Material and fabrication considerations for the CANDU-PHWR heat transport system

Notes sur les matériaux et la fabrication du circuit de caloportage du CANDU-PHWR

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Abstract

CANDU PHWR Nuclear Systems have used carbon steel material for over 25 years. The accumulated operating experience of over 200 reactor years has proven this unique AECL approach to be both technically and economically attractive.

This paper discusses design, material and fabrication considerations for out-reactor heat transport system major components. The contribution of this unique choice of materials and equipment to the outstanding CANDU performance is briefly covered.

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Résumé

La filière CANDU PHWR utilise l'acier au carbone depuis 25 ans. L'expérience d'exploitation accumulée de plus de 200 réacteur-années a démontré que ce principe exclusif de l'EACL était intéressant, tant au point de vue technique qu'économique.

Le présent document traite des aspects conception, matériaux et fabrication des composants principaux du circuit du caloporteur hors réacteur. On y parle brièvement du rôle que ce choix unique de matériaux joue sur le rendement exceptionnel du CANDU.

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1. INTRODUCTION

The CANDU PHWR program began in the early 1950's by Atomic Energy of Canada Ltd. (AECL) in collaboration with the Canadian government, provincial utilities and Canadian industry. The first commercial plant - the 22 MW(e) Nuclear Power Demonstration unit (NPD) - went into operation 25 years ago in 1962. Since that time, CANDU plants have been demonstrating impressive performance results, consistently occupying several of the top places of the 500 MW(e) and larger commercial reactors in the world. To date, 29 CANDU plants of greater than 500 MW(e) have been committed, 19 of which are now operational (Table 1). Worldwide, AECL designed CANDU PHWR's have accumulated over 200 reactor years of operating time.

As Canada is one of the few countries to have developed its own unique nuclear power system, it is worthwhile to briefly explain some of the historical and economic background to the CANDU-PHWR.

When the Canadian nuclear program was launched in the 1950's, Canada, with a population of about fifteen million, had an industrial infrastructure with limited manufacturing expertise in power plant components. But Canada had abundant reserves of uranium. These factors determined the cornerstones of the CANDU program: the ability to utilize natural uranium fuel and cooperation with Canadian industry to develop the necessary expertise.

The ability to utilize natural uranium fuel was particularly important from a national standpoint both in terms of economics and freedom from dependence on external fuel supply, since it eliminated the need for an enrichment plant. The selection of a fuel cycle based on natural uranium required the use of a moderator of which heavy water was the most suitable and for which the manufacturing technology was available in the process industry.

A second cornerstone in the development of the CANDU has been cooperation between AECL and Canadian industry. When Canada undertook the initial design and development program of the CANDU-PHWR in commercial reactor sizes, a close relationship with Canadian industry evolved. Design concepts for the heat transport system configuration, took into account the existing manufacturing capacity in the country. From the beginning, factors such as ease of manufacturing, availability of materials and use of existing plant facilities and design capability were important considerations. As a result, nearly all major CANDU equipment and components were (and are) designed and manufactured locally in Canada. This has been achieved by integration of the design and material selection (such as carbon steel piping) to allow use of smaller equipment with relatively conventional material fabrication processes.

These factors were significant in the longstanding support given to the development of the CANDU system by the various levels of the Canadian government.

This paper will discuss various material and fabrication considerations for the CANDU-PHWR Heat Transport System (HTS) and show how the characteristics of the CANDU system adapt well to countries with industrial technology similar to that of Canada. This will be illustrated by the heat transport system design, material and fabrication as well as operating experience covering capacity factors, reliability, man-rem exposure and environmental impact.

TABLE 1

CANDU REACTORS IN OPERATION OR UNDER CONSTRUCTION

Name	Location	Capacity MWe net	In-service date
NPD	Canada	22	1962
Pickering 1	Canada	515	1971
Pickering 2	Canada	515	1971
Pickering 3	Canada	515	1972
Pickering 4	Canada	515	1973
Kanupp	Pakistan	125	1971
Rapp 1	India	203	1972
Rapp 2	India	203	1980
Bruce 1	Canada	825*	1977
Bruce 2	Canada	825*	1977
Bruce 3	Canada	825*	1978
Bruce 4	Canada	825*	1979
Point Lepreau	Canada	633	1983
Gentilly-2	Canada	638	1983
Wolsung-1	Korea	638	1983
Embalse	Argentina	600	1984
Pickering 5	Canada	516	1983
Pickering 6	Canada	516	1984
Pickering 7	Canada	516	1984
Pickering 8	Canada	516	1986
Bruce 5	Canada	825	1985
Bruce 6	Canada	825	1984
Bruce 7	Canada	825	1986
Bruce 8	Canada	825	1987
Cernavoda (5 unit station)	Romania	665 x 5	Late 1980s to 1990s
Darlington 1	Canada	881	1989
Darlington 2	Canada	881	1988
Darlington 3	Canada	881	1991
Darlington 4	Canada	881	1992
	TOTAL	20 635	

* Electrical equivalent (electricity plus process steam).

2. GENERAL REACTOR AND HEAT TRANSPORT SYSTEM DESCRIPTION

The CANDU reactor is contained within a low pressure tank called the calandria (Figure 1). Each of the fuel channel assemblies which run horizontally through the calandria is made up of two end fittings, a pressure tube and a calandria tube. The pressure tubes, which are the incore part of the fuel channel and are part of the pressure boundary of the heat transport system contain the bundles of natural uranium fuel. The annular space between the pressure tube and the calandria tube provides thermal insulation between the hot heat transport system and the cool moderator. The calandria contains two separate bodies of heavy water. One surrounds the calandria tubes and is at low temperature and pressure. Its purpose is to moderate or slow the fast neutrons, making a chain reaction possible. The other body of heavy water removes the heat of fission generated within the fuel as it is pumped through the fuel channels. This hot heat transport fluid is passed through the steam generator where heat is transferred to light water to generate steam.

The CANDU 600 MW(e) reactor has 380 fuel channels arranged in a square array within the calandria. The heat transport system is arranged into two circuits, one to each side of the vertical centre line of the reactor core, with 190 fuel channels in each circuit. The circuits are shown in Figure 2; each circuit contains 2 pumps, 2 steam generators, 2 inlet and 2 outlet headers in a "figure-of-eight" arrangement. Feeders connect the inlet and outlet of the fuel channels at the end fittings to the inlet and outlet headers respectively.

In the CANDU 600 HTS the heavy water exits from the channels at 310°C and returns to the channel inlets at 260°C. The pressure at the channel inlet is about 10 MPa. The net quality of the heavy water at the outlet headers is less than 4%.

The flow through the fuel channels is bidirectional (i.e. opposite directions in adjacent channels). The feeders are sized so that the coolant flow to each channel is proportional to channel power. The enthalpy increase of the coolant is therefore the same for each fuel channel assembly.

One of the advantages of the "figure-of-eight" arrangement is that in the event of a heat transport pump failure, the coolant flow in the circuit is maintained at approximately 70% of the normal value, thereby permitting continued reactor operation at reduced power.

The arrangement of the heat transport system within the reactor building is illustrated in Figures 3 and 4. The steam generators, HTS pumps and headers are located above the reactor; this permits the heat transport system coolant to be drained to the header elevation for maintenance of the HTS pumps and steam generators, and also facilitates thermosyphoning (natural circulation) when the HTS pumps are unavailable.

Each vertical centrifugal type HTS pump (Figure 5) has a single suction and double discharge. The rotational inertia of the pump-motor assemblies is sufficient to extend pump rundown so that coolant flow matches the reactor power decrease following a loss of power to the pump motors.

