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Assessment and management of ageing of major nuclear power plant components important to safety:

CANDU reactor assemblies

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FOREWORD

At present, there are over four hundred operational nuclear power plants (NPPs) in IAEA Member States. Operating experience has shown that ineffective control of the ageing degradation of the major NPP components (e.g. caused by unanticipated phenomena and by operating, maintenance, design or manufacturing errors) can jeopardize plant safety and also plant life. Ageing in these NPPs must therefore be effectively managed to ensure the availability of design functions throughout the plant service life. From the safety perspective, this means controlling within acceptable limits the ageing degradation and wearout of plant components important to safety so that adequate safety margins remain, i.e. integrity and functional capability in excess of normal operating requirements.

This TECDOC is one in a series of reports on the assessment and management of ageing of the major NPP components important to safety. The reports are based on experience and practices of NPP operators, regulators, designers, manufacturers, and technical support organizations and a widely accepted Methodology for the Management of Ageing of NPP Components Important to Safety which was issued by the IAEA in 1992.

The current practices for the assessment of safety margins (fitness for service) and the inspection, monitoring, and mitigation of ageing degradation of selected components of Canada deuterium–uranium (CANDU) reactors, boiling water reactors (BWRs), pressurized water reactors (PWRs) including the Soviet designed water moderated and water cooled energy reactors (WWERs), are documented in the reports. These practices are intended to help all involved directly and indirectly in ensuring the safe operation of NPPs and also to provide a common technical basis for dialogue between plant operators and regulators when dealing with age-related licensing issues. Since the reports are written from a safety perspective, they do not address life or life-cycle management of the plant components, which involves the integration of ageing management and economic planning. The target audience of the reports consists of technical experts from NPPs and from regulatory, plant design, manufacturing, and technical support organizations dealing with specific plant components addressed in the reports.

The nuclear power plant component addressed in the present publication is the CANDU reactor assembly. The work of all contributors to the drafting and review of this report is greatly appreciated. In particular, the contributions of L.A. Beresford and W.Z. Novak of the Atomic Energy of Canada Ltd (AECL), who drafted the report, are acknowledged. J. Pachner of the IAEA's Division of Nuclear Installation Safety and B.A. Shalaby of the AECL directed the preparation of the report. The report was updated in June 2000.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. Background

Managing the safety aspects of nuclear power plant (NPP) ageing requires implementation of effective programmes for the timely detection and mitigation of ageing gradation of plant systems, structures and components (SSCs) important to safety, so as to ensure their integrity and functional capability throughout plant service life. General guidance on NPP activities relevant to the management of ageing (maintenance, testing, examination, and inspection of SSCs) is given in the IAEA Nuclear Safety Standards (NUSS) Code on the Safety of Nuclear Power Plants: Operation [1] and associated Safety Guides on in-service inspection [2], maintenance [3] and surveillance [4].

The operation code requires that NPP operating organizations prepare and carry out a programme of periodic maintenance, testing, examination, and inspection of plant systems, structures and components important to safety to ensure that their level of reliability and effectiveness remains in accordance with the design assumptions and intent and that the safety status of the plant has not been adversely affected since the commencement of the operation. This programme is to take into account the operational limits and conditions, any other applicable regulatory requirements, and be re-evaluated in the light of operating experience. The associated Safety Guides provide further guidance on NPP programmes and activities that contribute to timely detection and mitigation of ageing degradation of SSCs important to safety.

The Safety Guide on In-Service Inspection (ISI) provides recommendations on methods, frequency, and administrative measures for the ISI programme for critical systems and components of the primary reactor coolant system aimed at detecting possible deterioration due to the influences of stress, temperature, irradiation, etc. and at determining whether they are acceptable for continued safe operation of the plant or whether remedial measures are needed. Organizational and procedural aspects of establishing and implementing an NPP programme of preventative and remedial maintenance to achieve design performance throughout the operational life of the plant are covered in the Maintenance Safety Guide. Guidance and recommendations on surveillance activities, for SSCs important to safety, (i.e., monitoring plant parameters and systems status, checking and calibrating instrumentation, testing and inspecting SSCs, and evaluating results of these activities) are provided in the Surveillance Safety Guide. The aim of the surveillance activities is to verify that the plant is operated within the prescribed operational limits, and conditions, to detect in time any deterioration of SSCs as well as any adverse trend that could lead to an unsafe condition, and to supply data to be used for assessing the residual life of SSCs. The above Safety Guides provide general programmatic guidance, but do not give detailed technical advice for particular SSCs.

Programmatic guidance on ageing management is given in Technical Report Series No. 338 “Methodology for the Management of Ageing of Nuclear Power Plant Components Important to Safety” [5] and in a Safety Practice “Data Collection and Record Keeping for the Management of Nuclear Power Plant Ageing” [6]. Guidance provided in these reports served as a basis for the development of component specific Technical Documents (TECDOCs) on the Assessment and Management Ageing of Major NPP Components Important to Safety. This publication on CANDU reactor assembly is one of such TECDOCs. TECDOCs already issued address: steam generators [7], concrete containment buildings [8], CANDU pressure tubes [9], PWR reactor pressure vessels [10], PWR reactor vessel internals [11] and metal components of BWR containment systems [12].

The CANDU reactor utilizes a pressure tube concept with heavy water moderator and coolant, natural uranium fuel and on-power refueling. A list of existing CANDU and Pressurised Heavy Water Reactors (PHWRs) is given in Table I. An array of fuel channels, containing the reactor fuel passes through a large cylindrical vessel called the calandria which contains the heavy water moderator and reflector. The pressure tubes, which contain the high pressure, high temperature coolant, form part of the fuel channel assembly and are isolated from the cold low pressure moderator by the carbon dioxide filled annular space between the pressure tubes and calandria tubes.

TABLE I. LIST OF EXISTING CANDU/PHWR NPPs

Station	First Unit in Service	# of Units per Station	Net output MW(e)	Owner**	Reactor Type
Pickering A	1971	4	4 × 515	OPG, Canada	CANDU
Pickering B	1983	4	4 × 516	OPG, Canada	"
Bruce A	1977	4	4 × 848	OPG, Canada	"
Bruce B	1985	4	4 × 860	OPG, Canada	"
Darlington	1990	4	4 × 880	OPG, Canada	"
Gentilly 2	1983	1	638	HQ, Canada	"
Point Lepreau	1983	1	640	NBEPC, Canada	"
Embalse	1984	1	600	CNEA, Argentina	"
Wolsung	1983	4	4 × 650	KEPCO, Korea	"
Rajastan 1	1973	1	90	NPCIL, India	"
Rajastan 2	1981	1	187	NPCIL, India	"
Rajastan 3	2000	1	202	NPCIL, India	
Madras	1984	2	2 × 155	NPCIL, India	PHWR
Narora	1991	2	2 × 202	NPCIL, India	"
Kakrapara	1992	2	2 × 202	NPCIL, India	"
Kaiga-1	1999	1	1 × 202	NPCIL, India	"
Kanupp	1972	1	125	AEC, Pakistan	CANDU
Cernavoda –1	1996	1	650	RENEL, Romania	PHWR

** OPG — Ontario Power Generation, HQ — Hydro Quebec, NBEPC — New Brunswick Electric Power Commission, CNEA — Comision Nacional de Energia Atomica, KEPCO — Korea Electric Power Corporation, AEC — Atomic Energy Commission of Pakistan, NPCIL — Nuclear Power Corporation Ltd, RENEL — Romanian Electricity Authority.

Many of the components in the CANDU reactor system are designed to have regular in-service inspection and can be replaced, if needed, during the design life of the station. There are many key reactor assembly components, however, which are simply not accessible and, therefore, are designed to require no inspection or maintenance over a normal operating lifetime.

The primary function of the reactor assembly is to provide moderator containment while locating and providing support for its internals (primarily the fuel channels and the reactivity control units). Further details are given in Section 2.

From a safety perspective the reactor assembly is required to:

(a) Maintain its fluid retaining capacity to ensure that the moderator and shield cooling systems can act as heat sinks during accident scenarios where coolant is lost from the heat transport system, and the reactor has been shutdown.

(b) Maintain its structural integrity, that is, the positioning and support of the fuel channels and the reactivity control units, during all postulated service conditions.

(c) Maintain the fluid retaining capacity and the structural integrity of the calandria vessel in the event of a single channel in-core LOCA. That is, provide emergency discharge pipes to vent moderator and heat transport system water, thus limiting any pressure increase inside the calandria.

(d) Maintain the fluid retaining capacity and the structural integrity of the shield tank during an accident involving a loss of heat transport system cooling and a loss of moderator cooling, with the reactor shutdown, to ensure that cooling of the calandria shell is maintained. That is, provide emergency discharge pipes to vent steam generated by boiling of the shield cooling water. (Note: this capacity may be provided as a part of the shield cooling system instead of by the shield tank.)

(e) Allow for the addition of light water to the calandria and/or the shield tank under operator control during extreme conditions.

In principle, failure of any of the components comprising the calandria assembly and its supports does not pose an immediate safety concern. In practice, failure of these components has a direct economic consequence and indirectly affects safety. For example, leaks from any of the compartments containing water would interfere with leak detection either in the vault or in the annulus gas system used to detect pressure tube leaks. At best, either of these would reduce the margin to shutdown, but, if severe enough, could directly lead to shutdown. Degradation of components containing the moderator could lead to the loss of heavy water or its dilution with light water. Failure of the moderator inlet nozzles into the calandria vessel may reduce the local sub-cooling, ultimately affecting performance of the moderator as a heat sink in a severe accident. In addition, the impingement of the flow directly onto the fuel channels could induce vibration, which could lead to leakage due to calandria tube rolled joint failure.

1.2. Objective

The objective of this report is to identify potential ageing mechanisms and degradation sites (locations) and to document the current practices for the assessment and management of the ageing of CANDU and Indian PHWR reactor assemblies.

The underlying objective of this report series is to ensure that the information on the current assessment methods and ageing management techniques is available to all involved directly, and indirectly, in the operation of nuclear power plants in the IAEA Member States.

The target audience includes nuclear power plant operators, regulators, technical support organizations, designers, and manufacturers.

1.3. Scope

This report describes the technical basis for the ageing management of the CANDU reactor assemblies to ensure that plants operate throughout and beyond the NPP design life while maintaining the required safety margins.

The scope of the report includes the following CANDU reactor assembly components:

- calandria vessel pressure boundary components (including calandria tubes)
- end shields
- shield tank
- moderator dump tank and dump ports
- calandria supports
- shield tank bearings.

Also included in this report is information related to the Indian PHWR reactor assemblies.

The report does not address life or life-cycle management of CANDU reactor assemblies because it is written from the safety perspective and life management includes economic planning.

1.4. Structure

The reactor assembly designs and component descriptions are discussed in Section 2. The design basis is presented in Section 3. The potential ageing mechanisms, susceptible sites, and failure modes are presented in Section 4. The monitoring and inspection methods are discussed in Section 5. Assessment methods are discussed in Section 6. Mitigation of ageing degradation is discussed in Section 7. The report concludes, in Section 8, with a description of an ageing management programme for CANDU reactor assemblies.

2. DESCRIPTION OF CANDU AND INDIAN PHWR REACTOR ASSEMBLIES

The reactor assembly is comprised of the calandria vessel, two end shields, end shield supports, and the reactor shielding. CANDU reactor assemblies can be grouped into three design categories typified by Ontario Power Generation Pickering A, CANDU 6 and Ontario Power Generation Bruce and Darlington stations. The major design differences between the three reactor types are summarized in Table II. Each of the three reactor assembly types incorporates a different reactor vault and calandria support design as illustrated in Figures 1–3.

