Prestressed Concrete Pressure Vessels for Nuclear Power Stations

by A. J. Harris,* A. Houghton Brown,** R. B. Hyde,** T. W. Spruce** and J. D. Hay***

INTRODUCTION

The nine commercial size nuclear power stations constructed or under construction in the United Kingdom are based on gas-cooled, graphite-moderated reactors.

The first seven in the series have reactors contained in steel pressure vessels connected by external ducts to heat exchangers. The increase in pressure vessel size with the progression in station capacity, coupled with an upward trend in coolant gas pressure, made the design of steel vessels reach towards practical limits for their construction. This inspired the consideration of prestressed concrete vessels.

It was soon established that, if the whole pressure circuit, embracing reactor and heat exchangers, was placed within one concrete vessel which also provided the radiation shielding, then a practical and economical design could be developed. This concept gave many advantages in cost, compactness and additional safety and a considerable potential for further increases in size.

*Harris & Sutherland, Consulting Engineers, London

**The Nuclear Power Group, Knutsford, Cheshire

***Sir Robert McAlpine and Sons, Limited, London

Sir R. McAlpine & Sons Ltd., to whom A. J. Harris was consultant, originated and developed this type of design for inclusion in the Nuclear Power Group's tender to the C.E.G.B. for the station at Oldbury. This tender was accepted and construction on site started in April, 1962.

BASIC REQUIREMENTS OF DESIGN

The safety of a nuclear power station is the first consideration in every design. It follows that the modes of failure of a pressure vessel must be predictable and should not be approached by any credible fault conditions; it is highly desirable that warning should be given by failure being slowly progressive. These requirements can be attained with a prestressed concrete vessel.

In practice, the vessel must be capable of construction in a way that satisfies the design requirements, and the plant requirements must be met with respect to support, penetrations of the vessel and access for installation and maintenance.

To satisfy the strength requirements, the structural behavior of the vessel should be substantially elastic up to proof test pressure (say 1.15 times the design pressure). Analysis of the behavior of the vessel in this range is necessary but difficult to carry out fully and accurately even with the extensive use of computers, photo-elastic analysis and other techniques. This is due to the massive nature of the structure, the pattern of penetrations and the lack of precise knowledge of the short and long term behavior of concrete under operating conditions due to shrinkage, creep, thermal stresses and moisture movement, particularly as the strains due to these phenomena are of the same order as the strains due to design loadings. It is therefore, at present, necessary to supplement mathematical analysis with model testing in confirmation of results.

To satisfy rupture requirements an ultimate load analysis is carried out in which various modes of failure are examined and the necessary forces provided to maintain equilibrium at the load factor decided upon. In the ultimate, the design should be such that the prestressing cables determine the failure. The ultimate tensile strength of a cable is easily determined by testing; in the Oldbury design, every cable can be withdrawn and tested at any time during the life of the vessel without closing down the plant. It is suggested that the load factor could safely be 2.0 to 2.5; though the factor was taken as 3.0 for the Oldbury design as this was the first vessel to be designed and a conservative approach was made as methods both of design and construction were not fully developed at that time.

There is no great problem in producing concretes of adequate workability with compressive strengths of up to 7000 p.s.i. at 28 days, and such concretes are more than adequate for a satisfactory vessel design. The physical properties of these high strength concretes for normal structures are well known, but there is little information with regard to their performance in large masses at elevated temperatures. Consequently an insulating and cooling system to reduce temperatures to an acceptable level, and an impermeable lining to avoid the effects of hot CO_2 upon the inner concrete surface and to ensure gas-tightness, are required. A steel membrane insulated on its inner face and with cooling water pipes attached to its outer face satisfies these requirements. Further advantages of a steel lining are gained by its use as concrete forms and its convenience for the fixing of attachments, such as cooling pipes, insulation studs, brackets and penetration liners.

The basis for the design of a liner is the calculated strain distribution to which it is subjected due to straining of the inner surface of the concrete vessel, and due to restrained differential thermal expansion between the liner and the concrete. It is anchored to the concrete at points such as penetrations, and it is considered necessary further to key it to the concrete at intervals over its surface in order to cause its strain distribution to approximate that of the vessels inner surface, and so limit any accumulation of strain, and excessive shear load on any particular attachment. In addition to the keys, ties are necessary to keep buckling within acceptable limits.

The liner thickness is chosen taking account of the desirability of it being thin to minimize the loads on the keys, the need for it to withstand evacuation of the vessel without collapse, and its use as concrete forms.

PRESTRESSING SYSTEMS

The ideal prestressing system for prestressed concrete pressure vessels should have tendons which are sufficiently flexible for handling, are as compact as possible, and have small relaxation under load and temperature; the anchorage, too, should be compact; such a system would have a guaranteed ultimate tensile strength in the range of 300-500 tons per cable. Irradiation tests carried out to date have not indicated any significant effects on concrete or high tensile wire at the flux level to which they are likely to be subjected.