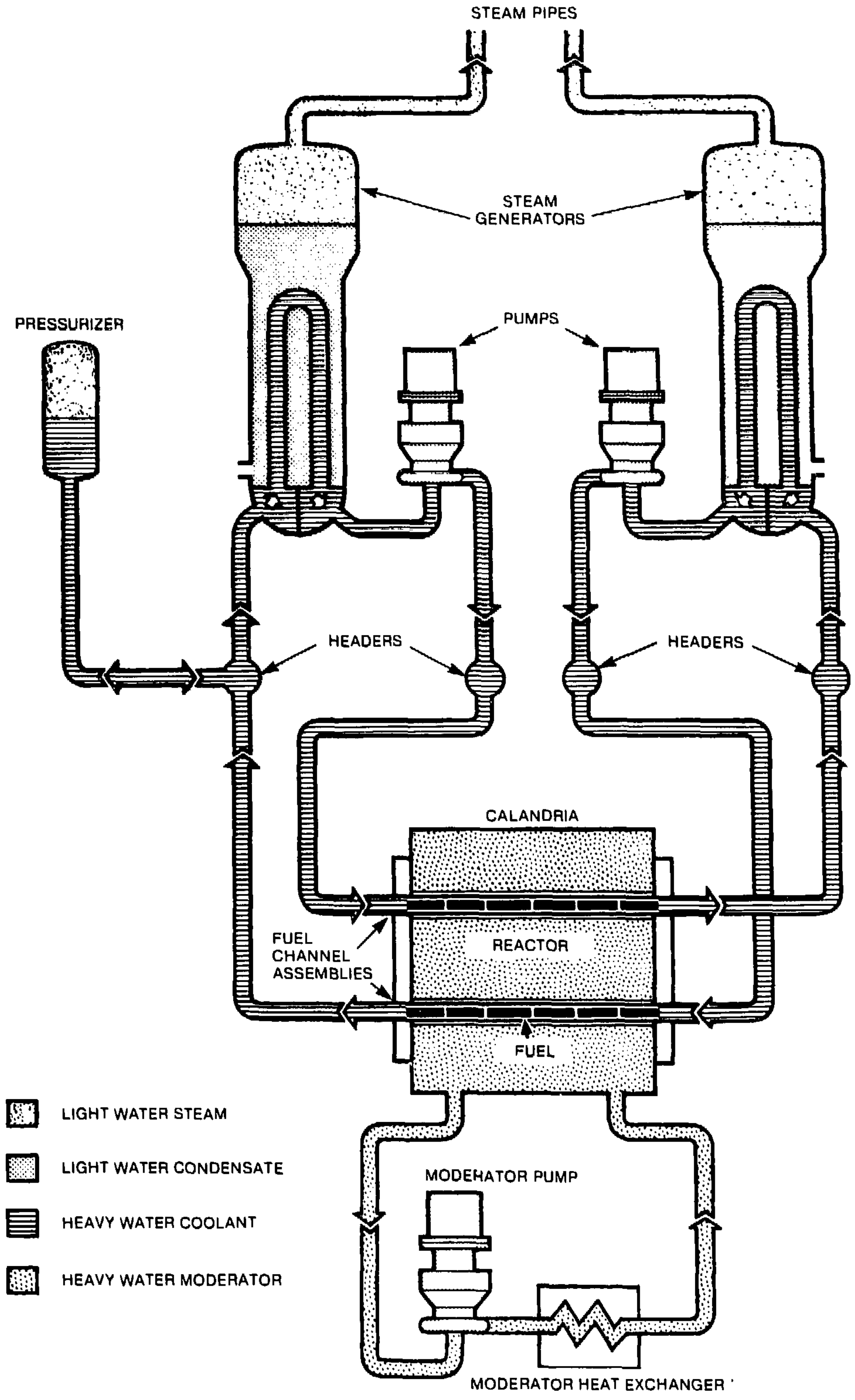


FIGURE 1 CANDU NUCLEAR STEAM SUPPLY SYSTEM

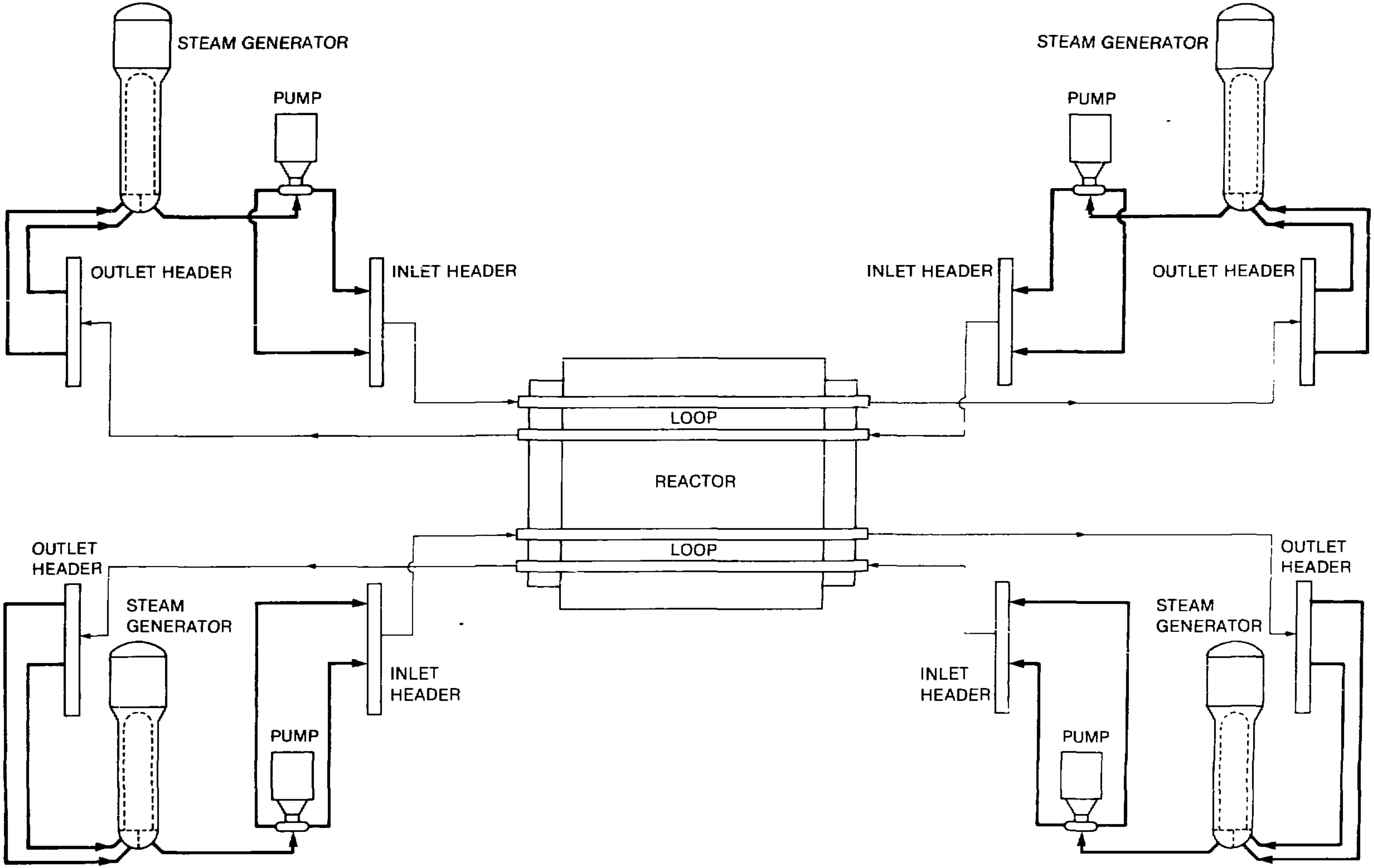
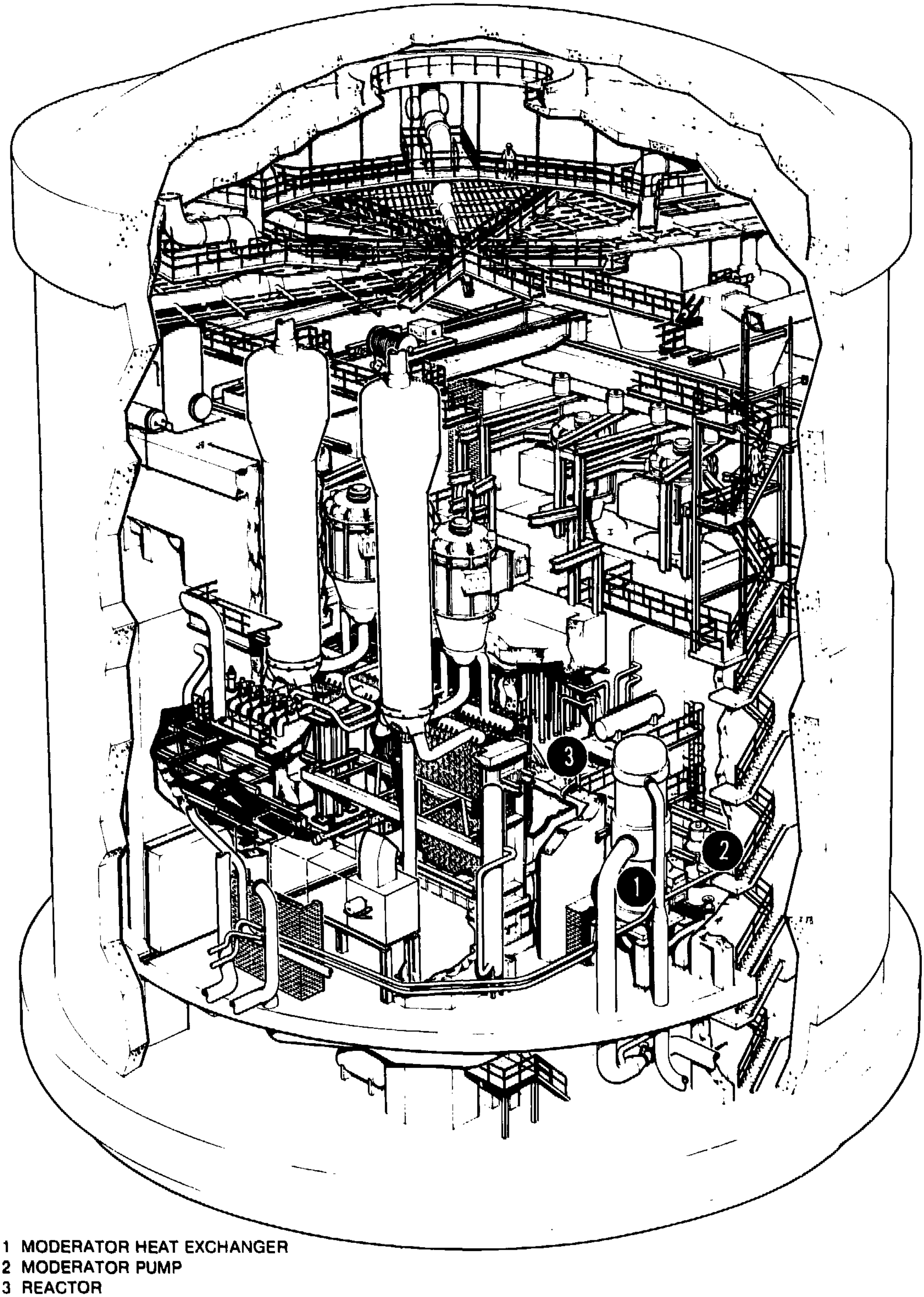


