Chapter 8 Process Design Evolution

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.

[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 ($lb\text{-}ft^2$)	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 Lubri-cated Tilting Pad Type	Oil Lubri-cated Tilting Pad Type	Oil Lubri-cated Tilting Pad Type	Oil Lubri-cated Tilting Pad Type	Oil Lubri-cated Tilting Pad Type	Oil Lubri-cated 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.

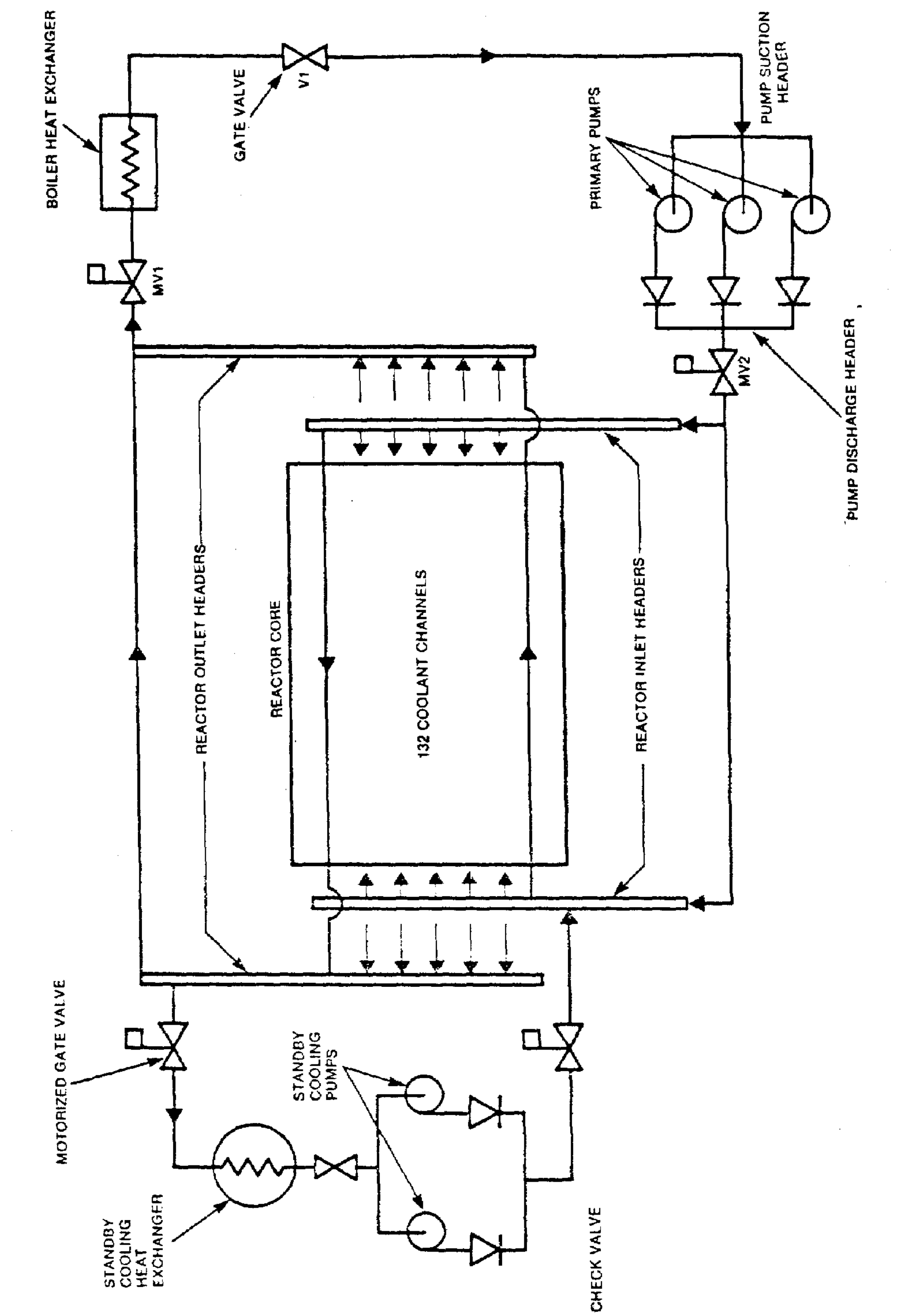

Figure 8.1 NPD main PHT circulating system

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 not trimmed as in all 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.

