Lecture II

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

by
A. Filipovic,
E.G. Price,
D. Barber and
J. Nickerson

par
A. Filipovic,
E.G. Price,
D. Barber et
J. Nickerson

Presented at the
International Conference of
Nuclear Equipment – Welding and Q.A.
Sarajevo, Yugoslavia
March 1987

Présenté au
congrès international sur l'équipement
nucléaire – soudage et assurance de qualité
Sarajevo, Yougoslavie
mars 1987

Atomic Energy
of Canada Limited
CANDU Operations

L'Énergie Atomique
du Canada, Limitée
Opérations CANDU

Sheridan Park Research Community
Mississauga, Ontario L5K 1B2
Tel. (416) 823-9040

AECL-9

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

by
A. Filipovic,
E.G. Price,
D. Barber and
J. Nickerson

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.

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

par
A. Filipovic,
E.G. Price,
D. Barber et
J. Nickerson

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.

Presented at the
International Conference of
Nuclear Equipment – Welding and Q.A.
Sarajevo, Yugoslavia
March 1987

Présenté au
congrès international sur l'équipement
nucléaire – soudage et assurance de qualité
Sarajevo, Yougoslavie
mars 1987

Atomic Energy of Canada Limited
CANDU Operations

L'Énergie Atomique du Canada, Limitée
Opérations CANDU

Sheridan Park Research Community
Mississauga, Ontario L5K 1B2

AECL-9421

INDEX

Page
1. Introduction 1
2. General Reactor & Heat Transport System description 3
3. Out-reactor Heat Transport System design & material 11
4. Fabrication considerations of the major HTS components 14
5. Operation experience 19
6. Conclusions & summary 28
References 28

FIGURES AND TABLES

Figure 1 CANDU Nuclear Steam Supply System 4
Figure 2 A heat transport system 5
Figure 3 Location of Main Moderator System equipment 6
Figure 4 CANDU 600 Heat Transport System – main circuit arrangement (plan and elevation) ... 7
Figure 5 Typical CANDU 600 heat transport pump 8
Figure 6 Feeder and header arrangement 9
Figure 7 Typical header 10
Figure 8 Comarative occupational doses for CANDU PHWRs, PWRs and BWRs 21
Figure 9 Radiation dose to the critical public group due to radioactive emissions from CANDU 600 power plants, estimated and actual 22

Table 1 CANDU reactors in operation or under construction 2
Table 2 Typical CANDU steam generator materials 15
Table 3 Capacity factors of CANDU PHWRs 19
Table 4 Western world ranking of water cooled reactors of more than 400 MW(e) 20
Table 5 Environmental impact of radioactive releases 23
Table 6 Equipment contribution of lifetime(1) in capability to December 31, 1985 24
Table 7 1985 heavy water upkeep costs 26

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

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.

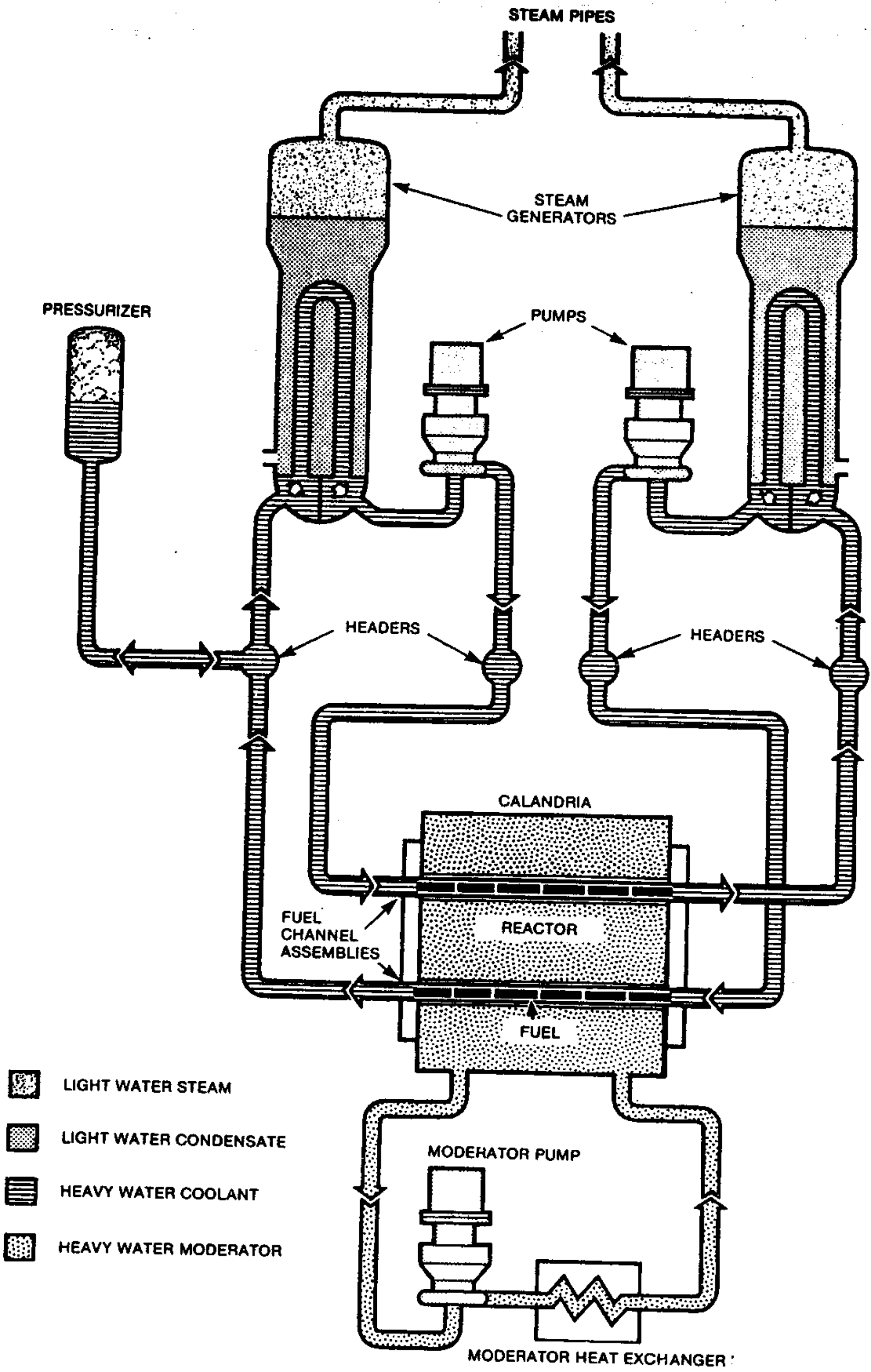


FIGURE 1 CANDU NUCLEAR STEAM SUPPLY SYSTEM

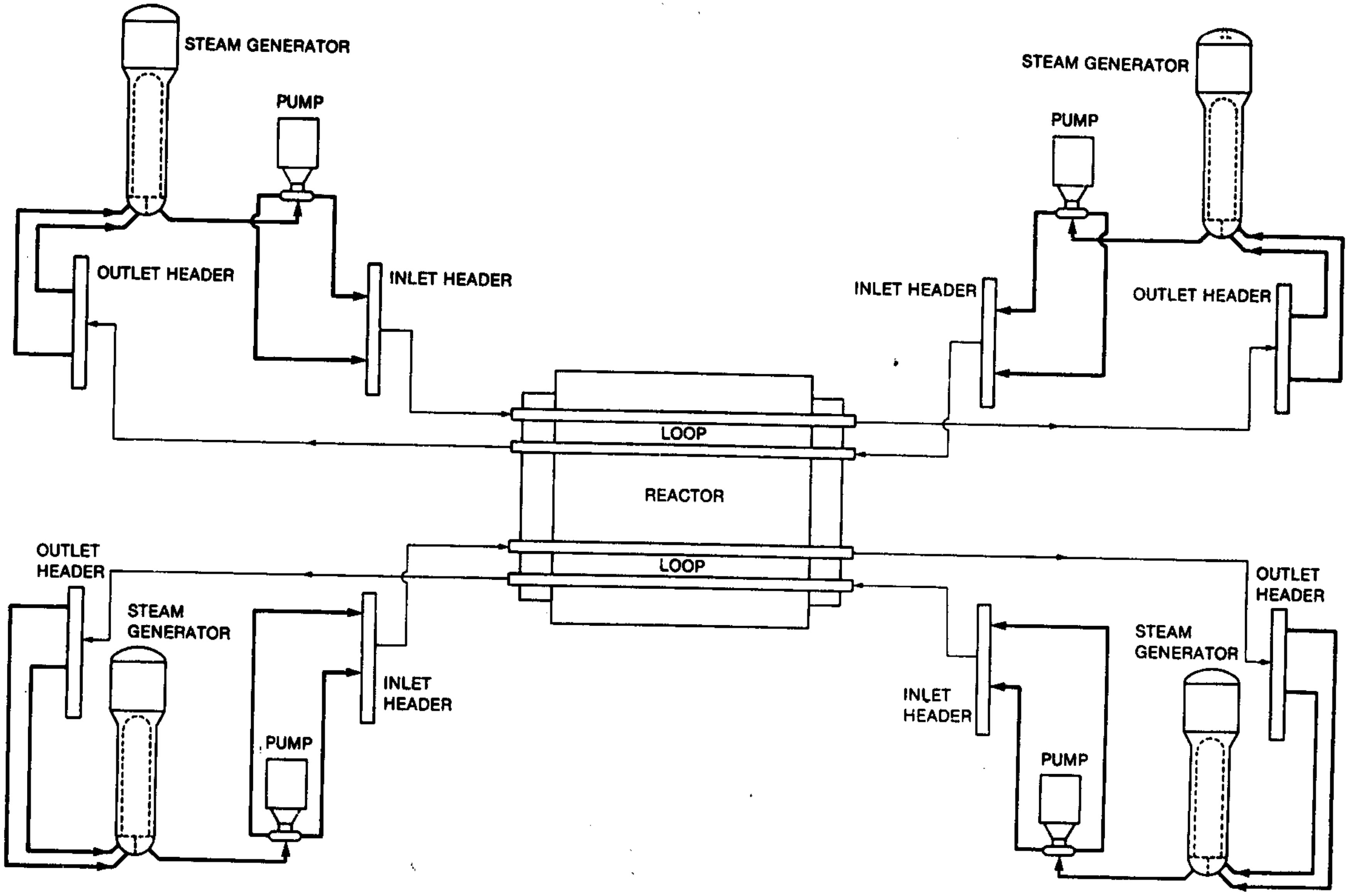
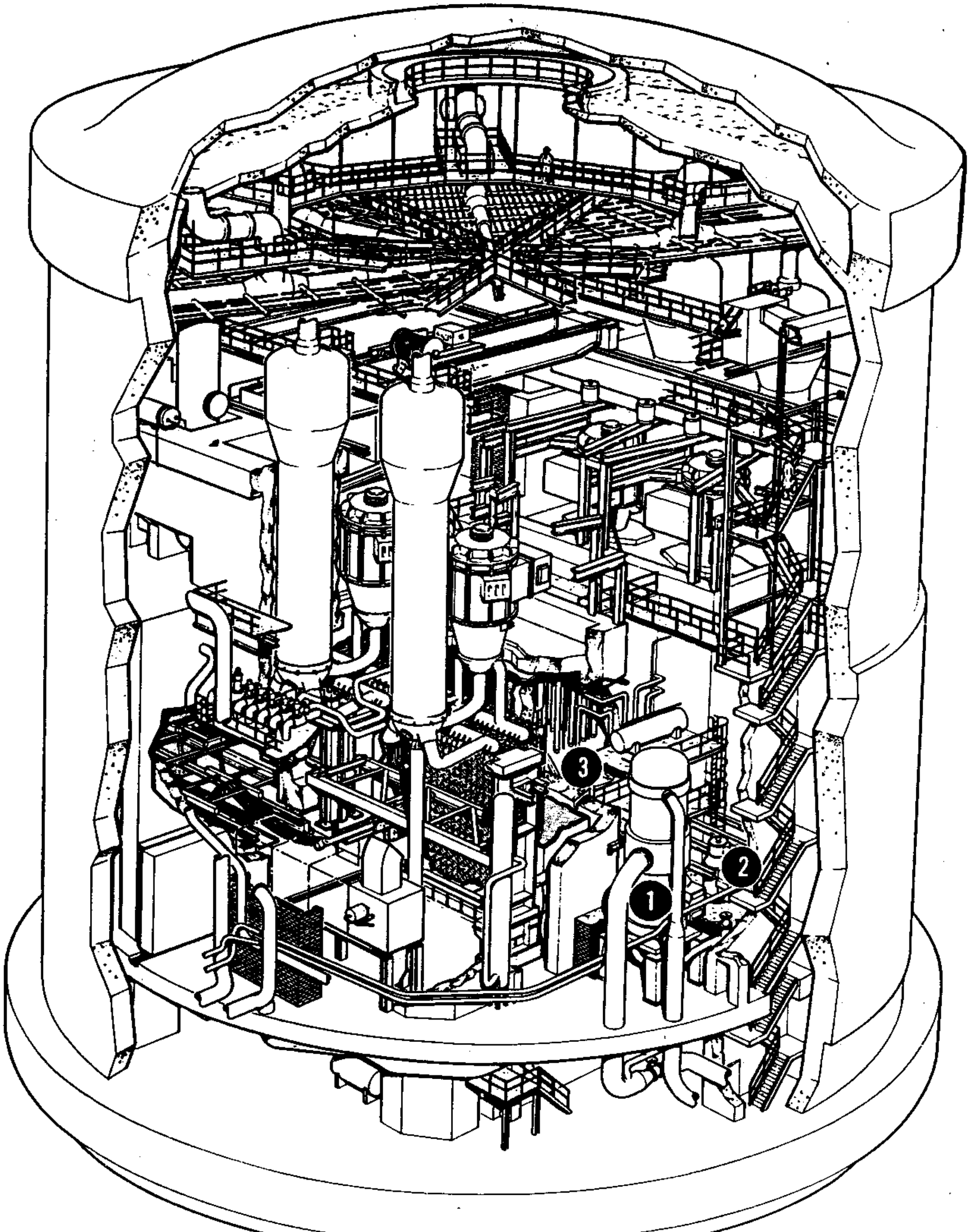
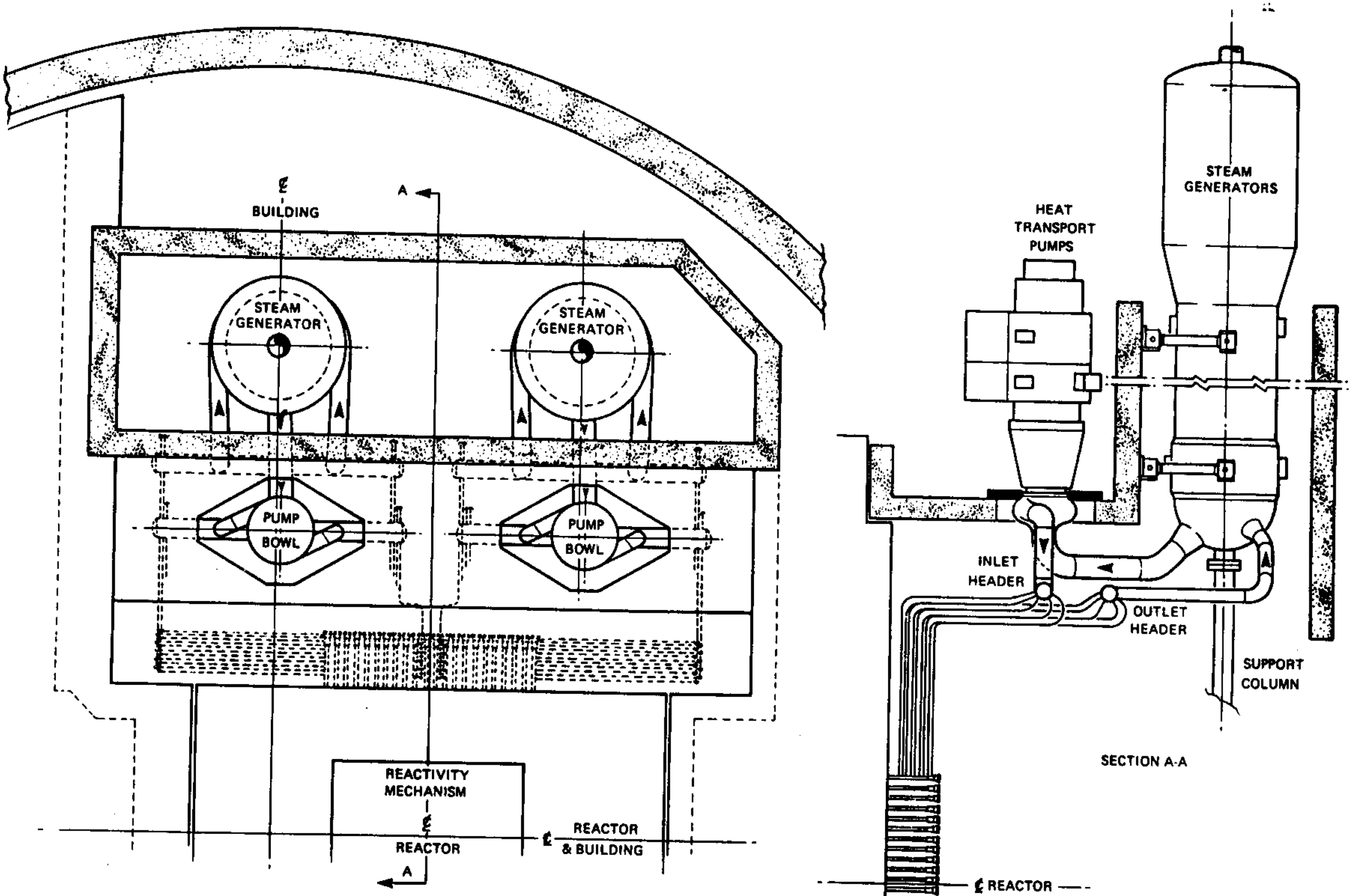