FIGURE 2 A HEAT TRANSPORT SYSTEM



1 MODERATOR HEAT EXCHANGER
2 MODERATOR PUMP
3 REACTOR

FIGURE 3 LOCATION OF MAIN MODERATOR SYSTEM EQUIPMENT

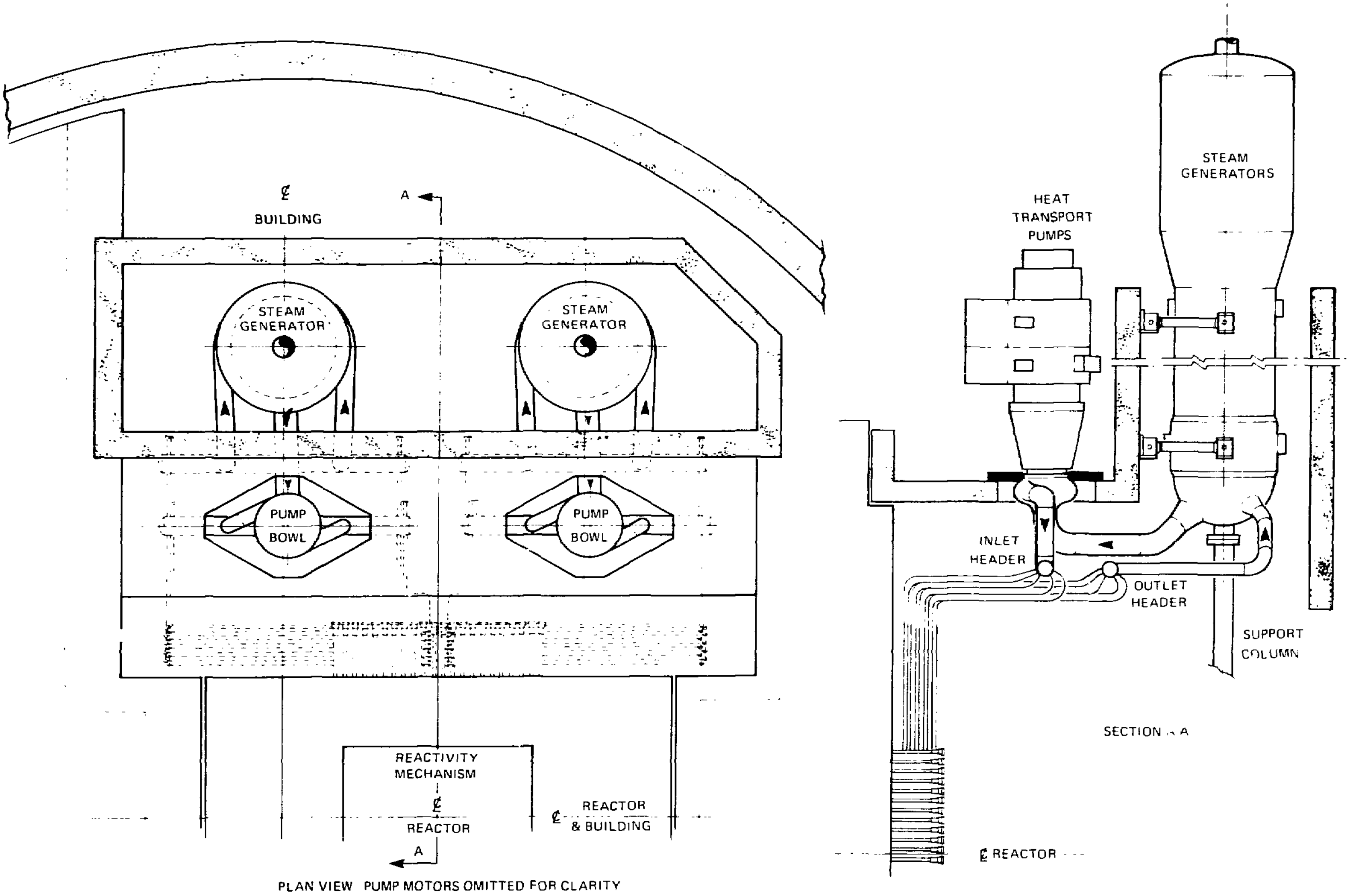
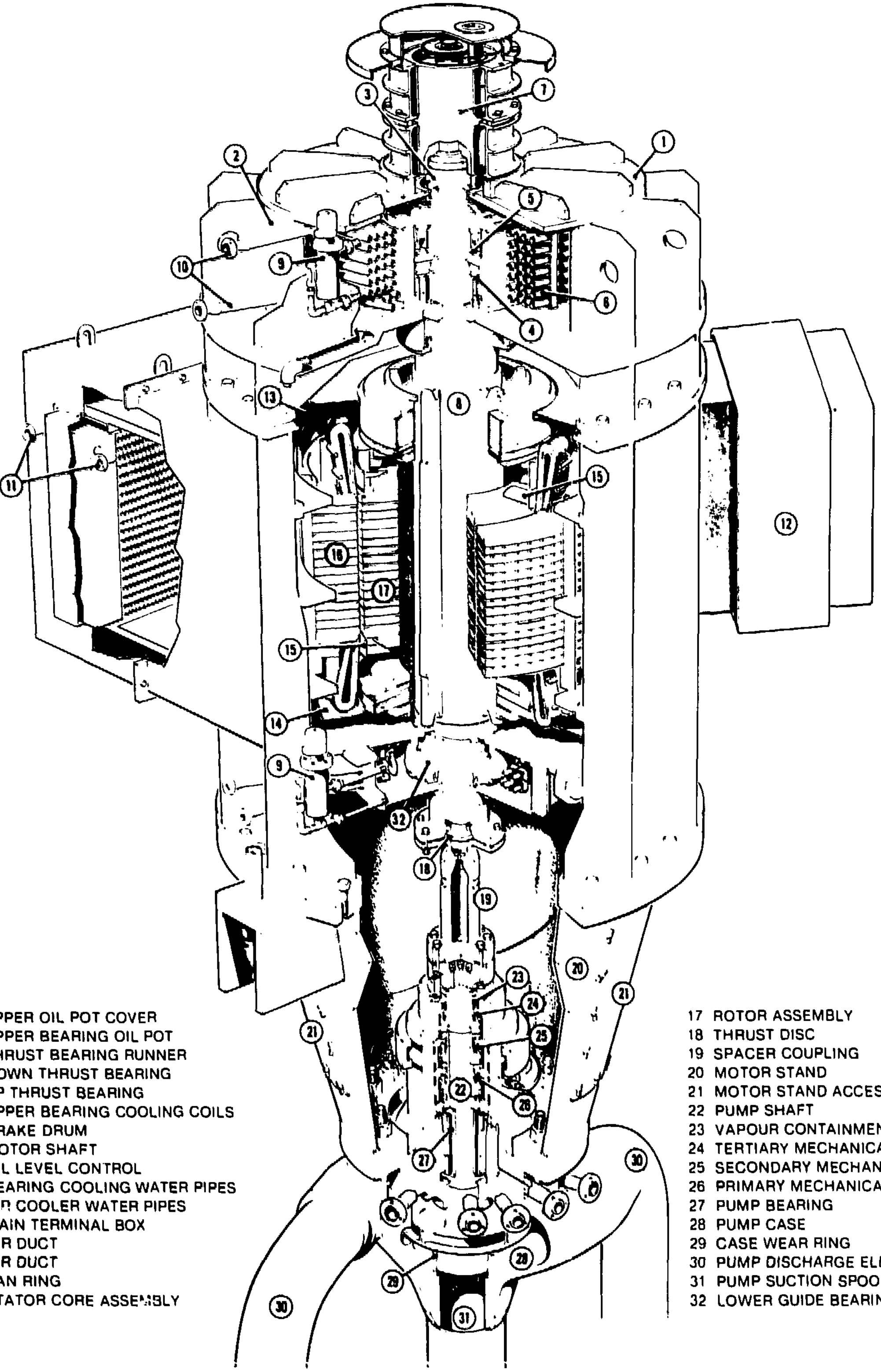


FIGURE 4 CANDU 600 HEAT TRANSPORT SYSTEM — MAIN CIRCUIT ARRANGEMENT (PLAN AND ELEVATION)



1 UPPER OIL POT COVER
2 UPPER BEARING OIL POT
3 THRUST BEARING RUNNER
4 DOWN THRUST BEARING
5 UP THRUST BEARING
6 UPPER BEARING COOLING COILS
7 BRAKE DRUM
8 MOTOR SHAFT
9 OIL LEVEL CONTROL
10 BEARING COOLING WATER PIPES
11 AIR COOLER WATER PIPES
12 MAIN TERMINAL BOX
13 AIR DUCT
14 AIR DUCT
15 FAN RING
16 STATOR CORE ASSEMBLY
17 ROTOR ASSEMBLY
18 THRUST DISC
19 SPACER COUPLING
20 MOTOR STAND
21 MOTOR STAND ACCESS DOORS
22 PUMP SHAFT
23 VAPOUR CONTAINMENT SEAL
24 TERTIARY MECHANICAL SEAL
25 SECONDARY MECHANICAL SEAL
26 PRIMARY MECHANICAL SEAL
27 PUMP BEARING
28 PUMP CASE
29 CASE WEAR RING
30 PUMP DISCHARGE ELBOWS
31 PUMP SUCTION SPOOL PIECE
32 LOWER GUIDE BEARING ASSEMBLY

FIGURE 5 TYPICAL CANDU 600 HEAT TRANSPORT PUMP

The steam generators feature (Figure 10) integral preheaters and steam drums. The heavy water coolant passes into the primary heads and through the U-tube bundle. On the secondary side, the feedwater enters the preheater section of the steam generator, which encompasses the lower portion of the cold leg of the tube bundle. The two phase light water-steam mixture rising from the U-tube region of the steam generator is passed through steam separation equipment to assure that the moisture content of steam leaving the steam generator is less than 0.25%. The liquid removed from the steam is returned to the tube sheet region of the steam generator via the annular downcomer. The circulation ratio for CANDU steam generators is approximately 6 to 1.