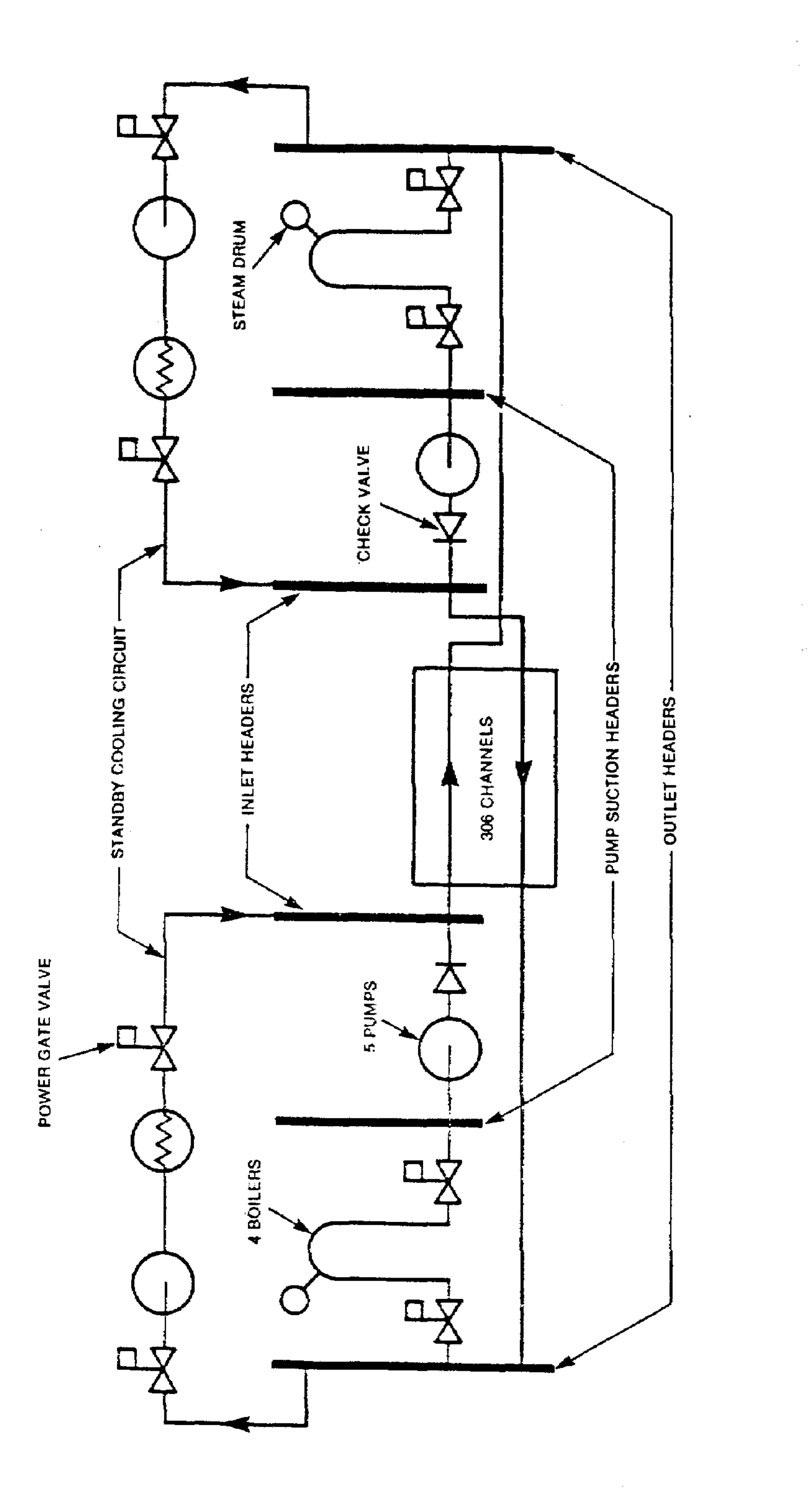

Figure 8.2 Douglas Point PHT main circulating system

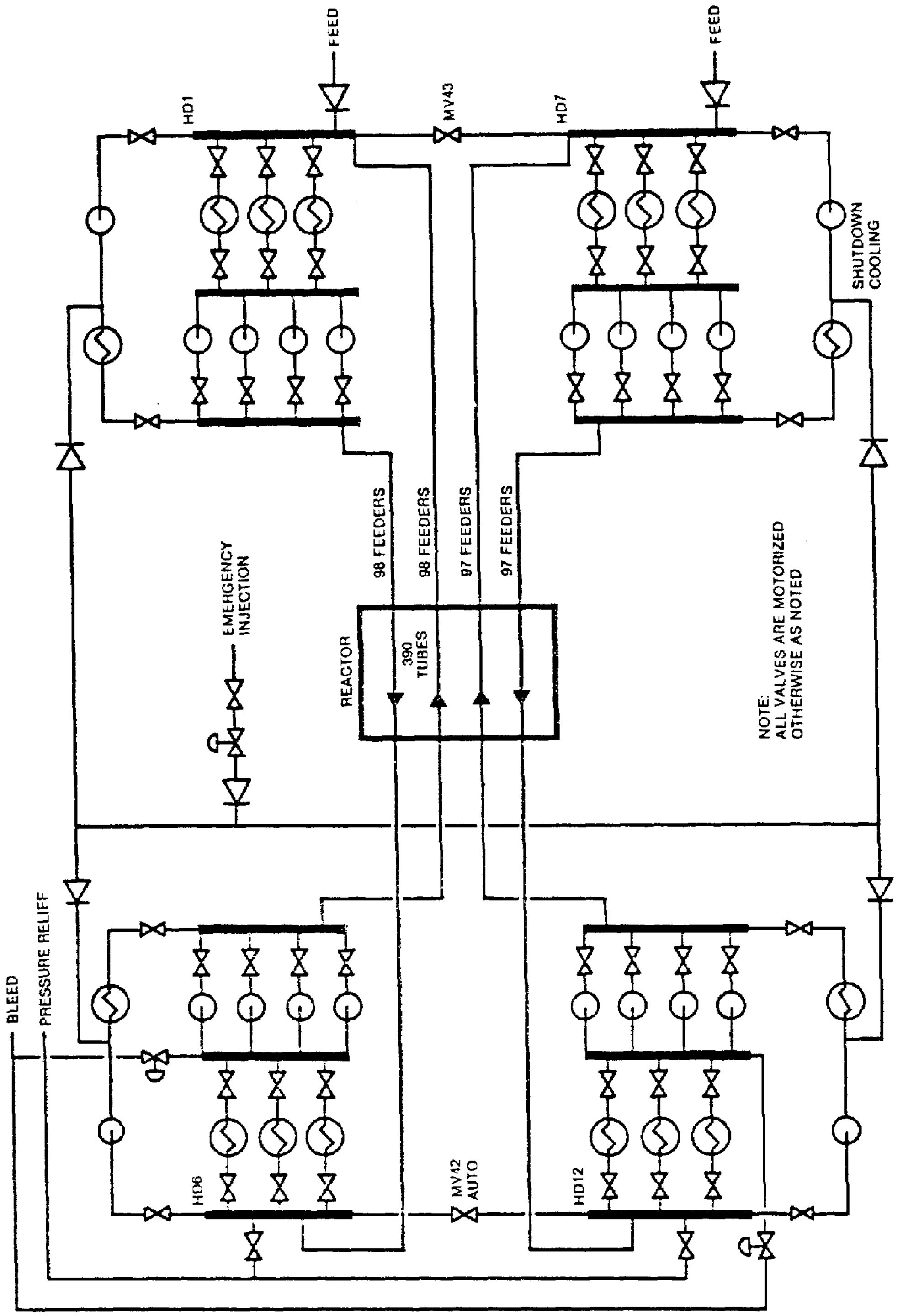