FIGURE 2 A HEAT TRANSPORT SYSTEM



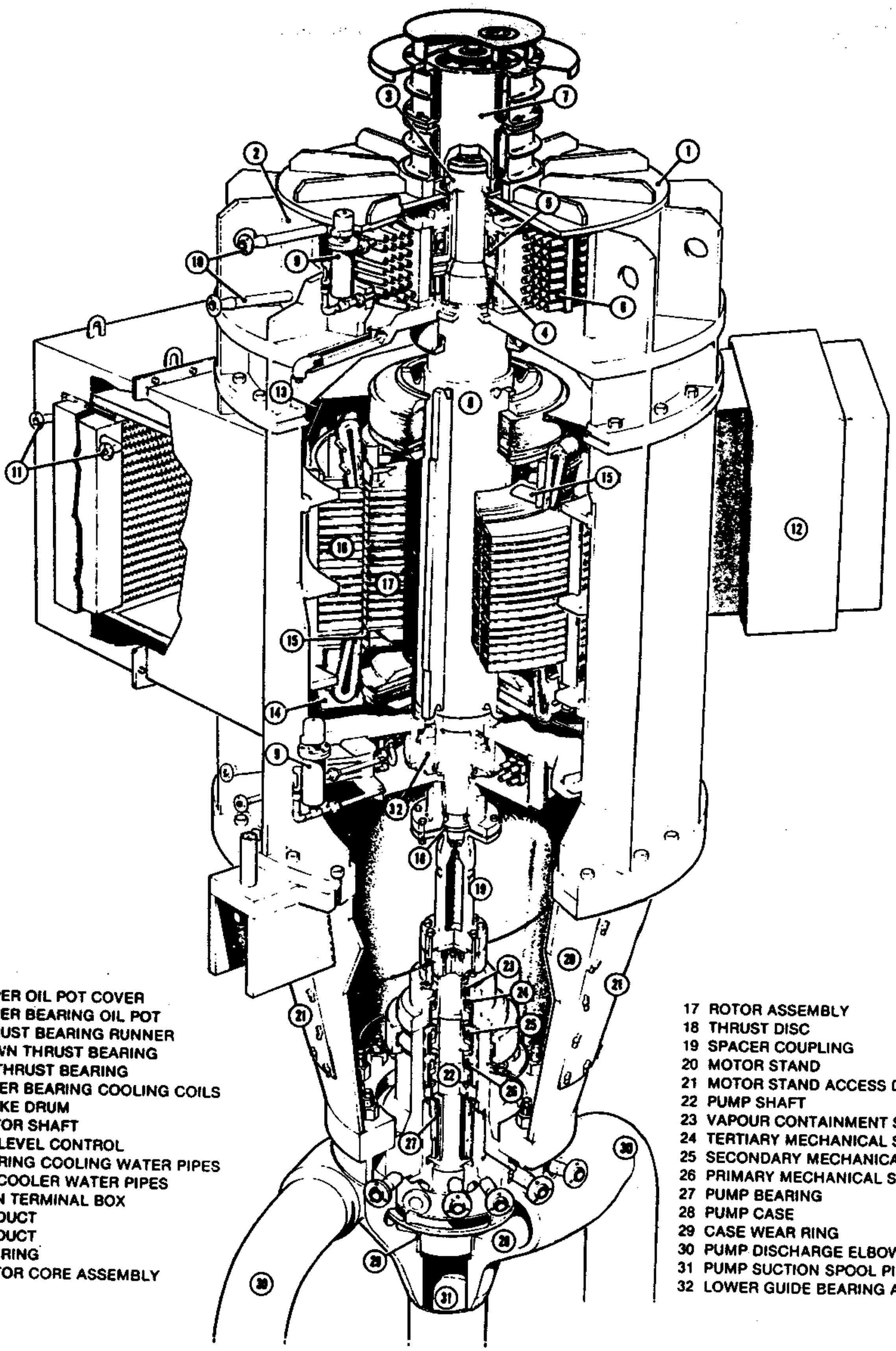
1 MODERATOR HEAT EXCHANGER
2 MODERATOR PUMP
3 REACTOR

FIGURE 3 LOCATION OF MAIN MODERATOR SYSTEM EQUIPMENT



PLAN VIEW - PUMP MOTORS OMITTED FOR CLARITY

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.

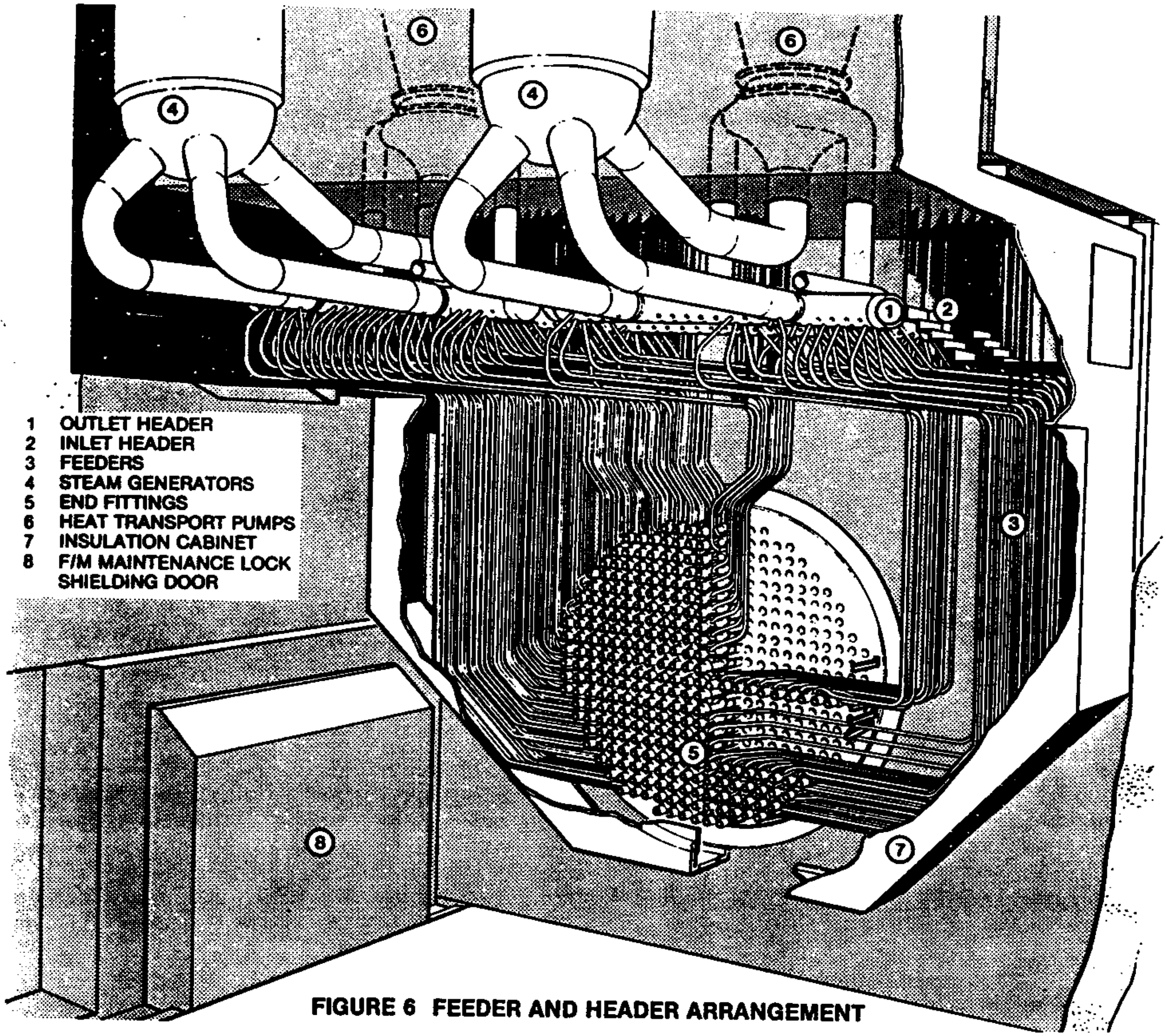


FIGURE 6 FEEDER AND HEADER ARRANGEMENT

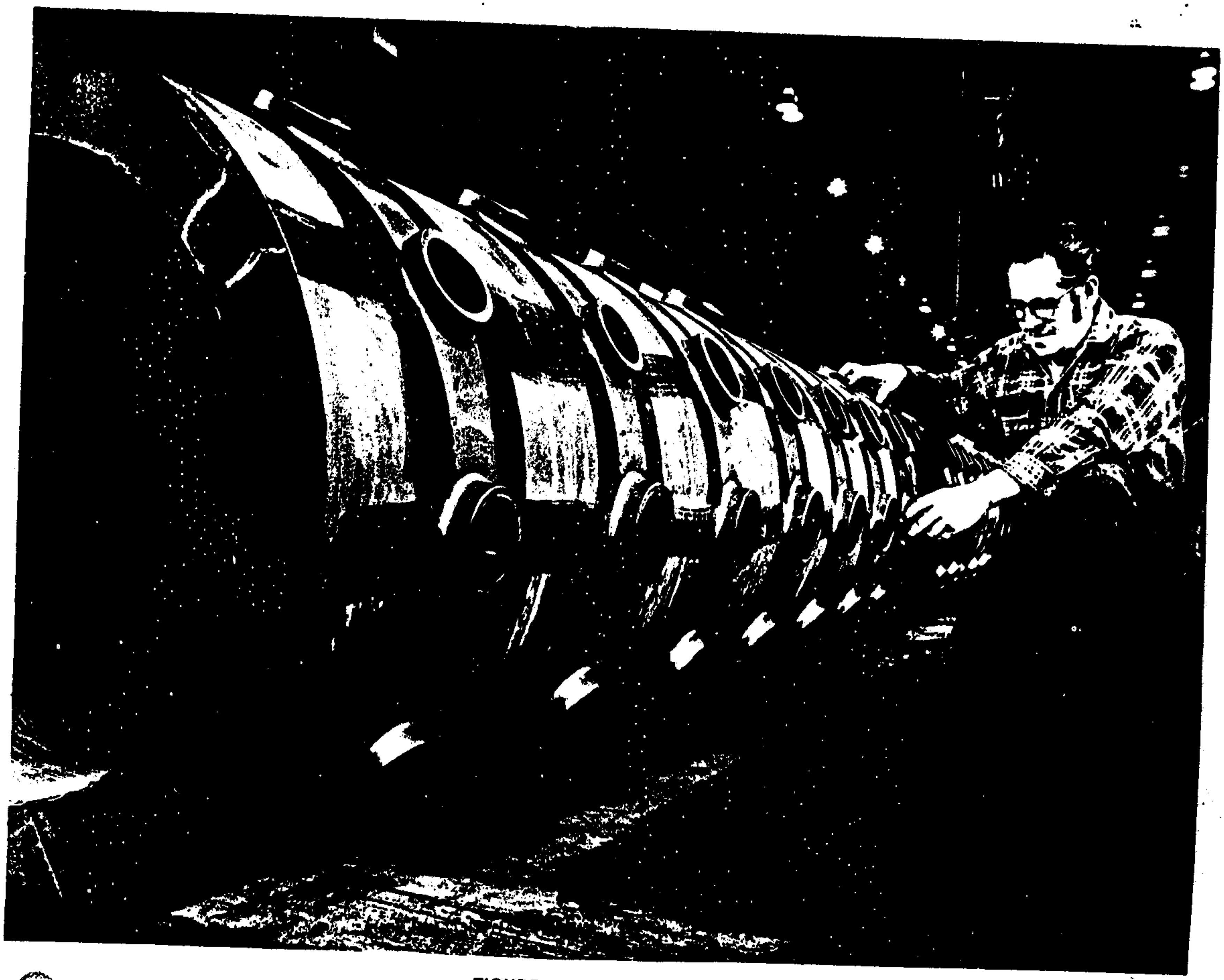


FIGURE 7 TYPICAL HEADER

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.

