CHAPTER 2
PROCESS DESIGN I

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SUMMARY

This chapter describes, in a general sense, the process of Process Design. Emphasis has been placed on establishing the philosophy of the design process so that the reader may be better equipped to carry out detailed design in a more meaningful way. Specific topics discussed include: other groups that the process designer interfaces with, documentation, design tools, Quality Assurance and design evolution.

2.1 The Design Process

2.1.1 Introduction

The process or methodology used to design process systems is evolving along with the evolution of the systems being designed. Herein, the more dominant and permanent features of the present process are outlined. Because the process involves the complete design, from first concept to resolving operating problems, the designer should be involved in all aspects to ensure a timely and meaningful resolution of existing problems and future designs. This dual requirement is the root of the conflicting demands on the designer's time: solve today's problems while providing good future designs.

Evolving management philosophy, advances in regulatory and code requirements, advances in analysis and design capability and changing design/operating requirements are some of the reasons why problems persist.

We can never hope to eliminate completely the future occurrence of such problems. But we can strive to reduce their probability of occurring or, failing that, their impact on our product. There are two general ways to proceed, perhaps in parallel:

(1) Establish improved design practices (ie. avoid future problems by being more certain of what we design today).

(2) Design more margin into our new plants to yield a more robust design (less interdependence of critical systems and more margin to engineering limits) which will give a station design that is more tolerant to future perturbations.

The following is the interaction situation applicable to the process systems area. A similar principle should be applicable to other areas. There are three aspects of process system design:

(1) Process Methods - for providing the methods and methodology to carry out the design process. This covers:

- identification and documentation of analysis concepts
- identification and documentation of design guides
- identification and documentation of design tools
- tool design, development and benchmark verification
- training other staff in methods.

(2) Process Development - for ensuring that the application of these methods is appropriate. This covers:

- identifying the specific correlations to use for heat transfer and pressure drop calculations
- coordinating lab testing that is needed to improve the design
- interpreting feedback from sites (tests plus commissioning).

(3) Process Design - (Heat Transport Systems, Safety Systems, Moderator Systems, Heat Exchanger, Pressure Vessels, Rotating Machinery, etc.) - responsible for carrying out the design; ie. the production aspects.

Figures 1 and 2 illustrate the interaction of these three aspects.

Problems and new ideas can and will arise from any area. Each task has to be assessed on its own merits and a plan laid out at that time as a function of the schedule, the task and the resources (including manpower and talents).

The concept stage involves the establishment of the main groundrules for the design. These include:

1) Seismic basis;
2) Codes and Standards, regulations;
3) Power required;
4) Man rem and reliability targets;
5) Degree of standardization and extent of generic basis.

The optimization stage includes consideration of:

1) Broadbrush treatment of thermalhydraulics;
2) Economic equations;
3) Engineering constraints
   a) velocity,
   b) critical power rates,
   c) Heat Transport System (HTS) quality, X,
   d) pressure tube thickness,
   e) fuel burnup,
   f) physical dimensions,
   g) pressures,
   h) temperatures,
   i) manufacturing limits.

2.1.2 Interaction With Other Groups

There are eleven main groups that the process designer interacts with:

1) other designers,
2) manufacturers,
3) project teams,
4) clients
5) regulatory groups,
6) commissioning teams,
7) operations,
8) analysis support teams,
9) laboratories,
10) quality assurance,
11) balance of plant.

Other design groups include:

1) reactor physics,
2) thermalhydraulics (safety aspects),
3) layout,
4) piping and stresses,
5) instrumentation and control,
6) fuelling machine,
7) other process system designers,
8) component designers,
9) structures (civil).

The reactor physics groups are concerned mainly with core design. One of the main interfaces between the PHT process system designer and the core designer is the void-reactivity and temperature-reactivity feedback to the core. That is, the void fraction and temperature of the coolant in the core affects the dynamic parameter of the core, reactivity. The core designer will also be interested in the moderator temperature and thus will interact with the moderator process designer.

The groups dealing with thermalhydraulic aspects of safety primarily need to know what the physical characteristics of the system are before they can carry out the safety analysis. These analyses center on pipe breaks and loss of heat sinks which jeopardize heat removal from the core. The primary heat transport system is, naturally enough, the center of attention. Detailed fault trees or Safety Design Matrices (SDM's) dictate the analysis to be done. Other process systems are naturally involved. For instance, the moderator can act as a heat sink and for some stations is an integral part of the shutdown safety system.

The layout groups, as the name implies, resolve the many tradeoffs required to achieve an economical layout with due consideration given to maintenance and man rem. The task is not at all trivial considering the complex nature of CANDU with many systems for power production (process, nuclear core, secondary side, pressure and inventory control, instrumentation and control, alternate heat sinks, etc). Thus the layout groups require the physical dimensions and weights of the process system.

The piping and stress groups ensure integrity of the process system boundaries (pipes). Naturally, these groups require knowledge of the pressures, temperatures and flows under steady and transient conditions as input to their design work.

Instrumentation and control (I & C) groups naturally need to know the characteristics of the systems they control. Full process simulations or simplified versions are used, depending on the need of the I & C designer.

The fuelling machine designer needs the thermalhydraulic characteristics of the primary heat transport system at the point of interface; the endfitting. Fuelling machine injection flow, and hydraulic ram design are items of interaction between the process and machine designers.

Other process systems of interest to the HTS designer are:

1) Moderator,
2) Shutdown Cooling,
3) Pressure and Inventory Control,
4) Endshield Cooling,
5) Purification.

Component designers include:

1) Pumps,
2) Valves,
3) Heat exchangers (including steam generators),
4) Pressure tubes,
5) Endfittings,
6) Vessels (such as pressurizers).

Finally there are the civil designers who provide the structures to support the components and systems.

All of the above design groups must interface to settle on a design suitable from all design points of view. To some extent, the process optimization code, AESOP, deals with this process of arriving at a suitable design. It is merely the starting point, however, for interaction between groups. Heavy reliance is placed on past practise and generic or repeatable design features. Standardization to some degree is essential since economics do not permit a design from scratch for each design. The concept of utilizing proven components is central to a stable advancement on the learning curve of process design. Controlled innovation and advancement is the governing philosophy.

Interaction with manufacturers (of pumps, heat exchangers, etc) is essential for proper process design. Because of knowledge already gained from interaction with the manufacturer, it is usually not necessary to contact the manufacturer during the conceptual and optimization stages. Once the broadbrush thermalhydraulics has been established, then the manufacturers are involved to some degree. Full involvement usually does not occur until the call for tenders.

Process designers are usually in contact with project teams on a continual basis from the time after a detailed design is completed (with the issue of the design description) to the completion of project work. The project team ensures the successful implementation of the design.