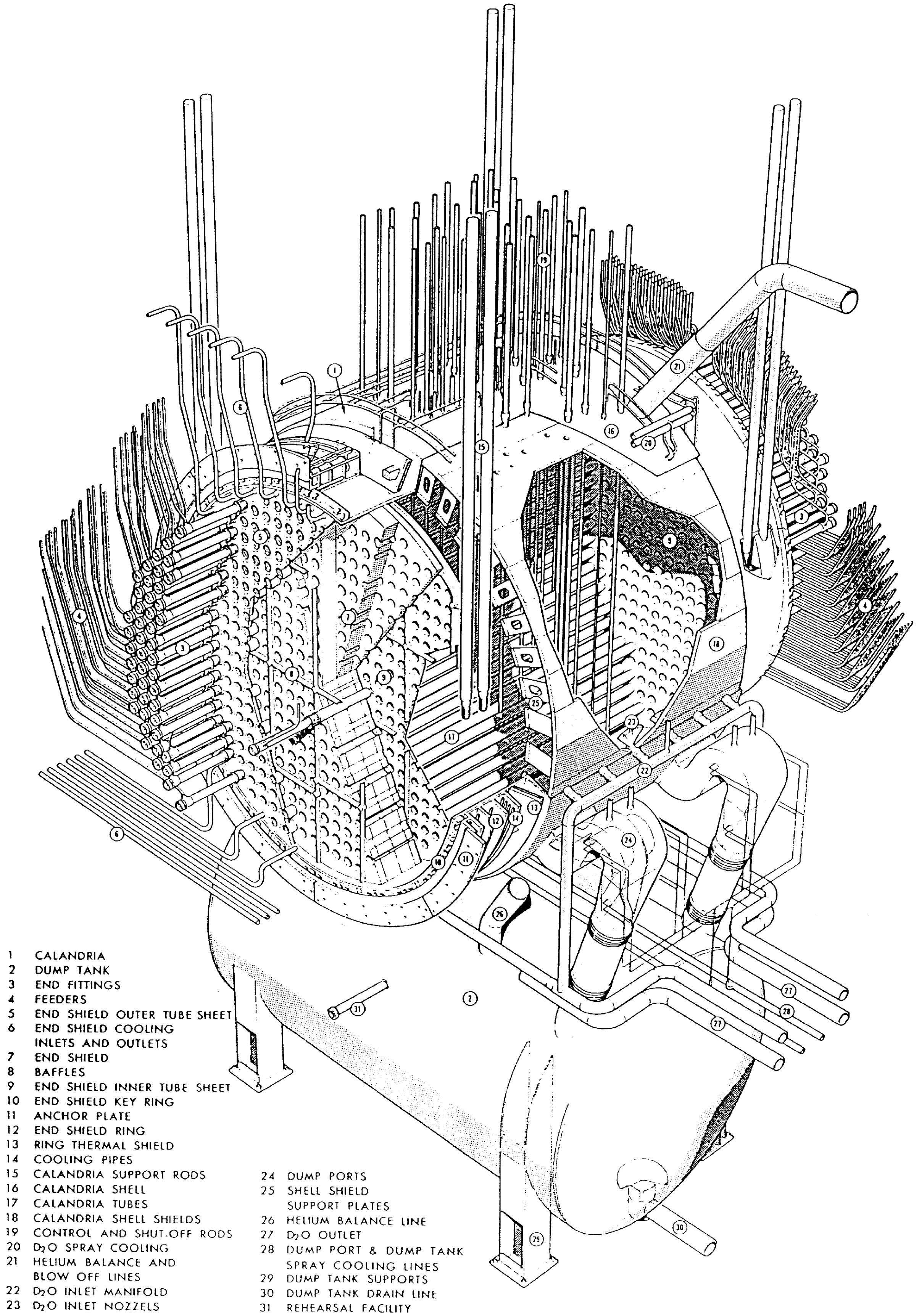
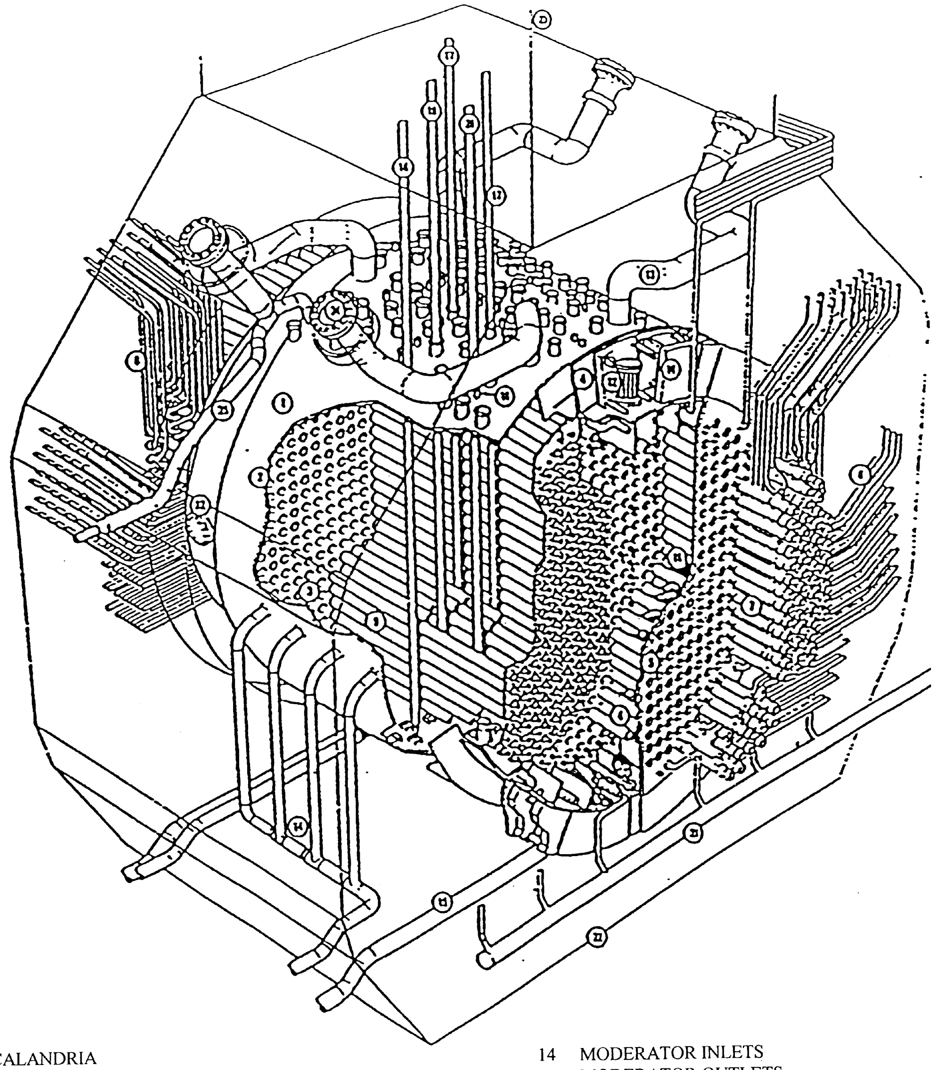
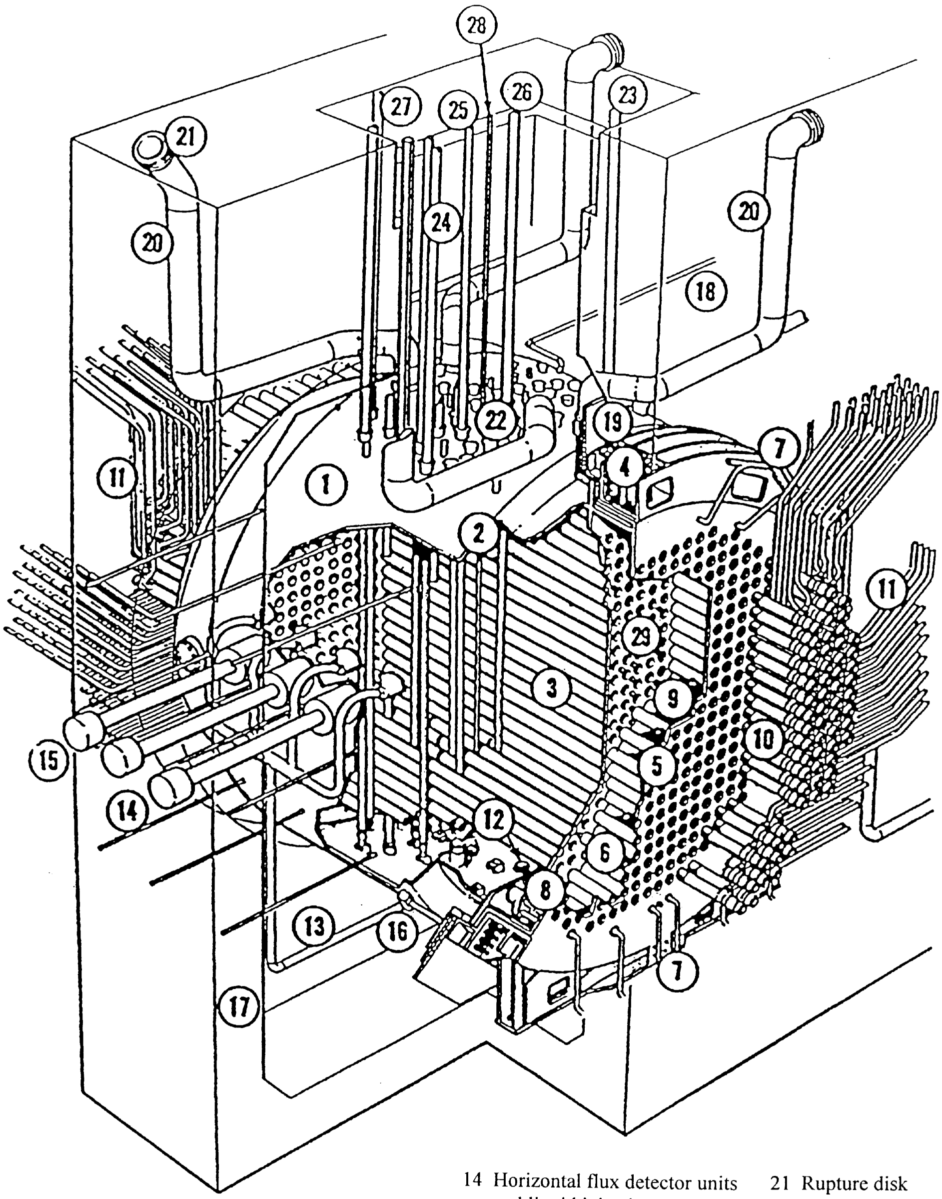


FIG. 1. Pickering A reactor assembly.



1 CALANDRIA
2 CALANDRIA SHELL
3 CALANDRIA SIDE TUBE SHEET
4 BAFFLE PLATE
5 FUELLING MACHINE SIDE TUBE SHEET
6 LATTICE TUBE
7 END FITTINGS
8 FEEDERS
9 CALANDRIA TUBES
10 SHIELD TANK SOLID SHIELDING
11 STEEL BALL SHIELDING END SHIELD
12 MANHOLE
13 MODERATOR DISCHARGE PIPES
14 MODERATOR INLETS
15 MODERATOR OUTLETS
16 SHUT OFF ROD
17 ADJUSTER ROD
18 VERTICAL FLUX DETECTOR
19 SOLID CONTROL ABSORBER
20 SOLID ZONE CONTROL UNIT
21 END SHIELD COOLING PIPING
22 SHIELD TANK
23 SHIELD TANK SHIELD TANK EXTENSION
24 RUPTURE DISC ASSEMBLY
25 MODERATOR OVERFLOW

FIG. 2. Bruce B reactor assembly.



1 Calandria
2 Calandria shell
3 Calandria tubes
4 Endshield embedment ring
5 Fuelling tubesheet
6 Endshield lattice tube
7 Endshield cooling pipes
8 Inlet-outlet strainer
9 Steel ball shielding
10 Fuel channel end fittings
11 Feeder pipes
12 Moderator outlet
13 Moderator inlet pipe
14 Horizontal flux detector units and liquid injection units
15 Ion chambers
16 Earthquake restraints
17 Reactor vault wall
18 Pipe to moderator expansion head tank
19 Curtain shielding slabs
20 Moderator discharge pipes
21 Rupture disk
22 Calandria nozzles for RCUs
23 Viewing port
24 Shutoff unit
25 Adjustor unit
26 Control absorber unit
27 Liquid zone control unit
28 Vertical flux detector unit
29 Calandria tubesheet

FIG. 3. CANDU 6 reactor assembly.

TABLE II. COMPARISON OF CANDU REACTORS

Item	Pickering A	CANDU 6	Bruce / Darlington
Number of fuel channels	390	380	480
Calandria vault	Air filled concrete vault	Water filled steel-lined concrete	Water filled steel shield tank
End shielding	Steel plates and water	Steel balls and water	Steel balls and water
Calandria support	Support rods	End shield supports	Shield tank support bearing assemblies

The Indian RAPS (Rajastan power station) and MAPS (Madras power station) reactor assemblies are similar in design to the Douglas Point prototype CANDU design while NAPS (Narora power station) and KAPS (Kakarpar power station) reactors are similar to the CANDU 6 design. The Douglas Point reactor was a prototype and is not discussed within this report as it has now been decommissioned. Pickering A has many features that are common to both Douglas Point and the Indian reactors which are described in this report. The design configuration of the NAPS and KAPS reactors is illustrated in Fig. 4. The major differences between these two reactor design types are summarized in Table III.

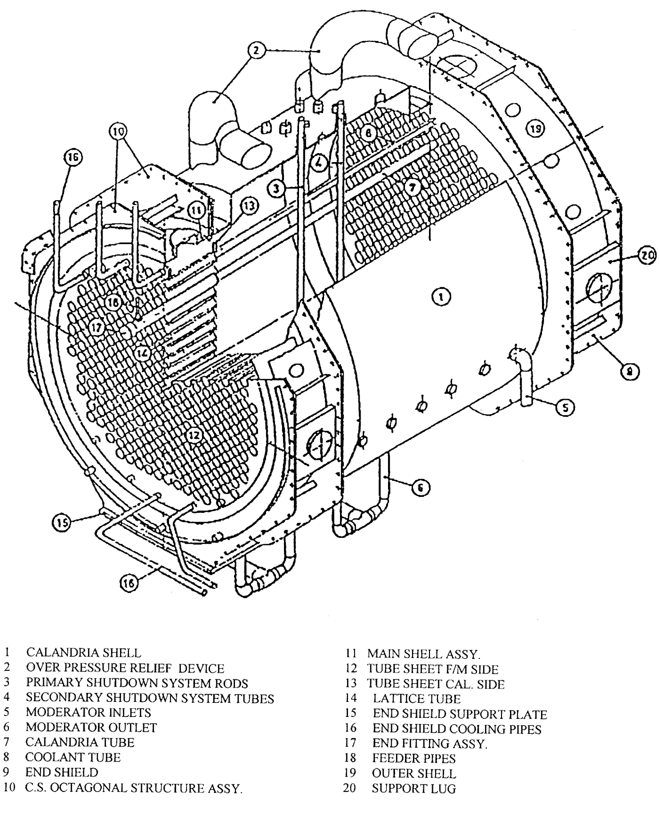


FIG. 4. NAPS/KAPS reactor assembly.

TABLE III. COMPARISON OF INDIAN PHWR REACTORS

Item	RAPS/MAPS	NAPS/KAPS
Number of fuel channels	306	306
Calandria vault	Air filled concrete vault	Water filled steel-lined concrete
End shielding	Steel plates and water	Steel balls and water
Calandria support	Support rods	End shield supports

2.1. Description of CANDU reactor assembly components

2.1.1. Calandria vessel

The calandria vessel is a horizontal, cylindrical, single walled, stepped shell enclosed at each end by tubesheets and spanned horizontally by calandria tubes. The stepped shell which is shown in Fig. 5, is comprised of a main shell with a smaller sub-shell at each end. Flexible annular plates welded to the main shell and the sub-shells form the shell wall at each step.

The tubesheets form a common boundary between the calandria and the end shields. The calandria tubes are arranged on a 11.25 inch (286 mm) square pitch to form a circular lattice array. The ends of these tubes are rolled into the calandria tubesheets by means of stainless steel inserts, one at each end, forming high integrity, leaktight, "sandwich joints".

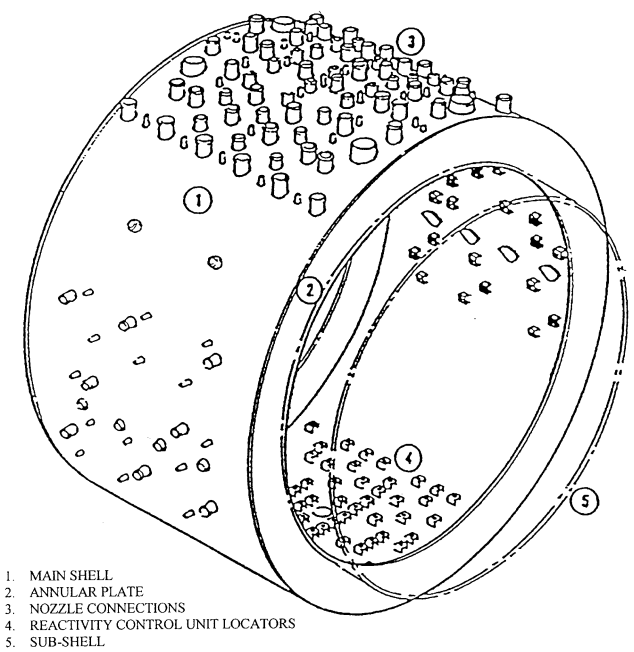


FIG. 5. Calandria shell.

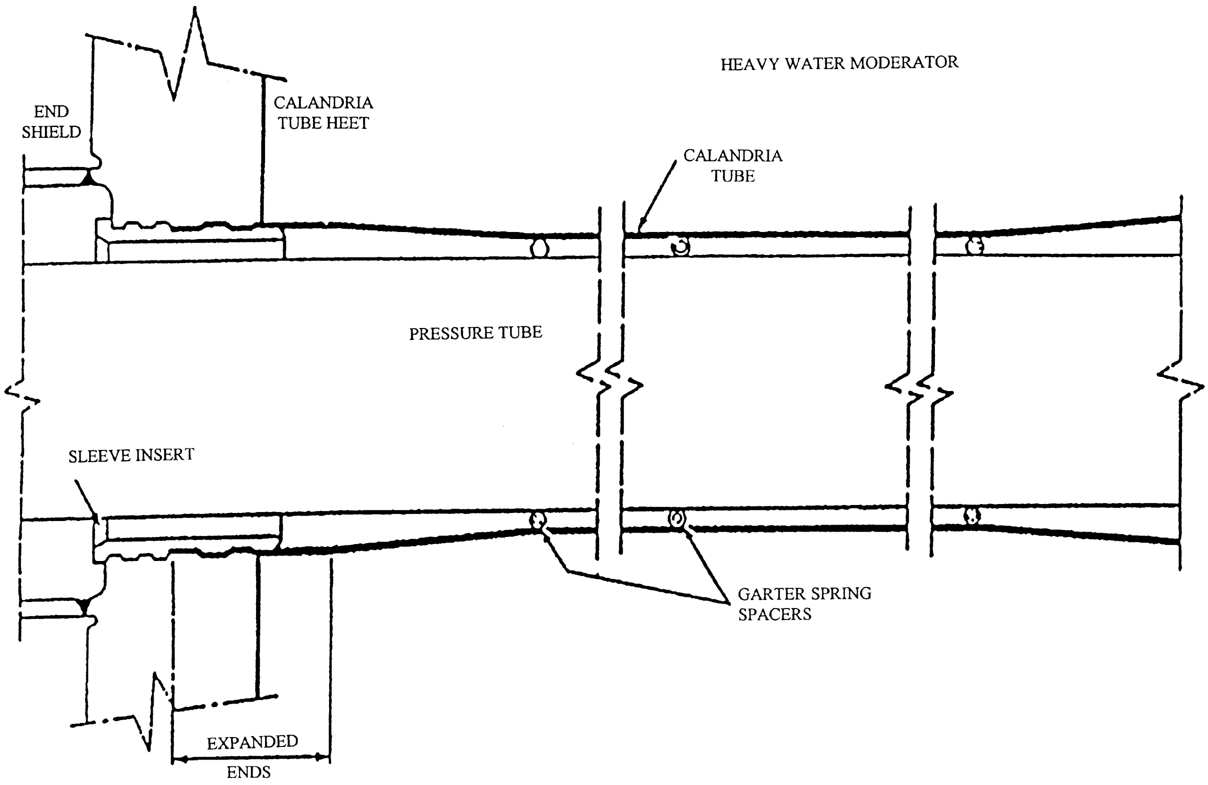


FIG. 6. Calandria tube rolled joint.