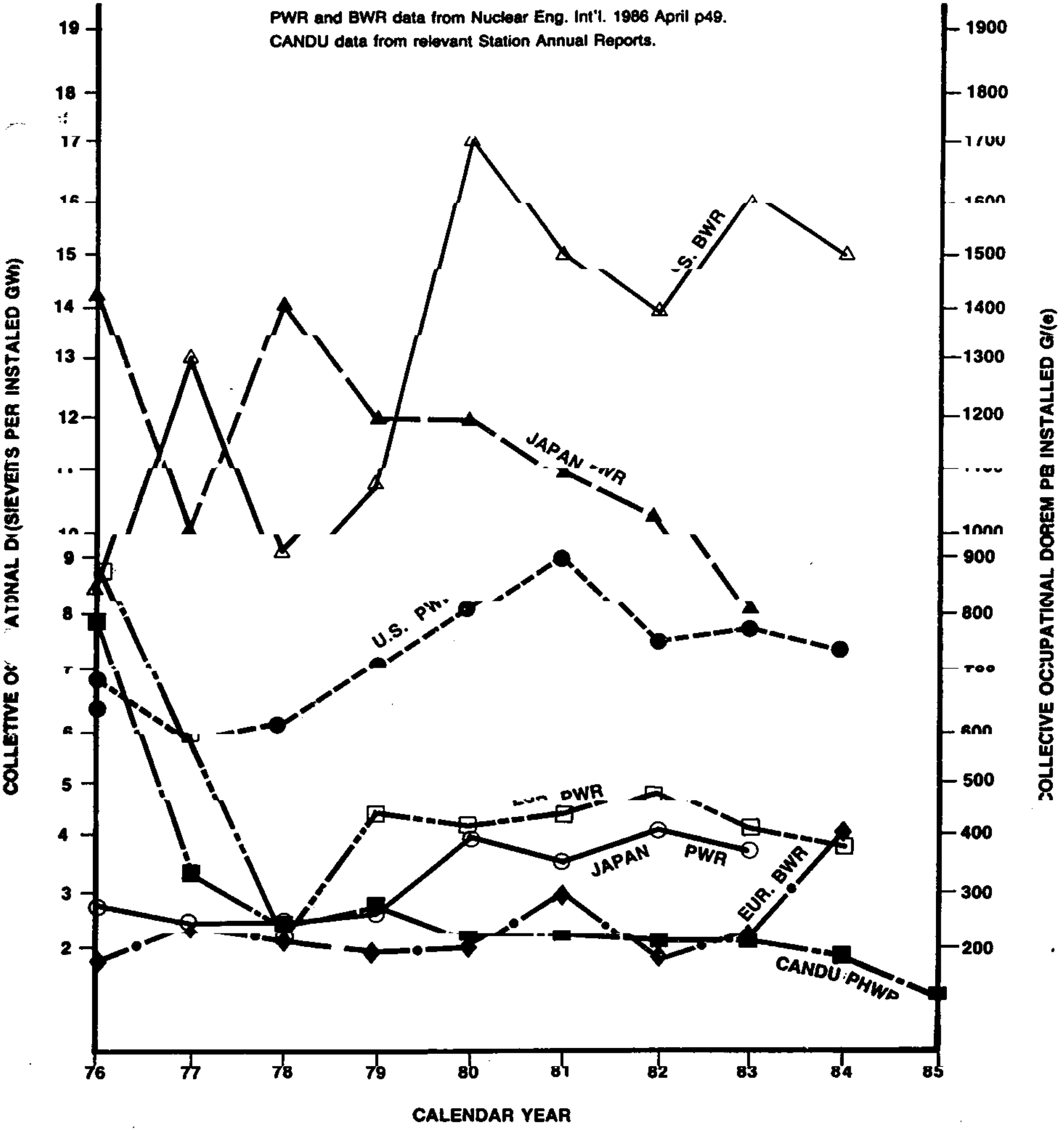

PWR and BWR data from Nuclear Eng. Int'l. 1986 April p49.
CANDU data from relevant Station Annual Reports.

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

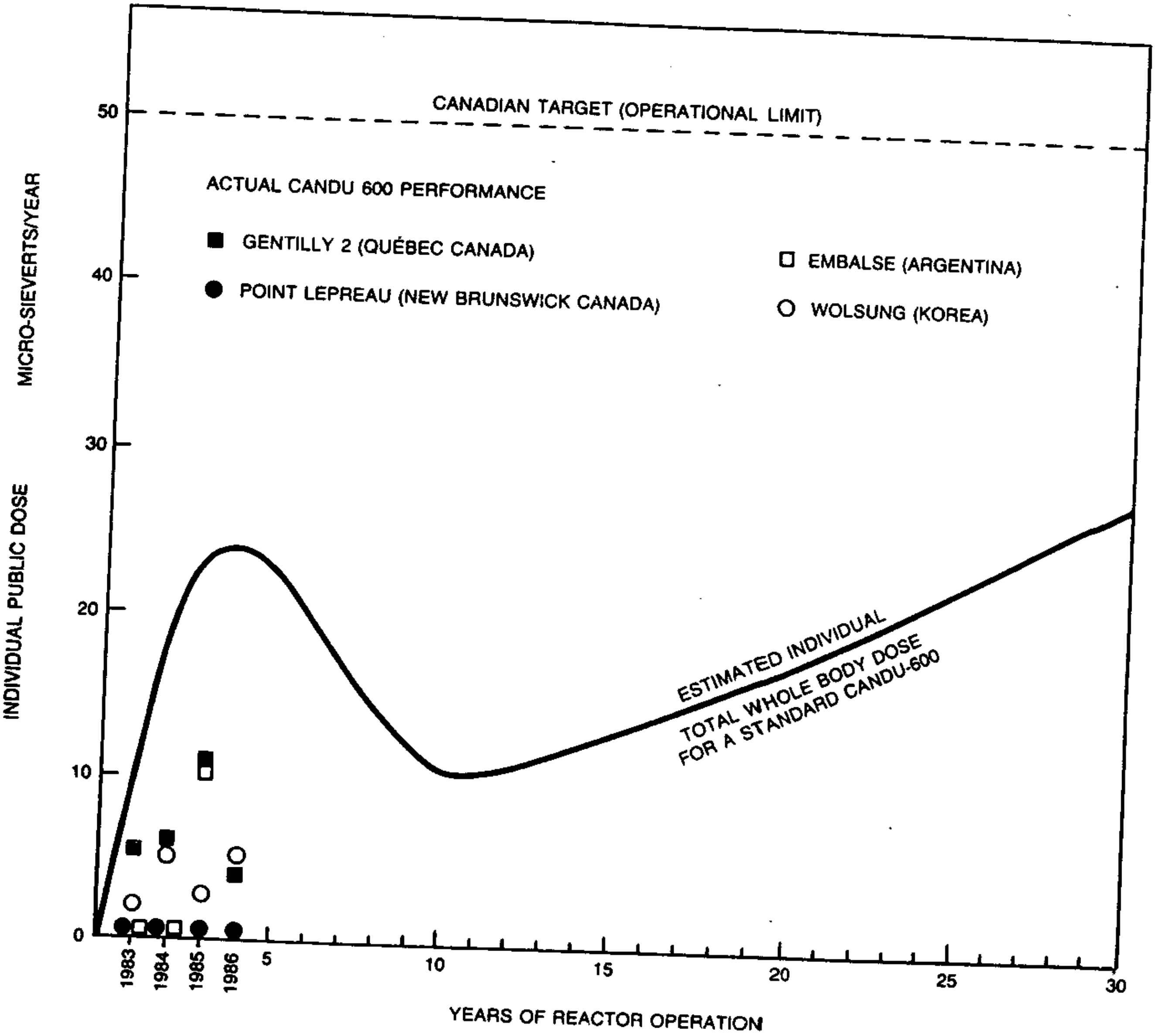


FIGURE 9 RADIATION DOSE TO THE CRITICAL PUBLIC GROUP DUE TO RADIOACTIVE EMISSIONS FROM CANDU 600 POWER PLANTS, ESTIMATED AND ACTUAL

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.

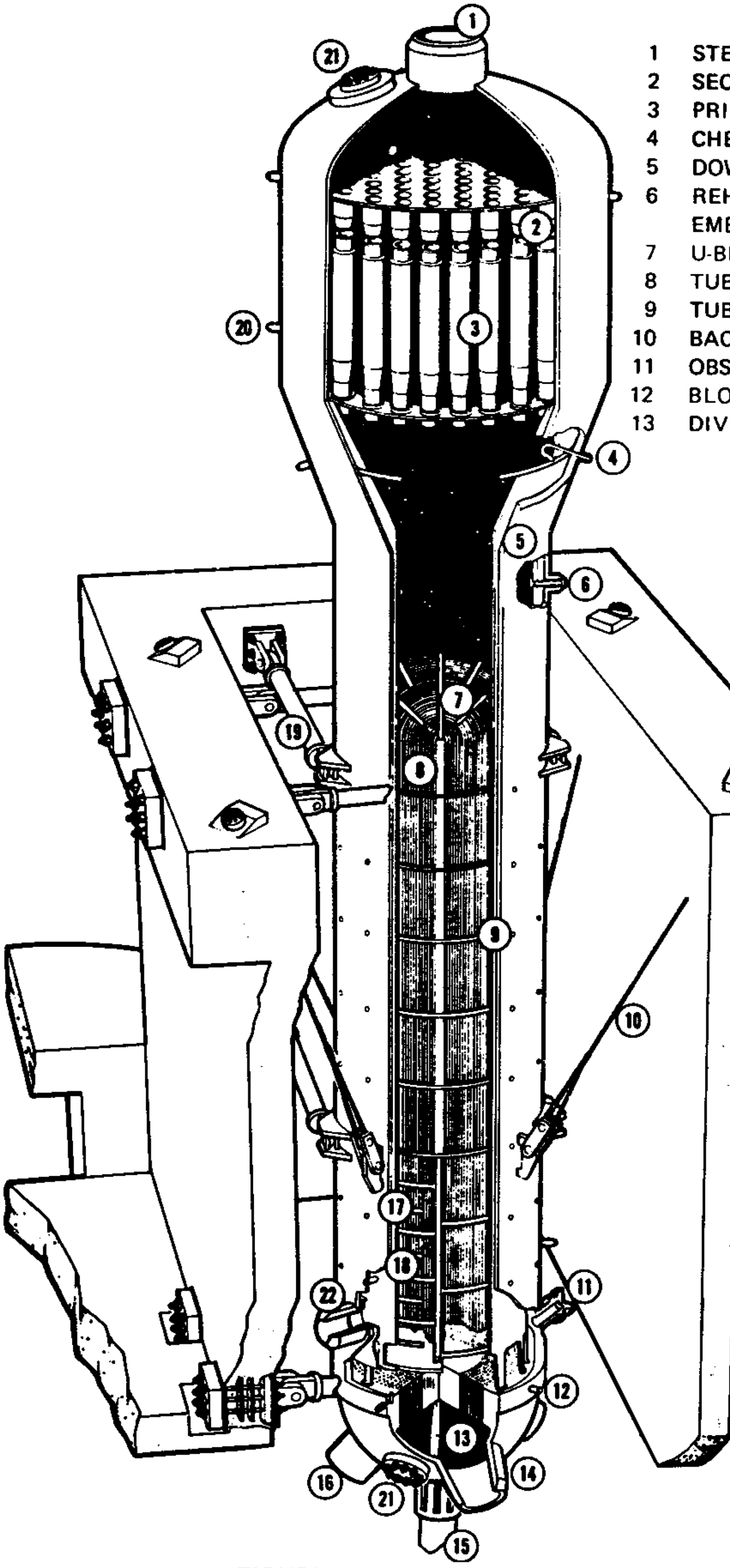
Typically, at Pickering A & B and at Bruce A & B, the Heavy Water Upkeep Unit Energy Costs are only 2 to 4 percent of Total Unit Energy Costs. The 1985 performance is shown in Table 7 (taken from Reference 1).

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.

REFERENCES

1. "Final Analysis of the Single Phase Erosion/Corrosion Test Programme for Reactor Inlet Headers" J.M. Kenchington, B.M. Pearson, E.V. Murphy, Canadian Nuclear Association Annual Conference, Montreal 1983.

2. Ontario Hydro CANDU Operating Experience, R.W. Batholomew, L.W. Woodhead, S.G. Horton, G.R. Fanjoy, Ontario Hydro NGD-9 (1985).

Lecture 11

PRICE: £1.00

ISSN 0020-3483

FIFTEENTH JOHN PLAYER LECTURE

WELDED STEEL FOR OFFSHORE CONSTRUCTION

Professor Harry COTTON

The properties of structural steel plates have been improved greatly in response to North Sea requirements. Weld metal properties for positional welding are not adequate; this deficiency significantly increases costs.

This lecture is intended to be presented at an Ordinary Meeting of the Institution in London on Wednesday 28th March 1979 at 6.00 p.m.

PROCEEDINGS 1979 VOLUME 193 No. 26

FIFTEENTH JOHN PLAYER LECTURE

WELDED STEEL FOR OFFSHORE CONSTRUCTION

Professor H. C. COTTON, CEng, MIMechE, FIProdE, FIM, FWeldI
Chief Welding Engineer, The British Petroleum Company Limited, Britannic House, Moor Lane, London EC2

1 HISTORICAL

Steel

Within the experience of everyone alive today the use of steel as a structural material has been commonplace. In any industrial conurbation we have only to look around to find ourselves surrounded by steel constructions of every sort: buildings, towers, bridges—they are everywhere. We could be forgiven if we were to believe that they have always been part of our environment. Yet it is only comparatively recently that man acquired sufficient skill to be able to mass produce steel sufficiently strong and cheap to allow for its economic use in large structural applications.