Figure 8.3 Pickering PHT circulating system

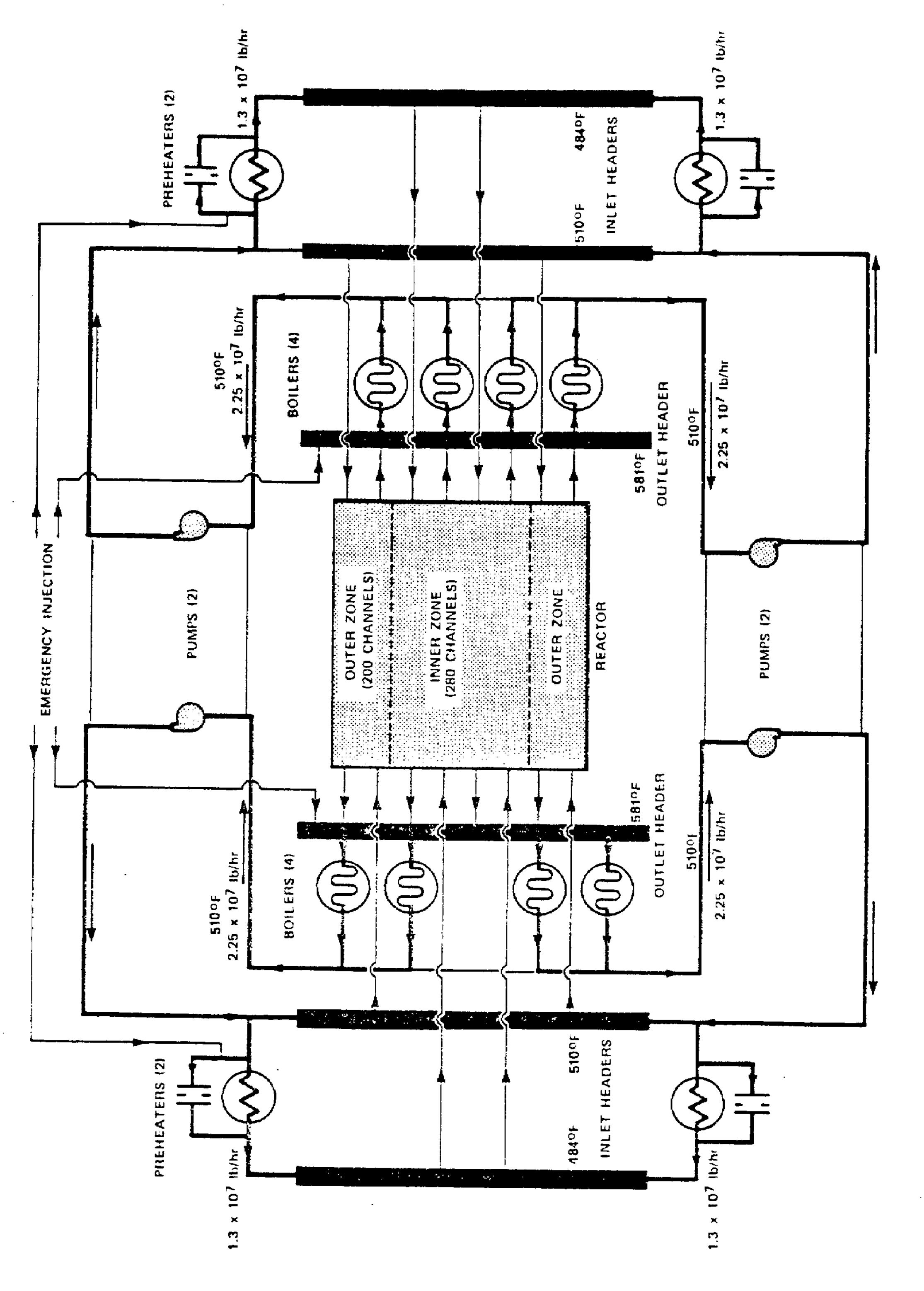

Figure 8.4 Bruce heat transport system