Client interaction occurs throughout the life cycle of a plant, starting with the demand or need for a station. Interaction usually centers around meeting their requirements for a timely and adequate design. Some involvement is required for training and analysis liaison. If the client has a large technical staff, this second involvement dominates, usually because the client assumes responsibility for some systems.

Regulatory groups include the Atomic Energy Control Board, MCCR, or other provincial regulators of non-nuclear aspects of mechanical design.

Interaction with commissioning teams is required for the feedback to the designer and for the feedforward to the adequate commissioning of a station.

Operational feedback is another essential source of design information. In addition, operational problems are often resolved with the help of the designer through design modification or analysis clarification.

The designer is usually in close contact with analysis support teams which include outside computer and computer code support teams as well as inhouse analysts and computer codes. For the process designer, the process equations involved are invariably a derivative of the equations discussed in Chapter 18.

Laboratories provide the design with essential information on fundamental elements of the process design. Topics range from valve capacity certification to verification of fundamental equations.

Quality Assurance (Q/A) teams provide inhouse verification of the design process in it's totality through the process of design reviews, guidelines and procedures and, to some extent, training and information liaison. Although programs provide essential overviews and coordination of the assurance of quality, the fundamental responsibility for quality lies with the designer.

Since AECL does not handle the balance of plant (non-nuclear components), it is necessary to interact with the balance of plant (BOP) supplier which could be a consulting firm such as CANATOM, or a client, such as Ontario Hydro.

This brief discussion of the groups that the designer interacts with, illustrates the complexity of the design process. Interaction with any or all occurs at each stage of the process. This makes for a highly dynamic process.

The dynamics of the process cannot be preordained as in a computer program. Required are individuals who have knowledge of, and wisdom in the ways of, the design process so that they can act appropriately as the need dictates.

2.1.3 Design Documents

Proper documentation is a key element of the design process. Without it the growth along the learning curve is severely hampered. It provides some degree of insulation from staff turnover and some measure of continuity and evolution. Since many people are involved in the development of a CANDU station, adequate documentation is required to span the space and time inherent in the design process and beyond. Quality Assurance guidelines and the regulatory bodies require it, as do other groups which require design documentation as the building block for their work. The documentation list includes:

1) Design Requirements (DR),
2) Design Descriptions (DD),
3) Station Data Manuals,
4) Design Manuals (DM),
5) Safety Reports,

6) Technical Descriptions (TD),
7) Generic Design Deviations (GDD),
8) Supporting memos, design calculations, studies and reports,
9) Commission Procedures,
10) Equipment Dockets.

The Design Requirement is a statement of just that. No attempt is made at any description of the design details but invariably the requirements are written with the system history in mind. The Design Description gives the details of the final design. There is no legal requirement at present for a single document covering the design philosophy or methodology, although such documentation is necessary. At present, supporting memos, design calculations, studies, design guides and reports plus generic design deviations provide this philosophy.

The Station Data Manual provides a convenient listing of key data on the system. The DR, DD and Data Manual are the main documents handed over to Project Engineering by the system designers. The Project team then combines these to form the Design Manual.

Technical Descriptions are comprehensive reports written by the designer for prospective clients. Safety Reports are provided by the safety groups, while commissioning procedures are provided by the projects, both with support from the designer. Life cycle equipment dockets are maintained at the site by the site owner.

2.1.4 Design Tools - Overview

The optimization code used is AESOP, formerly CAP73. From this code, the first cut at PHT conditions is obtained (see Figure 3). Applying engineering judgement, these first estimates are modified in a search for a more practical set of design conditions. AESOP can be used in a perturbation mode to assess these altered conditions from the point of view of economic feasibility. During these stages, considerable consultation with most of the groups of Section 10.2 takes place to ensure design feasability. The extent of consultation depends, naturally enough, on the degree of deviation from past designs. With this phase completed, detailed calculations can begin.

The computer codes, SOPHT, NUCIRC, and BOILER are presently used for detailed design calculations. Prior to SOPHT, a recent AECL acquisition from Ontario Hydro, the code HYDNA was used. From the preliminary feeder layout and process conditions, the Reactor Inlet Header to Reactor Outlet Header pressure drop, ΔP_{H-H}, can be estimated using NUCIRC for the channel with the worst flow, power, and resistance combination from a pressure drop point of view. From this ΔP_{H-H}, the other feeders can be sized. BOILER is used, in parallel, to estimate the heat transfer area or heat transfer performance of the steam generators given inlet enthalpy and pressure from AESOP (or more precise updates from NUCIRC). The system geometry is given to the full circuit version of NUCIRC for a steady state simulation of the primary heat transport system. Refined estimates of pump head and flow requirements are usually made at this stage. Alternatively, the steady state version of SOPHT can be used. SOPHT is also used in the transient version with preliminary control systems to analyze transient behaviour. The whole process is iterative, with engineering judgement supplied throughout to guide the analysis.

Typical output from AESOP is:

1) Thermal core power or heat transferred to the coolant, Q;
2) Shape factors for the radial core power and coolant flow, β_p and β_f (average to maximum, typically ∼0.85);
3) Maximum channel flow (typically ∼25 kg/s based on a limit of 10 m/s);
4) Critical Power Ratio;
5) Reactor Outlet Header (ROH) quality (typically 4% or less);
6) Number of fuel channels;
7) Fuel channel length;
8) ROH Pressure;
9) Reactor Inlet Header (RIH) Temperature;
10) Rough estimates of ΔP_{H-H}, heat losses, etc.

These data inputted to SOPHT, NUCIRC and BOILER allow the detailed calculations to proceed.

NUCIRC is used to size feeders according to a selection among criteria of constant enthalpy at the ROH, constant critical power ratio (CPR) in each channel, constant channel flow or some variant of these criteria. Feeder sizing is done ensuring parallel channel flow stability. Interaction with the stress analyst and layout groups ensure feasability of design. Figure 4 gives an indication of the degrees of interaction generally required.

SOPHT is generally used in the steady state to give overall circuit pressure, temperature and quality profiles and in the transient mode for transients such as:

1) Reactor Trip
2) Turbine Trip
3) Class IV Power Failure
4) Stepback
5) Power Manoeuvring
6) Rapid Cooldown

and other transients. These transients have a two-fold purpose: as input for stress analysis and to assess performance to ensure adequate net positive suction head (NPSH) for the PHT pumps, sizing of surge lines and other process design needs.

2.1.5 Quality Assurance

Quality is the essence of good design and is the responsibility of the individual. As such, quality cannot be split off from the design process; it is the design process. However, some measure of assurance of quality is attained by specific guides, as follows.