Typical arrangements of the feeders, end fittings and reactor inlet and outlet headers are shown in Figures 6 & 7.

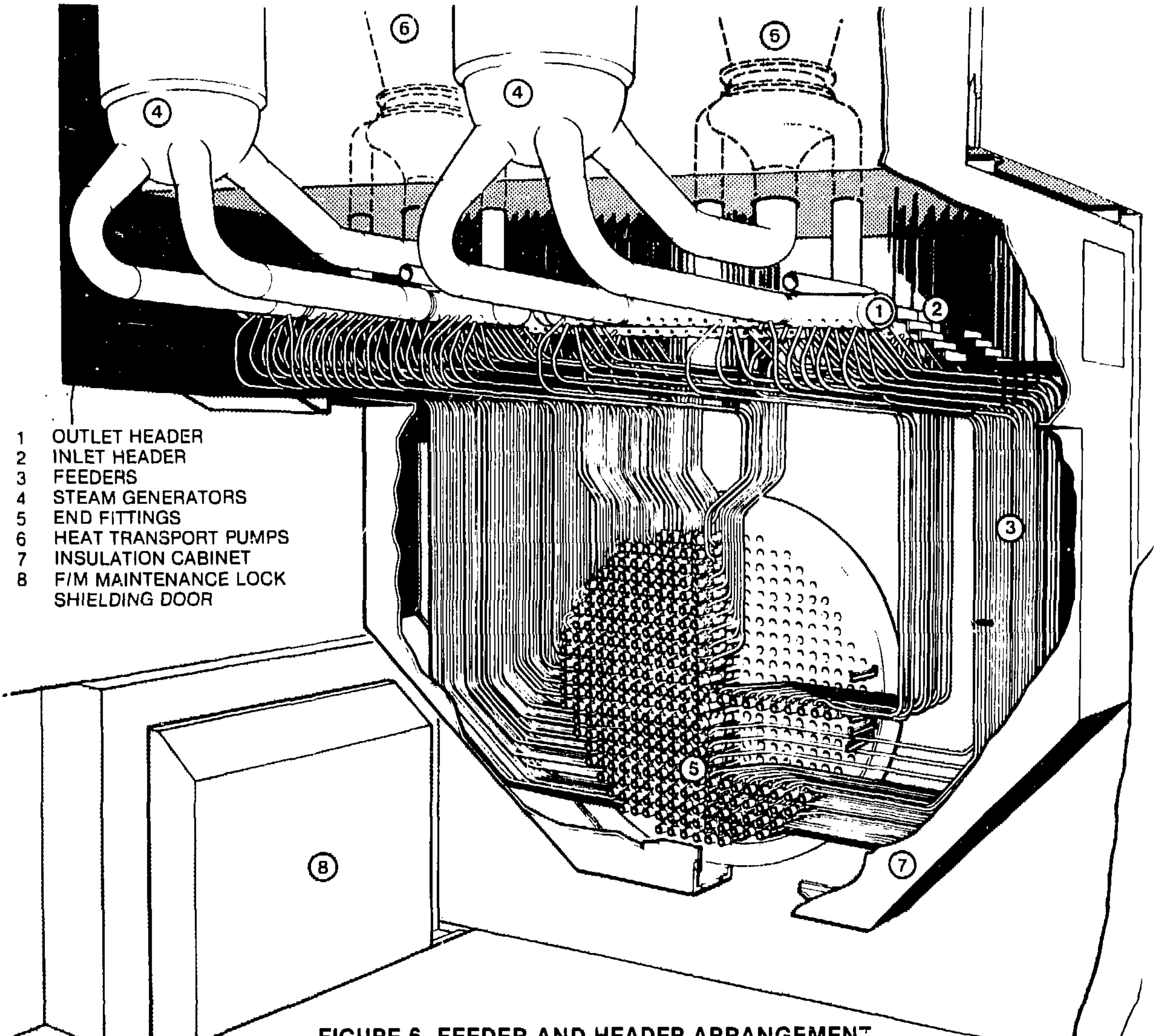


FIGURE 6 FEEDER AND HEADER ARRANGEMENT

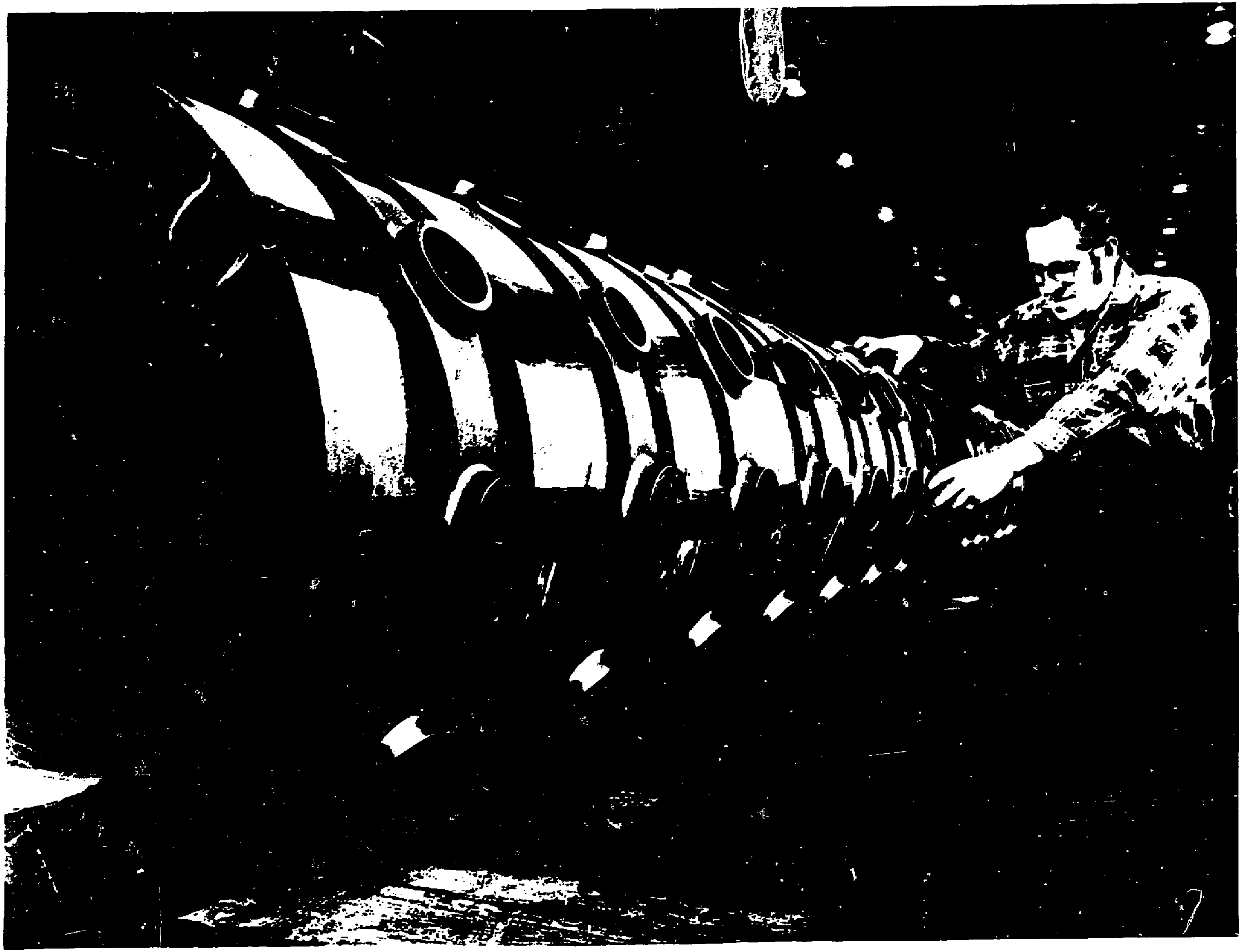


FIGURE 7 TYPICAL HEADER

3. OUT-REACTOR HEAT TRANSPORT SYSTEM DESIGN AND MATERIAL CONSIDERATIONS

The CANDU Heat Transport System (HTS) has features similar to other water cooled reactors, but one of the unique features is the use of carbon steel as the out-of-reactor pressure boundary material (with the exception of the steam generator tubes). With the carbon steel HTS circuit, the capability and manufacturing facilities within Canada were able to be more utilized for supply of the components. This section deals with the design and material considerations, particularly with regard to selection of carbon steel.

Carbon steel has a long and successful history as a power plant material in fossil-fired stations. Fabricators and construction site personnel are used to handling this material. The decision to use carbon steel in both the CANDU-PHWR heat transport system and in the secondary systems was made in the late 1950's for the NPD reactor at Rolphton, Ontario. This policy has been maintained in all CANDU nuclear steam plants with consistent success.

A number of advantages have been identified with the choice of carbon steel. These are:

(a) Cost

Carbon steel piping is less expensive than the alternative, stainless steel, by a factor of three for both the capital cost and the installed cost.

(b) Availability/Familiarity

Carbon steel has well known mechanical properties and is available in a wide range of product forms from many suppliers.

(c) Assembly

The procedures for welding carbon steel are well developed and allow greater latitude in parameters than procedures for low alloy steels and stainless steels. The majority of the piping is of a size that does not require post weld heat treatment. Thus construction is simplified and construction time is shorter than that for higher alloyed steels. Most of the piping is to SA106B requirements and supplied in the normalized condition. Bending of feeders is used to minimize welds and eliminate fittings.