The great columns and arches of the London railway termini rely almost entirely upon wrought and cast iron for their structural elements. Piers and jetties adorning our seaside resorts date from much the same period and, in the absence of proper care and maintenance, owe their present existence to the use of those same materials.

When John Player, the South Wales foundry master, died in 1931 he had been associated with the steel industry for seventy years. During that period he had had the unique experience of witnessing the first use of steel in a major structural application through to the completion, at the time of his demise, of that great monument to Sir Ralph Freeman—The Sydney Harbour Bridge.

Bessemer commissioned his first converter in Sheffield as early as 1860 but the quality of the product was unreliable and the process unsuited to the phosphoric iron ores widely available in Europe. In the USA ore suitable for use with the acid lining was present in abundance and acid-Bessemer steel continued to be produced in that country until 1960 when it was supplanted by the LD process.

It is, therefore, no surprise that we must look to the USA for the first use of bulk steel in a structure. In 1874 Eade chose steel for his huge arch bridge over the Mississippi at St Louis: it was an innovation. His determination to adhere to the stringent requirements of his steel specification brought his supplier, Butcher Steel Works, to the verge of bankruptcy. That bridge still stands today carrying loads far greater than the designer ever envisaged. Its success established steel as a reliable structural material and earned the reputation and fortune of Andrew Carnegie. Others were not so convinced and as late as 1880 Eiffel was still so distrustful of European steel that he chose wrought iron for the arches of his masterpiece the 160 m arch of the Garabit viaduct over the River Tuyère in France. It was the 'swan-song' for wrought iron in structural engineering. An event of the greatest importance had just occurred which made wrought iron redundant.

Exactly one hundred years ago, in 1879, the invention by Gilchrist and Thomas at Middlesbrough, England, of the basic furnace lining was to cause a revolution in steel making. It was speedily applied to the Bessemer converter and very soon after to the open hearth furnace invented by Siemens and Martin in Birmingham a few years earlier. The vast deposits of phosphoric iron ore in Europe and elsewhere could now be exploited to make cheap steel. As a consequence the price of structural steel fell by 75 per cent in the next ten years and the viability of a structural steel industry was established. It was just in time! During a period of five years in the 1880's more than one hundred iron railway bridges in the USA collapsed because of the unreliable quality of the material and its unpredictable behaviour both in tension and compression.

The alacrity with which the great entrepreneural engineers of the Victorian period took advantage of new inventions is startling. Fowler and Baker realized instantly that the use of steel would permit the construction of huge cantilever bridges previously impossible. Within ten years of the first public demonstration of the principles of the basic furnace they proposed to use some 64 000 tonnes of basic open hearth steel to construct the longest clear spans in the world: the crossing of the Firth of Forth.

The huge quantity of steel used in the construction of the Forth Bridge was approximately equal to that consumed in making the offshore platforms for Forties Field: it was equally successful. The desirable properties of steel as a structural material had been more than amply demonstrated but more than half a century was to pass before a method would become available which would permit its valuable properties in tension to be fully utilized. That missing technique was welding.

Welding

The history of welding dates back several thousand years but it was not until 1918 that it could be trusted sufficiently for it to be used in the construction of a small welded barge (1). Electric welding had been invented before 1900 but even in 1934 attempts were still being made to promote the use of oxy-acetylene welding in the construction of steel barges. This was because electric welds made with the bare wire and wash coated electrodes available up to that time were weak and porous. It was about 1936 before electric welding began to be recognized

0020-3483/79/0193-0193 $02.00

as a potentially reliable technique for the fabrication of large structures.

The introduction of welding was eventually to transform the established principles of design and construction in steel but in those early days rivetted designs were only slightly modified for welding. The widespread and precipitous adoption of welding was hastened, perhaps unduly, by the demands of the 1939–1945 World War so that by 1955 the incessant clatter of the rivetter's hammer was rarely heard in the great shipyards of Clyde, Tyne and Tees. Perhaps it is significant that one of the last ships to be constructed with a rivetted hull was HM Royal Yacht: it was a measure of confidence factor. In the short space of ten years or so welding had supplanted entirely the use of rivetting in steel structural engineering but this hasty change was not without its mishaps.

The loss of many Liberty ships and T2 tankers during and just after the war was hard to explain: had it not been for the exigencies of the war it would have been intolerable (2). After hostilities ended, losses continued and the sinking of the *Flying Enterprise* in the North Atlantic and the break up of the tanker *World Concord* during her trials in the Irish Sea received wide publicity in the press and on television. Such brittle fractures were not new but the monolithic nature of welded constructions magnified their effect. It was in this atmosphere that the oil industry took its first tentative steps into offshore prospecting for oil and gas.

Early offshore platforms

Interest in the possibility of producing hydrocarbons from offshore locations increased rapidly in the 1950's when self-elevating mobile platforms began operating in the Gulf of Mexico and in the Middle East. These strange constructions, on the whole, behaved well in the warm water of those sub-tropical seas (Fig. 1). Semi-killed and balanced carbon/manganese steel in thickness even up to 75 mm was used frequently for the hulls and legs of 'jack-up' barges. Fixed platforms were constructed from fairly thin wall seamless tubes to API Standards. Brittle fracture was not thought to present much of a risk in such constructions even in temperate climates and, as a result, notch ductility requirements were minimal. For most scantlings no Izod or Charpy properties were specified although balanced steel with a high ratio of manganese to carbon was sometimes specified for the thick legs of 'jack-up barges'. However, welding procedures were properly qualified and welds subjected to non-destructive testing, where this was practicable. Low hydrogen basic coated electrodes began to be used for joining the cans of the thick legs. These constructions performed well in the relatively calm warm waters of the Gulfs.

This opportunity to gain experience in the exploration and production of oil and gas and in the laying of pipelines in these 30 m deep sub-tropical seas was a valuable exercise in preparing for the greater challenge which was soon to come. The great sedimentary basins of the North Sea were thought to be rich in hydrocarbons: the findings of the Groningen gas fields in Holland seemed to confirm this possibility.

A self-elevating platform *Sea Gem* exploring a possible site in the West Sole area was successful in locating the first gas field to be discovered in the North Sea. It was the overture to the systematic exploration and development of the whole of the North Sea oil and gas fields. At the moment of its triumph in December 1965 the rig collapsed.

The report of the Court of Inquiry held by HM Government to discover the cause of the failure bears a striking similarity to that of the inquiry into the collapse of the Melbourne Kings Bridge which had occurred two or three years earlier (3). Fatigue and weld underbead hydrogen cracks had combined to initiate catastrophic

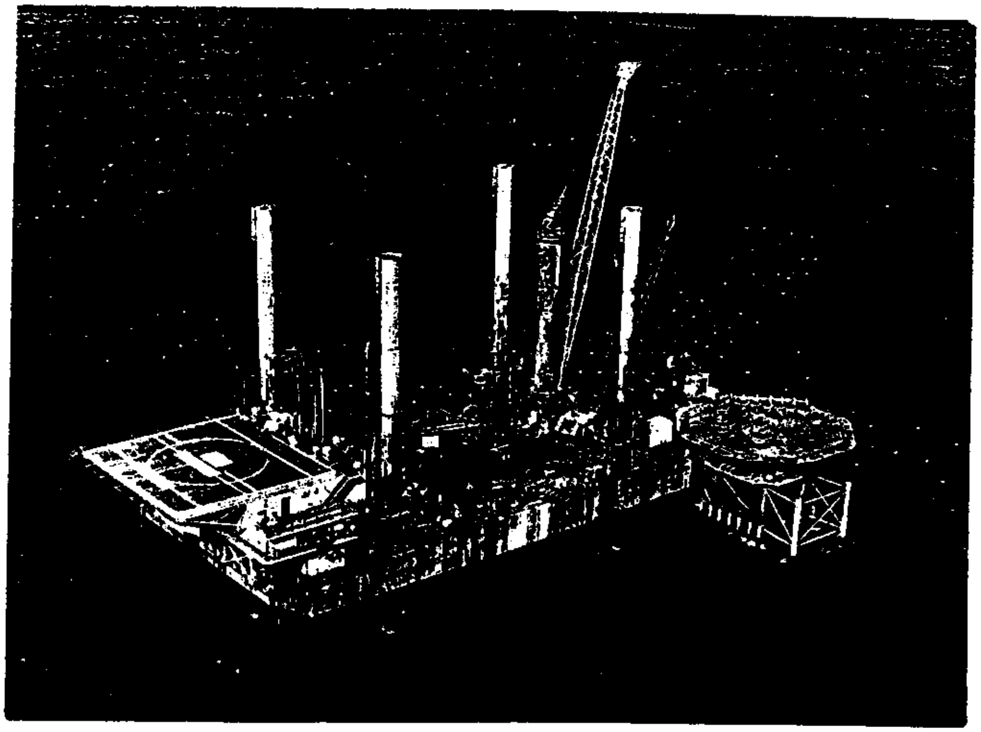


Fig. 1. Jack-up barge *ADMA Constructor* at work offshore. Abu Dhabi, 1962

brittle fracture. Both failures had happened in the middle of winter in temperate climates but the air temperature was hardly sub zero centigrade. Practices which had been shown to be successful when used in sub-tropical climates were demonstrably insufficient for safe operation in the 0°C–10°C range of ambient temperature. It was hard to believe that a shift in average temperature of only about 10°C could have such a dramatic effect upon the reliable behaviour of a welded steel construction.

2 BRITTLE FRACTURE

The oil industry had been as much affected by the inexplicable behaviour of welded steel structures as any other. The break up of the T2 tanker *Schenectady* while tied up at a wharf had been a salutary warning of what was to happen to many ships of the same breed. Several storage tanks had collapsed culminating in the loss of two large crude oil storage tanks in 1951 at Fawley, England. The cause of these failures received the most detailed attention.

The Ship Structure Committee of the US Navy approached the problem largely by studying the mechanism of fracture propagation: the British tackled factors affecting the initiation of 'fast fracture' as it came to be called.

Pellini's fracture safe design procedure was elegant in its simplicity: but in practical applications in the use of thick structural steel it proved to be a very costly technique (Fig. 2) (4).

Tipper and her associates made a study of the behaviour of notches in metals, notably carbon steel, at static rates of strain. This investigation was to lead to the fracture mechanics approach.

Both the Pellini and Tipper techniques are readily applicable to base metal but unexpected difficulties were experienced in refining and interpreting the more economic but much more difficult initiation theory in respect of the behaviour of weld metal.

The divergence in the objectives of British and American investigators was to lead to endless difficulty and misunderstanding. Even today a certain lack of co-ordination in effort is still present and the situation is particularly difficult for those working in the oil industry where five of the seven majors, the so called 'Seven Sisters', are American.

Tipper's work on the significance of notches and their acuity in processes leading to the initiation of low stress fracture in structural steels soon revealed the extreme sensitivity of such steel to strain rate effects. The so called 'notch ductile structural steels' can show considerable brittleness if the rate of loading is sufficiently high: carbon/manganese steel weld metals are similarly affected. Pellini concerned himself mainly with dynamic strain rates exemplified by his explosion bulge test which was singularly suited to the needs of the US Navy.

Difficulties in using explosives in civil applications resulted in the development of the cheaper and simpler drop weight test (DWT) (5). In offshore applications the drop weight test has come to be used to assess the probable performance of base metal in resisting propagating fast fracture whilst the crack opening displacement (COD) test is being applied increasingly to the study of weld metals. However, the Charpy V test (C^v) is still the most widely used workshop technique for estimating the notch ductility both of structural steels and of weld metal. The validity of this is in question because of the poor correlation between COD properties and C^v absorbed energy values (Figs. 3 and 4).

An inquiry into the collapse of the Fawley crude oil storage tanks led to a recommendation that steel with thickness greater than 12.5 mm should, in the Charpy V impact test, show an absorbed energy of at least 20 J (15 ftlb) at the service temperature. As a result, a balanced steel with 20 J (15 ftlb) min at 0°C (BS 2762 Gr NDII) was widely adopted about 1955 for storage tank shells and for offshore rigs and platforms. For thicker strakes, say over 30 mm, 20 J at −15°C was recommended. The importance of section thickness in promoting brittle fracture was thus recognized. In later work, strength also was shown to be an important factor requiring enhanced absorbed energy for equivalent toughness. The required minimum average absorbed energy was raised for stronger structural steel to 48 J (35 ftlb) at the service

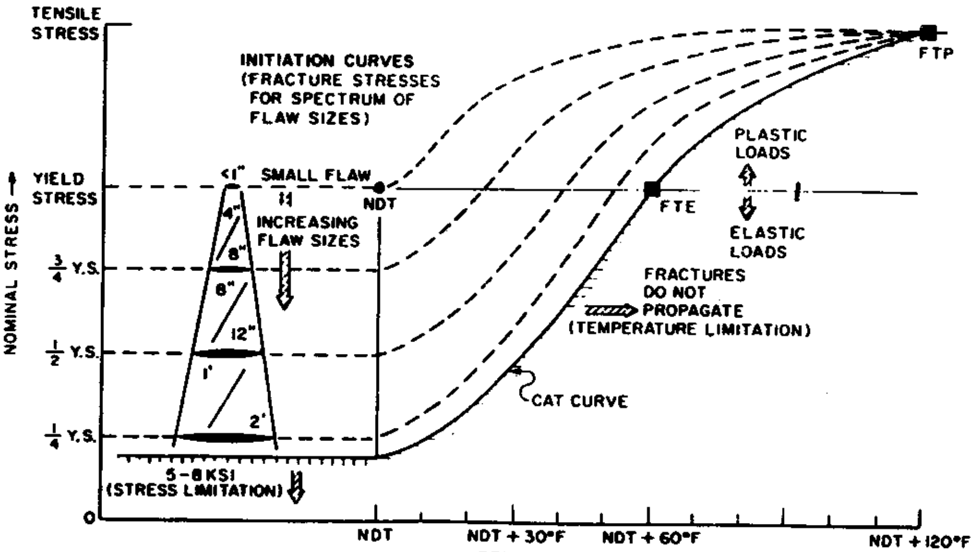


Fig. 2. Generalized fracture analysis diagram (Pellini)