Quality in all phases of a nuclear power plant from concept to operation has always been recognized as a requirement. In recent years, a more formalized approach has been necessary. This had its beginnings in the manufacturing industries and we now have a series of four standards (CSA Z299 series) for the quality assurance of manufacture of nuclear equipment. Other standards are being initiated under the CSA N286 series. They consist of

CSA N286.0 General Requirements for Q/A of Nuclear Power Plants
N286.1 Q/A of Procurement
N286.2 Q/A of Design
N286.3 Q/A of Construction & Installation
N286.4 Q/A of Commissioning
N286.5 Q/A of Operation
N286.6 Q/A of Decommissioning.

As required by the N286.2 Design Quality Assurance Standard and the current AECL-EC Quality Assurance Manual, it is AECL's policy to establish and implement Design Verification programs for all work. Ontario Hydro and other utilities also adhere to these or similar standards.

Design Verification is the confirmation that design meets specified requirements. It is the responsibility of each designer to obtain appropriate design verification, and to file evidence of the verification in Section 290 of the Technical Documentation System.

Design verification is good engineering practice.

The Design Verification Branch in the Engineering Quality Assurance Department, Design and Development Division monitors and coordinates design verification programs and helps to ensure that overall project design verification requirements are met.

However, standards by themselves are not sufficient. There must be an attitude which recognizes the necessity and importance of Q/A by all those who must comply by these standards. With the proper attitude, there will come commitment, and with commitment, quality will result. There is the danger, already voiced by many, that we are being swamped by paper and bureaucracy in our Q/A programs. It is clear we must show common sense in minimizing the paper and bureaucracy while retaining the quality.

2.2 Design Evolution

2.2.1 Introduction (taken from Reference 1)

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 requirements 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*.

The evolutionary changes that have taken place are discussed below.

2.2.1.1 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 pumps have gone from 16 in Pickering to 4 in Bruce, Gentilly-2 and Darlington. The number of steam generators have gone from 12 in Pickering to 8 in Bruce to 4 in Gentilly-2 and Darlington. Table 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.

2.2.1.2 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 2 gives a more detailed comparison of the features of different steam generators.

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* Gentilly-2 is the first of the CANDU 600 designs; others are Lepreau, Cordoba and Wolsung.

2.2.1.3 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 3 and 4.

2.2.1.4 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 verical 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 below.

Heavy Water in Core per MW Thermal

	M^3/MWt
NPD	.410
Douglas Pt.	.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. The table below indicates the achievements to date.

MW Thermal per Meter Length of Fuel Channel*

	MWt/m
NPD	.163
Douglas Pt.	.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 Pt. 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 accompaning increase in PHT pressure).

2.2.1.5 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.

*Calculated by taking total MW thermal divided by total length of fuel channels.

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

1) Amount of equipment.

2) Frequency of failure, servicing, inspection.

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 very 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 designs 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 field.
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.

2.2.2 Nuclear Power Demonstration Station, NPD

Figure 5 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 checkvalves 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 hold up of heavy water in this region. The core itself, consists of two fuel bundle types. The central region has 19 element bundles and the outer region has 7 element 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.

2.2.3 Douglas Point

Figure 6 shows 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. But 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, checkvalves 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.

2.2.4 Pickering A and B

The Pickering stations are similar in loop-configuration to Douglas Point, as shown in Figure 7. 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 lead to 12 operating steam generators and 12 operating pumps with 4 reserve pumps. Component isolation was still possible but checkvalves 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 2 provides an excellent overview of the philosophy behind the Pickering A station.

2.2.5 Bruce A and B

Figure 8 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 600, Darlington, etc.), 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 9 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.

2.2.6 CANDU 600

The CANDU 600 has been discussed at some length in Chapter 1. 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 lead 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 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 was 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.

2.2.7 Darlington A

The HTS schematic for Darlington A is similar to the CANDU 600. The reactor is a Bruce reactor (480 channels-13 bundles/channel). Process conditions were taken very close to the CANDU 600 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 600 design.

The HTS for Darlington was designed by Ontario Hydro with design support from AECL. AECL retained design 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.

2.2.8 CANDU 950

The HTS schematic for the 950 MW station now being proposed is shown in Figure 10. The increase in power beyond Bruce and Darlington pushed manufacturing capabilities, once again, to their limits. Eight steam generators are required while four pumps are retained, although these pumps will be larger than any constructed for such a purpose. The number of channels has increased to 600, making the core configuration non-optimum (radius larger than optimum for the channel or core length). Decreased fuel burnup results but, nevertheless, the economies of scale make the trade-off worthwhile. Maximum channel flow was set at 210,000 lbm/hr (compared to 189,000 lbm/hr for CANDU 600 and Bruce and 200,000 lbm/hr for Darlington A) based on increased confidence in erosion/corrosion limits. The CANDU 600 fuel channel was adopted (12 bundles/channel).

This station is still in the early design stage.

2.2.9 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 3.

Future PHT 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 (eg: 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.

REFERENCES

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3 Power Generation, Resources, Hazards, Technology and Costs, P.G. Hill, The MIT Press, Cambridge, Massachusetts, USA, 1978.

TABLE 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

TABLE 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 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 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 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