(d) Compatibility with the Environment

The resistance of carbon steel to general corrosion, localized corrosion, erosion corrosion, impurity attack and activity transport is very suitable for the 300°C heavy water environment in the HTS. Major factors relating to the environment compatibility of carbon steel are reviewed bellow:

General Corrosion

The separation of the heat transport heavy water from the moderator heavy water enables the water chemistry in both systems to be optimized. As no reactivity control is done in the CANDU-PHWR heat transport system, its water chemistry is optimized to minimize corrosion, corrosion product transport and the activation of the mobile corrosion products. Chemical additions for reactivity control are made to the low temperature moderator system. The actual long-term corrosion rates of carbon steel, as determined from corrosion coupons exposed to heat transport system heavy water at operating CANDU PWHR plants, average less than two (2) micrometers per year. Thus the total corrosion over the life of the plant will be less than 0.1 mm. This is less than 15% of the design basis corrosion allowance for large diameter components.

The resistance of carbon steel to corrosion is based upon the maintenance of a film of magnetite (Fe_3O_4) on the carbon steel. This magnetite film is developed by a conditioning treatment prior to reactor operation. It is maintained by controlling the pH within the range 10-10.5 and keeping low dissolved oxygen concentrations, typically less than 15 micro g O_2/kg D_2O. Under such conditions the corrosion rate of carbon steel continuously decreases to extremely low rates. The low oxygen conditions are easily maintained.

Atmospheric corrosion is neglible in the warm dry atmosphere of the reactor vault since the atmosphere is dried to recover heavy water moisture.

Localized Corrosion and Impurity Attack

The factors affecting localized corrosion of carbon steel, notably caustic concentrations do not occur in the CANDU HTS piping system. Impurities such as low concentrations of chlorides do not cause stress corrosion cracking as they can with stainless steel. The heat transport system is maintained at a high purity by ion exchange equipment and impurity levels do not become a problem. Oxygen concentrations are maintained at very low values in the non-boiling CANDU plants and although measurable are still low in the boiling systems.

Compared to stainless steel with its susceptibility to stress corrosion cracking or sensitization cracking in oxygenated environments, carbon steel is an optimum choice.

Erosion Corrosion

Feeders are sized to ensure heavy water velocities are below design limits that have been established by testing and experience to minimize erosion or erosion corrosion effects. Generally, 17 m/s is used as a design limit.

A joint AECL/Ontario Hydro (Reference 1) test program was carried out between 1980 December and 1982 April, i.e. for a period 482 days, to assess the erosion-corrosion of carbon steel piping at a temperature of 300°C and at velocities of 9.5 m/s, 23 m/s and 38.1 m/s. The water chemistry was generally maintained at pH values (measured at 25°C) between 10 and 11 and with dissolved oxygen concentrations below 15 micro g O_2/kg H_2O. The test pieces included 90° elbows and straight pipe.

The uniform metal loss rate found in the test program confirmed the very low rates found from corrosion coupon measurements at Pickering NGS 'A' which indicate rates of 2 to 3 micrometers per year, or 60 to 90 micrometers over 30 years. These values are only 3 percent of the corrosion allowance of 2700 micrometers.

At the 38 m/s flow rate, which is more than twice the actual maximum flow rate, pitting to a depth of 50 micrometers was observed. No pitting was observed at the lower velocities of 23 m/s and 9.5 m/s.

This work confirmed the design limit used. In addition wall thickness measurements at operating plants have not detected any wall thickness loss on bends or straight sections of feeders.

Activity Transport

During reactor operation, small amounts of corrosion products (called crud) are released from the walls of the piping and are transported throughout the HTS circuit. Deposition of this crud on the fuel for a period of days or weeks would cause it to become radioactive and upon release from the fuel the now irradiated crud could deposit on the out-reactor circuits where it would contribute gamma radiation to the operating environment. The pH range specified for the CANDU-PHWR HTS coolant has been chosen not only to achieve low crud release rates from the carbon steel but also to discourage the deposition of the crud on the fuel. As a result the activation of the crud is minimized. The degree of activation of the crud is further reduced by controlling the impurity levels in the materials used for the HTS components, particularly cobalt content, because of the activation of Co^{59} to Co^{60} which could occur as crud resides within or passes through the reactor core.

4. FABRICATION CONSIDERATIONS OF THE MAJOR HTS COMPONENTS

General

In this section, various fabrication aspects of the major out-reactor components used in the heat transport system are covered with particular emphasis on the pressure boundary aspects. The components included are the steam generators, the HTS pumps, HTS auxiliary system valves, the feeders and headers and main HTS piping.

However, prior to discussing individual components, a few comments are appropriate regarding material toughness. Designers and users are well aware of the need for good fracture toughness in the nuclear pressure boundary materials. This is needed in order to ensure brittle fracture does not occur and to provide resistance to the growth of any defects that may have been undetected.

AECL therefore specifies that pressure boundary components of the heat transport system, are capable of meeting an RT_{NDT} (Nil-Ductility Reference Temperature) of -6.7°C (+20°F) or lower. The reasons are:

(i) This allows the system hydrostatic test at site to be done at 26.7°C (80°F) which fully meets the ASME Code recommendation of a test temperature of 60°F above the RT_{NDT} temperature. A higher RT_{NDT} would require heating of the system during hydrostatic testing.

(ii) With a low Nil-Ductility Reference Temperature, the heat transport system when shutdown during service, can be pressurized in the ambient condition. This increases flexibility of operation of the CANDU system, allowing relatively short heatup times.

(iii) Also, indirectly the specification of a low RT_{NDT} results in a better quality of steel, since it is only achieved by good control of chemical composition, melting practice, material forming processes and heat treatment.

Our experience is that the RT_{NDT} temperature of -6.7°C (+20°F) or lower, can be obtained on all the carbon steel components, even on tubesheets of the size required for CANDU steam generators.

A further consideration that generally applies to all HTS components is cobalt concentration. Cobalt has been identified as a major contributor to radiation fields in many reactor systems. Trace quantities are present in all steels. Thus any cobalt containing corrosion particulate that is circulated through the reactor becomes radioactive from its cobalt content. AECL has found it practical to specify and obtain low cobalt content (typically less than 0.01%) at a small cost premium, on all HTS pressure boundary components.

Steam Generator

CANDU steam generators (Figure 10) both on the secondary side as well as the primary side, are designed and fabricated to the rules of ASME Section III Class 1 with additional AECL requirements imposed in some areas. Typical materials are given in Table 2. The exceptions to the carbon steel grades are the tubes and the tubesheet overlay.

TABLE 2

TYPICAL CANDU STEAM GENERATOR MATERIALS

Shell	SA516-70
Heads	SA516-70
Tubesheet	SA508 C1-2
T/S Overlay	Ni-Cr-Fe
Nozzles	SA541 C1-2
Internal Shrouds	A515 or A516
Tubing	Ni-Fe-Cr

Because of the ability to control the chemistry of the primary circuit to a high pH and low oxygen, use of carbon steel provides an economic benefit in material cost and weldability. The relatively small diameters and lower design pressures of CANDU steam generators does not necessitate high strength low alloy steel plate to achieve reasonable shipping weights. Hence, low cost, readily weldable SA-516 Gr70 plate is used for the shell as opposed to say SA-533 plate. For instance, the steam drums in CANDU-600 steam generators are typically 4 m diameter and 73 mm wall thickness.

Tubesheets are forgings with emphasis placed on steel making and forging practice to achieve high steel cleanliness. A Ni-Cr-Fe weld metal of composition compatible with the tube material and of high integrity is deposited on the primary side of the tubesheet by techniques that keep distortion to a minimum. The welding process itself is the prerogative of the manufacturer and both MIG and submerged arc processes have been used satisfactorily. Tubesheets are typically 2.5 m diameter and 380 mm thick.

The secondary side shell and the primary and secondary heads are formed from plate. The plate material must meet both the requirements of the ASME pressure vessel code and the additional requirements of the AECL specification. Supplier's fabrication processes are reviewed to assure the material can meet the required properties. Emphasis is placed on appropriate through - thickness properties to prevent problems such as lamellar tearing. All the heads for a CANDU 600 steam generator are made as one piece. Two piece heads are not excluded but they are not necessary for the size of head used in the CANDU 600 plants.

For the shell and nozzle welds, submerged arc and manual shielded arc welding techniques are generally used. For welds finished from one side with restricted access to the opposite side, TIG root pass techniques are used. AECL specifies requirements for preheat before thermal cutting, preheat for all pressure boundary welding and additional NDE of weld preparation sufaces prior to welding. Surface NDE requirements are also specified for first and final passes of welds in addition to the ASME Section III requirements.

HTS Pumps

Typical CANDU HTS pump is shown in Figure 5. As with other primary side components, the pump pressure boundary is designed, built and tested to the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Class 1. The pressure boundary includes the pump casing and the pump cover which is mounted on the top of the casing and sealed by a double gasket. The casing consists of a vertical bottom suction nozzle, the main bowl and two horizontal discharge nozzles.

In CANDU reactors, the pressure tube and fuel design characteristics lead to higher head, lower flow heat transport pumps compared with those of the PWR. Hence the pump characteristics (e.g. specific speed number) allow the use of a volute type casing rather than one with internal diffusers around the impeller.

The CANDU pump bowls are a relatively simple one-piece carbon steel casting. The pump casing is SA-216 Grade WCC, and weighs approximately 7000 kg. with a 50 cm pump suction nozzle and two 40 cm discharge nozzles.

The cover is a welded fabrication of two forgings. The horizontal cover flange and vertical cylinder (stuffing box) are of ASME SA-350 Grade LF2, ultrasonically inspected carbon steel. The stuffing box also contains the pump shaft seals. The cover assembly weighs approximately 2200 kg.

Pump shafts are of forged steel, containing not less than 11% chromium. SA-479 type 410 is the typical specification used. Shafts are typically 200 mm diameter and 1.8 m long.