The prestressing force may be applied to the pressure vessel either externally or within the thickness of the concrete. Tendons applied externally would either take the form of very large tendons on special saddles or many layers of smaller tendons wrapped on to the concrete or arranged so that they may be jacked off the concrete at frequent intervals. Tendons may be accommodated within the thickness of the concrete in ducts, thus giving a very compact arrangement albeit an associated problem of placing the concrete around the ducts. Corrosion resistance is easier to obtain in ducts, particularly if the tendons are to be replaceable.

INTER-RELATION OF VESSEL SHAPES, PLANT LAYOUT AND PRESTRESSING

There are two basic shapes for the pressure vessel, the cylinder and the sphere.

The reactor core, in this type of reactor, is a right vertical cylinder requiring access from the top for fuel handling, control etc. In the integral design the boilers are best placed surrounding the core as great complication is introduced to the plant if they are placed above or below. For economy of space, the cylinder is the obvious choice to contain plant arranged in this way. If the ends are closed by flat slabs, there is the further advantage of a flat floor which can accept plant supports in any location and a flat soffit parallel to the top of the core which simplifies the design of the fuel handling plant and reduces length of charge tubes, hence the height of the charging machine and of the building generally.

The authors have carefully investigated the relative costs of spherical and cylindrical vessels to contain equivalent plant in the range from 200 to 800 psig design pressure and for sizes from 50 to 100 ft. in diameter and in all cases find the cylinder to be the less costly. These costs took into account the effect on station layout and probable construction methods.

For pressure containment a simple sphere is the mathematical optimum. It would at first appear to be amenable to detailed stress analysis but this advantage fades when a prestressing system is imposed. Whatever arrangement of prestressing cables is adopted, it is necessary to provide for anchors and the only solution appears to be the addition of ribs to the outside of the sphere, and the uncomplicated stress pattern immediately disappears.

With increase in size and pressure the problem of locating the anchorages becomes more acute and it would seem that the external shape of the vessel would become increasingly cubical or at best a series of right vertical cylinders.

It is generally considered that the major problems in cylindrical vessels are associated with the ends and the conditions of fixity at junction of wall and ends. Various schemes have been proposed to avoid this problem by introducing a hinge at this junction, but no satisfactory solution has been found. However, detailed analysis and model testing have shown that the stresses in areas of fixity are not excessive when a suitable prestressing arrangement is used.

The two basic structural forms available for closing the ends of the cylinder are the flat slab and the dome. Various forms of hemispherical dome have been suggested, such as the Marcoule hemisphere and the tension dome. These systems result in a considerable increase in the overall height of the vessel with extra length of prestressing cables. They also result in increases in the length of the standpipes and the distance from the top of the core to the charge floor. This, in turn, has an adverse effect on rates of charging and discharging, increases the height of the charge machine and charge hall, and of course gives considerable cost penalties.

A thick flat slab can be designed with greater ease of construction and a smaller overall height. The slab can be prestressed with cables in two or more directions across the slab, or circumferentially outside the standpipe zone.

The basic way of stressing a cylinder is to dispose the tendons vertically and circumferentially, the circumferential tendons being anchored on a series of vertical ribs on the external surface of the walls.