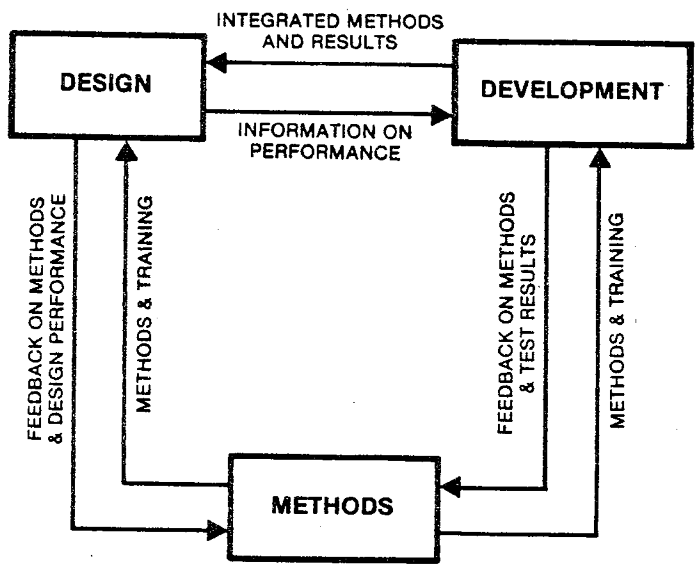

FIGURE 1 GENERAL INTERACTION PROCESS

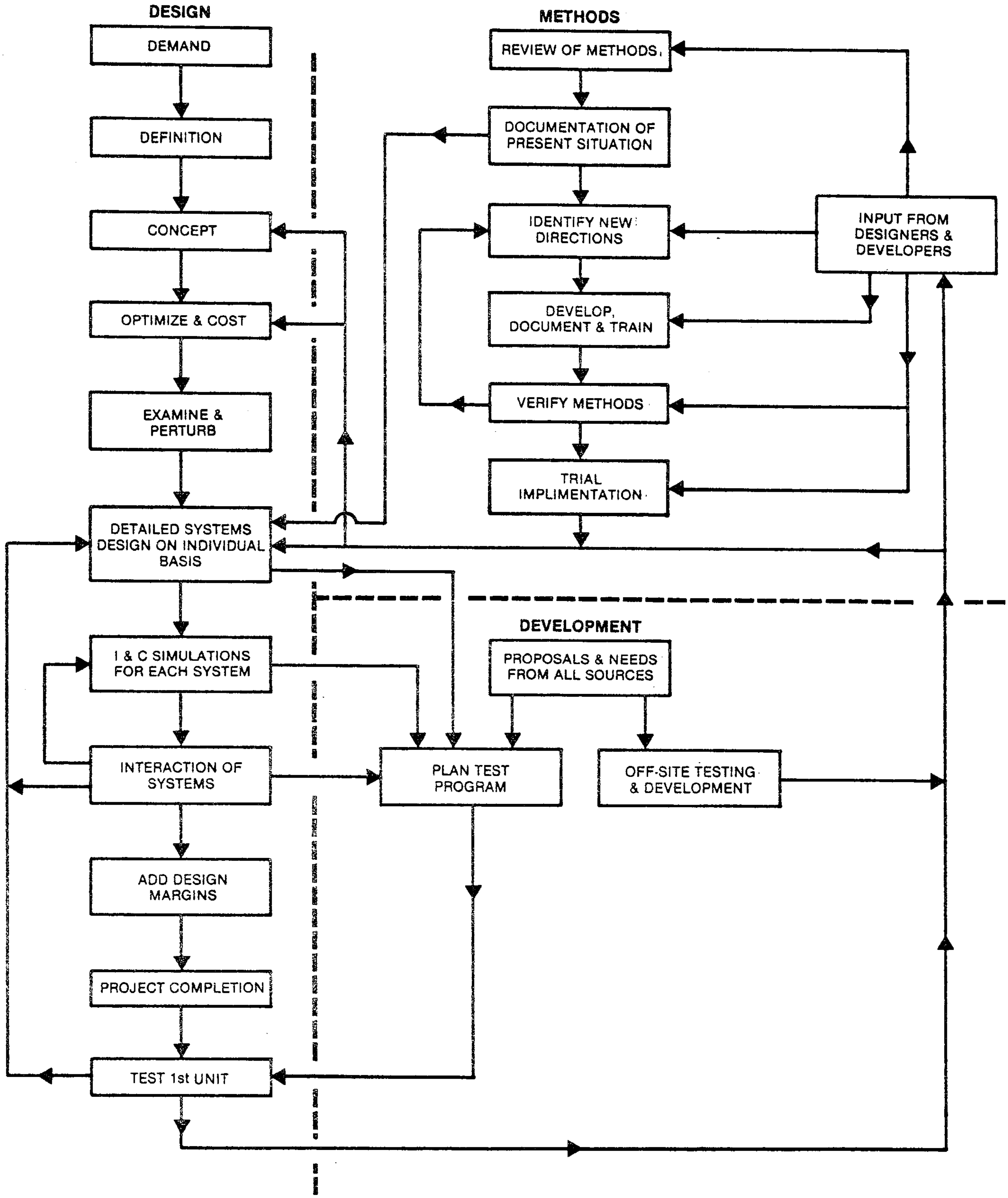

FIGURE 2 DETAILS OF INTERACTION PROCESS

SELECT INDEPENDENT VARIABLES
AND GROUND RULES
(EXAMPLE: POWER, NO. OF CHANNELS)

↓

ESTIMATE REMAINING PARAMETERS
(EXAMPLE: TEMPERATURE, PRESSURES)

↓

PERFORM TURBINE CYCLE CALCULATIONS
(STEAM FLOW, PRESSURE, HEAT BALANCE, ETC.)

↓

CALCULATE THERMAL POWER = GROSS ELECTRICAL
POWER X TURBINE HEAT RATE

↓

PERFORM REACTOR PHYSICS CALCULATIONS
(1 GROUP POINT KINETICS, BURNUP,
REFLECTORS, ETC.)

↓

CALCULATE THERMAL POWER =
(NO. OF CHANNELS X CHANNEL POWER X POWER FROM FACTOR)
— LOSSES = NET HEAT TO COOLANT

↓

CALCULATE HTS FLOW = THERMAL POWER/CHANGE IN ENTHALPY

↓

CALCULATE PRESSURE DROPS AND STEAM GENERATOR AREA

↓

CALCULATE PUMP POWER AND HEAD

↓

UPDATE HEAT LOSS AND ELCTRICAL LOAD

↓

ITERATE TO GET CONSISTENCY IN POWERS/REACTOR DIMENSIONS

↓

CALCULATE CRITICAL POWER RATIO, FUEL SHEATH
TEMPERATURE, PRESSURE TUBE THICKNESS, D_2O
INVENTORY, CORRECTIONS TO FUEL BURNUP

↓

CALCULATE COSTS (INCLUDING PENALTIES FOR
VIOLATING CONSTRAINTS, SUCH AS, VELOCITY,
CPR, QUALITY)