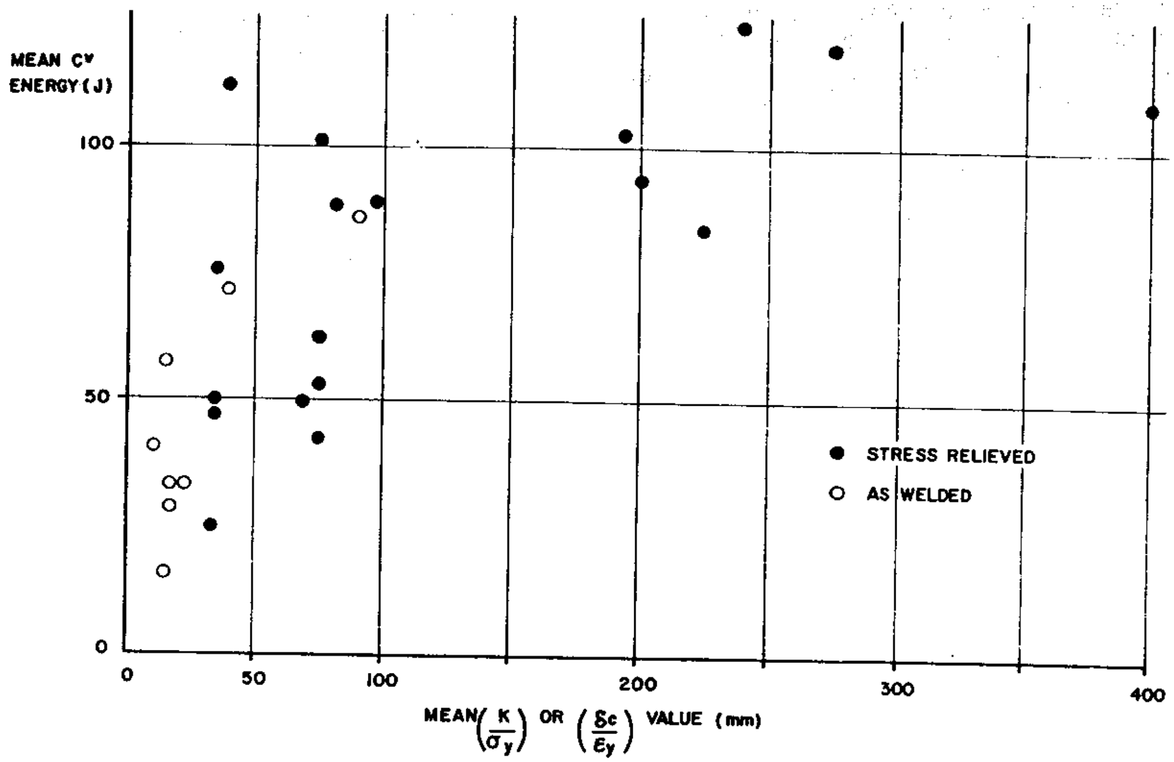


Fig. 3. Comparison between mean COD $\delta c/\varepsilon y$ and mean Charpy V energy

temperature. The 20 J criterion was thus identified as being adequate only for a limited range of application viz: thickness, strength and rate of loading.

Fine grain killed steel meeting the requirements of BS 2762 Gr NDII had been used for the legs of *Sea Gem*: in terms of the accepted philosophies of that time it should have been more than adequate. In the event this proved to be optimistic. Having in mind the strain energy in the collapsing system it was later concluded that, should fast fracture once initiate, no structural steel then available could have been relied upon to arrest the running crack. The cause of the initiation of the fractures was examined minutely.

A chapter of accidents starting with brittle fracture in the tie bars supporting the barge from the jacks was found to be the cause of the failure. Tiny surface cracks in the gas cut edges of the bars had extended to a critical length by the action of cyclic loads, the tips of the growing cracks had strayed into material embrittled by welding. This had caused them to fracture at a low applied stress. Cyclic stress in the jacks had caused small cracks to coalesce in the welds attaching them to the deck of the barge. Trivial imperfections one might have thought in such a huge structure but, like the Kings Bridge, Melbourne, they led to total collapse. The lurch of the structure was identified as having been the cause of fast fractures initiating in the low hydrogen site welds connecting the 75 mm thick cans of the legs. The dynamic fracture running into the base metal found little resistance from the NDII material and, despite its 50 J Cv or more at the service temperature, propagated as a flat fracture through the leg. It was a classic brittle fracture repeated sequentially through the ten legs of the platform. Total collapse was inevitable.

Mistakes made in the construction of the Kings Bridge related mainly to the poor weldability of the material of the bridge (BS 968): this deficiency was not present in *Sea Gem*

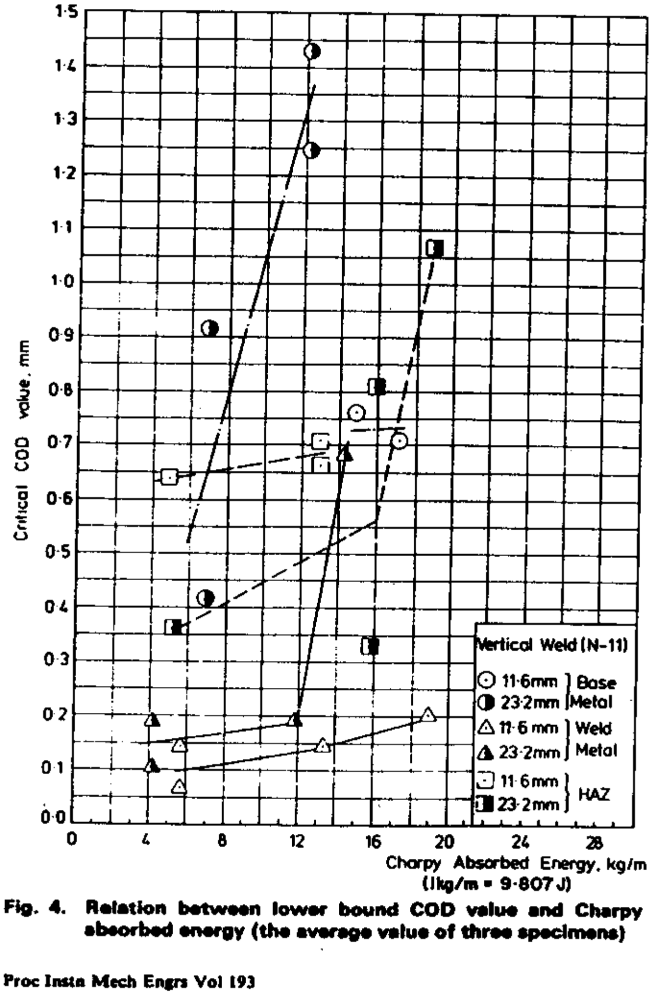
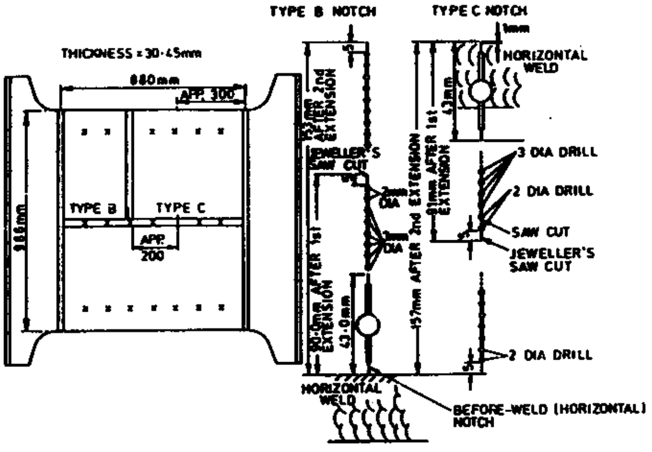


Fig. 4. Relation between lower bound COD value and Charpy absorbed energy (the average value of three specimens)

(6). However one unusual aspect was the great thickness of the legs (75 mm): the site welded joints had not been thermally stress relieved (PWHT). The precise effects of stress relief were hard to define at that time and are still being debated even at the present day. However many Codes and Standards had fixed an upper limit of thickness for non-post weld heat treated weldments. The reason for this requirement was not made clear but many fabricators distrusted the reliability of welded joints in thick structural steels in the 'as welded' condition. Work was set in hand to study this matter.

A few years earlier A. A. Wells had discovered in a classic piece of work through the medium of the cross welded wide plate tensile test (Fig. 5) the damaging effects that welding could have upon steel as a result of the strain ageing mechanism (7, 8). However the use of killed steel was thought to overcome this effect. Strain age embrittlement of the base metal as a result of multi-run welding methods employed for field welding such steel seemed unlikely. But the possibility that weld metal itself could be damaged in this way provided an inviting explanation of the cause of low stress crack initiation in the joint. It was clearly desirable to pursue this line of investigation but the means of doing so were not at hand. Charpy V tests were found to be too insensitive to detect the presence of such damage and the cost and difficulty of making a statistically relevant inquiry using 75 mm thick welded wide plate tests was neither feasible nor acceptable. The knowledge that post weld heat treatment can wipe out strain age damage effects was encouraging and as an interim measure it was resolved not to use plates thicker than 40 mm unless the welds could be post weld heat treated in the stress relieving range of temperature (580°C–620°C). It was an unpopular decision which gave rise to much adverse comment. This new requirement led to the node method of construction, a technique which was quite new and which necessitated significant changes in the layout of plant used in the construction of offshore platforms.

'Jack-up' barges are not very suitable for use in the stormy waters and unpredictable weather of the North Sea. This is because of the requirement for very calm weather during jacking up and down operations. These difficulties were to be solved by the introduction of semi-submersible rigs such as *Sea Quest* shown in Fig. 6. In this construction plate thickness was limited to 40 mm maximum and fully killed fine grain steel was specified for parts of primary structural importance. Low hydrogen basic coated electrodes were specified for all the main joints and seams and 100 per cent non-destructive testing (NDT) was specified for all welds. In the absence of a technique suitable for evaluating weld metal notch ductility in what seemed to be a meaningful way, severe limitations on the size of allowable imperfections were applied. Full penetration welds were specified for the connections between the legs and the main braces. Because of the great diameter of the legs many internal stiffeners were required to improve strength and to resist external pressure in the submerged condition. As a result the structure was subjected to severe restraint and shrinkage stresses.



TYPE B NOTCH: HAZ OF VERTICAL WELD (1 mm FROM FUSION LINE)

TYPE C NOTCH: HAZ OF HORIZONTAL WELD

Fig. 5. Wells cross welded wide plate tension test as used by BP

3 LAMELLAR TEARING

The unprecedented intensity of non-destructive testing, particularly ultrasonic, revealed a new and costly problem associated with the large fillet welds. The steel seemed to be unexpectedly weak when required to support the shrinkage stresses inherent in the large fillet welds employed. Delamination in the area of the weld heat affected zone was discovered: the cracks were parallel to the plate surface (Fig. 7). It was a new experience in such an application for which no solution was immediately at hand. Similar effects had already been experienced in attempting to weld the diagrid core supports for the Magnox reactors. No satisfactory

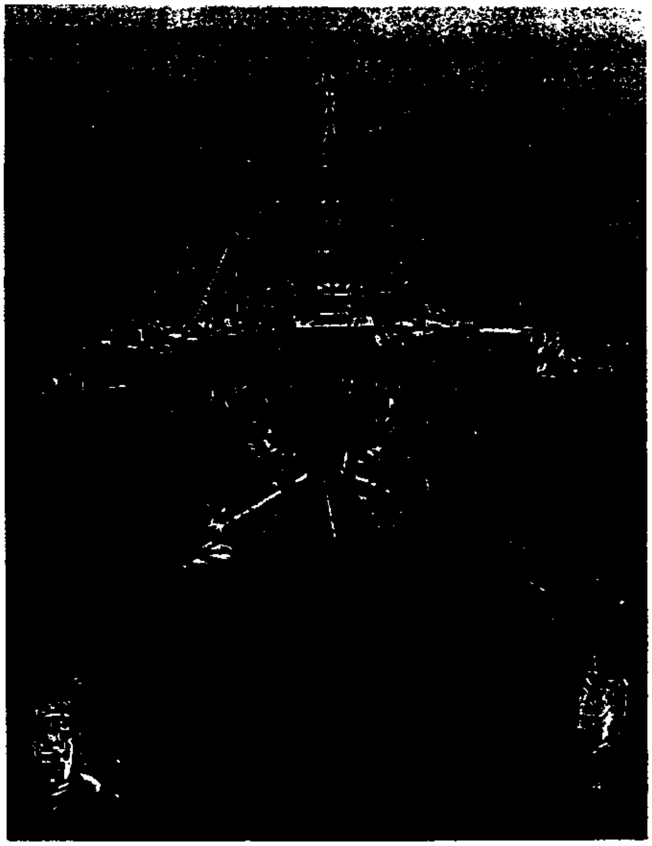


Fig. 6. Semi-submersible drilling barge *Sea Quest*

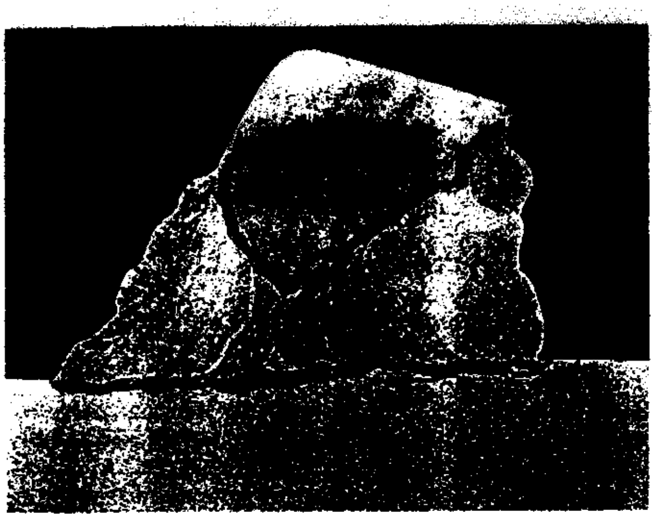


Fig. 7. Lamellar tearing beneath a double sided full penetration T-joint

technique for the welding of steel sensitive to this effect other than costly and time consuming weld buttering procedures was known. These were applied with catastrophic effects upon delivery times. The problem seemed to affect those structures where the maximum importance was placed upon the integrity of the welded connection. Perhaps the problem was common but previously it had not been noticed because of failure to apply NDT techniques suitable for the detection of such imperfections. The cause of this deficiency (lamellar tearing) (9) had not then been isolated but a clue to the cause of this unpleasant effect became evident from an unexpected source.