The impellers are typically martensitic stainless steel casting to SA-487 Class CA6NM. Impellers are single stage, 0.86 m in diameter and weighing 365 kg.

Valves

The use of valves has been avoided entirely in the main circuits of the Heat Transport System. In the heat transport auxiliary systems, such as Pressure and Inventory Control and Shutdown Cooling, gate and globe valves are used for isolation and flow routing purposes and control valves for feed and bleed control. The valves used are extremely reliable and incorporate design features specifically to minimize leakage to atmosphere (bellows seals on low-stroke valves, live-loaded packing on long-stroke valves).

As with the main heat transport system, the principal material of construction for the heat transport auxiliary systems is carbon steel. Hence, valve bodies are typically castings to ASME SA-216 Grade WCB or equivalent carbon steel forged material. Low cobalt content is specified as described previously and our experience is that it can be obtained at a small premium. Because of its high cobalt content, Stellite is not accepted as a hard facing material. Where hard facing is needed, cobalt-free alloys are currently specified. Cobalt-free hard facing alloys have been used in CANDU systems since the early 1970's.

The valve gland is an important area of material selection. For valve stems, the materials specified are required to have qualities of dimensional stability, wear resistance, and low friction for satisfactory operation. For control valves, oxidized Zircaloy, 17-4 pH SS, and Inconel 625 are typically used. When martensitic stainless steel (e.g. ASME SA-276 and SA-479 Tp 410) is used, controls on hardness and low levels of dissolved oxygen in the system lessen the susceptibility to the intergranular stress cracking experienced in some LWR-s.

Where a bellows seal is specified, Inconel 600 is typically chosen as the bellows material because of its resistance to fatigue. In a packed gland, the packing materials are specified and the packing is live-loaded by means of disc springs to a specific stress. This results in virtually zero leakage.

Feeders, Headers and HTS Piping

The feeder/header and end fitting arrangements for CANDU 600 are shown in Figure 6. An inlet and an outlet feeder connect each fuel channel to the large diameter HTS piping system. Each feeder consists of a single small diameter (38 mm to 88 mm dia.) pipe run starting with a mechanical connection at the fuel channel and ending at the welded connection at the header nozzle. In between the ends, each feeder consists of various straight runs and bends that vary from approximately 30° to 90°. There are no T-junctions or valves in the feeders. The 380 feeders at each end of the reactor run from the fuel channels vertically up the face of the reactor and then horizontally across and above the fuelling machine area to the reactor headers. Due to the fuel channel arrangement, the feeders are grouped in arrays of small diameter pipes following essentially parallel paths from the reactor face to the headers. Feeder lengths vary from 6 to 20 meters. The feeders are enclosed in an insulated feeder cabinet and experience hot dry atmosphere during reactor operation.

Feeders are designed and fabricated to the requirements for Class 1 components of the ASME Boiler and Pressure Vessel Code Section III. They are fabricated from seamless carbon steel, SA-106 Gr B pipe with additional mechanical property and cleanliness requirements to ensure good forming, welding and service performance. The feeder pipe is typically produced from fully killed Electric Furnace steel, cold drawn to achieve tight dimensional tolerances and normalized. Feeders are fabricated typically by bending and swaging operations using double random length pipes (9 - 11 m long) in order to minimize the number of welds. Particular attention is given to the feeder pipe surface finish, low Cobalt content (Co < 0.006%) and very low inclusion content in the steel to provide a highly reliable piping system. Also, special measures are taken to ensure corrosion protection of the feeder pipe material during transportation, fabrication, storage and site installation.

The reactor inlet and outlet headers (shown in Figure 7) are essentially manifolds. The CANDU 600 has four inlet headers (approximately 6.4 m long x 0.37 m I.D. x 57 mm thick) and four outlet headers (approximately 6.5 m long x 0.41 m I.D. x 64 mm thick). The requirements for good mechanical properties and tight dimensional tolerances of the header and the use of extruded feeder nozzle connections required the development of specialized material and manufacturing technology. As a result of close cooperation between AECL and industry, this has been fully accomplished.

The Reactor Header body material is typically produced either by vacuum arc remelt or electro slag remelt process to meet required mechanical and AECL specified chemical and cleanliness requirements. The feeder and main HTS piping nozzle connections to the reactor headers are typically manufactured by an extrusion process applied to the base seamless carbon steel material of the header e.g. SA-106 Grade B. This process provides an optimum nozzle configuration for the feeder-to-header connections both from the structural reliability viewpoint and for the hydraulics of the circuit. Thus the need for a large number of set-on or set-thru nozzle forgings with the associated welding is eliminated via use of the extruded nozzles.

Manufacturing of Reactor Headers is monitored by AECL from early stages of steel making to the final heat treatment and machining to ensure a high reliability product. The finished headers are then sent to the feeder/header fabricator, who attaches the upper section of each feeder to form the feeder modules that are subsequently shipped to site. The feeder/header frame assemblies involve relatively conventional pipe bending and welding technology similar to that used in many conventional fossil-boiler shops.

The main HTS system piping of the CANDU 600 uses SA106 Gr. B seamless carbon steel pipe and SA-105 and SA-181 Gr. II forged fittings with additional chemical, mechanical and NDE requirements. The major portion of the HTS contains 40, 46 and 50 cm dia, schedule 100 piping. In addition to the ASME Section III Code requirements, AECL requires the piping to meet additional requirements on: Cobalt content, tight cleanliness requirements, tighter dimensional tolerances, higher frequency of mechanical testing (both ends of each length of pipe) and tighter NDE requirements. Although the ASME code allows use of the seam welded piping, the AECL approach has been to use seamless piping exclusively to enhance overall system reliability.

5. OPERATIONAL EXPERIENCE

The CANDU PHWR's have achieved an enviable performance record not only in high capacity factors and reliability (Tables 3 and 4) but also in low man-rem exposures of the operating personnel (Figure 8) and a low environmental impact from the radioactive materials which are released to the environment (Figure 9 and Table 5). Many factors have contributed to this good performance, including the reliable performance of the CANDU primary heat transport system and process components.

One of the most meaningful ways of quantifying component experience is in terms of the incapability caused by them as a percentage of attainable production in the time period under consideration. If a generating unit is able to operate at full power all of the time, the Capability Factor would be 100% (and the Incapability Factor would be 0%). In practice, the Capability Factor is less than 100% because of outages (full shutdowns) and deratings (operating at less than full power). Hence, the Incapability Factor indicates the inability of a unit to operate at full power all of the time.

TABLE 3

CAPACITY FACTORS OF CANDU PHWR's

Name	In Service Date	Life Time CF(%)	1986 CF(%)
Pickering - 8	86 Feb 28	96	96
Pt. Lepreau	83 Feb 1	92	94
Bruce - 5	85 Mar 1	92	97
Bruce - 7	86 Apr 10	90	90
Bruce - 3	78 Feb 1	88	84
Bruce - 4	79 Jan 18	87	93
Bruce - 1	77 Sep 1	85	65
Bruce - 6	84 Sep 14	84	79
Pickering - 5	83 May 10	83	90
Pickering - 7	85 Jan 1	83	75
Pickering - 4	73 Jun 17	82	83
Wolung - 1	83 Dec 28	80	80
Pickering - 3	72 Jun 1	77	69
Pickering - 6	84 Feb 1	77	75
Bruce - 2	77 Sep 1	77	57
Pickering - 2(1)	71 Jul 29	65	0
Pickering - 1(1)	71 Dec 30	64	0
Gentilly-2(2)	83 Oct 1	63	68
Embalse (2)	84 Jan 20	59	59

(1) Shutdown for pressure tube replacement.

(2) Capacity Factors are lower than Availability Factors due to grid restrictions.

The equipment which has caused incapability at the Pickering A and B, Bruce A and B Nuclear Generating stations over the lifetime of those plants is shown in Table 6 (taken from Reference 2). As can be seen from the table there are three groups of equipment e.g. Group A - those associated with the reactor (fuel, pressure tubes, on power refuelling), Group B - process components associated with the heat transport system and other process systems (steam generators, heat transport pumps, heat exchangers, valves, feeders, headers and HTS piping) and Group C - turbine and generator, instrumentation and control, and others.

TABLE 4

WESTERN WORLD RANKING OF WATER COOLED REACTORS OF MORE THAN 400 MW(e)

Year 1985(1)		Year 1986(2)	
Plant	Capacity Factor (%)	Plant	Capacity Factor (%)
Hamaoka-1	99.01	Ikata-2	99.96
Shimane	98.51	Mihama-3	99.95
PT. LEPREAU	97.38	Genkai-2	99.44
BRUCE-1	96.16	St. Lucie-1	99.42
Grohnde	95.98	Ohi-2	99.38
WOLSUNG	94.35	BRUCE-5	97.31
Salem-1	93.93	Calvert Cliffs-2	94.91
Loviisa-1	93.00	Olkiluoto	94.17
PICKERING-7	92.96	PICKERING-8(a)	94.04
Oconee-1	92.85	PT. LEPREAU	93.96
Unterwesser	91.97	BRUCE-7	93.68
Loviisa-2	91.70	Kori-6(a)	93.37
Grafenrheinfeld	90.80	BRUCE-4	93.14
Nine Mile Point	90.77	Takahama-3	93.05
Ginna	90.37	Forsmark-1	92.46

(a) Since generating first electricity in 1986.
(1) Nucleonics Week 1986 Jan. 30 Vol 27 No. 5.
(2) Nucleonics Week 1987 Feb. 5 Vol 28 No. 6.