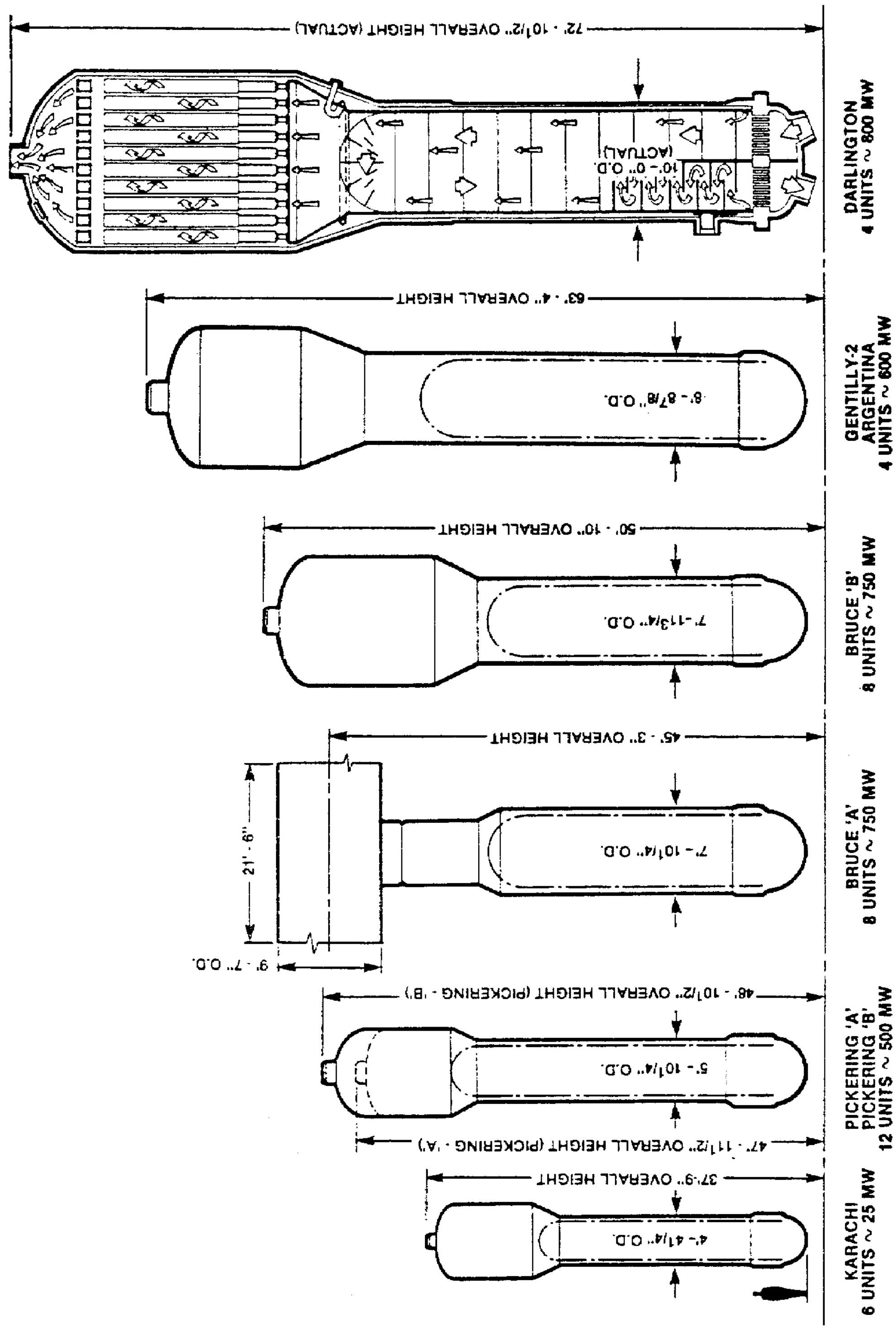

Figure 8.5 Steam generators - relative sizes

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.