↓

REPEAT AS PER SEARCHING ROUTINE TO FIND OPTIMUM

FIGURE .3 OPTIMIZATION SCHEME

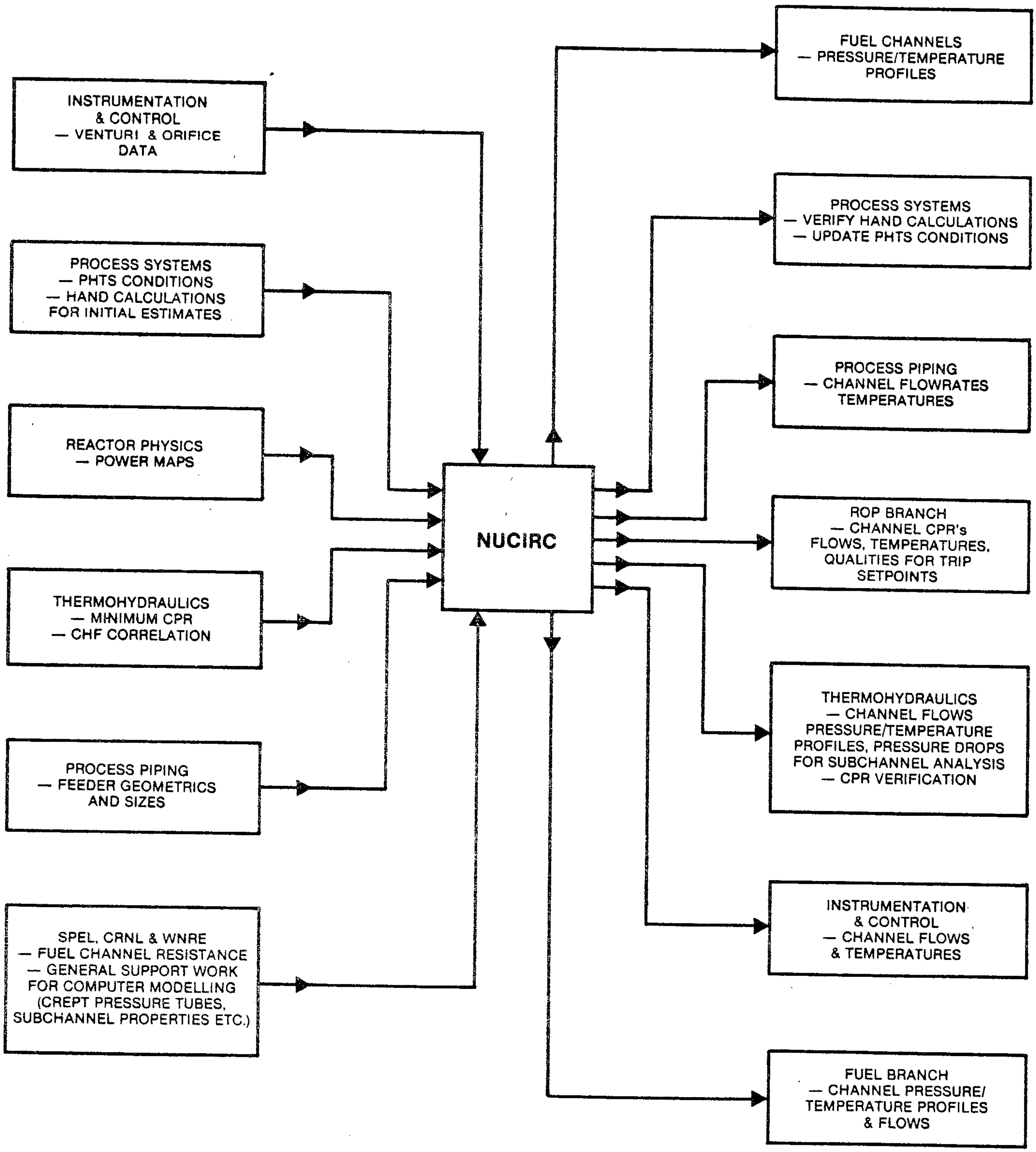

FIGURE 4 NUCIRC INTERACTION