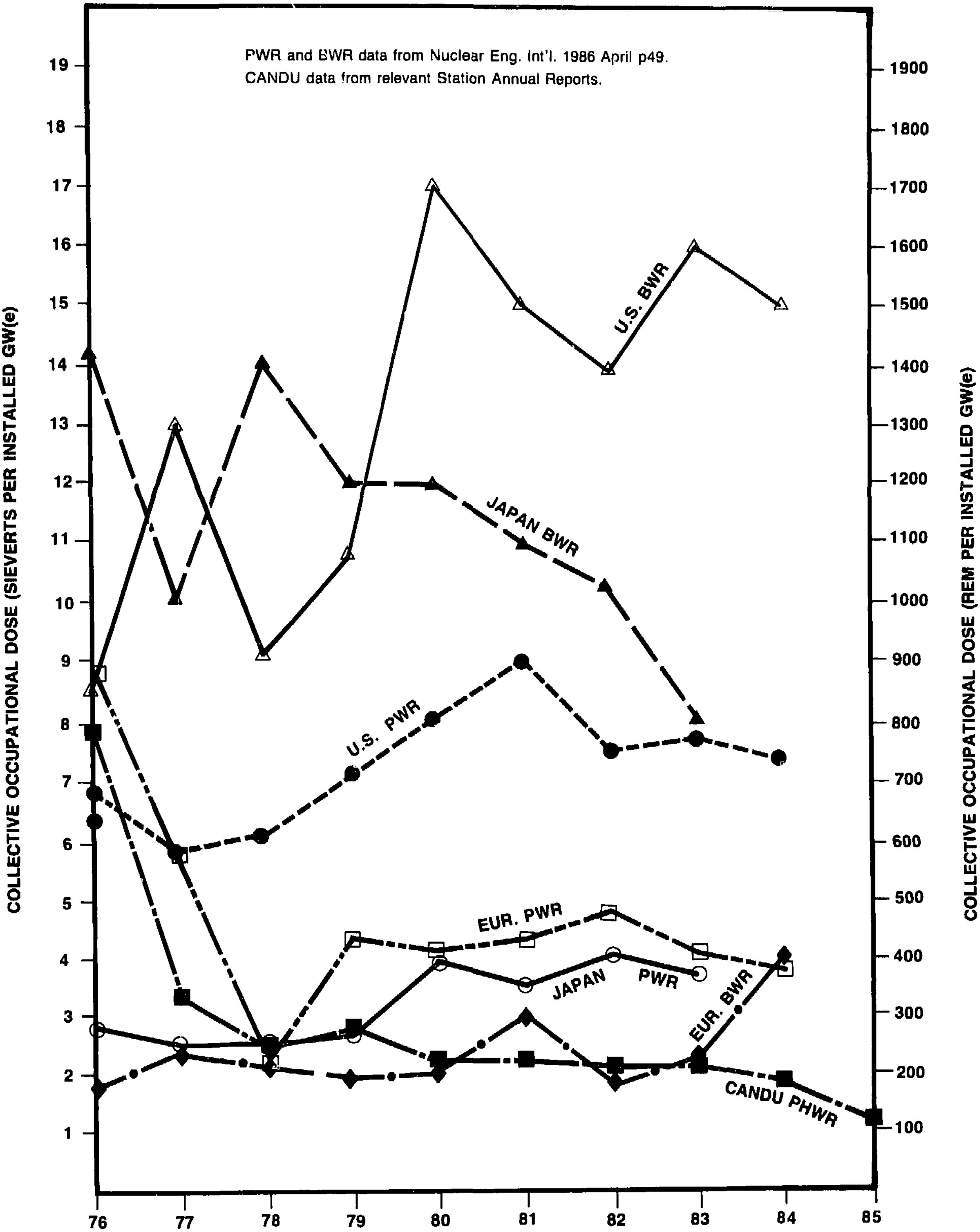


FIGURE 8 COMPARATIVE OCCUPATIONAL DOSES FOR CANDU PHWRs, PWRs and BWRs

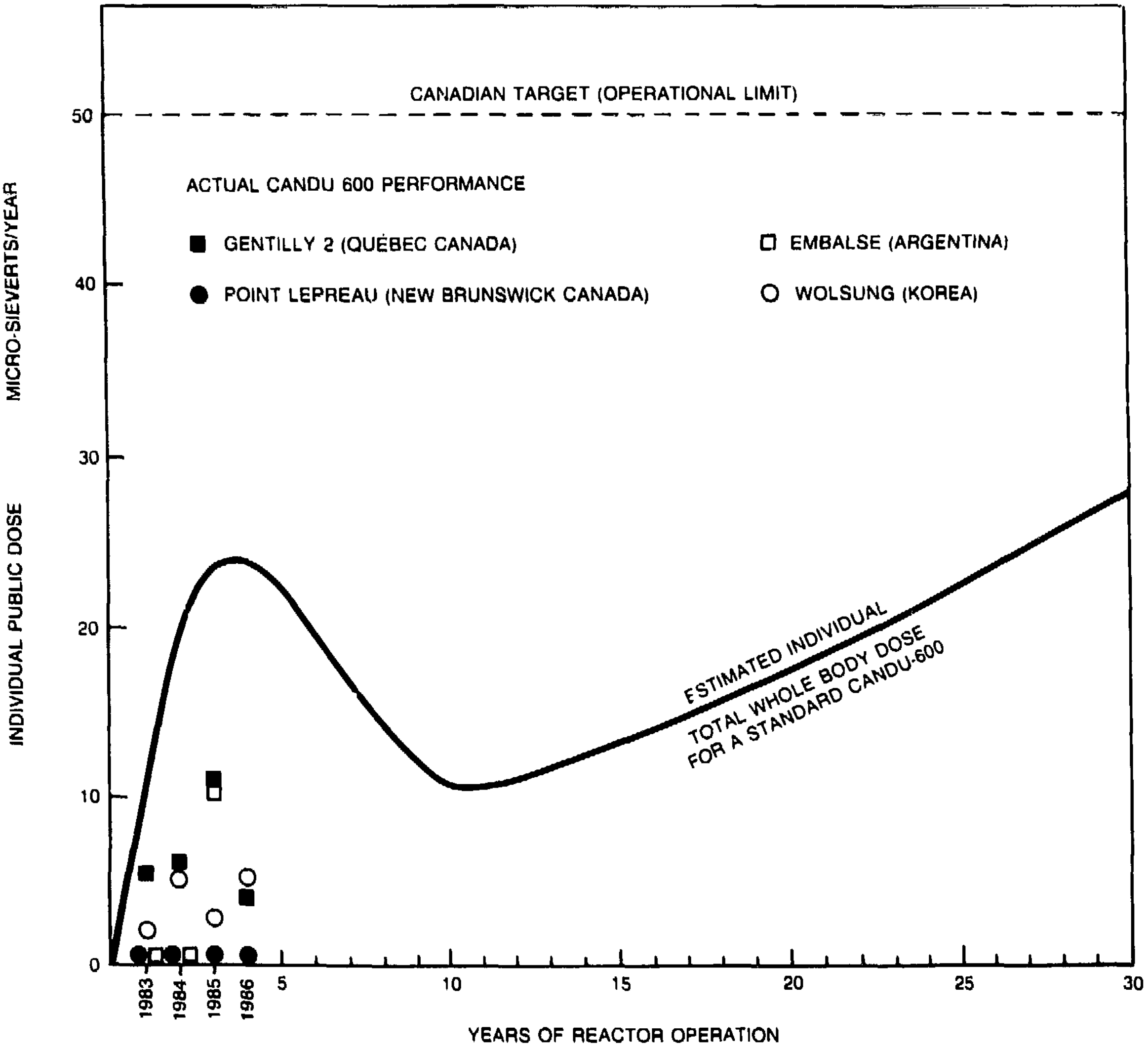


FIGURE 9 RADIATION DOSE TO THE CRITICAL PUBLIC GROUP DUE TO RADIOACTIVE EMISSIONS FROM CANDU 600 POWER PLANTS, ESTIMATED AND ACTUAL

TABLE 5

ENVIRONMENTAL IMPACT OF RADIOACTIVE RELEASES

ANTICIPATED AND ACTUAL 1985 WHOLE BODY PUBLIC DOSE AT CANDU 600 STATION BOUNDARY

	Predicted Dose Rates to a Member of the Public Critical Group Microsieverts/Year	Actual 1985 Dose Rates to a Member of the Public Critical Group* Microsieverts/Year
GASEOUS EMISSIONS		
Noble Gases	2.0	3.0
Tritium	1.5	0.9
Particulates	0.2	0.4
Radioiodines	0.2	0.4
Carbon-14	0.2	0.2
Total Airborne	4.1	4.9
LIQUID EMISSIONS		
Tritium	5.0	0.3
Total Beta-Gamma	2.0	1.0
Total Waterborne	7.0	1.3
Total Dose to Member of Public Critical Group	11.0	6.4

* Based on the Average CANDU 600 release being released at the Gentilly-2 site.

TABLE 6

EQUIPMENT CONTRIBUTION OF LIFETIME(¹) INCAPABILITY TO DECEMBER 31, 1985

Cause of Incapability	Incapability (%) Pickering NGS-A	Pickering NGS-B	Bruce NGS-A	Bruce NGS-B
Group A				
On-Power Fuelling	0.6	0.2	0.6	0.0
Fuel	0.1	0.0	0.0	0.0
Pressure Tubes	12.4	0.0	1.1	0.0
Group B				
Steam Generators	0.4	0.1	1.5	0.0
Heat Transport Pumps	0.2	0.1	0.6	0.0
Heat Exchangers	1.0	3.3	0.1	0.0
Valves	0.4	0.4	0.2	0.6
Feeders, Headers and HTS Piping	0.0	0.0	0.0	0.0
Group C				
Turbine and Generator	6.5	6.6	4.4	0.7
Instrumentation and Control	0.5	1.1	1.4	2.0
Other	1.5	1.9	3.1	5.4
Total Equipment Incapability	23.6	13.7	13.0	8.7
Labour Dispute(²)	2.1	3.4	0.7	4.5
Station Incapability Factor	25.7	17.1	13.7	13.2
Station Capability Factor	74.3	82.9	86.3	86.8
Number of Units	4	3	4	2
Unit Years Since In-Service	54.5	5.6	31.5	2.1

---

(1) Lifetime means since in-service date of each unit.
(2) 1985 Labour dispute plus 1972 Labour dispute for Pickering NGS-A.