A schematic of a typical calandria tube rolled joint is shown in Fig. 6. The two tubesheets, the calandria shell and the calandria tubes form part of the pressure boundary for the heavy water moderator as shown in Fig. 7.

The calandria tubes provide access through the calandria for the fuel channel assemblies. They also serve to insulate the hot fuel channels from the relatively cool moderator and act as axial stays in holding the calandria together against the internal pressure of the moderator.

Guide tubes for the reactivity control units (RCUs) penetrate the calandria, passing between the calandria tubes and screw into locators on the inside of the calandria shell. Reactivity control unit thimbles are welded to nozzles on the calandria shell at each control unit location. They serve to provide the reactivity control units with a path from outside the reactor vault into the calandria interior. In the case of the vertical units, the thimbles extend upward through the reactivity mechanism deck. The weights of these control units are supported by the thimbles.

In most reactors, the heavy water moderator enters the calandria through nozzles located on both sides of the calandria shell, and exits through nozzles at the bottom of the calandria.

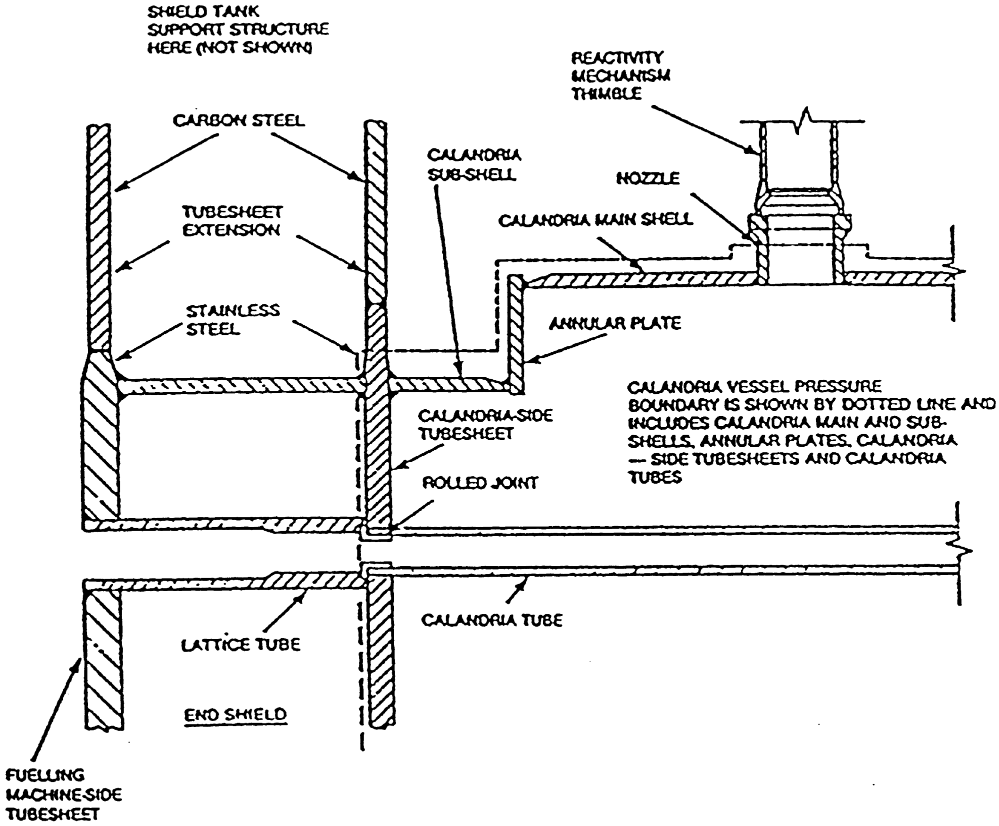


FIG. 7. Calandria vessel pressure boundary.

The upturned, fan shaped inlet nozzles are designed to promote well mixed moderator flow to all areas of the calandria, without causing vibration. In all reactors, the moderator outlet nozzles are located at the bottom of the calandria.

The calandria vessel is provided with nozzles for attachment of 18 inch (457 mm) diameter emergency discharge pipes. These nozzles are located at the top of the calandria main shell and the discharge piping extends upward. Each pipe is capped by a rupture disc assembly outside the reactor vault or the shield tank. Each rupture disc assembly is covered with a loose light gauge stainless steel protective cover to prevent mechanical damage and ingress of dust particles into the disc assembly. The discharge pipes provide an outlet for the moderator and coolant inside the calandria in the event of a postulated pressure tube and calandria tube failure.

A helium cover gas system is provided above the moderator for normal pressure regulation in the calandria and which is purged to limit deuterium concentration in the emergency discharge piping and the vertical reactivity control unit thimbles.

The calandria shell, tubesheets, nozzles, emergency discharge pipes, reactivity control thimbles and guide tube locators are made of austenitic stainless steel type 304L. The calandria tubes are made of seam welded annealed zirconium alloy while the calandria tube insert is made of double annealed type 410 stainless steel. The step in the calandria shell serves to locally reduce reflector in a low flux region of the core, thus reducing the D_2O inventory, and to provide the shell with flexibility to accommodate differential thermal expansion of stainless steel and zirconium.

2.1.2. End shields

The calandria vessel is provided with two end shields. Each end shield consists of a horizontal cylindrical shell enclosed by two tubesheets and spanned horizontally by lattice tubes. The inboard tubesheet, called the calandria tubesheet, is common to the end shield and the calandria vessel, except on some of the very early plants. The outboard tubesheet faces one of the fuelling machines and is, therefore, called the fuelling tubesheet. One end shield is welded to each end of the calandria shell. A typical end shield/calandria shell assembly is shown in Fig. 7.

The ends of the lattice tubes are joined to the tubesheets by a combination of rolling and welding. The lattice tube to calandria tubesheet joint employs a butt weld. At the opposite end the lattice tube is welded to and rolled into the fuelling tubesheet to eliminate the crevice. The lattice tube to tubesheet joints were designed to eliminate any geometry which could lead to crevice corrosion between austenitic stainless steel components.

Fuel channel assemblies pass through the lattice tubes and the calandria tubes and are supported by bearings in the lattice tube. A typical section through the end shields showing this arrangement is shown in Fig. 8.

The calandria tubesheet is exposed to the heavy water moderator on one side and a flow of demineralized shield cooling water on the other side. The space between the fuelling tubesheet, the calandria tubesheet and the lattice tubes in all except the Pickering A reactors is filled with carbon steel shielding balls. In the Pickering A end shield, solid steel slabs were used. A gap between the tubesheets and the steel slabs was provided to facilitate the circulation of cooling water. The steel balls or plates and the cooling water provide the necessary biological shutdown shielding.

The water, which is circulated through the end shields, removes heat generated in the end shields by absorption of nuclear radiation and the heat transferred to them from the heat transport and moderator systems.

The end shields are made entirely of austenitic stainless steel type 304L, while the shielding balls and slabs are made of carbon steel. The low carbon variety of stainless steel is used for the calandria and end shields to limit carbide precipitation due to welding and hence susceptibility to stress corrosion cracking.

2.2. CANDU reactor assembly variants

2.2.1. Pickering A reactor assembly

The Pickering A reactor assembly is shown in Fig. 1. The assembly consists of a calandria vessel complete with two end shields, a moderator dump tank located below the calandria, vertical RCUs and ion chambers.

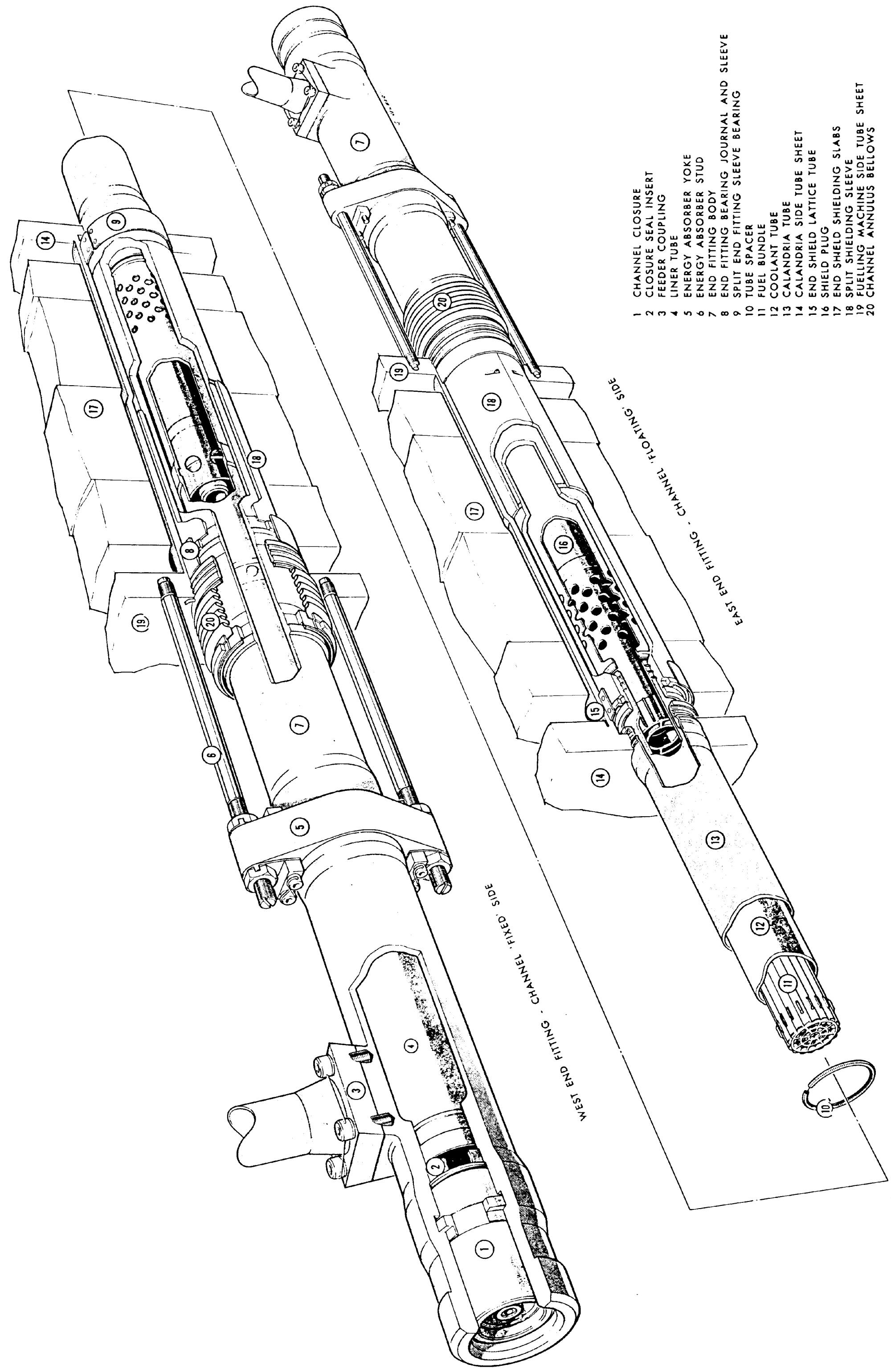


FIG. 8. Fuel channel assembly.

The calandria vessel is supported from the top of the calandria vault by eight rods made of hot rolled carbon steel to ASTM A 107 Grade 1035. The support rods are sheathed in Inconel 600 to protect them from corrosion. Each end shield is fitted with two thin and two thick forged steel shielding slabs made of carbon steel to ASTM A243 Class C. The slabs are in contact with the shell, but gaps between the shielding slabs and the two tubesheets are provided to accommodate the flow of demineralized cooling water. The calandria support rods are each threaded into an insert, made of carbon steel to ASTM A 105 Grade 1, which, in turn, is threaded into each of the thick shielding slabs. Bellows are used to seal the threaded support rod holes from the end shield cooling water thus preventing water from leaking out through the end shield shell opening. The support rods are housed inside penetrations embedded in the calandria vault end wall. A support platform located on the floor of the boiler room supports the calandria vessel via the support rods and support rod nuts as shown in Fig. 9. The calandria support assembly is provided with hydraulic jacks to facilitate vertical adjustment of the calandria position.

One end shield is locked, by means of an end shield key ring, to the calandria vault end wall. The opposite end shield is not restrained, to allow it to move as the calandria vessel undergoes thermal expansion.

The calandria vessel is connected to the moderator dump tank by means of four goose neck shaped dump ports. These ports act as water traps and are located near the bottom of the vessel. Helium pressure in the dump tank normally keeps the moderator up in the calandria. When the pressure is equalised with the calandria cover gas, the moderator falls into the dump tank and the chain reaction stops. The dump ports are made of austenitic stainless steel type 304L. They are rectangular in section at their joint with the calandria shell. At the joint with the dump port their cross section is circular to accommodate bellows which provide flexibility to accommodate thermal expansion of the components.

The inner periphery of the calandria shell is lined with a total of twenty thermal shell shields. Each shield is 4-7/16 inches thick and supported at each end by two support plates which are welded to the shield slab and bolted to the calandria annular plate. Each bolted connection consists of four bolts and a shear pin locked into place, following installation, by welds. The shell shield slabs are made of austenitic stainless steel type 304L while the bolts and the shear pin are made of stainless steel type 321.

The calandria shell is provided with two moderator inlet manifolds located on either side of the calandria just below the vessel centre line. They each supply a set of six upturned fan shaped nozzles feeding the reactor core. The shape and orientation of the nozzles prevent direct impingement of the incoming flow on the calandria tubes and promotes uniform flow distribution. There are also four moderator outlets located at the bottom of the calandria shell.

During reactor operation with a reduced moderator level and during shutdown following the moderator dump, all internal exposed components are subject to heating due to radiation. To prevent overheating of internal components not in continuous contact with the moderator, the calandria vessel is provided with 25 spray nozzle clusters.

These are located at the top of the calandria shell and are arranged in two systems with each system having its own separate external piping connected to the moderator recirculation system.

