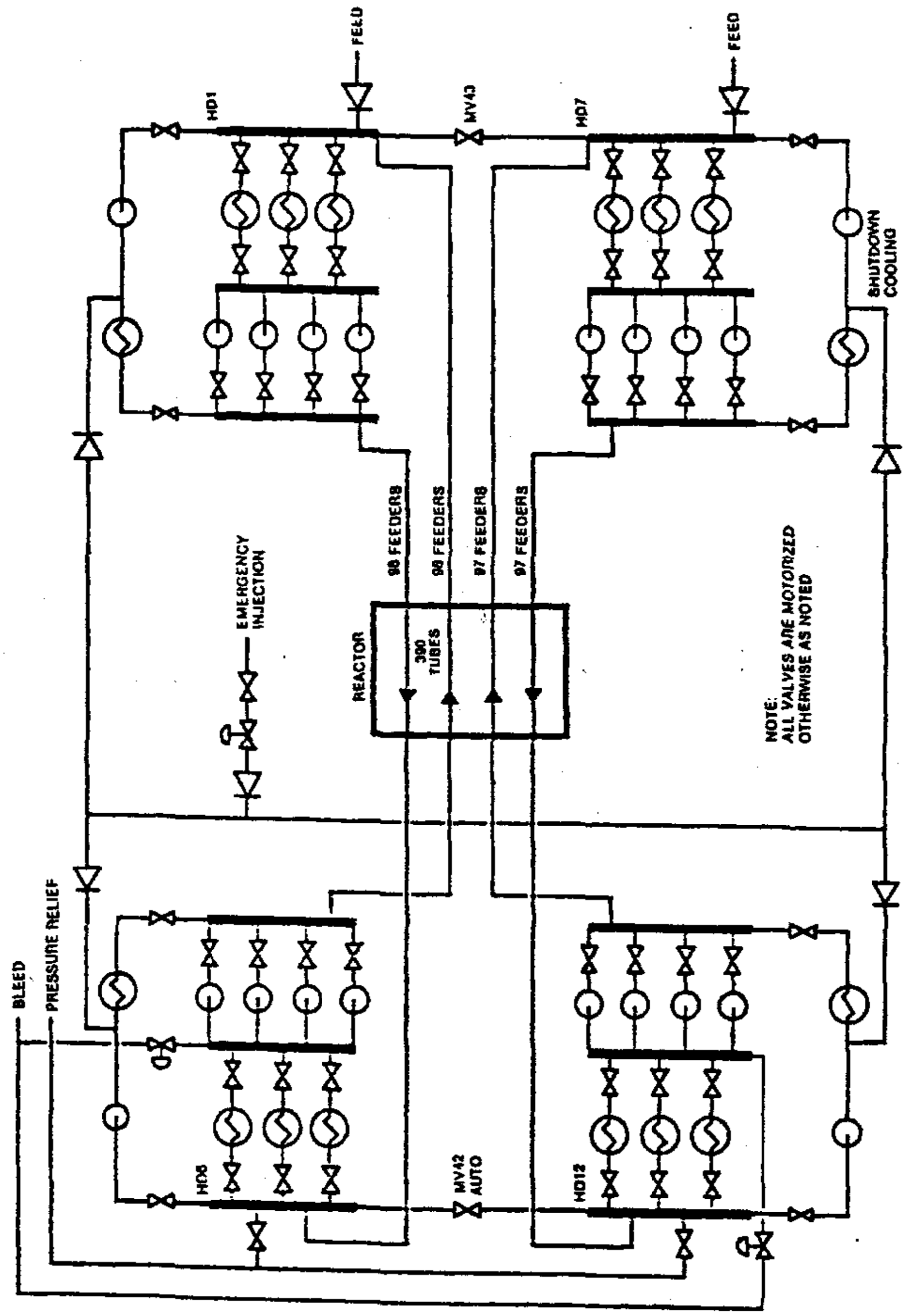

Figure 8.3 Pickering PHT circulating system

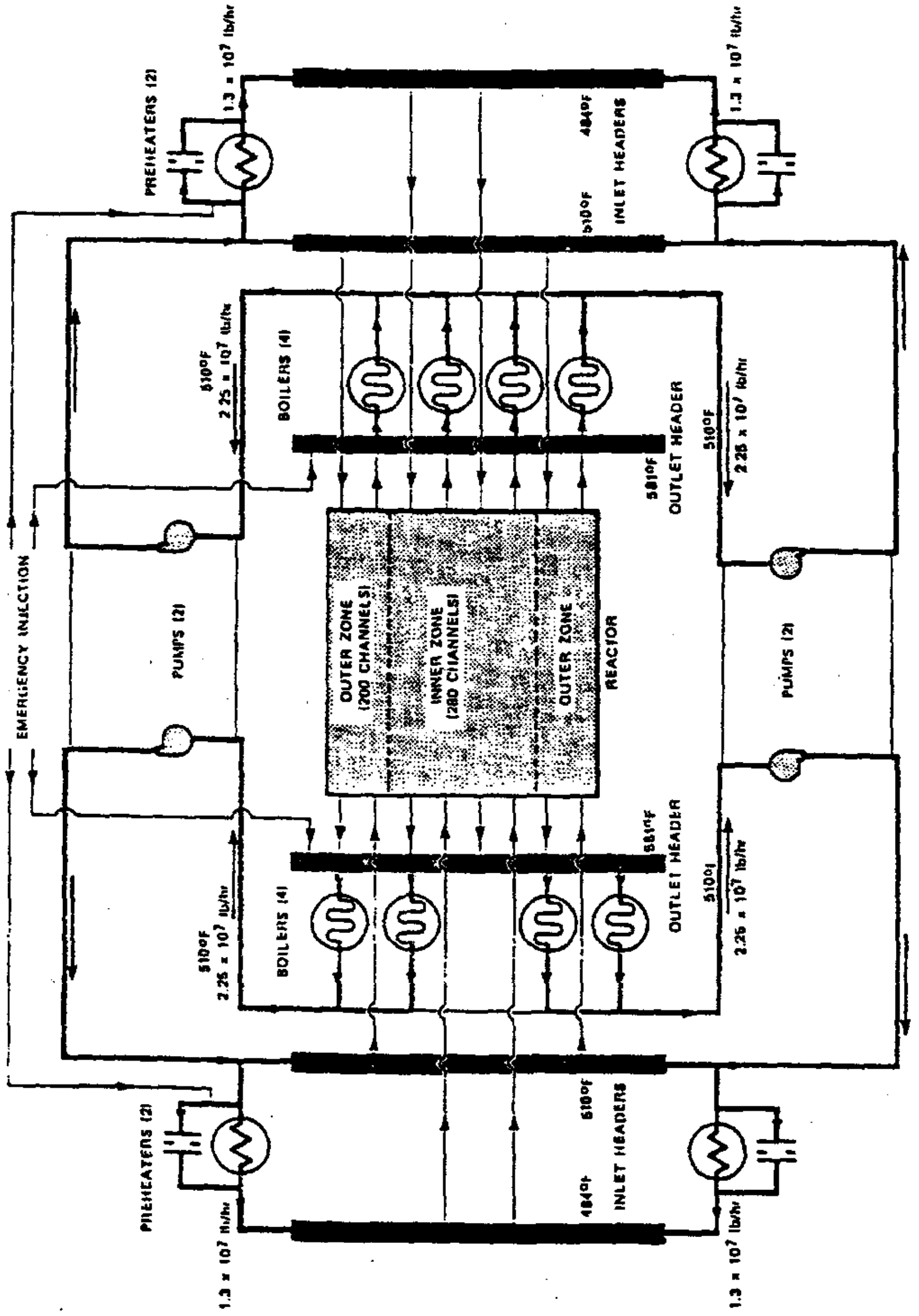

Figure 8.4 Bruce heat transport system

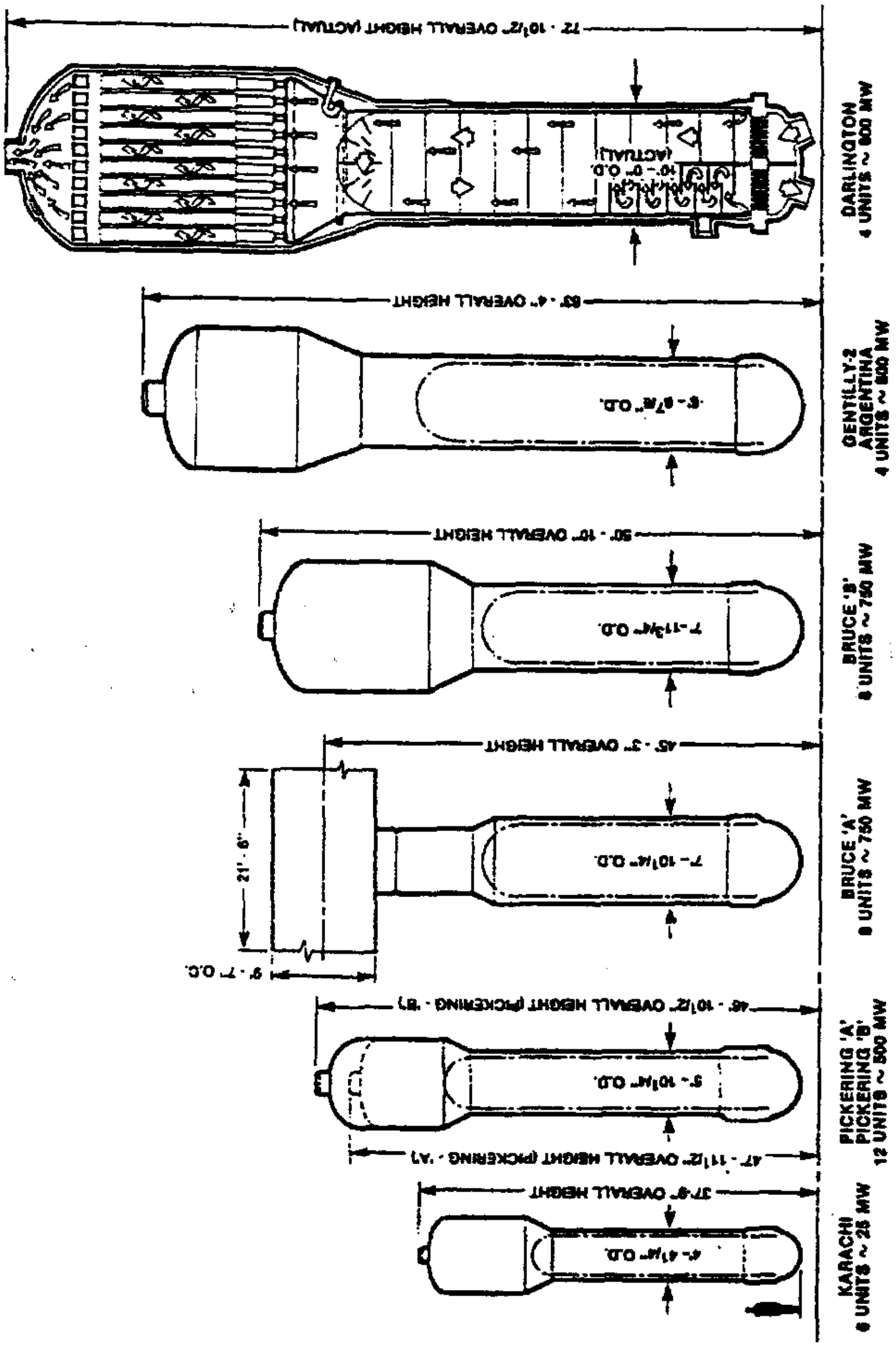

Figure 8.5 Steam generators - relative sizes

8.11 CANDU 6

The CANDU 6 has been discussed in previous chapters. Suffice it to say that the figure of eight loop was adopted as per the Pickering design. But, as per the Bruce design, a lower number of components were used. Increased confidence in two-phase flow led to the use of boiling under normal conditions in the PHTS. Erosion / corrosion concerns at the steam generator inlet limited the quality to 4.5% at this position or nominally 4% at the ROH. Erosion/corrosion concerns also limited single and two-phase velocities to 15.25-16.75 m/s (50-55 ft/s). The presence of boiling required a surge tank or pressurizer to accommodate the larger shrink and swell during transients. The pressurizer is used for pressure control (using heaters and steam bleed valves) while inventory control remained with feed and bleed. This is the same as for the Bruce design because, although the Bruce design is nominally single phase, it's larger size and the presence of some boiling required a surge tank approach. The heat transport system schematic is given in figure 8.6.

8.12 Darlington A

The HTS schematic for Darlington A is similar to the CANDU 6. The reactor is a Bruce reactor (480 channels-13 bundles/channel). Process conditions were taken very close to the CANDU 6 since that was the state of the art at that time. The optimization program showed that higher pressure tube pressures, higher qualities and higher velocities were economical. But the state of the art engineering limits on pressure tubes, qualities and velocities forced the optimization to stop at these limits, the same limits as for the CANDU 6 design.

The HTS for Darlington was designed by Ontario Hydro with design support from AECL. AECL retained responsibility between the headers (RIH, feeders, endfittings, channels, ROH) while Ontario Hydro assumed design responsibility for the rest of the system. All other HTS's were designed completely by AECL.