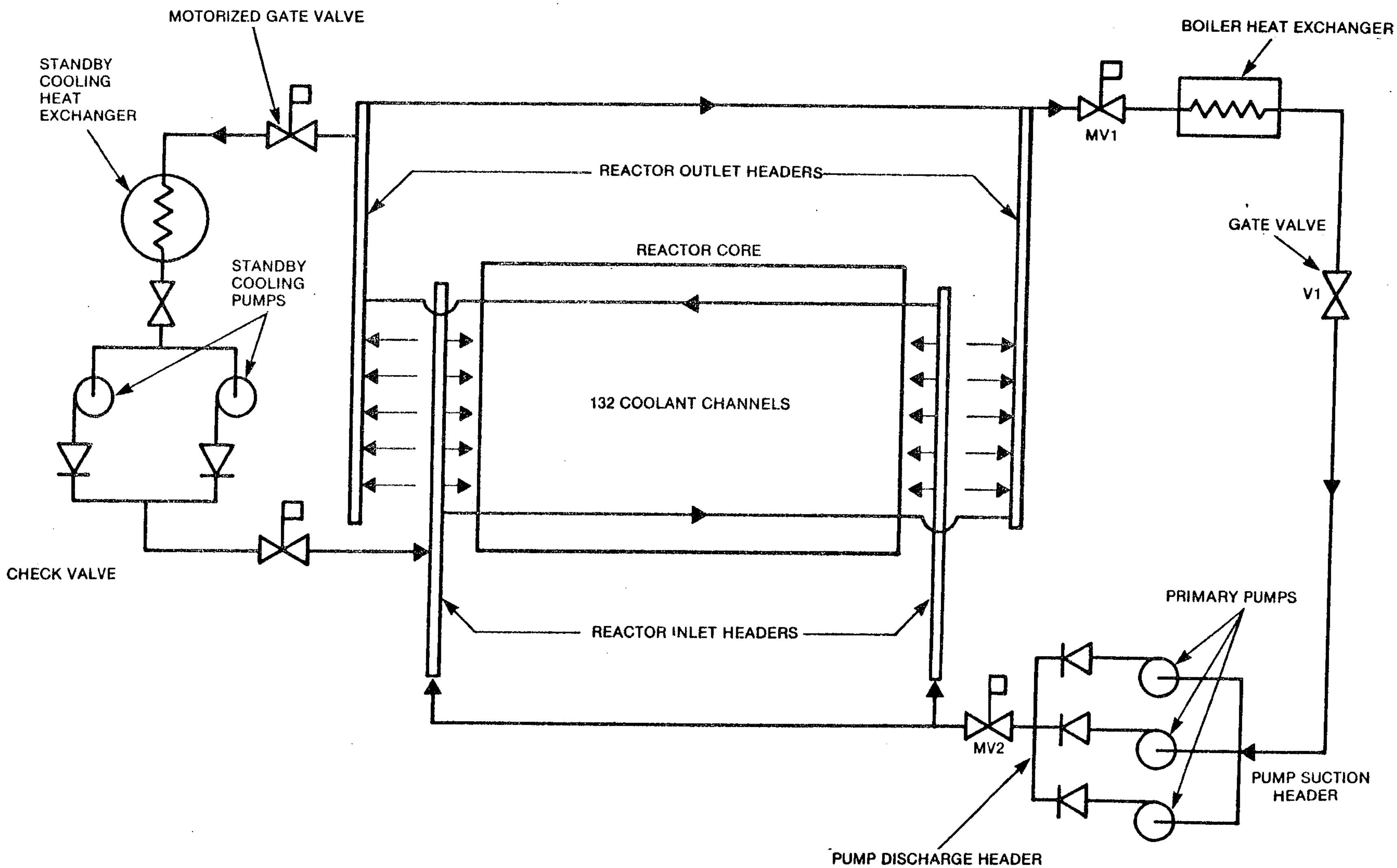

FIGURE 5 NPD MAIN PHT CIRCULATING SYSTEM

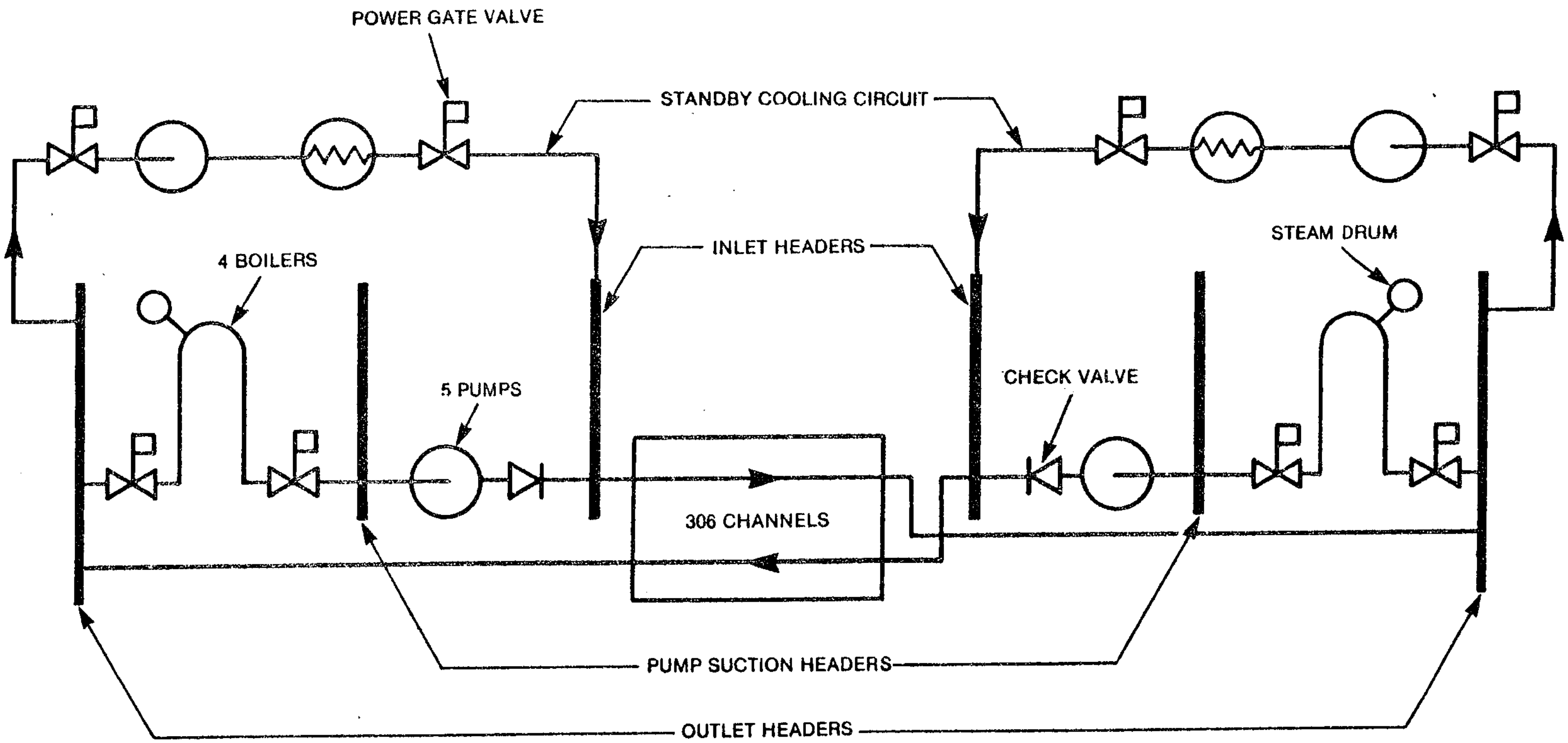

FIGURE 6 DOUGLAS POINT PHT MAIN CIRCULATING SYSTEM