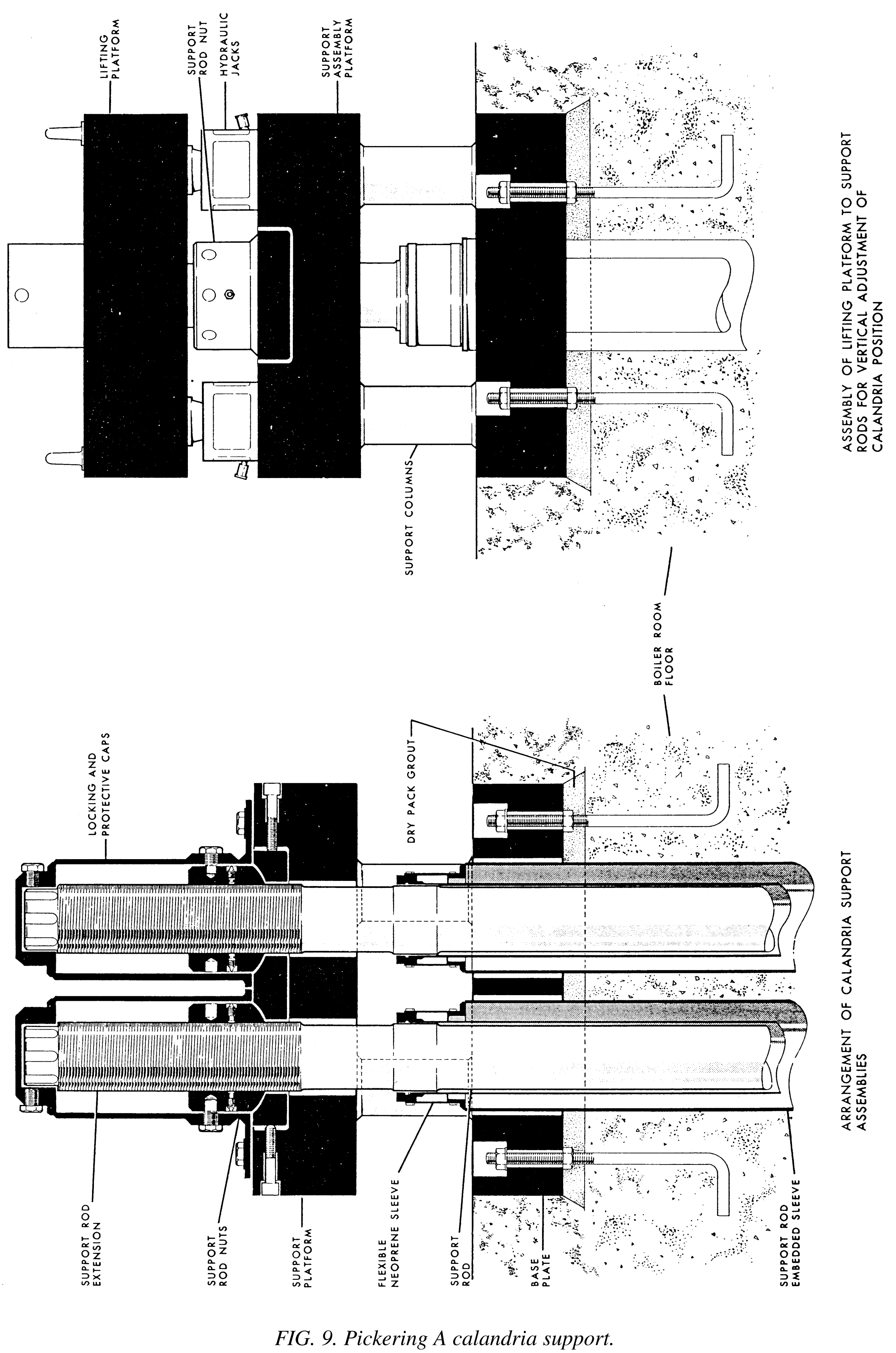


FIG. 9. Pickering A calandria support.

The spray nozzles operate continuously and were designed so that each spray nozzle system operating alone can provide the calandria vessel with a complete spray coverage.

To reduce vault concrete heating by radiation emitted from the calandria shell step area, a water cooled jacket called the "ring thermal shield" is installed over the calandria sub-shell. This ring consists of eight identical pairs of shield slabs, enclosed at their edges, arranged in a ring and connected in series by water circulation piping. The ring segments are made of 2-1/2% and 3-1/2% nickel steel to ASTM A203 Grades A and B. They are attached by means of brackets made of nickel steel to ASTM A 203 Grades A, B and E to the end shield ring embedded in the calandria vault concrete end walls. The piping interconnecting the ring segments are called hairpin connectors. They are made of 1-1/4 inch schedule 80 carbon steel pipe to ASTM A 106 B.

Two 18 inch combination helium moderator cover gas balance lines and moderator overpressure protection pipes are welded to nozzles at the top of the calandria shell. Additionally, a total of 47 reactivity mechanism thimbles of three different sizes are also welded to nozzles at the top of the calandria. Both the thimbles and overpressure protection pipes are made of austenitic stainless steel type 304L.

2.2.2. Bruce and Darlington reactor assemblies

The calandria vessel on these projects is installed inside a shield tank rather than a concrete reactor vault. The shield tank is a welded carbon steel vessel with double end walls. A rectangular extension on top of the shield tank supports the reactivity mechanism deck. A typical shield tank assembly is shown in Fig. 10. The end shields are welded to and form an integral part of the shield tank end walls.

The shield tank contains demineralized water, steel slabs and steel balls to provide biological shutdown shielding. This water is circulated through the shield tank to provide cooling for the end shields, calandria shield tank and their attachments.

Stiffeners inside the shield tank prevent distortion due to the hydrostatic pressure of the water. The shield tank is connected to a head tank which is vented to atmospheric pressure, inside containment.

The reactivity control unit thimbles, moderator emergency discharge pipes and the moderator inlet and outlet piping penetrate the shield tank.

The thimbles for the vertical reactivity control units are welded to the calandria nozzles at the top of the calandria shell. They extend upward and penetrate the reactivity mechanisms deck. Each thimble is provided with a stainless steel bellows which seals the thimble to the reactivity mechanism deck. The reactivity mechanisms deck is also sealed to the building structure by a triplicated containment seal made of EPDM rubber.

The horizontal thimbles are welded to the calandria nozzles located on one side of the calandria shell. They extend through the shield tank and exit through penetrations in the tank side. Each thimble is sealed to the shield tank penetration by means of stainless steel bellows.

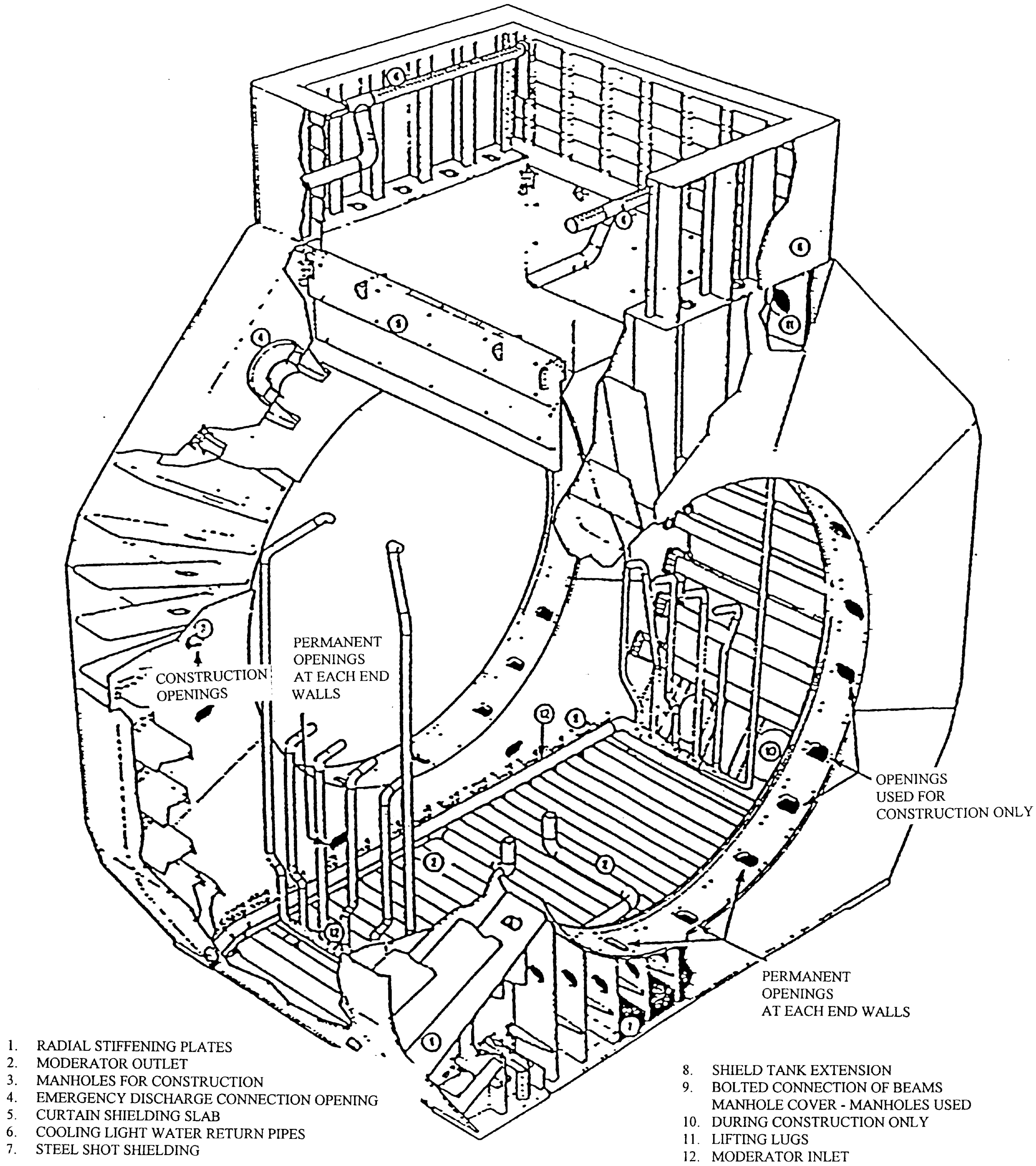


FIG. 10. Shield tank assembly.

In the Bruce B and Darlington reactors, the heavy water moderator enters the calandria through two sets of nozzles located on the opposite sides of the calandria shell, and exits through two nozzles at the bottom of the calandria. In the Bruce A reactor the heavy water moderator enters through 16 nozzles in the bottom of the calandria and flows up the booster guide tubes before discharging into the vessel through the booster outlet nozzles near the top of the calandria. Another supply of moderator enters via a bypass line and six inlet nozzles at the top of the calandria. Discharge from the calandria is through two discharge nozzles, located at the bottom of the calandria shell. All moderator piping within the shield tank forms an integral part of the shield tank assembly. The shield tank walls are provided with nozzles to facilitate butt welding of both internal as well as external moderator pipes. Pipe hangers and supports within the shield tank are all stainless steel.

The shield tank assembly is supported by four support bearing assemblies as shown in Fig. 11.

2.2.3. CANDU 6 reactor assembly

The configuration of the CANDU 6 reactor assembly is shown in Fig. 3. The entire assembly is supported within the concrete calandria vault by end shield supports. Each end shield support is provided with an integral embedment ring for direct concreting into the calandria vault end walls. A sectional view of the calandria vault and calandria vessel assembly is shown in Fig. 12 while a sectional view through the end shield support is shown in Fig. 13.

The calandria vault is a six-sided structure of reinforced concrete supported on reinforced concrete bearing foundation walls. The inner surface of the vault is lined with carbon steel to provide a leak-tight seal for containment of the shield cooling system demineralized light water. The liner is welded to the calandria assembly embedment ring to provide a leaktight seal. Both the vault and the water within the vault provide operational shutdown shielding for the immediate surrounding areas. The light water also provides cooling for the calandria assembly and the vault concrete.

The end shield supports consist of a flexible stainless steel support shell and an annular support plate combination, welded to a carbon steel embedment ring.

The outboard end of the support shell is welded to the periphery of the end shield fuelling tubesheet while the inboard end is welded to the inner edge of the annular support plate. The outer edge of the support plate is welded to the embedment ring.

Each embedment ring consists of a cylindrical shell and annular ring elements which are stiffened by radial gussets at regular intervals around the circumference.

The purpose of the stainless steel support shell and annular support plate arrangement is to accommodate the differential radial and axial movements between the calandria assembly and the calandria vault.

At one end the calandria assembly is fixed to the vault end wall to limit seismic response. The annular support plate at this end is provided with restraint bolts distributed around the annular plate circumference thereby securing that plate rigidly to the concreted-in embedment ring. The calandria shell is connected to the embedded support directly.

To prevent overheating of the embedment ring and the vault concrete, cooling water is circulated through carbon steel pipes embedded within the ring concrete. Additional shielding in the form of a curtain plate and a shielding slab are provided around the inner periphery of each embedment ring. The shielding curtain and the shielding slab are made of carbon steel and are bolted directly to the embedment ring. The arrangement is illustrated in Fig. 14.

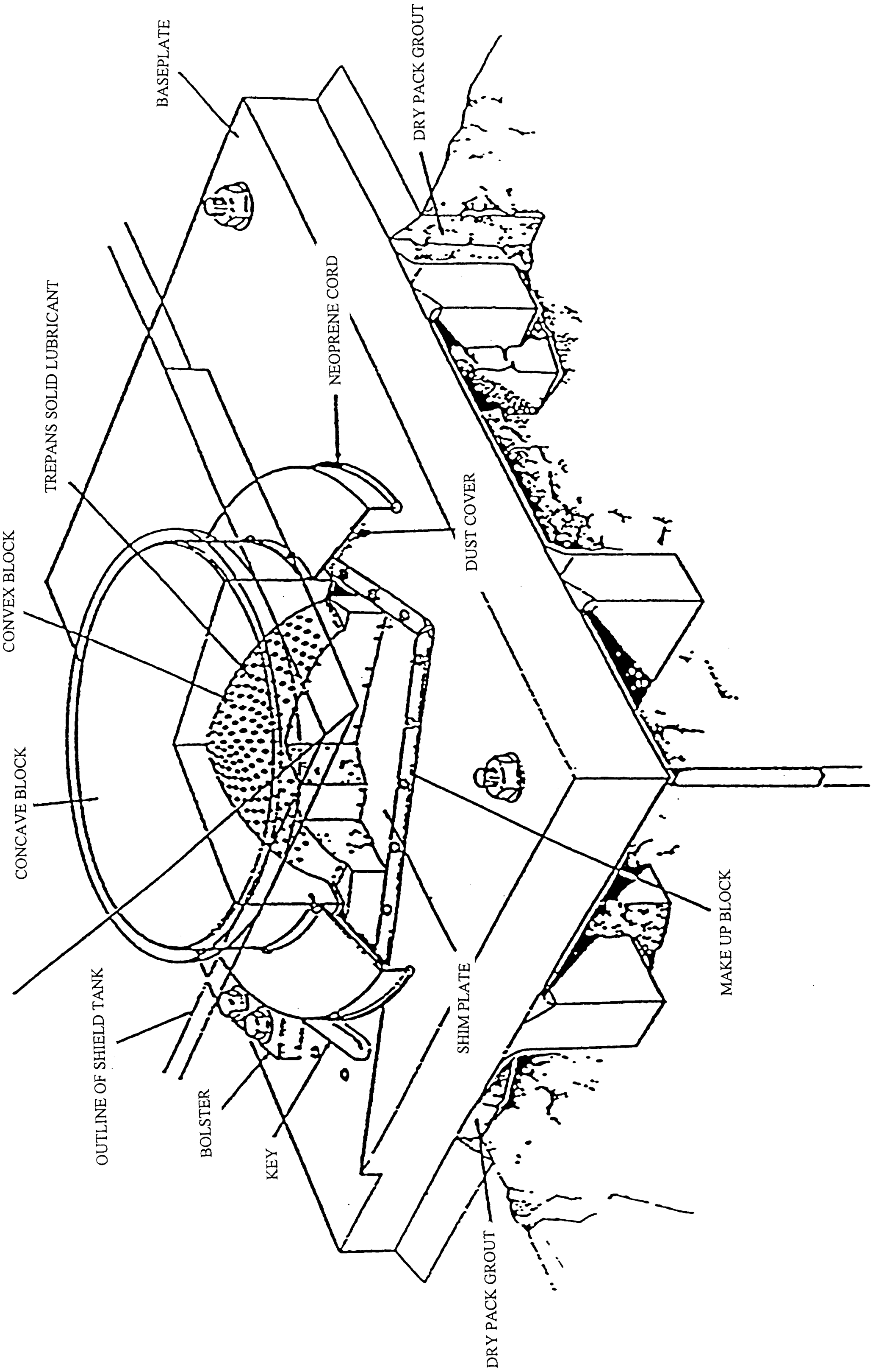


FIG. 11. Shield tank support.