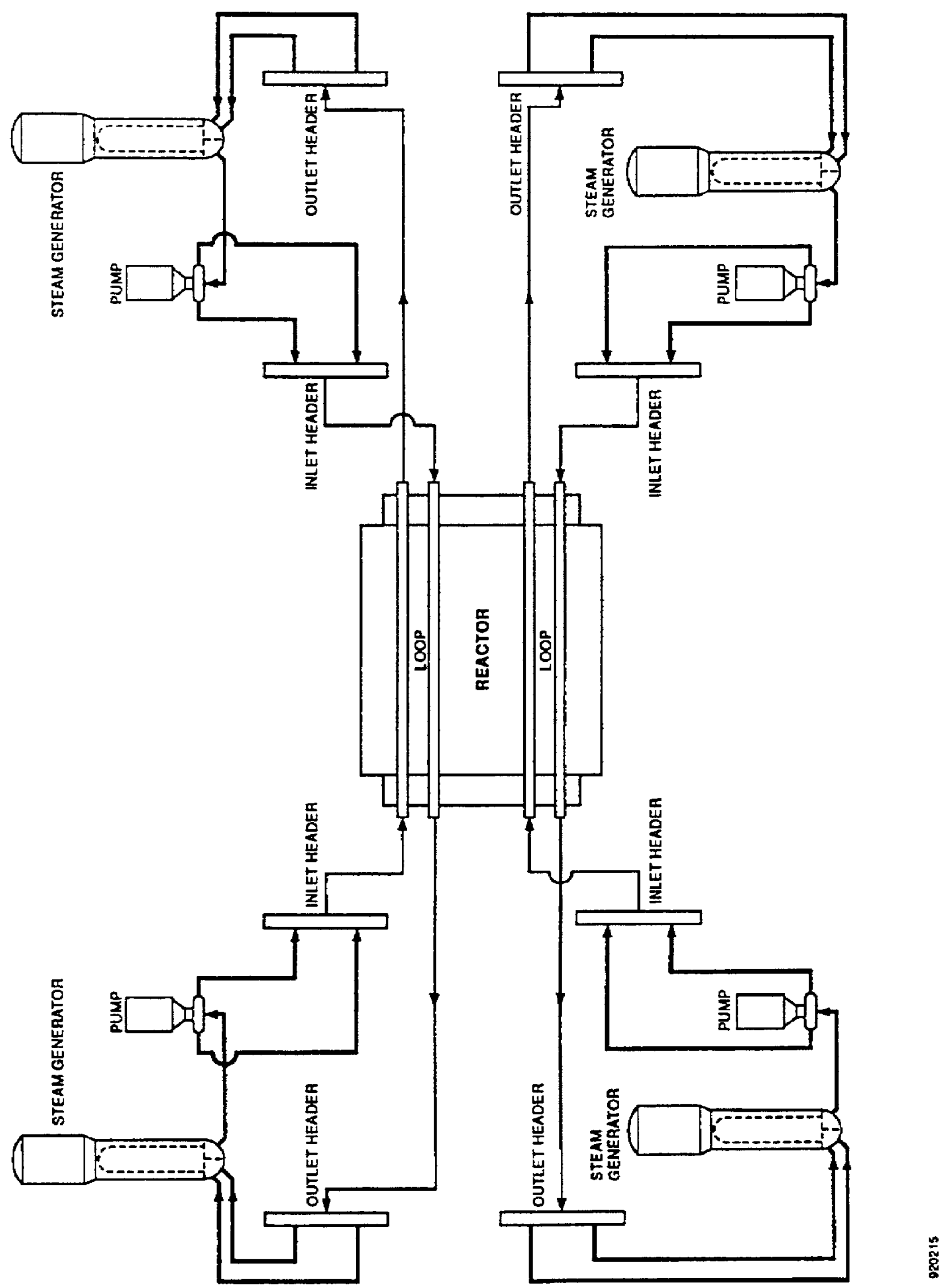

Figure 8.6 CANDU 6 heat transport system [Source: CAN95]

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.