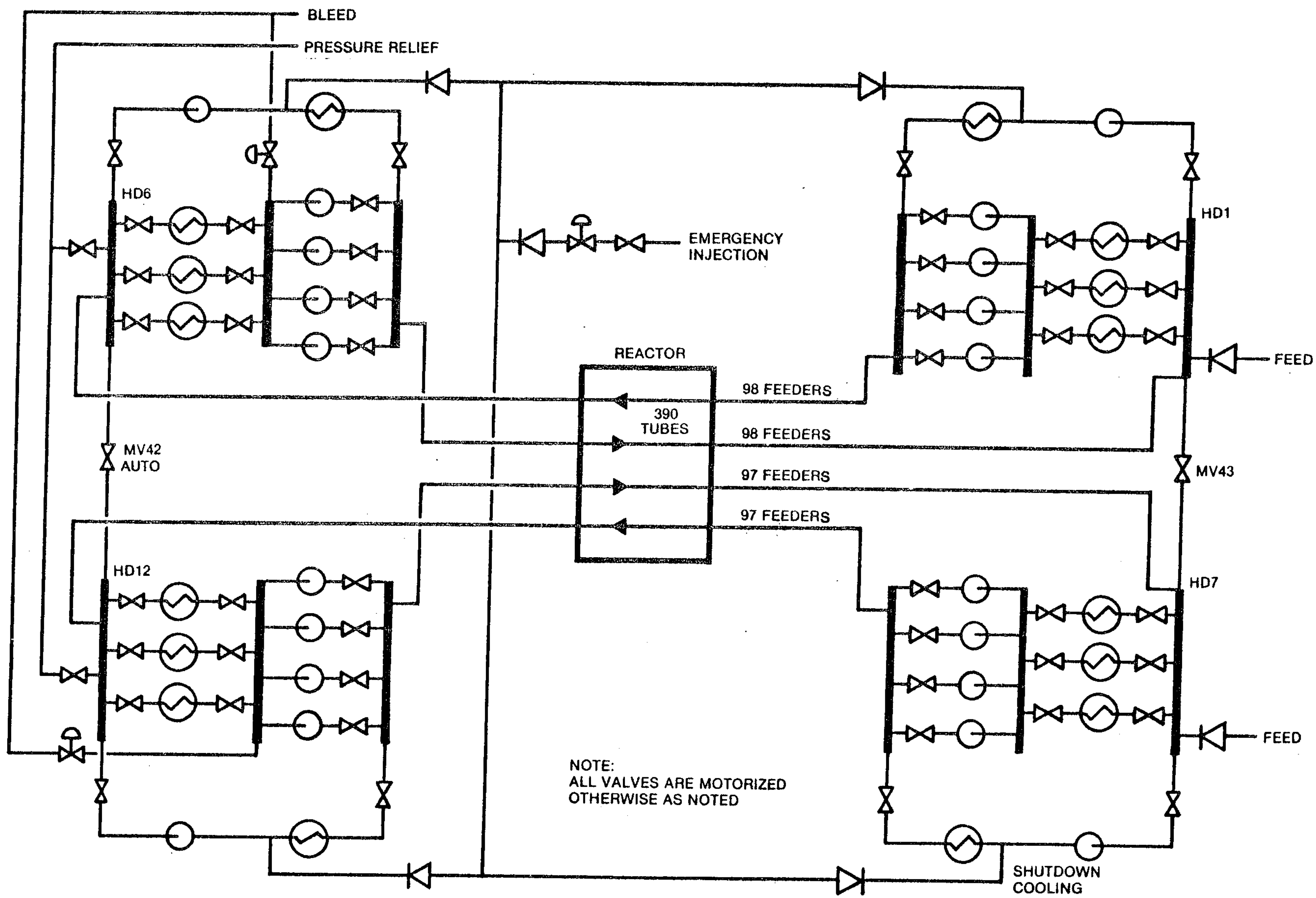

FIGURE 7 PICKERING PHT CIRCULATING SYSTEM

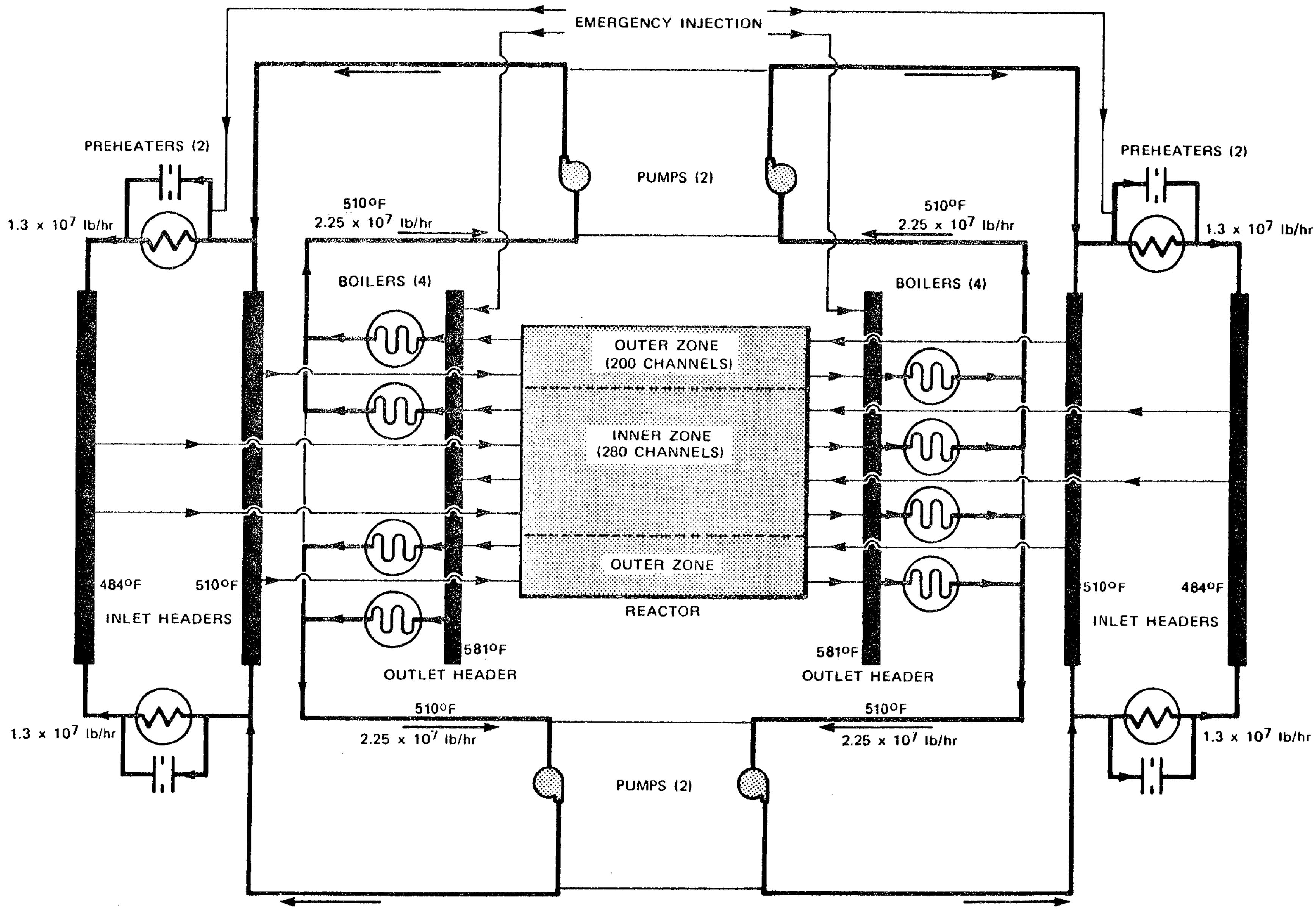

FIGURE 8 BRUCE HEAT TRANSPORT SYSTEM