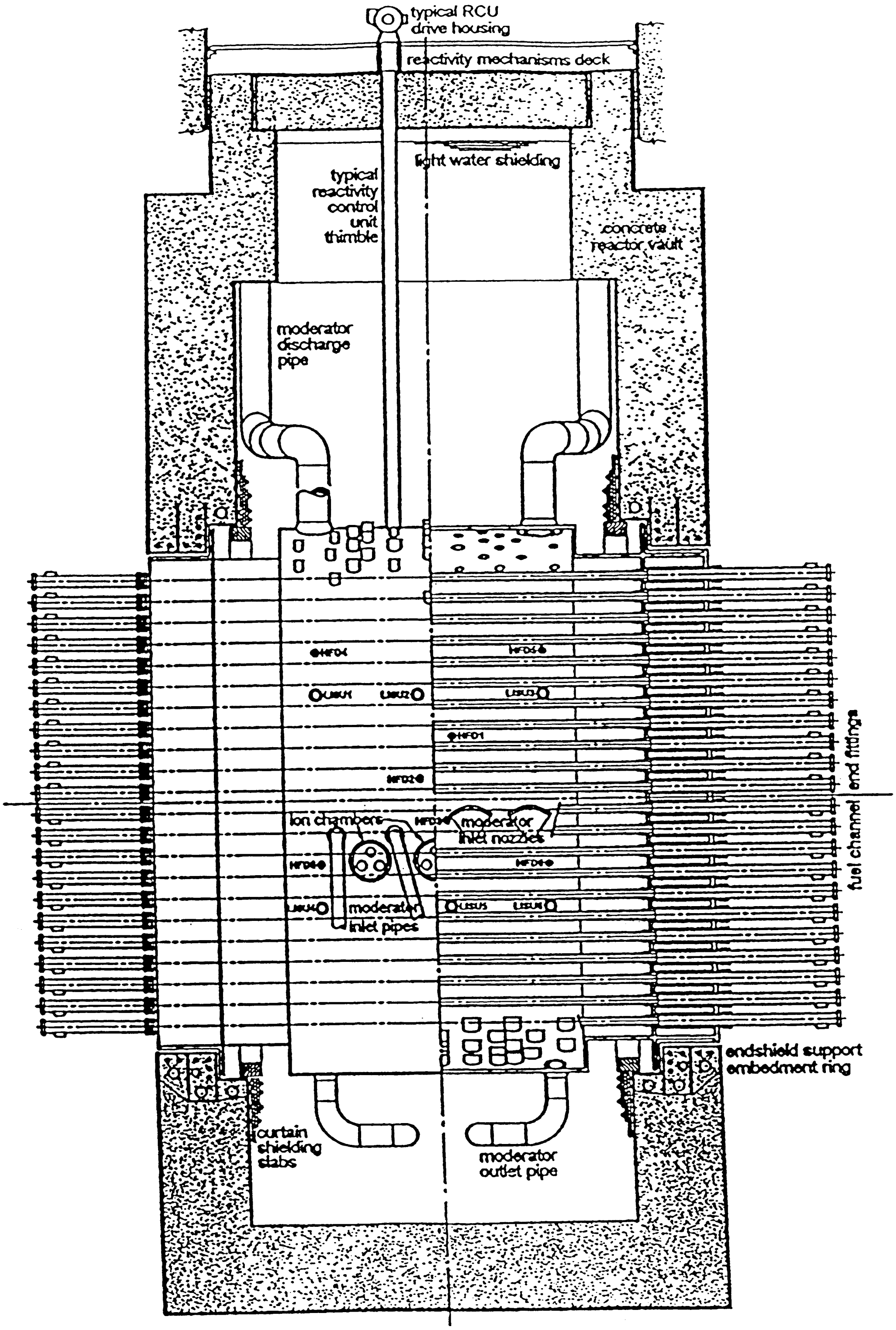


FIG. 12. Side view of CANDU 6 calandria.

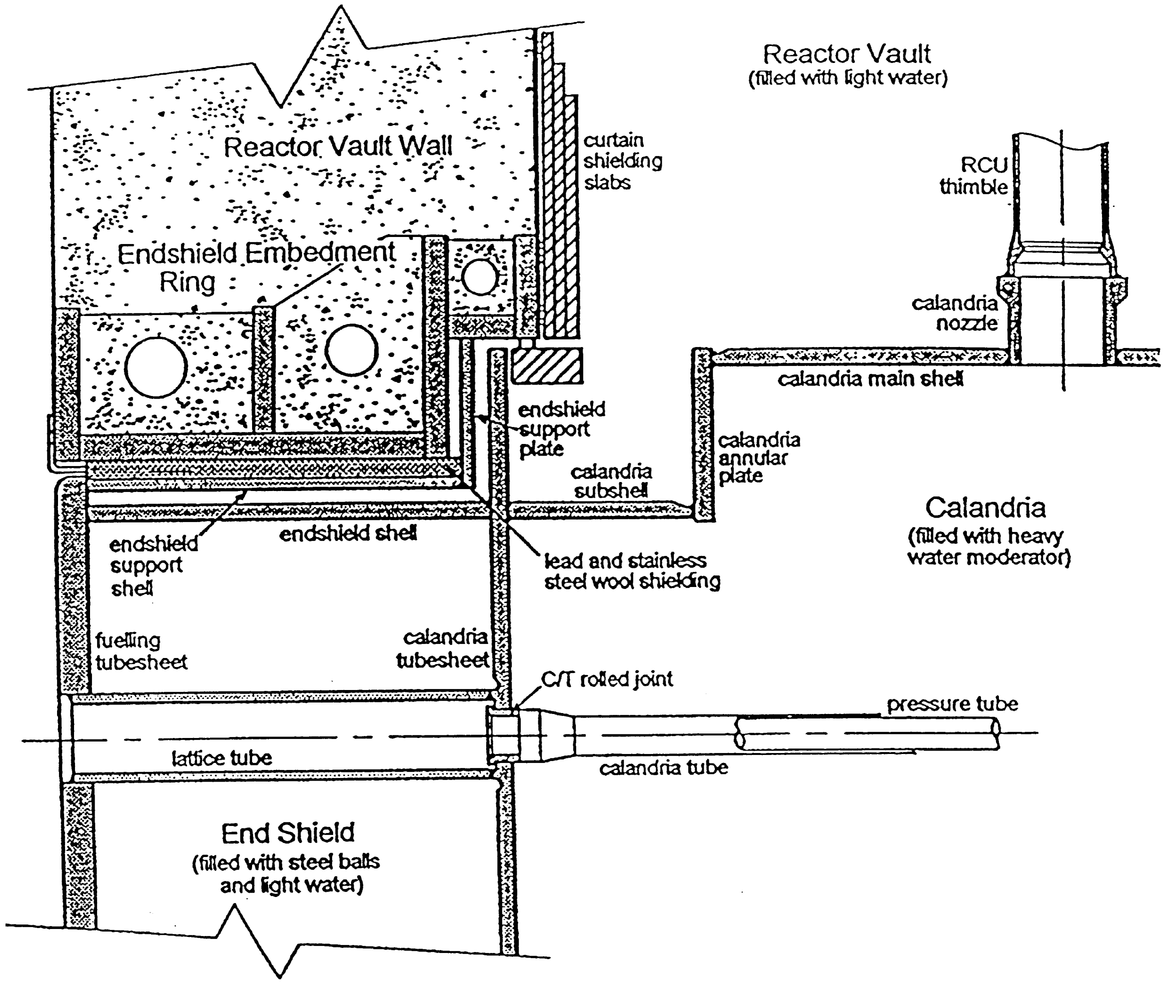


FIG. 13. CANDU 6 end shield support.

The space between the embedment ring and the support shell and annular support plate combination is made up of a radial and annular air gap. To prevent excessive radiation streaming through this gap to the adjacent fuelling machine vault, the cylindrical gap is filled with lead and stainless steel wool installed in alternate layers and held in place by strands of wire around the gap. A retaining ring made of carbon steel angle is welded to the vault face of the embedment ring to retain the shielding wool, as shown in Fig. 14.

The calandria shell is provided with nozzles for the attachment of the vertical and horizontal reactivity control unit thimbles, pressure relief pipes and the moderator recirculation pipes. With the exception of the flux detector thimbles, all reactivity control thimbles are attached to their respective calandria nozzles by full penetration corner welds. The flux detector thimbles and piping are attached by full penetration butt welds.

The heavy water moderator enters the calandria through two sets of four nozzles located on opposite sides of the calandria shell and exits through two nozzles at the bottom of the calandria.

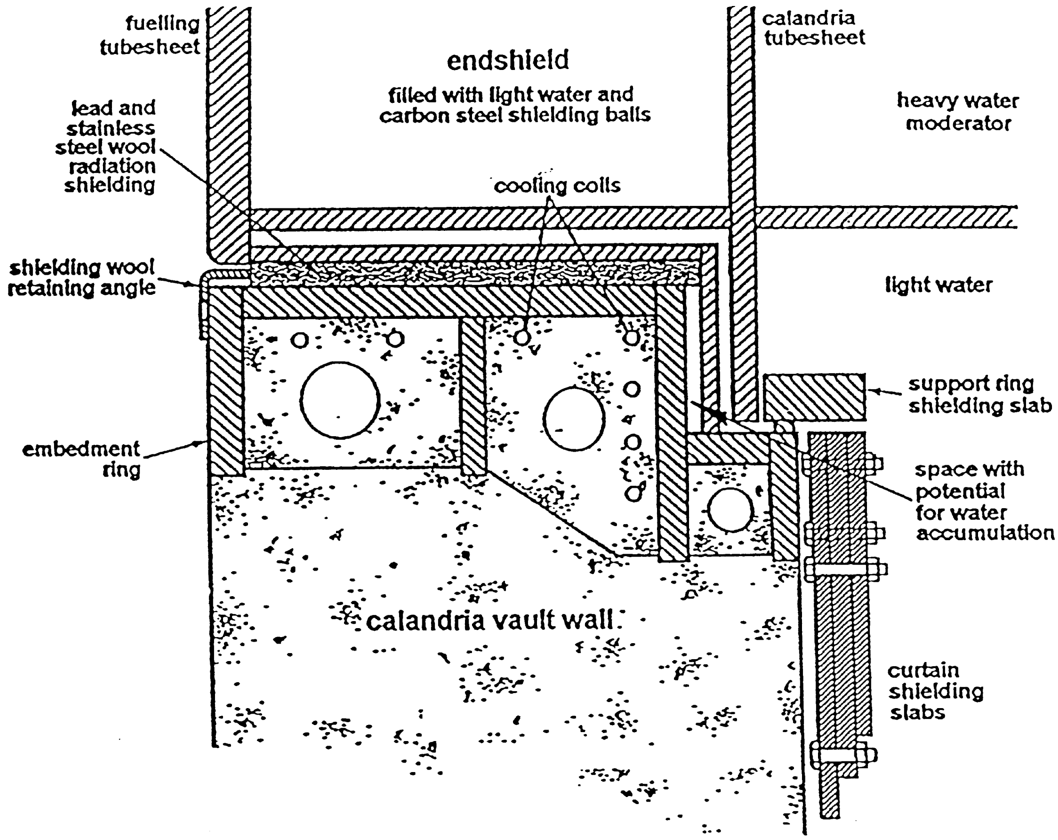


FIG. 14. CANDU 6 calandria support annular gap.

2.3. Description of Indian PHWR reactor assembly designs

2.3.1. Rajastan (RAPS) and Madras (MAPS)

In the RAPS and MAPS reactors the calandria is a horizontal single walled cylindrical vessel made of austenitic stainless steel. At each end it is closed off by flat tubesheets with 306 penetrations for the calandria tubes. The calandria tubes are made of nickel free Zircaloy-2 and are attached to the tubesheets by means of a special design rolled joint. The calandria tubes are spaced on a 228.6 mm square lattice. At each end the calandria shell is stepped down in diameter. An annular plate between the smaller diameter sub-shells and the calandria main shell provides flexibility for the differential thermal expansion between the main shell and the calandria tubes.

The calandria shell is stiffened by external, water cooled stiffening rings. Four pairs of hanger rods are attached to the stiffening rings, two pairs per ring, to support the calandria. The end shields are not connected to the calandria, they are supported in the vault walls as described below. The calandria vessel is connected to a dump tank through a port located at the bottom of the calandria shell. The moderator is discharged through the dump ports into the dump tank to effect a reactor shutdown.

An external nozzle, located at the top of the calandria, contains an 813 mm diameter pressure relief device. Six housings for the reactivity control mechanisms extend above the calandria. They are arranged in three pairs symmetrically about the N-S reactor centerline. The moderator inlet and outlet manifolds are located inside the calandria shell. They are designed to introduce the moderator into the calandria at a very low velocity and avoid turbulence so that streamline flow through the vessel will take place. This gives the minimum average moderator temperature and avoids vibration problems.

The calandria is equipped with 34 spray clusters. These provide a drenching spray through the entire calandria interior to prevent overheating of vessel components not in contact with the moderator. Cooling spray nozzles are also located in the dump port transition section and the expansion joint to supply spray cooling for the lower part of the calandria system and the assembly structure. The spray nozzles are arranged in two systems, each system having its own separate external piping fed from the moderator circulation system. Each system provides sufficient coolant to remove the heat generated by absorption of radiation. The calandria stiffening rings are cooled with heavy water using a duplicate arrangement and the support hanger rods are also cooled by heavy water from the moderator system.

Two circular end shields, containing steel slabs and cooling water, are located in the north and south end walls of the calandria vault opposite the ends of the reactor. They are provided with 306 penetrations allowing passage for the reactor coolant tube assemblies. The shields form part of the calandria vault enclosure and provide shielding to reduce the radiation fields in the fuelling machine vaults to a level which permits access during shutdown. The shields are an integral part of the reactor and provide for location and support of the coolant tube assemblies containing the reactor fuel. Each end shield is mounted concentrically within an end shield ring which, in turn, is grouted into the calandria vault wall.

The end shields consist of a tube and shell structure containing a steel slab core and water passages. The penetration tubes joining the two end shield tubesheets are precision machined to allow installation of the coolant tube assembly support bearings.

The entire calandria vessel with the exception of the inlet and outlet manifolds and the calandria tubes is fabricated from austenitic stainless steel type 304L to ASTM A-240.

2.3.2. Narora (NAPS) and Kakrapar (KAPS)

In the NAPS and KAPS reactors, the calandria is a horizontal cylindrical vessel with stepped down ends. The entire calandria structure, with the exception of the calandria tubes, is made of austenitic stainless steel type 304L designed and fabricated in accordance with the requirements of the ASME Code, Section III, Subsection NC. The calandria tubes are made of Zircaloy-2. The design feature of the calandria assembly are shown in Fig. 4.

The calandria vessel is closed off at each end by an end shield. The end shields, which consist of two tubesheets joined together by 306 penetration tubes and shell, serve to support the entire calandria assembly. The end shields are grouted into the reactor vault end walls and the entire vault is filled with light water. The end shields contain steel balls for shielding. Light water circulation is provided for irradiation heat removal.