Appendix 1. Comparison of Bruce A, Bruce B and Darlington

1.1 Introduction

An overview of the differences between Bruce A, Bruce B and Darlington A has been made, concentrating on the nuclear portions of the designs. An overview of the difference between Bruce A and B is also given. Generally, differences between stations arise since the industry is on a learning curve. The equipment suppliers, the designers and the regulatory agencies all contribute their share of progressive and retro-grade changes. All of the difference outline below are a result of this phenomenon.

1.2 The two zone design decision

Prior to the design of Bruce A, no power reactor in operation experienced boiling in the primary heat transport system (except for a brief period at NDP during an experimental stage). The two zone system for Bruce A was therefore devised to increase the heat transfer in high power fuel channels without experiencing boiling, increasing the system pressure, increasing channel flow, or boiler area; channel flow was limited to 190,000 lbm/hr. As illustrated in Figure A1.1, to increase the heat transfer using a single zone system required lowering the RIH temperature (increased steam generator area) raising the ROH temperature (i.e., increasing ROH pressure), permitting HTS boiling, lowering steam drum pressure and hence temperature, or some combination of the above. Boiling was not permitted in the HTS. The ROH pressure could not be raised without incurring a burnup penalty due to increased pressure tube thickness. The secondary side conditions could not be changed without an efficiency penalty and an increased turbine cost due to the larger size resulting from lower pressures. This left the one possibility of lowering the RIH temperature. This is not possible in a single zone system without increasing the boiler area, given the above constraints. The 2 zone system evolved, therefore, as a means to lower the RIH temperature of those channels in the centre of the core (inner zone) which nominally have a higher power rating than the outer channels (outer zone).

This was achieved by dividing the D_2O from the boilers into 2 parts: one cooled by the preheater and one bypassing the preheater (see Figures 1 and 2). This bypass flow is thus hotter than the preheater outlet flow. The bypass flow supplies the outer zone and the preheater flow supplies the inner zone. Thus, boiling is prevented in all channels.

At a later date, the reactor power was uprated and, as a result, some boiling occurs in some outer zone channels. This was judged acceptable based on increased confidence of boiling gained in the interim. However, no net boiling was predicted for the ROH.

1.3 Ramifications of the two-zone system

The above design decision to go to the 2 zone system led to the majority of difference between Bruce and Darlington. At the time of the Darlington A design, confidence of a boiling design was already expressed in the 600 MW(e) design. Hence, Darlington A heat transport system design was based on the 600 MW(e) concept even though the reactor was basically that of Bruce. This meant that boiling, resulting in up to 4%

quality at the ROH was permitted and that a single zone was adequate.

Separate Preheaters vs. Integral Preheaters

The Bruce concept dictated that the preheater and the boiler be separated to permit a preheater D_2O bypass flow. Thus, Bruce has separate preheaters while Darlington has integral preheaters. The feedwater train routing, number of valves and control design for each plant reflects this difference.

Process Piping

The PHT piping is different to reflect the pipe routing requirements as shown in figures 8.4 and 8.6.

PHT Pumps and Motors - Trimmed Flow

The PHT pumps of Bruce are larger than those of Darlington since full flow is needed for the outer zone channels at Bruce; all channels at Bruce have the same design flow. Trimmed flow is used at Darlington since the inlet temperature is constant for all channels; only enough flow is provided to match the power input of that channel to give a constant enthalpy rise for all channels.

Pressurizer Size

The pressurizer size needed for the boiling core of Darlington is 2247 ft^3 compared to 1200 ft^3 of Bruce. The extra volume is required to meet the increased swell and shrink needs resulting from increased void formation and collapse.

Shutdown Cooling System

The separate preheater of Bruce allowed their use in a Shutdown Cooling System. However, full PHT inventory and normal PHT circulation are required for its operation. A separate Maintenance Cooling System is required for maintenance requiring partial draining of the heat transport system (pumps, steam generators, etc.). However, Darlington A has a system similar to the maintenance cooling system at Bruce, but called the Shutdown Cooling System, which is used for both shutdown and maintenance cooling.

1.4 Boiler size considerations

The state of the art in boiler design dictated that eight boilers be used at Bruce. Larger boilers were deemed feasible by the time of the Darlington A design and four integral preheater "light bulb" type steam generators were chosen.

1.5 One vs. two loops

Also following the state of the art thinking on safety concepts and environmental regulations, the two loop concept, as per the 600 MW(e) design, was chosen for Darlington. This limits the building overpressure upon a loss of primary coolant and prevents fuel failures in the unfailed loop. The single loop concept was considered adequate at the time of the Bruce design. This single loop design can lead to reverse flow through a failed pump, unlike the two loop concept.