Hydrogen induced cracking (HIC)

The oil industry amongst other things handles large quantities of sour gas containing wet H_2S: the pH varies from about 3–5. Such gas has been handled successfully for many years in hot finished seamless pipe. Pipe of this type, as its name implies, has a high finishing rolling temperature of 1050°C or thereabouts.

In the late 1960's the increasing demand for oil and gas brought about an equivalent increase in the diameter of oil and gas transmission pipelines which necessitated a change from seamless to longitudinally welded pipe. This increase in diameter together with the enhanced hoop stress resulting from the higher operating pressures being applied in such pipelines led to an increase in the wall thickness and strength of the pipe. Field welding practices for transmission pipelines are such that the thermal input of the welding process is, of necessity, very low. Severe limitations must be placed upon the chemical composition of the pipe, particularly in respect of carbon and certain alloying materials, if heat affected zone cracking is to be avoided. Thickness is also an important parameter as it increases quench rate as a consequence of the increase in mass: this also aggravates cracking. Thin wall pipes with low carbon and alloy content (carbon equivalent) are thus favoured for line pipes. Controlled rolling offers a technique for combining all these desirable properties with relatively low manufacturing cost (**10**). In pipelines, tensile strength (TS) is not a very important parameter, the design wall thickness required to resist hoop stress is based upon yield strength (YS) only and YS/TS ratios up to 90 per cent are acceptable. In making steel plate a significant increase in yield strength can be achieved by reducing grain size. Controlled rolling which consists of rolling a plate strongly in the range of temperature 700–850°C is a highly efficient technique for achieving the required fine grain. It has a secondary less desirable effect which under some conditions of operation can be dangerous. Some pipes of control rolled steel when exposed to wet H_2S conditions delaminate in a manner high reminiscent of lamellar tearing (Fig. 8).

There are numerous ways in which wet H_2S may come to be present on a pipe wall surface but the results are for practical purposes all the same. The nascent hydrogen produced on the steel surface as a result of corrosion is inhibited by the H_2S from combining into the molecular form. Atomic hydrogen is thus able to enter the steel where it collects around inclusions and voids giving rise to pockets of intense pressure (Fig. 9). Work at BP resulted in the development of a test to assess whether or not a steel of a given quality is susceptible to such effects (**11**).

Many hundreds of samples of steel of different qualities were tested in this way and from the results it was concluded that the problem could be attributed partly to alloy segregation and banding but mainly to the morphology of the inclusions in the steel. In particular, type II manganese sulphide inclusions were identified as being especially important because these are heavily deformed by the controlled rolling process. This leads to the development of plate type inclusions with a preferred orientation parallel to the plate surface. It was shown that the shape of these inclusions could be modified to preserve a more acceptable shape by the addition of certain rare earth metals (REM) such as cerium or lanthanum (Misch metal) or by the addition of calcium (**12**).

a) AS ROLLED 96 HRS. X 50

b) AS ROLLED 192 HRS. X 100

Fig. 8. Delamination of control rolled steel after 96 hours and 192 hours exposure to brine solution saturated with H_2S (pH 5)

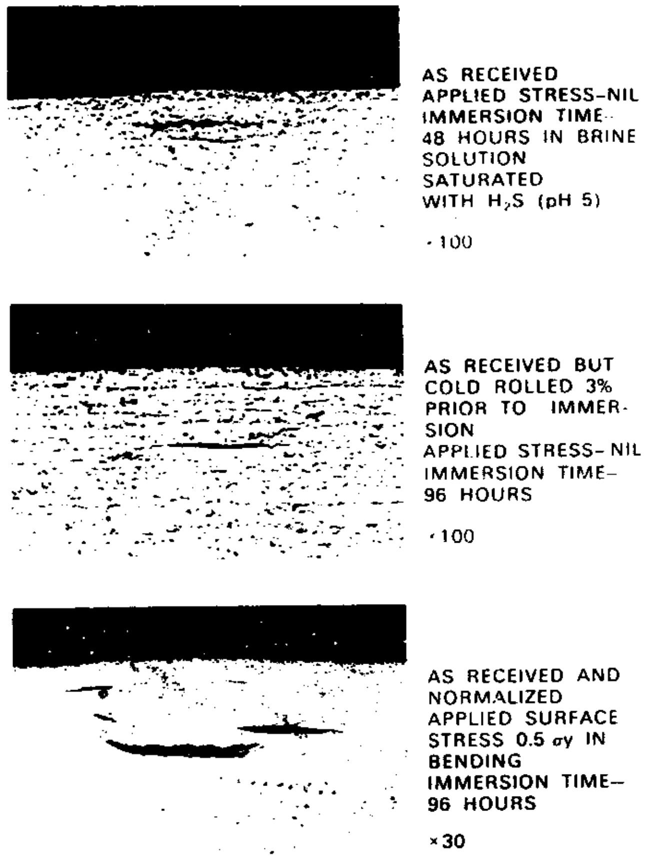


Fig. 9. **Blistering and bulging as a result of internal hydrogen pressure. Note: Subsequent mechanical or thermal treatments have practically no effect upon the hydrogen induced cracking which is strongly affected by the shape and distribution of inclusions**

These various possibilities were studied at BP but it was decided that, provided it was technically feasible, the elimination of the greater proportion of the more undesirable inclusions would provide the safest result. Vacuum degassing and desulphurizing to unprecedented low levels was evidently necessary but it was difficult to find any steel maker willing and able to make the trial heats. Finally after a world wide search two mills prepared to try to meet our requirements: the results surpassed our greatest hopes. The steels produced were highly resistant to hydrogen induced cracking (HIC) even when strongly control rolled.

The close similarity between the mode of failure for lamellar tearing and that of HIC could not be ignored. Tests were made incorporating highly restrained multi-run fillet welds and in these tests the samples of vacuum degassed steel with sulphur content between 0.001 and 0.004 per cent were found to be practically immune to lamellar tearing. These experiments (1972) were the first in the production of Z quality steel having enhanced through thickness (Z direction) properties. They led to the general adoption of a new grade of structural steel in offshore construction and elsewhere (**13**).

4 Z QUALITY STEEL

The first use of this new grade of steel was prompted by requirements for offshore platforms of greatly increased size to allow for the production of oil from Forties Field. Forties, located at a water depth of 135 m and 150 km from the Scottish shore, was the first large oil field to be discovered in the British Sector of the North Sea. The extrapolation of the platform size was hard to grasp (Fig. 10).

The required thickness at the branch to chord connections ranged from 50–125 mm and numerous stiffeners were required to transfer the stress from chord to brace: full penetration fillet welds were specified (Fig. 11). The size of the investment was immense and it was vital to get on stream at the earliest possible moment: any delay arising out of lamellar tearing was unacceptable.

Ten thousand tons of Z quality steel was ordered for Forties platforms. It was used in all critical areas including node connections and not a single case of lamellar

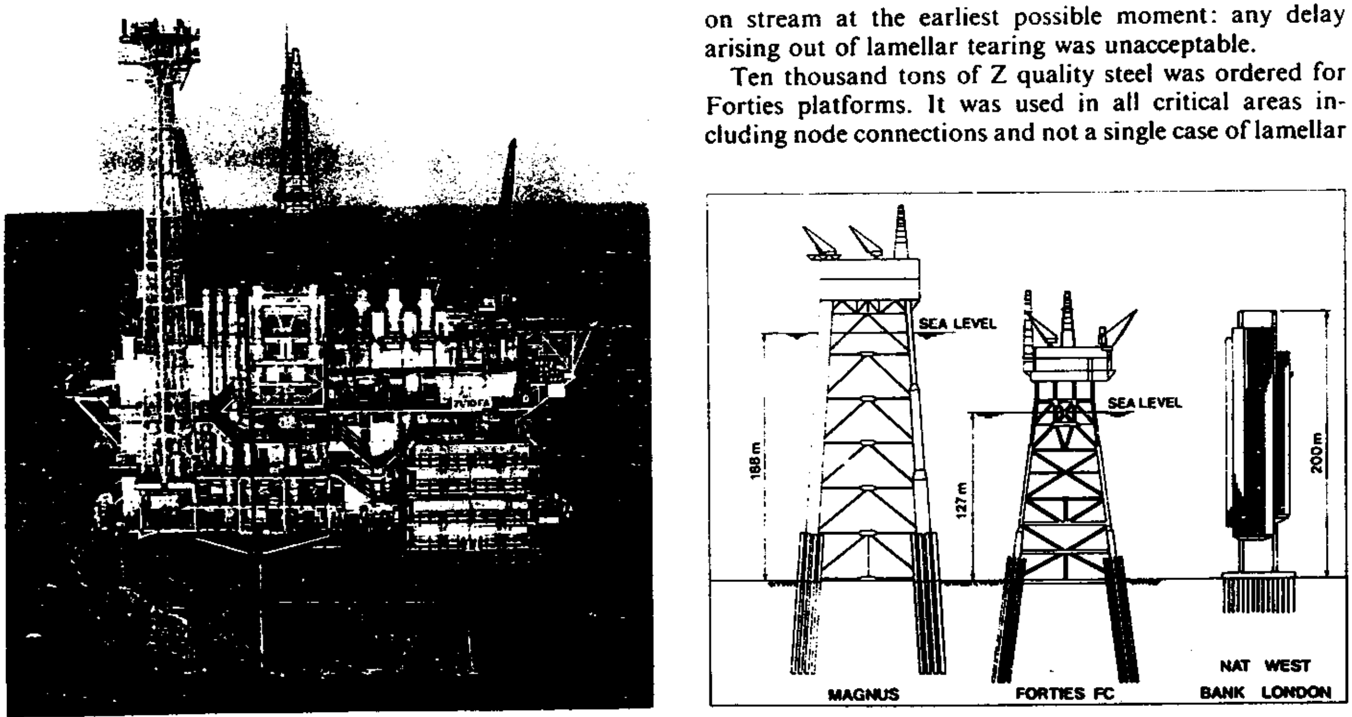


Fig. 10. Forties platform FA and size comparison with West Sole

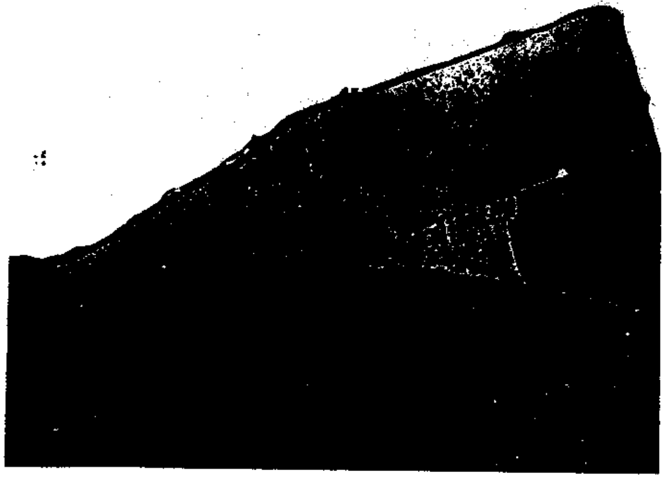


Fig. 11. Multi-run brace to chord welded connection

tearing was experienced where this new grade of steel was used (Table 1). The use of Z quality steel in critical areas of North Sea platforms such as nodes has now become common practice. The small premium payable is miniscule if compared with only one day's lost production and rig and platform construction times can be reduced significantly when precautions against lamellar tearing do not have to be applied.

The huge volume of weld metal required to make a typical Forties node entailed the employment of very many welders. A rapid welding method was required but the design of the nodes was very complicated and it was evident that much of the weld metal would have to be deposited in positions other than the flat. It was known that the notch ductility of welds made in positions other than the downhand could be inferior and a search was made for a hand held welding process that could deposit weld metal at high speed with good notch ductility. The result was very unsatisfactory.

Table 1. Mechanical properties and chemical composition of lamellar tearing resistant steel (Z quality) used for Forties 1972

Element %	Arithmetic mean	Smallest variate	Largest variate
C (× 100)	14.3	13	15
Si (× 100)	46.8	43	51
Mn (× 100)	146.9	140	154
P (× 1000)	6.2	5	7
S (× 1000)	2.0	1	4
Cu (× 100)	14.6	13	16
Nb (× 1000)	2.7	2	4
Al (× 1000)	33.8	18	47
Carbon equivalent	0.43	42	45
Mechanical properties			
Yield strength, N/mm^2	396	358	447
Tensile strength, N/mm^2	545	517	571
Charpy V (long. at −20°C, Joules	220.4	160	254
Through thickness properties			
Yield strength, N/mm^2	384	338	429
Tensile strength, N/mm^2	547	452	583
Reduction of area, %	61.6	36	73
Elongation, %	29.1	19	38

5 WELDING DEVELOPMENTS

During the period 1936–1950 there was rapid development in the field of the welding of structural steel. Many new welding processes made their appearance and a wide range of welding electrodes suitable for manual metal arc welding was developed. This period saw the first appearance of solid extruded rutile, rutile/lime and basic low hydrogen electrodes and the gradual disappearance of asbestos wound and dipped electrode coatings (**14**). By the use of such electrodes welds with mechanical properties more or less equal to those of the parent plate could be achieved. The period of the 1939–1945 war and the immediate post war boom period can be regarded as one of great progress but since then little has been achieved in this field. Welding has failed to keep pace with the improvements which have come about in the quality and variety of structural steels. The welding characteristics of the manual metal arc consumables presently available have remained largely static over the last twenty-five years or so in respect of their handleability, slag removal, weld appearance, etc. The mechanical properties of the welded deposit is also not noticeably different from those achievable in the early 1950's.

Compared with the use of electrodes available twenty-five years ago the speed of manual welding shows little change and the probability of achieving the required standard of weld without extensive repair has hardly improved. This compares very unfavourably with the extraordinary improvements which have come about in respect of the structural steel itself where progress has been phenomenal. The take off widely anticipated about 1960 in the use of a wide variety of hand held automatic welding processes which were then becoming available has not been realized. Only the flux cored self shielded semi-automatic welding process 'Inner-shield' has found application in the positional welding of offshore platforms (**15**). When embarking upon the construction of Forties Field platforms the search for a high speed hand weld welding process was at first fruitless, but more importantly even the best manual metal arc welds were found to have significant deficiencies in respect of their notch ductility.