It is observed that Group B (which covers the out-of-reactor process components associated with the heat transport system and other process systems) has made a relatively small contribution to the overall station incapability factor. For instance, steam generators, HTS pumps and valves together have only caused 1.8% incapability at Pickering A and 2.3% incapability at Bruce A. Feeders, headers and HTS piping equipment have not caused any incapability at any CANDU nuclear plant. This effectively illustrates the high reliability of CANDU process components.

Process components in the CANDU-PHWR are not only required to provide high reliability and high maintainability but they must also provide very low heavy water leakage. This particularly applies to pump and valve seals.

The heat transport pumps operate continuously at high temperature and pressure. This rigorous environment combined with the large shaft sizes makes these seals the most critical of all CANDU pump seals. Within Canada, an extensive, in-depth technology of high reliability HTS pump seals (that have virtually zero leakage) has been developed by AECL and Canadian industry. Both long seal life (3 to 5 years) and short replacement times have been achieved. Also, as an example of maintainability, motors do not have to be removed, nor do large pumps have to be dismantled to change shaft seals.

In the CANDU-PHWR, the valve requirements are similar to those for other reactor types, that is they must open, close or regulate flow with high reliability and with acceptably low leakage to the atmosphere. However, the need to minimize heavy water leakage has led to significant improvements in the design, manufacture and application of the valves used for heavy water service.

In order to minimize heavy water upkeep costs and incapability, the following approaches are applied:

1. The number of heavy water valves is minimized.

2. The number of ordinary water valves in heavy water recovery areas is minimized.

3. Valves have special design features to minimize leakage, such as:

    (a) Minimum mechanical joints (welded connections and seal welded bonnets).

    (b) Zero leakage valves (bellows valves, diaphragm valves).

    (c) Special developed live-loading of valve stem packings via springs.

    (d) Double packing with leakage collection at the midpoint.

It should be noted that, where isolation is occasionally required and valves are not provided, temporary ice plugs are used. For example, to isolate and drain a pressure tube for inspection or maintenance, ice plugs are formed in the inlet and outlet feeder pipes using jackets filled with liquid nitrogen. These jackets are permanent installations.

The successful application of the approaches to preventing the escape of heavy water from CANDU pumps and valves is demonstrated by the good heavy water upkeep experience. Heavy water upkeep is the cost of replacing any heavy water losses and upgrading any downgraded water to restore its isotopic purity to about 99.8 weight per cent.

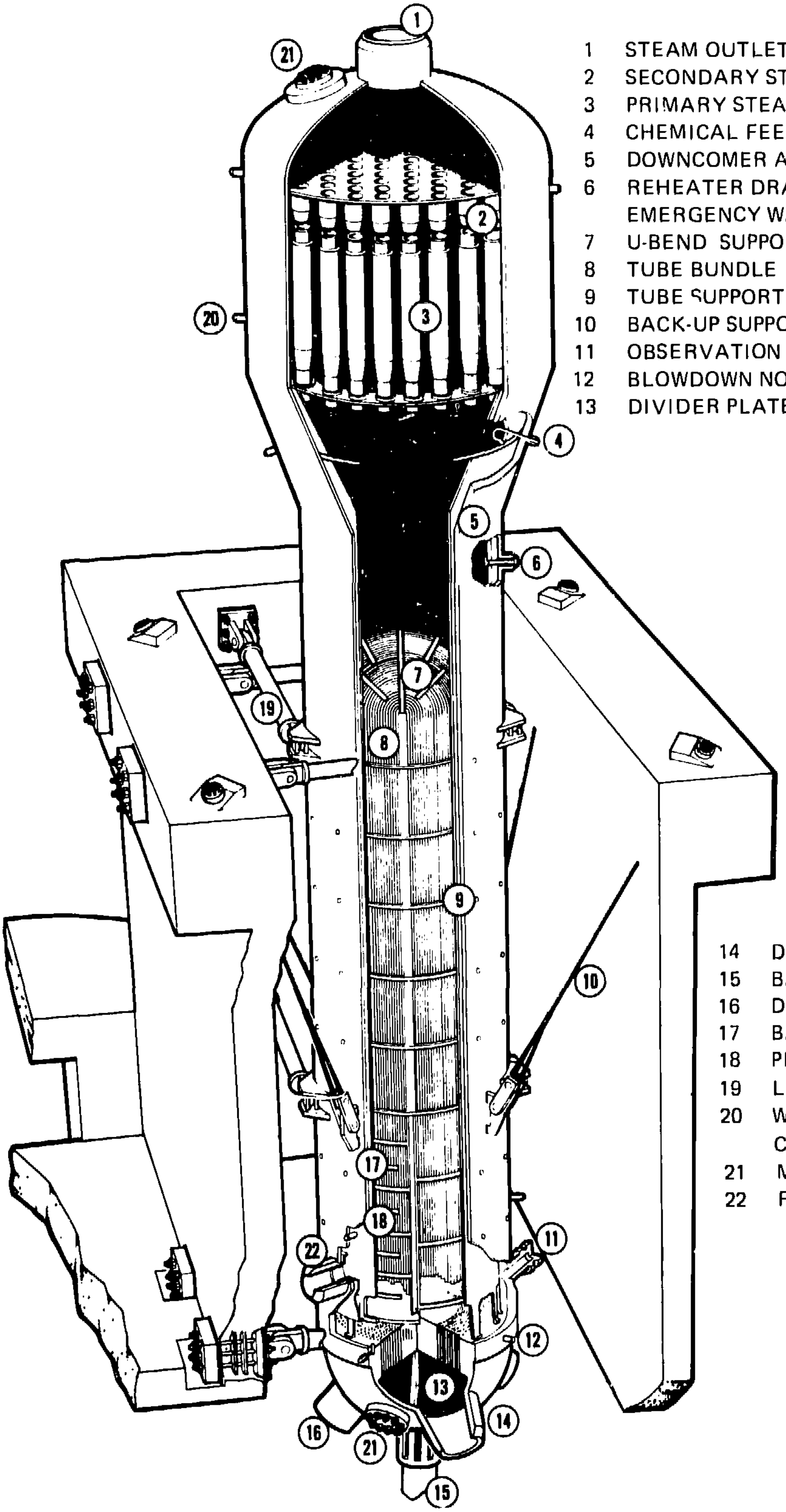
Typically, at Pickering A & B and at Bruce A & B, the Heavy Water Upkeep Unit Energy Costs are only 2 to 4 percent of Total Unit Energy Costs. The 1985 performance is shown in Table 7 (taken from Reference 1).

TABLE 7

1985 HEAVY WATER UPKEEP COSTS

	Pickering NGS-A(1)	Pickering NGS-B	Bruce NGS-A	Bruce NGS-B
Total Unit Energy Cost ($/MWhe)	23.3	44.6	23.2	43.5
Heavy Water Upkeep Unit Energy Cost ($/MWhe)	0.9	0.7	0.3	0.3
% of TUEC	3.9	1.6	1.3	0.7

(1)Heavy water upkeep costs are based on Units 3 and 4 only. Pickering NGS-A Units 1 and 2 were shutdown for large scale fuel channel replacement.



1	STEAM OUTLET NOZZLE
2	SECONDARY STEAM CYCLONES
3	PRIMARY STEAM CYCLONES
4	CHEMICAL FEED NOZZLE AND HEADER
5	DOWNCOMER ANNULUS
6	REHEATER DRAINS RETURN AND EMERGENCY WATER SUPPLY NOZZLE
7	U-BEND SUPPORTS
8	TUBE BUNDLE
9	TUBE SUPPORT PLATE
10	BACK-UP SUPPORTS
11	OBSERVATION PORT
12	BLOWDOWN NOZZLE
13	DIVIDER PLATE
14	D_2O INLET NOZZLE
15	BASE SUPPORT
16	D_2O OUTLET NOZZLE
17	BAFFLE PLATE
18	PREHEATER
19	LATERAL SUPPORTS
20	WATER LEVEL CONTROL TAPS
21	MANWAY
22	FEEDWATER NOZZLE

FIGURE 10 600 MW STEAM GENERATOR

6. CONCLUSIONS AND SUMMARY

The paper has dealt with a wide range of material and fabrication aspects of the out-reactor process components of the CANDU-PHWR heat transport system. In summary, some of the key considerations and conclusions are:

(a) The CANDU PHWR provides separation of the HTS from the low temperature moderator circuit. Hence, as no reactivity control is done in the HTS, the design and chemistry is optimized for the carbon steel pressure boundary material.

(b) In the HTS, carbon steel is the principal material used for the pressure boundary of the out-of-reactor process components (with the exception of the steam generator tubes).

(c) Specific design and operational measures are taken to control corrosion, erosion, corrosion product transport and the activation of the mobile corrosion products. Additional measures to achieve good fracture toughness result in advantages in flexibility of system operation at low temperatures, should this be needed.

(d) From a fabrication point-of-view, carbon steel has advantages of economics, well-known mechanical properties, ease of fabrication and welding, and wide availability in the required product forms.

(e) CANDU PHWR's with carbon steel HTS have achieved an enviable performance record. This has been not only high capacity factors and component reliability but also low heavy water upkeep costs, low release of radioactive materials to the environment, and low man-rem exposures to the operating personnel.

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