1.6 Process optimization

For Darlington design, an optimization computer code was available which was not available for the Bruce design. Consequently, the flows, temperatures and pressures of both designs are different.

Darlington was optimized to generally higher values of the main process parameters compared to Bruce, as shown in Table 8.1. Initially the channel flows limit for Darlington was, as per Bruce, 190,000 lb_m/hr. Measurements at Bruce A G.S., however, showed that some channels were operating in excess of 200,000 lb_m/hr and the Darlington figures has since been updated for 200,000 lb_m/hr with a resulting drop in ROH quality from 4% to 2%.

1.7 Boosters vs. adjusters

The Bruce A design uses boosters for reactivity insertion during poison over-ride whereas all subsequent reactors use adjusters. This reflects a reassessment of the Bruce A experience from points of view of economics, safety and complexity.

1.8 Magnetic filters

Advances in magnetic filter design prompted the use of these filters on Darlington to augment PHT purification and to reduce the heat loss due to purification. However, experience at Bruce A indicates reduced purification flow requirements and, hence, the magnetic filters may not be economical.

1.9 Process control

In the area of process control, Bruce A was designed with digital control for the Reactor Regulating System, the Demand Power Routine, the Unit Power Regulator and the Boiler Pressure Control. Analogue control is used for the Boiler Level Control and the Pressure and Inventory Control. Current thinking on Darlington A is to incorporate all control functions into the main computer as digital controllers. This gives greater flexibility for generating enhanced control routines if desired or needed after commissioning and is cost effective if a main computer is being used in any case.

1.10 Separate vs. common steam drum

Because of difficulties being experienced at Pickering A in drum level control of the 16 separate drums, a common drum for a bank of four boilers was chosen for Bruce A. Experience gained in the interim plus the fact that Darlington only has 4 steam generators led to the decision to have a separate drum for each boiler.

1.11 Seismic considerations

Darlington A was designed to more stringent seismic requirements than Bruce A. The Bruce A concept of hanging the boilers from the fixed drum and also hanging the preheaters, allowed for flexibility for thermally induced motion. Seismic snubber requirements were not stringent and hence the cost was acceptable. The more stringent requirements for Darlington A and the fact that a common drum was not available for support led to fixed boilers and pumps plus an expansion loop in the primary pump suction line.

1.12 Critical heat flux

Bruce A was designed at AECL based on a critical heat flux correlation as developed by Krishnan, the Krishnan Lower Bound Correlation, for 37-Element fuel bundles.

A critical power ratio limit of 1.29 was set as the design criterion. For Darlington A, the design criteria set by Ontario Hydro was a 10% improvement on the Lower Bound Correlation but with a CPR limit of 1.39; this is presently susceptible to a redefinition pending the outcome of the recent tests on 37-Element fuel at CRNL and Westinghouse (Canada).

1.13 Differences between Bruce A and Bruce B

<u>Operating and Design Pressures</u>

Bruce A trip set point is 70 psi above normal operating pressure, whereas the Bruce B reactor trip set point is 100 psi above normal operating pressure. The Bruce B value will reduce the incidence of spurious trips.

The Bruce A relief valve set point is 50 psi above normal operating pressure, whereas the Bruce B relief valve set point is 80 psi above the normal operating pressure to reduce the incidence of spurious operation.

Bruce B has an outlet header operating pressure 18 psi above the Bruce A value. This is the highest pressure practical without changing pressure tube thickness. This has a small benefit on CPR.

<u>Preheater Design</u>

The preheater internals for Bruce B were strengthened and the preheater bypass and rupture disc eliminated. This is to eliminate the possibility of excessive damage to the preheater internals due to certain secondary side line failures.

<u>Steam Generator Design</u>

The Bruce A arrangement consists of a cross-drum design with a common drum serving four steam generators. Warm-up and cooldown rates were severely limited by high stress levels in the Tee-Junction area.

The Bruce B arrangement consists of integral steam drums for each steam generator which permits warm-up and cooldown at the design rate.

<u>Seismic Design</u>

On Bruce A all nuclear structures were analyzed on the basis of a dynamic analysis in both the horizontal and vertical directions based on the maximum hypothetical earthquake that can be expected at or near the Bruce A site.

On Bruce B all structures, components and systems are seismically qualified. Two levels of earthquake are defined. The design basis earthquake (DBE) and the site design earthquake (SDE). In addition, three categories of qualification are defined. Category A systems must retain their pressure boundary integrity or structural integrity during and following the specified earthquake. Category B systems must retain their pressure boundary and remain operating (or operable) during and/or after the specified earthquake. Category C systems must retain their pressure boundary integrity during and after and be operable after the specified earthquake.