Manual metal arc welding

Several different welding processes are in use for offshore construction. These range from very low heat input, high hydrogen processes such as are used widely for the field welding of submarine pipelines to low and intermediate hydrogen high heat input processes used almost exclusively for welding the longitudinal welds in structural tubes and pipes. The effect of these huge differences in thermal input upon the notch ductility of weld metal and its heat affected zones can be very large. The position of welding is also important. These effects can sometimes be discerned vaguely by Charpy V testing but the COD test is thought to provide more accurate information. The assistance of the Welding Institute was sought in examining this problem. They were asked to test by means of COD a wide variety of electrode

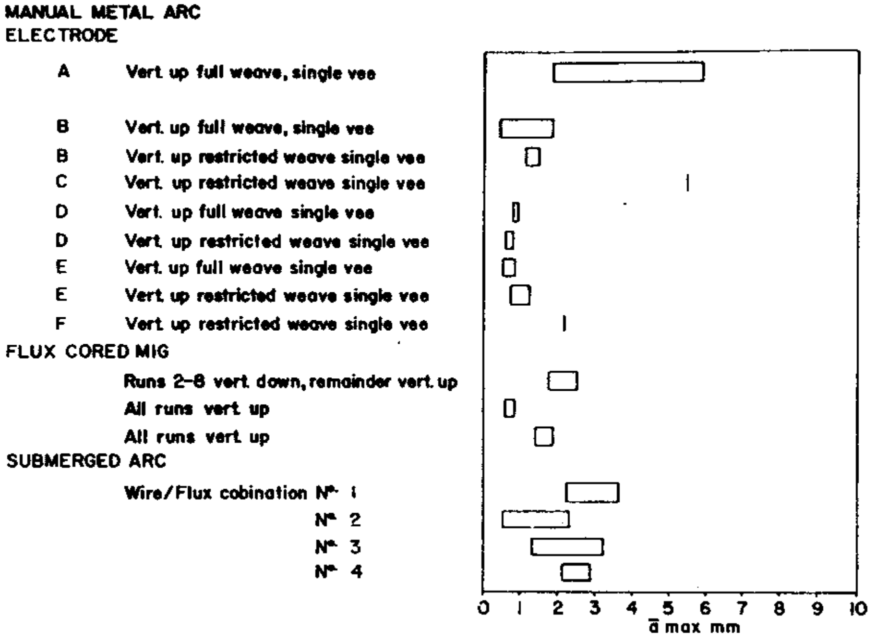
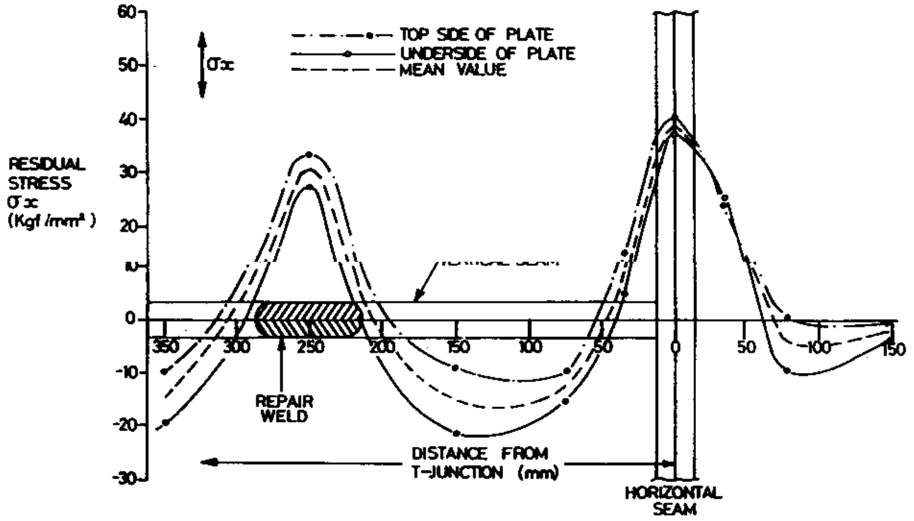


Fig. 12. Range of values of allowable flaw size for weld metals in 'as welded' condition; showing pronounced scatter in COD results (Welding Institute for BP)

consumables, welding procedures, welding positions, etc. and to assess the effect of post weld heat treatment. To simplify the number of variables, only two thicknesses were tested, 50 mm and 63 mm; the material chosen was limited to BS 4360 Grade 50D. The results of this inquiry were most disconcerting. None of the manual metal arc welding consumables available at that time met, in the vertical welding position, the minimum value of COD specified. This made the choice of weld metal for node construction very difficult. Even for the best consumables available and using the most complicated welding procedures some risk of failure remained if lower bound COD values were used in calculating allowable flaw sizes (Fig. 12) (**16**).

For welds in the 'as welded' condition, i.e. not post weld heat treated, the calculated critical flaw size in welds in plate 50 mm and thicker in the vertical position was unacceptably small. The cost of meticulous non-destructive testing and concomitant repair work would be very great but more than that the delay in completing the work would be extremely costly. Repair welding itself was found to have an alarming effect upon the distribution of residual stresses, so much so that the repaired weld in the non-stress relieved condition was unacceptable (Fig. 13).

The BP work and that of The Welding Institute showed the benefits deriving from stress relief by post weld heat treatment to be very substantial (**17**). The allowable flaw size in welds thicker than 40 mm was significantly larger than for the 'as welded' condition (Fig. 14). This arose partly because of an improvement in COD but also because of the significant reduction in the stress assumed to be applied to the imperfection under consideration as a result of the relief of residual welding stresses (Fig. 15).



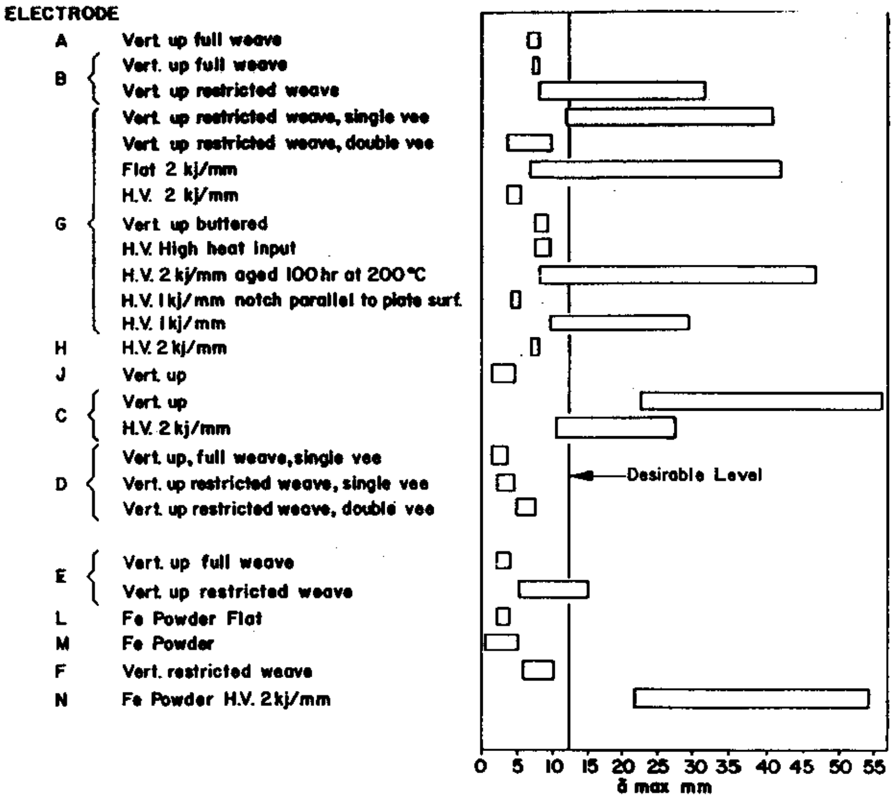


Fig. 14. Range of values of allowable flaw size, $\bar{\delta}_{max}$, for manual metal arc weld metals (stress relieved by PWHT) (Welding Institute for BP)

Deficiency in the notch ductility of manual metal arc welds derives from an insufficient proportion of desirable micro-structure in the finished weld. For positional welding, at the present time, optimum impact and COD properties can only be achieved in commercial vertical welding by utilizing recrystallization effects. This entails the use of very small individual beads or runs to build up a weld of the required size by using a multi-run technique. The fairly fast cooling rates of the reheated metal resulting from the application of such procedures produces significant grain refinement in the metal of the previous weld pass (**18**).

Almost all welds contain cracks or crack-like imperfections; they arise as a result of various mechanisms including hydrogen, reheat and solidification cracking. The significance of such imperfections is strongly dependent upon the properties of the micro-structure at the exact tip of such flaws (Fig.

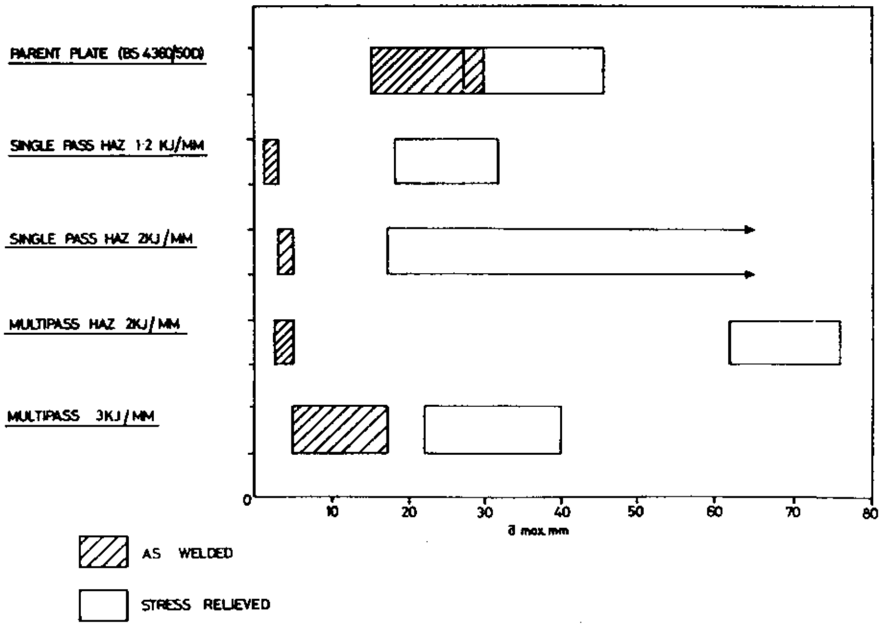


Fig. 15. Comparison between the range of values of allowable flaw size, $\bar{\delta}_{max}$, for parent plate in the 'as welded' and in the stress relieved condition (Welding Institute for BP)

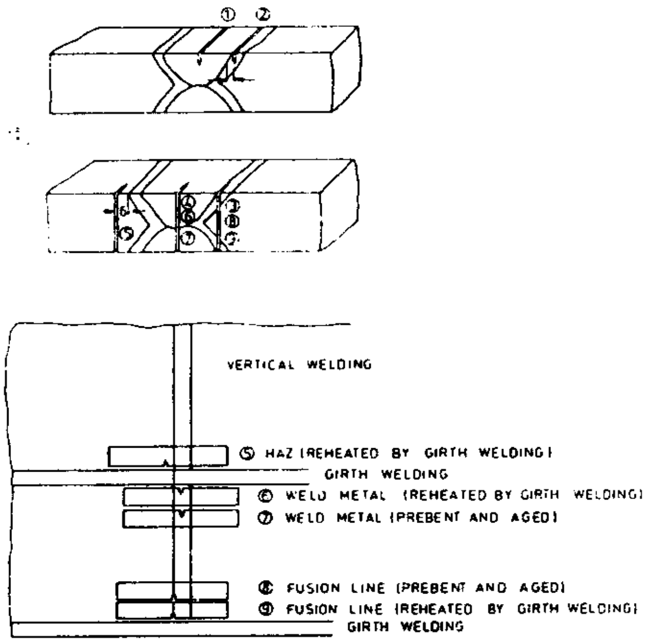


Fig. 16. Notch locations for COD testing to evaluate variations in micro-structure across the weld

16). For weld metals in carbon-manganese steel the metallurgical structure 'acicular ferrite' has been identified as being highly beneficial in achieving good notch ductility (Fig. 17). However the certainty of achieving this tough structure in welding positions other than the flat is poor. Welds made in the vertical position of welding seem to be specially unreliable in this respect. Recent studies indicate that the type, size and distribution of inclusions has an important effect in the nucleation of acicular ferrite in preference to the less desirable bainite and Widmanstatten structures which so frequently occur (Fig. 18).

The acicular ferritic structure has been shown to nucleate on non-metallic inclusions and this nucleation appears to be favoured when the oxygen content of the weld metal is within a rather narrow range of about 0.02–0.04 per cent. The effectiveness of oxide particles in nucleating the desired micro-structure is evident but even so coarser and less desirable phases can easily prevail unless transformation temperatures are rather precise (19).

In vertical welding, especially in the manual mode, the effectiveness of the gas shroud generated by the melting flux and shielding the weld pool from excessive oxidation is unreliable. This is largely because of geometric effects associated with manual operation. This inability to control accurately the oxygen content of vertical weld deposits may be the reason that it is so difficult to achieve good notch ductility in vertical welds deposited at a high rate. Similarly attempts to increase the speed of welding by using electrodes heavily coated with a flux rich in iron powder have been less than successful because of the relatively poor notch ductility of the weld deposit. This also has been attributed to the increased oxygen and inclusion content arising perhaps out of the attenuation of the self generated gas shield (20).

Submerged arc welding

Submerged arc welding fluxes have been improved greatly over the last few years and the reduction of oxygen content of such welds has been identified as one reason for the enhanced notch ductility. The use of this process is limited to the flat position so it finds little application in welding complicated node connections for example. So despite all these improvements it is difficult to take advantage of them in the location of chord to brace 'hot spots' where enhanced notch ductility is specially desirable. The geometric complexity in such locations necessitates the use of manual welding. However the submerged arc welding process is used extensively in making the axial welds in large structural tubes and in pipes for pipelines and can be applied for circumferential or girth welds when the work piece can be rotated. In such applications the use of twin and multi-arc techniques, hot and cold wire additions, cut wire and iron powder additions and flux with improved electrical power carrying capacity have been used to good effect (21).