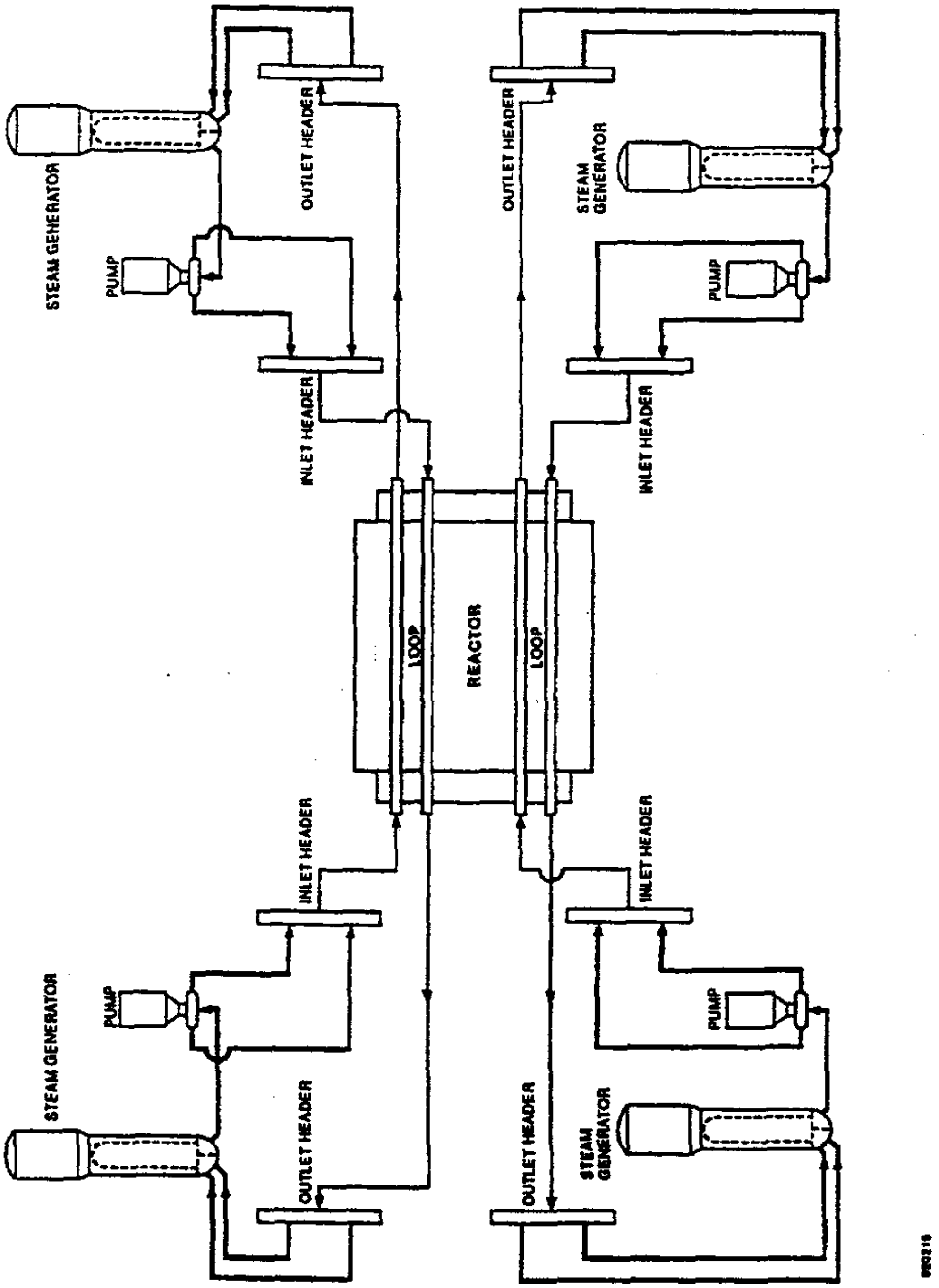

Figure 8.6 CANDU 6 heat transport system [Source: CAN95]

8.13 The Future

The future will see continuing emphasis on reliability and maintainability (R&M), quality assurance, reduction in radiation dose, and capital cost reduction. The excellent performance record of Pickering A and Bruce is to be maintained in future stations through a vigorous program of R&M and a common sense approach to Q/A. Radiation dose to the operating staff must continue to be kept to a minimum. A renewed effort on capital cost reduction must be instituted. All areas of cost, from engineering, to fabrication, to construction, and to commissioning, must be carefully scrutinized to bring about real savings. The overall schedule should be critically examined with a view to shortening it since the overall schedule time (concept to in service) has a major effect on total cost due to the cost of borrowing money and the large initial capital outlay inherent in the CANDU concept. See, for instance, page 218 of Reference [HILL78].

Future HT process designs will also reflect the evolution in the state of the art, notably in the following areas:

1) Critical heat flux,
2) Erosion/corrosion velocity limits,
3) Single and two-phase pressure drop and heat transfer correlations,
4) Thermosyphoning,
5) Safety guidelines and requirements,
6) Stability aspects of two-phase flow,
7) Two-phase pump performance requirements,
8) Pump seals,
9) Process modelling (e.g., pressurizer, headers, boilers),
10) Creep of fuel channels,
11) Fuel design (fretting, hydraulic characteristics),
12) Power output and other constraints as required by clients,
13) Feeder sizing criteria.