The calandria is provided with 12 moderator inlet nozzles, 6 on each side of the calandria near its horizontal centerline. Diffusers welded to these nozzles inside the calandria uniformly distribute the moderator throughout the vessel. Four moderator outlet nozzles are provided at the bottom of the calandria shell. They are located slightly off the vertical centre plane of the vessel.

The top of the calandria shell contains 35 penetrations for housing the various types of reactivity control mechanisms. There are 14 penetrations for the primary shutdown rods and 12 for the secondary shutdown rods.

The calandria shell is provided with four nozzles for connection to the overpressure relief piping. Rupture discs are provided at the opposite ends of relief pipes to provide protection against overpressurization of the vessel during accidents involving simultaneous rupture of a calandria tube and a coolant tube. The space in the calandria above the moderator free surface and that in the overpressure relief piping is occupied by helium cover gas.

2.4. Design measures for managing ageing degradation

There is an old saying that "prevention is better than a cure". This is a philosophy to which everyone in the nuclear business subscribes. Mitigation is the next best thing to prevention and is also practised at CANDU stations where ageing effects cannot be designed out.

The effects of embrittlement by radiation are minimised by choice of materials which are only affected to a limited and harmless degree by the service conditions. High ductility austenitic stainless steel and Zircaloy 2 are the preferred materials. Carbon steels are used only in areas where distance and shielding reduces the fluence to acceptable levels.

Corrosion is minimised by correct choice of materials; cleanliness during manufacture and construction; control of water chemistry and atmospheric conditions during operation and particularly during shutdown and maintenance work when normal procedures are interrupted. The water chemistry standards for all systems and modes of reactor operation are published in the station Chemistry Control Manual. This manual also lists the corrective actions to be taken in case chemistry monitoring reveals a non-compliance with the standards. A review of the chemistry control performance records at the Ontario Power Generation stations showed an excellent compliance with the specifications.

Local slabs of carbon steel are used to provide thermal shielding of concrete exposed to high flux. In some cases cooling pipes are also embedded in the concrete to prevent overheating and deterioration of concrete strength. The use of such piping is generally avoided where possible because of corrosion problems experienced on early CANDU plants. Humidity in the atmosphere is controlled below the threshold level where corrosion initiates.

CANDU stations generally operate as base load providers and are subject to very little in the way of operating cycles. Fatigue is therefore not a particular concern, except for a few components which have been subject to vibrating loads due to turbulent flow conditions. These conditions are now recognised and corrected during commissioning. Significant increases in flow rates are not permitted without a satisfactory assessment of potential vibration problems. Features that promote vibration are recognized during design review and eliminated. These precautions and mitigating actions also serve to eliminate mechanical damage due to vibration induced fretting wear. Provision of generous clearances and firm support to delicate components has also mitigated fretting problems.

Mitigation of creep, growth and stress relaxation phenomena is again approached by choice of the best materials and control of the stress, temperature and flux causing the effect. The subject of pressure tube creep is dealt with in another report, which also covers the creep sag of the calandria tubes. Within the calandria, stress relaxation only affects some bellows and springs used to tension the RCU guide tubes. The tension in these units can be measured and adjusted, using maintenance tooling provided to all stations.

The calandria assembly and support components are not required to be subject to regular in-service inspection because of choice of material and since each known ageing mechanism has been accounted for in the design. The only exception to this is the calandria tube, where information on tube sag is provided by the fuel channel pressure tube inspection. Inspection of other calandria assembly components is performed when required.

Although all CANDU reactor assemblies employ the common concept of horizontal fuel channels installed within the calandria vessel, different methods of supporting the assembly are used. For example, in some designs the calandria is installed within a water filled shield tank which is supported at the bottom by bearings designed to support the weight and to accommodate thermal expansion of the assembly. In other designs the calandria assembly is supported by embedment rings grouted into the end walls of a water filled, carbon steel lined concrete reactor vault or suspended by support rods within a air filled concrete reactor vault. As a result of these design differences some of the postulated ageing mechanisms do not apply to all CANDU reactor assemblies. They are in fact limited to certain design features employed in the specific reactor types.

3. DESIGN BASIS

3.1. Functional/performance requirements

The CANDU reactor assembly is designed to fulfill the following design requirements:

(a) A design life of 30 years, or more for newer designs, without regular inspection or maintenance.

(b) Materials used must be able to withstand prolonged exposure to the following environmental conditions (as applicable):

- radiation from nuclear fission
- free oxygen, free deuterium and gadolinium nitrate in the high purity heavy water moderator
- demineralized and treated light water in the end shields and calandria vault or shield tank
- helium cover gas
- dry carbon dioxide atmosphere in the fuel channel annulus
- air and vapour atmosphere in the fuelling machine vaults and calandria vault.

(c) The design, analysis, choice of materials, fabrication, examination, inspection and testing must meet with the requirement of CSA standards CSA-N285.0, CSA-N285.2, CSA N285.6 and the appropriate subsections of Section III, Division I of the ASME Code, as defined in the CSA Standards.

(d) Provide support for the fuel channels and in-core reactivity control units.

(e) Contain the heavy water moderator in the calandria.

(f) Contain shield cooling water in the end shields and shield tank or calandria vault.

(g) Provide shielding for the fuelling machine vault.

(h) Use materials with a low neutron capture cross section and avoid the use of materials containing elements that become strongly activated by radiation i.e., Cobalt and Antimony.

(i) Provide for thermal expansion, strain, creep and growth induced changes in geometry.

(j) Minimise thermal loss from the heat transport system.

(k) All in core components are to be replaceable.

(l) The sealed fuel channel annulus between calandria tube and pressure tube is to be monitored for leak detection.

3.2. Safety requirements

As part of the overall CANDU safety philosophy, the moderator and shield cooling systems are required to be:

(a) at low (nearly atmospheric) pressure

(b) at low (well below 100°C) temperatures.

In addition, the reactor assembly is designed so that the failure of a calandria tube, or any other localized failure of the moderator pressure boundary, does not result in the failure of the structure as a whole and is tolerable from a safety point of view. Therefore, the reactor assembly must:

(a) allow the moderator system to remove the decay heat of the fuel, following shutdown, during a Loss of Cooling Accident (LOCA) combined with Loss of Emergency Core Cooling (LOECC) and Loss of Class IV Power (LOCIVP);

(b) allow the shield cooling system to remove the heat from the reactor structure and shielding during normal operation and other events, to the extent that appropriate stress levels are maintained which will ensure that the integrity of the fuel channels can be maintained (alternatively, it may be shown by analyses that the fuel channel integrity can be maintained despite loss of this system or its support services);

(c) be qualified to withstand a design basis earthquake and retain pressure boundary integrity;

(d) maintain structural integrity (ie. the positioning and support of fuel channels and reactivity control units) and retain pressure boundary integrity during applicable events (including a pressure tube failure) identified in the Probabilistic Safety Analysis Report and in the Safety Design Guides.

The reactor assembly is designed to operate over the design life without regular in-service inspection or maintenance. The calandria vessel is protected against overpressure by pressure relief valves in the moderator cover gas system which are regularly inspected and tested. Additionally, the calandria is also provided with rupture discs, which provide overflow protection in the event of a pressure tube and calandria tube rupture. These rupture discs are periodically inspected for signs of deterioration and replaced on as required basis. In the Bruce and Darlington reactors, the reactivity mechanism deck on top of the shield tank forms part of the reactor containment. The deck is sealed to the reactor building by an elastomer seal which is inspected and tested on regular basis.

4. AGEING MECHANISMS

The calandria vessel, end shields, calandria supports (and the shield tank, where applicable) are large components permanently installed in areas of limited accessibility within the reactor building and are not designed for replacement. These components are designed to operate without maintenance over the design life of the plant. Their replacement or in-situ repair would be difficult, expensive and require an extended plant shutdown. The ability of these components to maintain their structural integrity under various operating conditions is key to achieving or extending the plant design life.

The following potential ageing mechanisms were identified for the reactor assembly components:

- neutron irradiation embrittlement
- stress corrosion cracking (SCC)
- corrosion
- erosion
- fatigue
- stress relaxation
- creep, growth and sag
- wear.

Each of these ageing mechanisms, including relevant operating experience, is discussed in detail in the following sub-sections. The potential for affecting the component design life was assessed using the following grading system with results reported in Table IV:

L	=	little or no concern for end of life
M	=	credible ageing mechanism
H	=	potentially life limiting degradation
N/A	=	ageing mechanism is not applicable.

4.1. Neutron irradiation embrittlement

Metals subjected to fast neutron irradiation exhibit an increase in tensile strength and a corresponding reduction in ductility or fracture toughness.

4.1.1. Calandria vessel

The calandria vessel and associated components making up the reactor assembly are made of high ductility austenitic stainless steel type 304L welded together with type 308L filler. Research has shown that the degree of neutron irradiation embrittlement of this material is a function of the cumulative fluence and the temperature at which the metal was irradiated [13] [14]. Additionally weld metal is more susceptible to embrittlement than the base metal. This is due to the presence of delta ferrite in the weld. The ASME B and PV Code now specifies upper and lower limits on the weld metal delta ferrite content. The upper limit is to minimise embrittlement in service and the lower one to prevent solidification cracking of the weld during fabrication [15]. The AECL reactor component fabrication specifications place a further restriction on the high limit, to ensure the calandria vessel is well away from the transition to brittle behaviour.

The ASME Code does not require austenitic stainless steel material to be impact tested. Instead it specifies tensile tests with total elongation requirement for new material of 40 for base material and 35% for the welds.

In a typical CANDU calandria, the welds that are subject to the highest fast neutron flux are located at the inside surface of the calandria tubesheet. The flux at this location is 7.5×10^{15} $n.m^{-2}.s^{-1}$, E >1 MeV. Based on the most current work performed for the CANDU 9 reactor, which has a design life of 60 years and a capacity factor of 90 %, the total integrated flux, or fluence, in the tubesheets at the end of the design life will be 1.3×10^{25} $n.m^{-2}$, E >1 MeV.

Research has shown that Type 304L austentic stainless steel irradiated by fast neutrons at the calandria normal operating temperature of 60°C will experience an increase in both the yield and the ultimate strengths. This increase in strength initially is very rapid up to a fluence of approximately 5×10^{24} $n.m^{-2}$, E >1 MeV.

TABLE IV. EFFECT OF POTENTIAL AGEING MECHANISMS ON COMPONENT LIFE

	Material	Irradiation embrittlement	SCC	Crevice corrosion	General corrosion	Erosion	Fatigue	Comments
Calandria Shell	SS 304L	L	L	L	L	L	L	
Tubesheets	SS 304L	L	L	L	L	L	L	
Welds	SS 308L							
- annular plate to main shell		L	L	L	L	L	L	
- subshell to annular plate		L	L	L	L	L	L	
- subshell to tubesheet		L	L	L	L	L	L	
- tubesheet		L	L	L	L	L	L	
- nozzles to shell		L	L	L	L	L	L	
- RCU thimble to shell		L	L	M*	L	L	L	*Pickering A only
Shell shields*	SS 304L	L	L	L	L	L	L	*Pickering A only
Moderator inlet nozzles	SS 304L	L	L	L	L	L	M	
Dump ports*	SS 304L	L	L	L	L	L	L	*Pickering A only
Dump bellows*		L	L	L	L	L	L	*Pickering A only
Calandria tubes	Zr. 2	L	L	L	L	L	L	Creep/sag - L Rolled/Joint Stress Relaxation - L
Spray clusters*	SS	L	L	L	L	M	L	*Pickering A only
Calandria support rods*	CS	L	L	N/A	L	N/A	L	*Pickering A only
End shield embedment ring								
- CANDU 6 only	CS	L	N/A	M	L	L	L	
- Pickering A only	CS	L	N/A	N/A	L	L	L	
Shield tank bearings***	SS & Bronze	L	L	L	L	N/A	N/A	***Shield Tank Reactors only Mechanical Wear - M
End shields	SS 304L	L	L	L	L	L	L	
Ring thermal shield*	Ni Steel	L	M	L	H**	M	L	*Pickering A only **External only.
Shield tank***	CS	L	L	L	L	L	L	***Bruce and Darlington only

MEANING OF RATING SYMBOLS: L = LITTLE OF NO CONCERN FOR END OF LIFE, M = CREDIBLE AGEING MECHANISMS, H = POTENTIALLY LIFE LIMITING, N/A = NOT APPLICABLE

The strengthening effect than decreases and there is relatively little change up to a fluence of about 3×10^{25} n.m^{-2}, E >1 MeV. While the material becomes stronger, the ratio of the ultimate to yield strength decreases indicating that the irradiated material is less ductile. Work performed for CANDU 9 established that, at the end of the 60 year design life, the total elongation in the tubesheet material subjected to a fluence of 1.3×10^{25} n.m^{-2}, E >1 MeV will be above 25% in the base material and above 15% in the welds. Ductility in other parts of the calandria, subjected to a lower fluence, will be higher. This also applies to material in any calandria vessel intended for a shorter design life and lower capacity factor such as the CANDU 6 calandria.

The calandria vessel design is required to comply with the stress analysis requirements of the ASME B&PV Code for all design conditions. The Code specifies allowable stress intensities based on new material yield and ultimate strengths. Applying the same criteria to determine allowable stress intensities based on actual irradiated material properties (ie increased yield and ultimate strength) would produce greater stress margins. Based on work performed for CANDU 9, the calandria material residual ductility is judged to be adequate for a service life in excess of 60 years. The potential of this ageing mechanism to impact on the design life is, therefore, rated L (low) in Table IV.

4.1.2. End shield

The end shields are fabricated from Type 304L stainless steel and filled with carbon steel shielding balls. The fuelling tube sheet, end shield shell and lattice tubes are exposed to lower fluences than the calandria tubesheet and the neutron embrittlement in these components, therefore, is not a concern. The fluence to which the carbon steel shielding balls will be exposed and their low stress level ensures that embrittlement is not a concern.

4.1.3. Calandria supports

The Pickering A calandria assembly is suspended from eight carbon steel rods, sheathed in Inconel 600, housed within tubular penetration in the reactor vault end walls. They are sufficiently shielded that neutron embrittlement of these components is not a concern.

The CANDU 6 calandria is supported by the end shields welded directly to embedment rings which are permanently embedded in the reactor vault end walls. Shielding water within the vault provides these rings with sufficient shielding so that neutron embrittlement is not a concern.

4.1.4. Shield tank

The Bruce A and B and the Darlington calandria vessels are supported by end shields which are welded into the shield tank end walls. The shield tanks are fabricated entirely of carbon steel and filled with shielding water. They are, therefore, sufficiently shielded so that neutron embrittlement is not a concern. Precautions were also taken against possible hydrogen embrittlement of carbon steel.

4.1.5. Calandria tubes

The calandria tubes are manufactured of Zircaloy 2 and installed within the reactor in a near-fully annealed condition. In service they are subjected to a high neutron flux and consequently undergo irradiation strengthening and some loss of ductility. There is considerable published information on the irradiation response of annealed Zircaloy-2 [16] [17], and this information has been confirmed by examination of calandria tubes removed from the reactors. Based on this information the calandria tubes will perform satisfactorily without need for replacement over the design life of the reactor.

4.1.6. Research support

Neutron irradiation, while increasing the strength of material, reduces ductility. Monitoring the irradiation embrittlement degradation over the life of a component is not possible as it requires fairly large samples to be removed from a component. It is possible however, to monitor the radiation flux and fluence which provides indirect information on the state of the material provided that information exists on the irradiation characteristics of the material. Because the temperature of the irradiation of some materials in CANDU reactors is relatively low, these materials are irradiated under CANDU conditions in a research reactor.