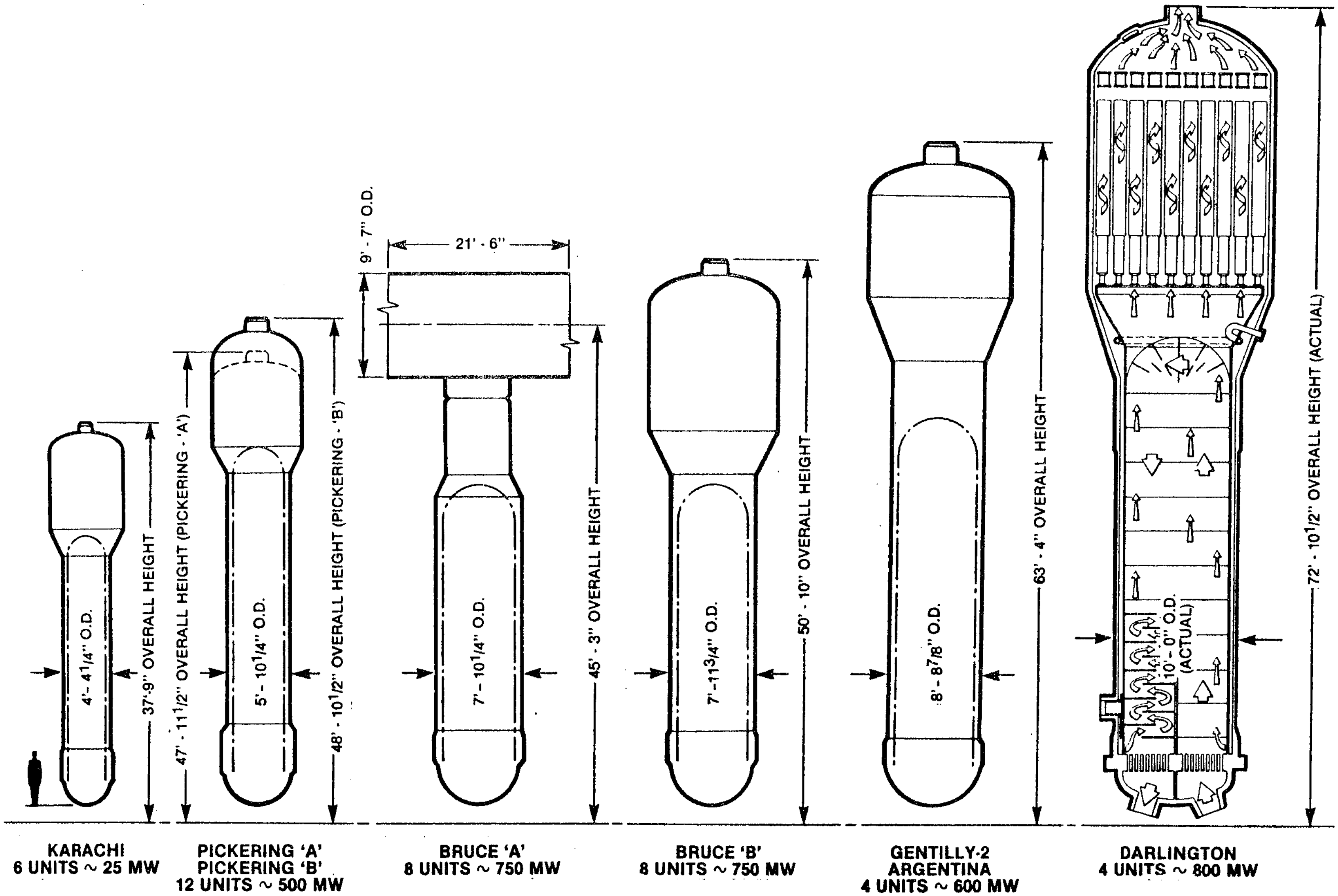

FIGURE 9 STEAM GENERATORS — RELATIVE SIZES

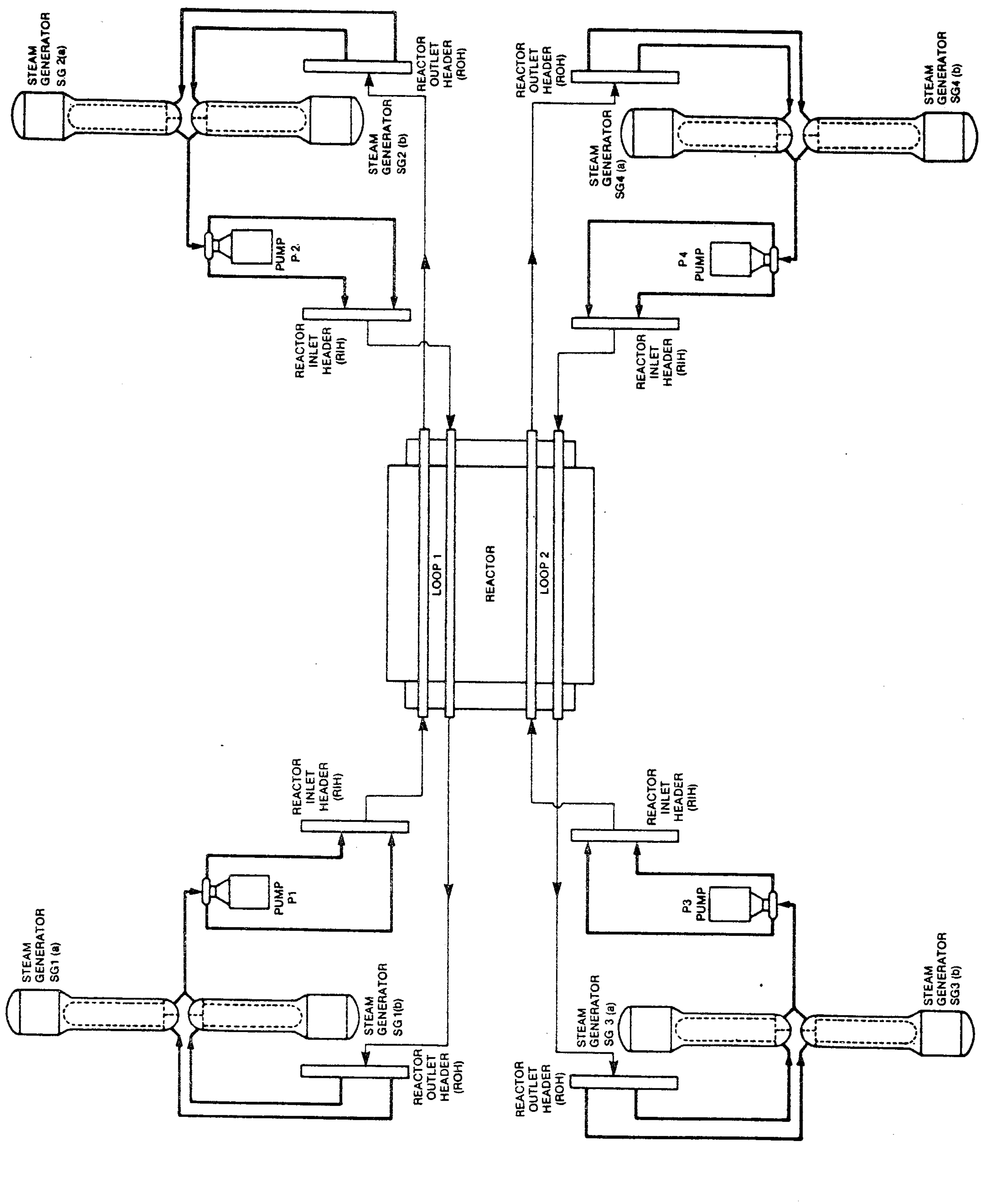

FIGURE 10 HEAT TRANSPORT SYSTEM