Heat Transport 'Pump' Design

The Bruce B pumps are equipped with an auxiliary impeller that assure adequate flow to the hydrostatic bearings during both forward and reverse turbining conditions. The Bruce A arrangement depended on the pump discharge pressure being higher than the pump suction pressure (i.e., forward rotation only). The pump feet strength are significantly higher on Bruce B due to the higher postulated burst pipe loads.

Heat Transport Pump 'Motor' Design

The solid flywheel was eliminated on Bruce B to reduce inspection requirements and ease motor disassembly. Bruce B has an improved brake. The Bruce A brake restricts operation under certain conditions. Improved bearing design on Bruce B is incorporated to give better acceptability and to maintain adequate lubrication during reverse rotation.

Fuel Channel Assembly Design

Several detailed design changes were made on Bruce B to accommodate the effects of axial creep.

Feeder Design

Several changes were made to the Bruce B feeder design to accommodate fuel channel creep.

Feedwater Control

With the independent steam generators on Bruce B, the feedwater control to each steam generator must be regulated. Trim valves are provided in the feed line to each steam generator downstream of the preheaters.

Table 8.7 Main Process Parameters and Features

Parameter	Bruce A	Bruce B	Darl. A	Darl.A Revised	
ROH pressure	1332	1350		1450	1450
ROH Temperature °F	579	579		591	591
ROH Quality %	.08	.08	3.8	2.0	
RIH Temperature °F	509/483	509/483	509	509	
Maximum Channel Flow	190,000	190,000	190,000	200,000	
# of channels	480	480		480	480
# of pumps	4	4		4	4
# of steam generators	8	8		4	4
# of preheaters	4	4		4	4
Type of preheater	separate	separate	integral	integral	
# of Zones	2	2		1	1
# of Loops	1	1		2	2
Channel Flow Type	not trimmed	not trimmed		trimmed	trimmed
Power Output	750	750		850	850
	(balance to BHWP)	(Balance to BHWP)			
PHT Pump Size	9,100 (Hot)	9,100 (Hot)		8,133 (Hot)	8,133 (Hot)
Pressurizer Volume (ft^3)	1200	1200		2247	2247

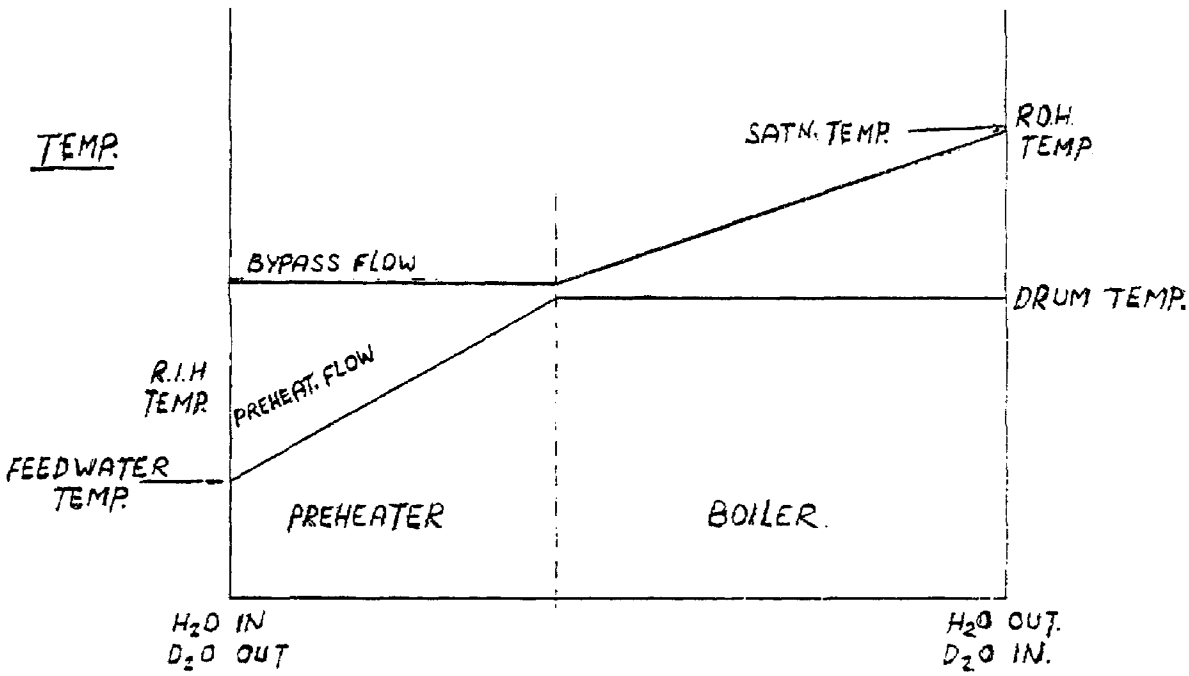

Figure A1.1 Bruce heat duty diagram