4.2. Stress corrosion cracking

Stress corrosion cracking (SCC) is a corrosion mechanism in which the combination of susceptible alloy, residual stress and an aggressive environment can lead to cracking of the material. The austenitic stainless steel type 304L of which the calandria and the end shields are made is susceptible to SCC in a chloride environment. An elevated temperature and the presence of oxygen tend to aggravate SCC of this material.

During fabrication of the stainless steel (304L) calandria and the end shields, care is taken to limit chloride contamination of the material. Fabrication specifications limit the chloride content in solvents and cleaners used during the course of manufacturing to 100 ppm. For NDE materials the content is limited to 250 ppm. During reactor operation, these components are exposed to the heavy water moderator and to shield cooling demineralized water. Both the moderator and the demineralized water are maintained at a high degree of purity and hence exhibit a very low chloride content. It is not possible to eliminate oxygen from the moderator because of D_2O decomposition due to radiolysis. In the absence of chloride, however, oxygen alone will not promote SCC in 304L material. The low temperature of the moderator system further reduces the possibility of stress corrosion cracking. The demineralized shield cooling water in the end shields and shield tank or reactor vault is fully deoxygenated and pH regulated to protect the carbon steel components.

In Pickering A, the reactor vault air environment, described in more detail in 4.3.3, has potential for initiation of SCC in the ring thermal shields. The potential impact of this ageing mechanism is rated M in Table IV.

4.3. Corrosion

4.3.1. Moderator pressure boundary

The heavy water moderator in a CANDU reactor is typically maintained at a pH_A of 4.5 to 7 and a high degree of purity which is achieved through chemistry control. The dissolved O_2 content of the moderator is in excess of 1 ml/kg D_2O, due to radiolysis and it is not possible to suppress this concentration. Dissolved O_2 content at this level is corrosive to carbon steel. For this reason all reactor assembly components exposed to the moderator or the moderator cover gas are made of type 304L stainless steel or Zircaloy 2.

4.3.2. *End shields and shield tank*

The demineralized light water contained in the end shields, shield tank or reactor vault is typically maintained at a pH between 10 and 10.5 and at a high degree of purity. The dissolved oxygen content of this water can be controlled and is maintained at a very low concentration.

The chemistry control of this water is achieved by circulating it through lithiated ion exchange resins which produces the required degree of alkalinity while at the same time removing chloride and corrosion products. Dissolved oxygen is scavenged by reaction with carbon steel and by hydrogen produced by the radiolysis of water. Generous corrosion allowances are provided on all carbon steel components. Chemistry control is monitored by grab sampling and chemical analysis.

Provided the water chemistry control is properly maintained, crevice or galvanic corrosion of the end shield and shield tank components is not a concern. A review of the chemistry control performance has shown good compliance with specifications, which ensures that corrosion is not a problem.

4.3.3. *Pickering A vault corrosion*

The Pickering A reactors differ from newer CANDU reactors in that the calandria/end shield assembly is suspended within an air filled calandria vault. To prevent overheating of the vault concrete, carbon steel pipes for the recirculation of cooling water (shield cooling water system) are permanently embedded in the vault walls. This system is also used to cool the ring thermal shields (RTS) which protect the concrete immediately facing the calandria annular plates from overheating. This results in the RTS carbon steel inlet and outlet cooling pipes being exposed to the vault environment. The presence of moisture and radiation in these air filled vaults results in the production of nitric acid and these cooling lines have been subject to significant corrosion as a result. The Pickering A reactor assembly contains other carbon and alloy steel components susceptible to corrosion in this environment. Table IV shows H rating for this ageing mechanism but remedial measures have been taken to reduce concerns due to exposure of components to the vault environment. Some components have been repaired or replaced, as described in 5.3.1.

4.3.4. *CANDU 6 calandria supports*

The design of the calandria and end shield support assembly in the CANDU 6 reactors incorporates an annular gap between the embedment ring and the calandria support plate as shown in Fig. 14. The gap is subsequently filled with a lead wool/stainless steel wire combination for shielding. There have been occasions at three reactors of this design where water leaked or was spilled and subsequently detected in this gap. At operating temperature this water will eventually dry out, but potential for some corrosion exists. The current design of the CANDU 6 calandria supports has been modified to incorporate drainage from the annular gap.

4.4. Erosion

4.4.1. *Moderator system*

The moderator flow velocity within the calandria shell is relatively low and the erosion of material from the calandria walls is not a concern. The moderator inlet nozzle diffusers are exposed to moderate fluid flow velocities. These velocities, however, are low enough so that diffuser erosion is not likely to occur.

In Pickering A, the moderator enters the calandria through spray clusters located at the top of the calandria shell as well as through the inlet nozzles. The purpose of these clusters is to provide moderator spray cooling to calandria internal components following infrequent moderator dump or during reactor operation with a reduced moderator level. The spray clusters are arranged in two independent systems, each fully capable of providing sufficient working spray to all areas of the calandria interior. Although there is a moderate potential for the erosion of spray cluster discharge nozzles, an assessment concluded that the use of an erosion resistant material (austenitic stainless steel), the redundancy of two systems, and the breakup of jets into droplets when the jets impinge on calandria tubes and RCU guide tubes, provides assurance that the system would provide satisfactory cooling even with some erosion damage to the spray nozzles.

4.4.2. End shield/shield tank cooling

The flow velocity of cooling water within the end shield and the shield tank is sufficiently low so that erosion is not a concern.

4.5. Fatigue

4.5.1. Moderator pressure boundary

During normal operating conditions, the pressures acting on the calandria vessel, calandria tubes, and end shields do not change appreciably. It was assumed that in the 30 year design life of the reactor, there will be a maximum of 150 startup and shutdown cycles. The total number of thermal cycles that were assumed, when the original design requirements were set and the fatigue analysis done was as follows. For the 30 year design life of the reactor, the predicted number of cycles at level A service conditions was 5100 and for level B service conditions was 710. Experience from reactors in service shows that the actual number of cycles that have been experienced is much lower than the number assumed for design purposes. The need for fatigue analysis for the calandria vessel, end shields, and calandria tubes was determined in accordance with the requirements of the ASME Code, Section III, Division 1, paragraph NC-3219.2. Evaluations, documented in the respective stress reports, concluded that a detailed fatigue analysis was not required.

4.5.2. Calandria internals

The moderator inlet nozzles in all except the Bruce A reactors are a fan shaped nozzle design. These nozzles are designed to distribute the moderator flow to all areas of the calandria without causing calandria tube vibration due to flow impingement.

A moderator inlet manifold in the MAPP reactor in India failed in 1989. In 1992 a partial failure of the inlet moderator nozzle occurred in the Pickering A Unit 4 reactor. Subsequent investigation attributed these failures to flow induced high cycle fatigue. All CANDU reactors designed after Pickering A are equipped with much stronger moderator inlet nozzles. Moderator piping systems are now designed not to generate turbulent conditions and they are carefully checked during commissioning.

4.6. Creep and stress relaxation

4.6.1. Calandria tube rolled joint stress relaxation

The calandria tube rolled joint is a sandwich type joint in which the calandria tube is compressed between the calandria tube insert and the calandria tubesheet bore. These joints form part of the moderator pressure boundary and must, therefore, be watertight. The joint also incorporates interlocking grooves and lands which provide mechanical strength against axial tensile loads arising from moderator pressure on the end shields.

During the rolling operation, local diametral expansion is produced in the calandria tube and the insert when the materials deform plastically as they are forced by the roller pressure into circumferential grooves in the tubesheet bore. The rolled joint pull out strength is dependent more on these extrusions, as they must be deformed or sheared-off, than on the calandria tube to tubesheet contact pressure. The irradiation strengthening of the materials results in a greater force required to flatten or shear-off the rings thus negating the effects of reduction in contact pressure. When performing pull out tests, the calandria tube almost invariably breaks before the joint fails.

Partial relaxation of the residual stress in these joints results in a reduction in contact pressure between the calandria tube and the tubesheet bore. The serviceability of calandria tubes for an extended life up to 50 years has been evaluated. The analysis showed a 40% reduction in the contact pressure after approximately 50 years of service. Leak tests and pullout tests have also been performed on test joints subject to representative load and thermal cycling. Fully representative ageing tests are not possible, but the results show that the joints tend to relax over the first 3–4 years of service and then stabilize. The tests and analyses that have been done both demonstrated the joint's ability to maintain sufficient strength and leaktightness for the life of the plant. Leaking calandria tube joints would be detected by the system monitoring the moisture content of the gas annulus system. To date the only reported case of calandria tube joints leaking in service has been at KANUPP which has a unique joint design, not used elsewhere.

4.6.2. Calandria tube sag

The weight of the fuel channel pressure tube and the fuel inside is partially supported by the calandria tube and creep sag of the pressure tube causes the calandria tube to deform. The sag may eventually result in contact between the calandria tubes and the horizontal liquid injection shutdown unit nozzles, which would lead to fretting wear. The clearances can be therefore monitored by the in-service inspection programme to anticipate the situation and ensure it does not occur.

For calandria tubes that are not located immediately above horizontal liquid injection unit nozzles, sag will only become a concern if the curvature becomes great enough to restrict the passage of fuel through the pressure tube or to prevent replacement of a pressure tube.

4.7. Mechanical wear

The calandria and its supports have no moving parts and hence wear is not a concern.

At Bruce and Darlington, the entire shield tank and calandria assembly is supported on four "Lubrite" bearings as shown in Fig. 10. The lubricant is a solid material which will last the life of the plant and which has been qualified to perform in the radiation and other applicable environmental conditions under the reactor. Each Lubrite impregnated bronze bearing block rests on a stainless steel shim plate within a recessed seat in the base plate, which in turn is permanently embedded into the reactor vault floor. The bearings are allowed to slide on top of the shim plate in response to the thermal expansion of the shield tank. The sides of the base plate bearing are provided with make-up blocks which serve to retain the shim plate and to limit the bearing travel without damaging the base plate. A bolster plate, bolted to the base plate, and a key guide the bearing assembly and prevent it from sliding off the base plate.

With two support bearings resting against the make-up blocks, the bearings at the opposite end of the shield tank must be free to move to accommodate thermal expansion of the shield tank. If the lubricant deteriorates, sliding of bronze on stainless steel is acceptable but the shield tank, the bearings and the reactor vault floor concrete will experience higher stresses. Bearing clearances can be monitored during planned shutdowns to ensure continued freedom of movement.

4.8. Deposition of radioactive particles in horizontal reactivity control unit bellows

The bellows assemblies that seal the moderator pressure boundary on the horizontal flux detector units and liquid injection shutdown units are each provided with a circulation line. This introduces a flow of moderator, intended to prevent stagnant water conditions in the bellows and the thimbles. Operating experience has shown that these bellows assemblies are becoming sources of radiation fields. It is postulated that radioactive particles suspended in the moderator water are deposited in the bellows when the flow velocity drops as the water passes from the small diameter circulation line into the larger diameter bellows.

The feasibility of cutting and plugging the circulation line, and cleaning the deposited material from the bellows is being considered. This is a problem of increasing radiation dose impeding access for maintenance and has no impact on public safety.

5. INSPECTION AND MONITORING

The calandria assembly and support components are not required to be subject to regular in-service inspection because of choice of material and since each known ageing mechanism has been accounted for in the design. The only exception to this is the calandria tube, where information on tube sag is provided by the fuel channel pressure tube inspection. Inspection of other calandria assembly components is performed when required. Monitoring and inspection methods for an early detection of ageing degradation are discussed in this section.

Moisture detectors are located in several strategic locations around the reactor and will operate if any leakage occurs. The source will then be searched out and a rectification plan formulated. The channel annulus gas system also detects leaks from either the pressure tube or the calandria tube and their respective rolled joints. Leaks between the moderator and shield cooling system are discovered when the moderator is downgraded with light water or when tritium is detected in the shield cooling water. In all cases, leaks are detected and rectified long before any safety concerns arise. Leakage of moderator into shield cooling or from shield cooling into the moderator normally carries an economic penalty but does not impact on the reactor safety. A gross leakage of the moderator can affect the reactor safety if loss of the moderator inventory results in the reduction in the moderator level in the calandria that leads to the calandria tubes being exposed to the cover gas. Analysis shows that a gross loss of the moderator would usually follow a pressure tube/calandria tube rupture and would be manifested by an increase in the reactor building pressure, reduction in heat transport pressure and a pressurizer low level. The reactors are instrumented to trip should any of those conditions occur.

5.1. Neutron irradiation embrittlement

The calandria and its support are constructed from materials which are considered to be immune to any serious embrittlement during the life span of the reactor. No provision has been made to place test specimens in the reactor for testing during the operating life to measure change of ductility. Some material has been and continues to be irradiated in research and material test reactors and tested to measure change of properties due to irradiation.

5.2. Stress corrosion cracking

The moderator and the shield cooling system chemistry specifications for the reactor startup, normal operation and shutdown are set to eliminate potential for SCC. Water samples from the moderator and shield cooling system are analysed at regular intervals to ensure proper purity and pH is being maintained and that the quantity of corrosion products in the system is below the allowable limit. Both systems have ion exchange columns to remove impurities and they are also monitored for any deviation from normal behaviour. The chemistry control records show good compliance with the specifications. SCC degradation therefore, has not been a concern, as long as the water and moderator chemistry controls are maintained.

5.3. Corrosion

5.3.1. Pickering A vault corrosion

The carbon steel water supply piping to the ring thermal shields, which suffered from corrosion by nitric acid (described in Sec. 4.3.3), is being replaced by stainless steel piping. This work was completed in 3 units at the time of writing. A corrosion monitoring system containing dew point monitors has provided information on the threshold humidity value to initiate corrosion in vault components. Atmosphere driers have been installed adjacent to each vault to maintain humidity below the threshold value. Vault components have also been visually and volumetrically inspected. Samples of deposits and corrosion product were removed for analysis and the ring thermal shield support brackets thickness was measured. These inspections are repeated periodically to ensure deterioration is under control. Ion chamber supports and some pipe hangers have also been replaced. The material thickness of the dump tank supports was successfully measured in Unit 4 using ultrasonic probes. Although the measurements showed the thickness to be acceptable, preparations are underway to sample material from the dump tank flexible support for additional verification of the thickness and for metallurgical examination of the material.

5.3.2. CANDU 6 calandria supports

The calandria supports are normally hot and dry so that corrosion is not possible. There have been cases when water has been spilled and accumulated in the support annulus. In more recent designs, a drain tube has been added to eliminate this situation.

5.3.3. Moderator pressure boundary, end shield and shield tank

To minimize corrosion due to trace contaminants, the purity of the moderator is monitored. The measurement of conductivity is the primary method employed using on-line conductivity meters with control room alarms. Periodic grab sampling and chemical analysis are used for verification of on-line monitors. Corrosion of the moderator pressure boundary components is not a concern as long as the moderator chemistry is properly controlled. Similar provisions are taken with the shield cooling water that circulates through the end shields and shield tank or calandria vault.

5.4. Calandria tube sag

Measurements of pressure tube sag, included in fuel channel inspection programmes, can be used to estimate the calandria tube sag. Tooling and instrumentation was also developed to allow sag measurement from vacant horizontal flux detector sites in some reactors. Calandria tube sag can only be directly measured during a pressure tube replacement. Inspection data obtained thus far indicate large clearances between the calandria tube and the liquid injection shutdown unit nozzles.

5.5. Mechanical wear

Recommendations have been made that one of the Lubrite shield tank bearings be removed after 5 years for inspection. This requires the shield tank to be raised. This inspection has not yet been performed at any of the Bruce or Darlington units which use these bearings.