6 STEEL SELECTION

The choice of the most suitable grade of steel to be used in the construction of offshore platforms is still in an early stage of development. BS 4360 Grade 50D (E) has been widely used but the choice of this grade seems to be arbitrary. For the common structural steels in the hot

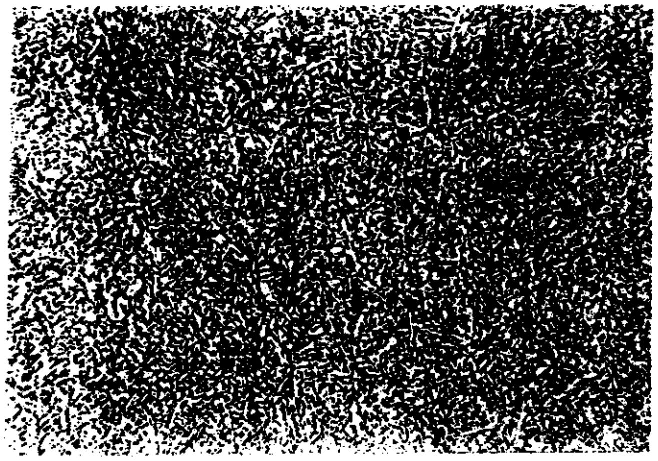


Fig. 17. Desirable weld metal micro-structure—acicular ferrite (×500)

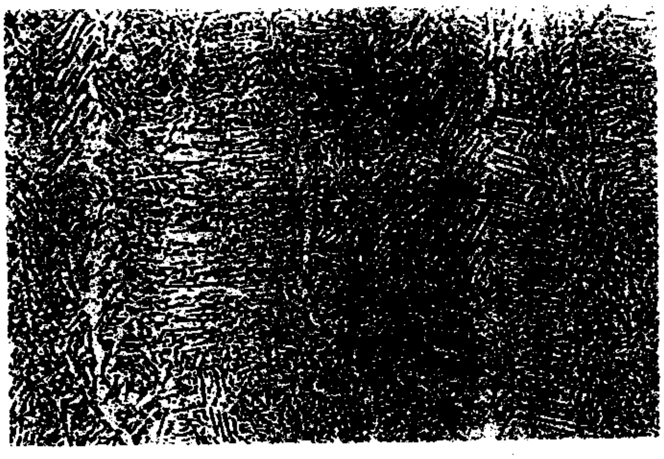


Fig. 18. Unsatisfactory weld metal micro-structure with poor notch ductility (×400)

finished or normalized condition Grade 50 appears to be the strongest grade which can be supplied in thickness up to 75 mm or thereabouts with a carbon equivalent not exceeding 0.41 per cent. This value has been favoured by ship classification societies as being the maximum composition which can be welded without preheat and without using low hydrogen electrodes (22). These criteria seem to be inappropriate when welding steel plates and tubes of great thickness.

Lack of interest in using stronger grades can be attributed to fears of poor fatigue strength when strong steels are welded.

Offshore constructions, particularly platforms which are exposed to the cyclic effects of wave loading may be at risk from fatigue damage. It should not be assumed however that these effects are common to the greater part of the structure. In fact in most structures the possibility of damage by these cyclic stress effects is confined to a relatively small number of highly localized zones. In a typical platform perhaps less than 20 per cent of the chord to brace connections will be affected. Naturally the exact proportion of joints at risk and their location varies with the particular design. For locations other than those subject to possible fatigue damage the wisdom of using Grade 50 steel is being re-examined.

Improvements in buoyancy which arise out of weight reduction can have important effects on the design of fixed platforms which are required to be towed into position. The effect upon tethered buoyant platforms could be even more significant.

The reduction in scantlings which could be achieved in some locations in all types of structures could reduce significantly the volume of weld metal required. Furthermore the load carrying capacity of fixed or buoyant structures can be improved by reduction in the weight of the jacket or hull itself.

Quenching and tempering of simple carbon/manganese steels with small additions of micro alloying elements can result in strong steel with excellent notch ductility and weldability. Heavy plates with thickness up to 55 mm in Grade 60 and 65 are now available and these can be used to considerable advantage in chosen locations in a platform (23). In locations where section modulus is not controlling and cyclic stress effects are not dominant the use of stronger steels can show important savings, thousands of tons of quenched and tempered high strength steel was used for Forties platform piling.

For locations where cyclic stress effects might give rise to fatigue crack growth if Grade 60 steels were to be used, other techniques have been applied or are being studied with the aim of providing alternative solutions to the problem.

7 FATIGUE CONSIDERATIONS

Where low stress high cycle conditions apply with a magnitude exceeding the threshold stress, significant improvement in fatigue life can be achieved as a result of a small reduction in stress at the 'hot spot' (24). This is not so for high stress low cycle conditions where large reductions in stress have only relatively small effects upon life. However the stress spectrum appropriate to typical platforms operating in North Sea conditions shows that, in properly designed structures, high stress fatigue is less of a problem than had previously been anticipated. For typical North Sea stress spectra a local thickening of the node together with the provision of a smooth transition between chord and brace can provide startling improvements. In some cases welding can be used to obtain the required thickness and geometry but this is not always economic because of the large quantity of weld metal which can be required to achieve the desired result.

For such locations castings or forgings might provide a useful alternative to the welded node (25). If castings are used the quality must be excellent. Desulphurizing and vacuum degassing as has been applied in the production of Z quality steel plate has now found some application in the production of suitably high quality castings. The use of these in conjunction with stronger steels for chord and brace might show very great savings in structures of appropriate design.

The fatigue life of welded connections can be reduced significantly by hydrogen charging effects and these are being studied intensely by the UKOSRP and elsewhere under the patronage of the European Coal and Steel Community (26). Their aim is to promote the efficient and safe use of steel in offshore construction.

Cathodic charging has been shown to have damaging effects upon fatigue life under conditions of excessive protection. Half cell potential needs to be carefully regulated and controlled if catastrophic effects upon fatigue life are to be avoided. The use of sacrificial anodes appears to entail no risks of this nature but impressed currents can be damaging if the half cell potential (Ag/AgCl) is more negative than about −0.9 V. The damaging effect of hydrogen charging appears to be time dependent, it being necessary to saturate the component before the damaging effects become manifest (27). Painting of structures subsequently to be submerged in the sea reduces the areas of steel to be protected especially in the period prior to the establishment of a colony of marine biological accretion (fouling). Painting has the effect of reducing the weight of anode which will be consumed in this first important stage after submersion. Perhaps, more importantly, it will be confirmed that the areas of steel exposed to cathodic charging effects are so reduced that hydrogen charging effects are minimal and saturation by hydrogen of a painted structure can never be achieved.

Other effects such as the action of sulphate reducing bacteria trapped beneath the layers of fouling and the competitive processes of hydrogen charging and calcium plugging are being studied but it is too early to draw meaningful conclusions (28). Meanwhile thickening and improving the contour at hot spots at the chord to brace connections might provide a cheap and effective solution to fatigue in such locations.

8 ECONOMIC CONSIDERATIONS

The foregoing remarks have emphasized the desirability of using special qualities and grades of steel. The increased cost of such steel is advanced frequently as a reason for

Table 2. Allocation of cost in developing oil field in deep water

Platforms installed	70%
Pipelines installed	17%
Terminals and berths	5%
Administration and miscellaneous	8%

not taking advantage of their improved performances either in construction or in service. Tables 2 and 3 show that for a large oil field in deep water this is false economy. Economies which might be valid for land applications can be irrelevant for offshore working. Even for a construction fabricated largely or completely on land, the cost of the steel itself will often turn out to be a very small if not insignificant proportion of the total investment.

Table 3. Cost of steel for development of offshore field

All steel offshore	6% of installed offshore cost
Steel in platforms	6% of installed platform cost
Node steel in platform	0.25% of installed platform cost
Node fabrication	0.75% of installed platform cost
Piling	2.75% of installed platform cost
Steel in submarine pipeline	10% of installed pipeline cost

The cost of offshore working compared with working on land is greatly increased and for the case of a submarine pipeline in deep water the cost of the completed line may exceed by a factor of five or more the cost of a similar construction on land (Table 4).

Table 4. Comparison between percentage relative cost of land and submarine pipeline

	Land	Submarine
Material	50	10
Coating and wrapping	6	5
Laying	38	60
Burying	—	18
Others	6	6

The cost of improvements in the weldability of steel used in offshore applications can be almost undetectable in comparison with the cost of the completed installation. The total cost of all the steel used in the development of a large oil field in deep water is only in the order of 6 per cent of the total cost of the installation. In this context the premium demanded for the supply of special steel grades seems to be irrelevant. The improved availability of steels with specially desirable qualities has overcome the only important objection to their use. The necessity of using manual metal arc welding processes to achieve adequate notch ductility in welded connections made in all positions other than the flat is very costly. The cost per kilogramme of deposited weld metal has become disproportionate and new high speed welding methods are required.

9 CONCLUSIONS

Techniques used presently to interpret the significance of COD traces lead to severe requirements for post weld heat treatment and the results obtained often preclude the use of high deposition welding techniques for much of the work involved in constructing a large platform.

Marked differences in the behaviour of a COD specimen can be produced simply by varying the compliance of the test rig. An improvement in machine compliance frequently results in breaking a specimen which might otherwise have indicated only a transitory hesitation in the load-displacement trace. As notch ductility is improved, special arrangements have to be made in test rig design so that sufficient compliance is available to cause the test specimen to break. The same problems in interpretation appear to apply to the COD test as bedevilled the Robertson and other wide plate test techniques which were aimed at the assessment of fast fracture arrest properties.

The compliance of real structures is obviously of great significance in determining the critical size of an imperfection. The conservatism inherent in present COD assumptions may be responsible for large increases in the cost and construction time of offshore platforms.

The relationship between the compliance of a real structure and that of a COD test rig should ideally be comparable and this would allow the breaking of the COD specimen to be the critical event. The apparent failure of the welding industry to keep pace with the advances made by the steel industry in furnishing better steels may be attributable as much to false assumptions in interpreting COD results for heterogeneous metals, such as weld deposits, as to any other cause.

ACKNOWLEDGEMENT

Permission to publish this paper has been given by The British Petroleum Company Limited.

REFERENCES

(1) MERCER, J. Trends in welding consumables—a preliminary centennial assessment. *Trends in steels and consumables for welding*, Welding Institute Conference, Nov. 1978.

(2) SMEDLEY, G. P. Responsibilities for materials reliability and safety. *The expanding responsibilities of the industrial materials technologist*, Institution of Metallurgists Conference, 1978.

(3) Report of the Royal Commission into the failure of the Kings Bridge, Melbourne, Commonwealth of Australia, 1963.

(4) PELLINI, W. S. and PUZAK, P. P. Fracture analysis diagram procedures for the fracture safe engineering design of steel structures. *Report NRL 5920*, Naval Research Laboratories, Washington, March 1973.

(5) ASTM E 208-69. Conducting drop weight tests to determine nil ductility transition temperature of ferrite steels.

(6) Report of the inquiry into the causes of the accident to the drilling rig *Sea Gem*. HMSO, Comnd. 3409, Oct. 1967.

(7) WOODLEY, C. C., BURDEKIN, F. M. and WELLS, A. A. Mild steels for pressure equipment at sub-zero temperatures. *Br. Weld J.*, 1964, 7.

(8) BURDEKIN, F. M. Initiation of brittle fracture practice in structural steels. *Br. Weld. J.*, 1967, 14.

(9) FARRAR, J. C. The effect of the hydrogen on the formation of lamellar tearing. *Weld. Research Int.*, 1977.

(10) McINTYRE, P. and BANKS, T. M. Stress corrosion induced cracked in steels or offshore applications. *European offshore steels research seminar*, Paper 19, TWI, 1978.

(11) MOORE, E. M. and WARGA, J. J. Factors influencing the hydrogen cracking sensitivity of pipeline steels. *Materials performance*, June 1976, 15, No. 6

(12) OONO, YANO, and OKAMURA. Improvement in steel properties by sulphide shape control. *Trends in steels and consumables for welding*. Welding Institute Conference, Nov. 1978.

(13) FARRAR, J. C. and DOLBY, R. E. Lamellar tearing in welded steel construction. Welding Institute, 1972.

(14) BS 639. *Covered electrodes for the manual metal arc welding of carbon and carbon manganese steels*, British Standards Institution, 1976.

(15) HARRISON, J. D. The effect of post weld heat treatment of the toughness of welds for an offshore platform. Institution of Metallurgists conference, Nov. 1976.

(16) JOHNSTON, G. O. What are the chances of failure? Probabilistic fracture mechanics. *Welding Institute Research Bulletin*, Feb. 1978.

(17) HARRISON, J. D. and PISARSKI, H. Fracture resistance of materials used in offshore fabrications. *European offshore steels research seminar*, TWI, 1978.

(18) BERKHOUT, C. F., VAN DER BRINK, S. and VAESSEN, G. H. G. Controlling weld toughness in M.M.A. and sub arc welds. *European Offshore Steels research seminar*, Paper 1, TWI, 1978.

(19) ABSON, D. J. and DOLBY, R. E. The role of non metallic inclusion in ferrite nucleation. *Trends in steels and consumables for welding*, Paper 25, Welding Institute conference, 1978.

(20) BONIZEWSKI, T. The effect of iron powder in basic low hydrogen all positional electrodes. *Trends in steels and consumables for welding*. Welding Institute conference, 1978.

(21) EAGER, T. W. Sources of weld metal oxygen contamination during sub arc welding. *Welding J.*, 1978, No. 3.

(22) *Rules and regulations for the construction and classification of steel ships*, Ch. D3219, Lloyds Register of Shipping, 1974.

(23) *Weldable C.T. high strength steels and their application in Japan*. Q.T. Sub Committee, Japan Institute of Welding Comm. IX.

(24) BRISTOLL, P. and ROELEWELD, J. Fatigue of offshore structures. Effect of seawater on crack propagation in structural steel. *European offshore steels research seminar*, Paper 18, TWI, 1978.

(25) WALKER, E. F. British Steel Corporation, private communication.

(26) WORDWORTH, A. C. and SMEDLEY, G. P. Stress concentrations at unstiffened tubular joints. *European offshore steels research seminar*, Paper 31, TWI, 1978.

(27) JOHNSON, R. *et al.* The effects of seawater corrosion on fatigue crack propagation in structural steel. *European offshore steels research seminar*, Paper 15, TWI, 1978.

(28) *Performance of offshore structures*, Institution of Metallurgists conference, Nov. 1976.

This lecture is published for delivery at an Ordinary Meeting of the Institution in London on 28th March 1979. The MS was received on 15th February 1979.