6. ASSESSMENT

6.1. Reactor assembly

The reactor assemblies were designed to be free of maintenance for the duration of the reactor design life. In assessing the condition of these components, the operating history is compared with design requirements for the component. When operating conditions have been maintained within the range allowed in the design specification, these components are expected to achieve and usually to exceed their design life without incident. When any excursions beyond the design conditions have been observed in the operation of the plant, an engineering assessment, based on analysis, prediction and inspection, is made on a case by case basis to establish the need for additional inspection or other remedial action. When a problem is discovered in one CANDU unit the other operators are advised and the implications for other plants assessed. If it is a generic problem a common solution is usually adopted and the design of future units will incorporate appropriate changes.

Predictions of the fuel channel pressure tube sag are used to determine when calandria tube to liquid injection shutdown unit nozzle contact will occur and appropriate action taken to prevent this from happening.

6.2. Calandria tube sag

The potential for contact between calandria tubes and the horizontal liquid injection nozzles is assessed using pressure tube sag measurements obtained as part of the fuel channel in-service inspection programme. These measurements and the predictions of future pressure tube sag are used to determine when the calandria tube to liquid injection nozzle contact will occur so that an appropriate preventative measure can be taken.

6.3. Neutron irradiation embrittlement

In the absence of irradiated material coupons, the embrittlement of austenitic stainless steel in each operating CANDU reactor can not be assessed directly. Instead, the embrittlement potential of the material is being assessed through research. Data generated from the research programme will be used to verify that the irradiation embrittlement is within acceptable limits.

7. MITIGATION

For the most part, the major subcomponents of the reactor assembly are not replaceable. To ensure that the component design life is achieved, the potential impact of the ageing mechanisms is addressed in the component design. This includes a judicious selection of material and design features aimed at producing a degradation tolerant design. Numerous material and fabrication specifications are prepared to ensure that materials are compatible with the operating environment and are free of contaminants and potential defects. Manufacturing, assembly and installation procedures are carefully considered in light of postulated ageing mechanisms before parts are created. The requirements of applicable design codes and standards are supplemented in cases where the codes and standards are considered to be difficult in addressing degradation.

Information about problems experienced in operating plants is conveyed to the reactor designers so that similar problems in future designs can be eliminated.

During reactor operation, operating conditions are monitored for compliance with the Chemistry Control Manual in order to minimize expected ageing degradation (mitigating ageing mechanisms). This manual lists acceptable operating conditions and corrective actions, including response time, that must be implemented when non-conformance is detected.

Age-related components failures, such as the moderator inlet nozzle failure in Pickering A are resolved on case by case basis as they happen. Mitigation in such cases includes analysis, repair and, where feasible, replacement (mitigating ageing effects). A failed calandria tube has been replaced in the Bruce A Unit 2. Calandria tubes have also been replaced in the Pickering A reactors. Replacement options and procedures for calandria tubes have been developed should the need to replace them in other plants arise.

8. AGEING MANAGEMENT PROGRAMME FOR CANDU REACTOR ASSEMBLIES

The information presented in this document indicates only limited ageing concerns for CANDU reactor assemblies. There are some concerns for the Pickering A type reactor assemblies relating to corrosion and stress corrosion cracking of the ring thermal shields, and erosion of the spray clusters and the ring thermal shield. The few general areas of concern relate to potential embrittlement of some stainless steel weld material and fatigue of the moderator inlet nozzles. If plants are operated beyond their design life, calandria tube sag can become a significant concern. Therefore a systematic ageing management programme (AMP) for CANDU reactor assemblies is needed to ensure their required functional capability throughout plant service life, including any extension beyond the design life.

The preceding chapters of this document dealt with important elements of an ageing management programme whose objective is to maintain the structural integrity and fluid retaining capacity of a CANDU reactor assembly throughout plant service life. Sections 2, 3 and 4 contain information on important aspects of understanding these components and their ageing. Sections 5 and 6 provide information on monitoring and inspection methods used for detecting ageing and assessing its effects. Sections 7 contains information related to mitigation of ageing.

This section describes how the above elements are integrated within a plant specific AMP for CANDU reactor assembly utilising a systematic ageing management process, which is an adaptation of the Deming's "plan-do-check-act" cycle for ageing management, Fig. 15. Such an ageing management programme should be implemented in accordance with guidance prepared by an interdisciplinary ageing management team organised at the corporate or owner's group level. For guidance on the organizational aspects of a plant ageing management programme and interdisciplinary ageing management team refer to IAEA Safety Reports Series No. 15 [18].

A comprehensive understanding of CANDU reactor assemblies, their ageing degradation, and the effects of degradation on the reactor assembly's ability to perform it design functions is a fundamental basis for the AMP. Knowledge of the plant, and of the impact of any degradation, is fundamental in making decisions about the monitoring and inspection requirements, evaluating monitoring and inspection results, and choosing any remedial strategies. Plant specific knowledge is enhanced by drawing on external experience related to behaviour of CANDU reactor assemblies.

In order to maintain the structural integrity and fluid retaining capacity of a CANDU reactor assembly throughout plant service life it is necessary to control within defined limits their potential aged-related degradation. Effective degradation control is achieved through a systematic ageing management process consisting of the following ageing management tasks, based on understanding of ageing:

- operation of the plant within specified operating conditions aimed at minimizing the rate of degradation, in particular, error-induced accelerated degradation (managing ageing mechanisms);
- inspection, monitoring and condition assessment consistent with requirements aimed at timely detection and characterization of any degradation;
- maintenance, i.e. repair, or replacement to correct or eliminate unacceptable degradation (managing ageing effects).

Existing ageing management programmes for CANDU reactor assemblies are focused on managing ageing mechanisms. This approach to AMP involves monitoring and controlling the operational environment aimed at minimizing degradation of reactor assembly components. Such an approach was chosen because of the limited accessibility of reactor assembly components, where detection of degradation is difficult, and where repair of any degradation would be costly.

A systematic ageing management programme for CANDU reactor assembly co-ordinates programmes and activities contributing to the above ageing management tasks in order to detect and mitigate ageing degradation before functional capability is compromised. This programme reflects the level of understanding of the CANDU reactor assembly, the available technology, the regulatory licensing requirements, and the plant life management consideration/objectives. Timely feedback of experience is essential in order to provide ongoing improvements in the understanding of the ageing degradation and in the effectiveness of the ageing management programme. The main features of the ageing management programme, including the role and interfaces of relevant programmes and activities in the ageing management process, are shown in Fig. 15 and discussed in the following sections.

8.1. Understanding ageing

Understanding ageing of CANDU reactor assembly is the key to effective management of its ageing. In addition it is vital with respect to integrating ageing management activities within a systematic ageing management programme, including managing ageing mechanisms through prudent operating procedures and practices (in accordance with technical specifications) and managing any ageing effects using proven maintenance methods. This understanding consists of: knowledge of the reactor assembly materials and material properties, operating conditions, possible ageing mechanisms, ageing effects and likely degradation sites, and data needed for assessment and management of ageing effects.

The understanding of CANDU reactor assembly ageing is derived from baseline data, operating and maintenance histories, and external experiences. This understanding should be updated on an ongoing basis to provide a sound basis for improvement of the ageing management programme consistent with operating, inspection, monitoring, assessment, and maintenance methods and practices.

The baseline data consists of the performance requirements, the design basis (including codes, standards, regulatory requirements), design documents, the manufacturers data (including material data), and the commissioning data (including pre-service inspection data). The operating history includes such things as service loadings and environmental conditions. The maintenance history includes design modifications, replacement parts/components, inspection records, and assessment and timing of maintenance performed. Retrievable up to date records of this information are needed for making comparison with applicable code, standards, regulatory rules, and other external experience.

External experience consists of the operating and maintenance experience of (a) CANDU reactor assemblies of similar design, materials of construction, and fabrication; (b) CANDU reactor assemblies with similar operating histories, even if the designs are different; and (c) relevant research results. It should be noted that effective comparisons or correlation with external experience requires a detailed knowledge of the reactor assembly design and operation. The present report is a source of such information. For example, Table IV presents results of the assessment of potential ageing mechanisms. However, this information has to be kept up to date using feedback mechanisms provided, for example by owner groups. External experience can also be used when considering the most appropriate inspection method, maintenance procedure, and technology.

8.2. Co-ordination of the ageing management programme

Existing programmes relating to the management of ageing include operations, surveillance and maintenance programmes as well as operating feedback, research and development and technical support programmes. Experience shows that ageing management effectiveness can be improved by co-ordinating relevant programmes and activities within an ageing management programmes utilising the systematic ageing management process. Safety

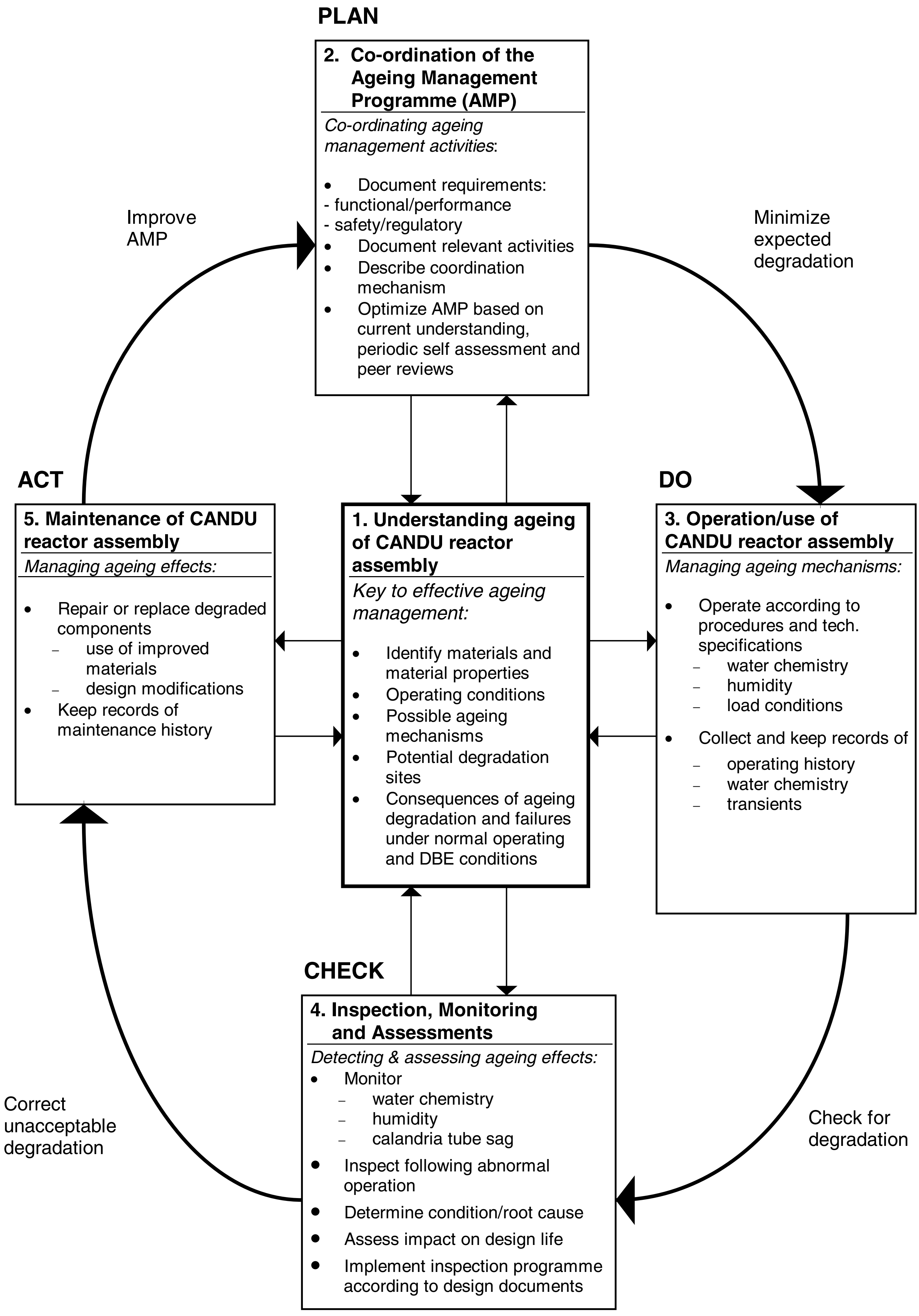


FIG. 15. Key elements of CANDU reactor assembly ageing management programme utilizing the systematic ageing management process.

authorities increasingly require licensees to define and implement such ageing management programmes for selected systems, structures, and components important to safety. The co-ordination of a CANDU rector assembly ageing management programme includes the documentation of applicable regulatory requirements and safety criteria, and of relevant programmes and activities and their respective roles in the ageing management process as well as description of mechanisms used for programme co-ordination and continuous improvement. The continuous ageing management programme improvement or optimization is based on current understanding of ageing of CANDU reactor assembly and on results of periodic self assessment and peer reviews.

8.3. Operation/use of CANDU reactor assembly

Plant operation has a significant influence on the rate of degradation of NPP systems, structures, and components. Exposure to operating conditions (e.g. temperature, pressure, humidity, radiation, and water chemistry) outside design limits could lead to accelerated and premature degradation. Since operating practices influence the reactor assembly operating conditions, NPP Operations Staff has an important role within the ageing management programme to minimize age-related degradation by maintaining operating conditions within design limits.

Operation of relevant plant systems, according to procedures, and monitoring and record keeping of relevant operational data (e.g. functional parameters and environmental conditions) also are essential for an effective ageing management programme. In particular, it is important to control and monitor the operating environment of inaccessible parts of the reactor assembly where detection and repair of degradation would be difficult and costly.

8.4. Inspection, monitoring, and assessment

CANDU reactor assemblies are designed to be maintenance free for the duration of a plant design life. No regular in-service inspection is therefore planned except for callandria tubes whose sag is measured through the fuel channel inspection programme. Inspection of other components of CANDU reactor assemblies is performed when required.

Operating conditions (e.g. water chemistry and humidity around reactor assembly) and possible water leakage (e.g. indicated by tritium in shield cooling water) are monitored, and when excursions or leakage are detected, an engineering assessment is performed to determine the need for and the type and timing of an inspection and mitigation. Current inspection, monitoring and assessment approach are described in Sections 5 and 6.

Systematic and effective record keeping is an important part of the inspection process. It is this data that underpins evaluation of the current condition as well as estimates of future performance. For visual inspection, permanent records are generally made of the condition of component at the time of survey, and may be used subsequently for trending behaviour (e.g. identifying active/inactive cracks, and monitoring crack growth or wall thinning). Records may consist of detailed drawings, photographs/videos, or a combination of these techniques. To avoid subjectivity, photographs recording the extent of degradation should, where possible, be backed up by quantitative measurements.

Quantitative data provided by other inspection and monitoring techniques also should be recorded appropriately. Guidance on the implementation of an effective system for data collection and record keeping for the purpose of ageing management is given in Ref. [6].

8.5. Maintenance, repair, and replacement

Maintenance and remedial work is implemented in response to an identified defect in the reactor assembly. Depending on the degree of degradation and the residual integrity (i.e. structural and leaktight) of the structure, the objective of a remedial measures programme might be one, or a combination, of structural and protective. Decisions on the type and timing of the maintenance actions are based on an assessment of the observed ageing effects, available decision criteria, an understanding of the applicable ageing mechanism(s), and the effectiveness of available maintenance technologies. Typical options that would be considered in response to unacceptable plant degradation are:

- Enhanced surveillance to trend progress of deterioration. This is often the initial approach adopted as part of the evaluation process during the early stages of degradation.

- Maintenance/operational changes to prevent deterioration from getting worse (if safety margins are acceptable). This might include modified operating conditions (e.g. reducing reactor power, particularly in the shorter term while repairs are planned).

- Local repairs to restore parts of a structure to a satisfactory condition.

- Replace component, where feasible.

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