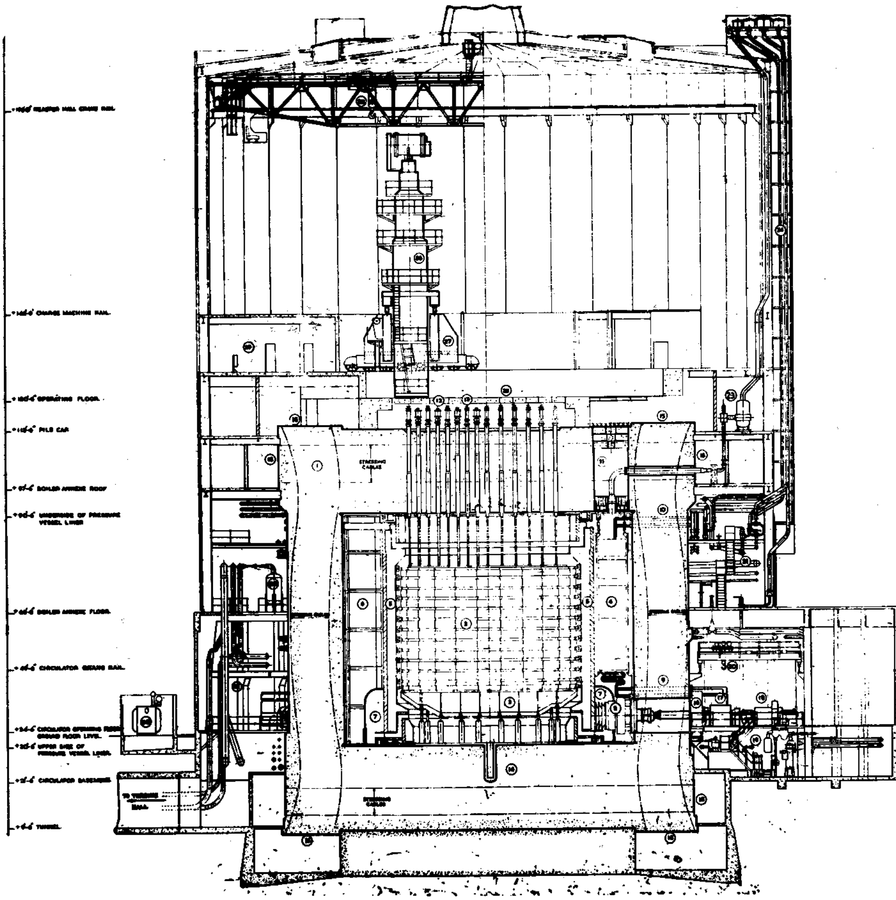
A more elegant solution is to combine vertical and circumferential prestress by using tendons in a helical pattern with layers of tendons alternately clockwise and counterclockwise, thus giving anchorages at the ends of the vessels only. This results in a very compact arrangement in which access to the anchorages may be obtained from permanent galleries which are used for the insertion and stressing of tendons during construction and are a permanent feature for inspection, testing and replacement at any time if required. This is the system which has been adopted for the vessels at Oldbury. To achieve a comparable facility with the circumferential and vertical stressing system for the cylinder or any system for the spherical vessel would require a complicated arrangement of galleries with the consequent expenditure of valuable space around the vessel.

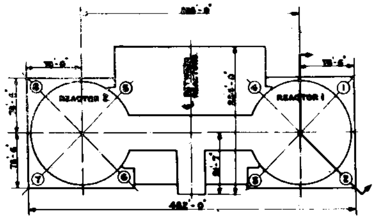
A reactor pressure vessel is of necessity penetrated at several places. The design of small openings is accomplished easily by replacing the concrete displaced by the opening with a steel tube the wall thickness of which is about 1/10th of its radius—the ratio being that of Young's moduli for concrete and steel. For larger penetrations the plate thickness so assessed would be beyond practical limits and in such cases secondary reinforcing steel could be introduced to reduce concrete stresses to acceptable levels. Since tendons are diverted around such holes, there is an exaggeration both of load stresses and of prestress.

DESIGN OF OLDBURY PRESSURE VESSELS

General Description

A typical cross-section of the vessel is shown in Fig. 1. The vessel is a vertical cylinder of 77 ft. internal diameter and 60 ft. internal height. The cylinder wall is 15 ft. thick and the end slabs 22 ft. thick. The ves-





KEY PLAN

REF	DESCRIPTION
1	PRE-STRESSED CONCRETE PRESSURE VESSEL
2	GRAPHITE CORE
3	CORE SUPPORT GRID
4	BOILER
5	BOILER SHIELD WALL
6	BOILER END PIECE
7	GAS CIRCULATOR OUTLET DUCT
8	GAS CIRCULATOR
9	BOILER FEED PENETRATIONS
10	HP & LP STEAM PENETRATIONS
11	BOILER LOADING SLOT
12	CHARGE STANDPIPE
13	CONTROL STANDPIPE
14	DEBRIS MORTUARY TUBE
15	PRESSURE VESSEL STRESSING GALLERIES
16	GAS CIRCULATOR SHIELD DOORS
17	GAS CIRCULATOR PONY MOTOR
18	GAS CIRCULATOR TURBINE
19	GAS CIRCULATOR AUXILIARIES
20	GAS CIRCULATOR CRANE 25 TON
21	STEAM AND FEED PIPEWORK
22	BOILER START-UP VESSELS
23	REACTOR SAFETY VALVES AND FILTERS
24	RELIEF VALVE PIPES TO ATMOSPHERE
25	CHARGE FLOOR
26	CHARGE/DISCHARGE MACHINE
27	CHARGE/DISCHARGE MACHINE GANTRY
28	CHARGE HALL CRANE 25 TON
29	B.C.D. ROOM
30	TRANSFORMERS

Fig. 1—Transverse Elevation of Prestressed Concrete Vessel at Oldbury Power Station

sel is constructed of high strength concrete, using limestone aggregate and sulphate resisting cement to give a minimum cube strength of 6000 p.s.i. at 28 days.

Each prestressing tendon is composed of twelve 0.6 in. nominal diameter high tensile steel strands; each strand is of 7 wires and has a minimum guaranteed ultimate tensile strength of 51,000 lb. giving a guaranteed minimum ultimate load for the tendon of 273 tons. The tendons are contained within seam welded mild steel tubes of 3½ in. o.d. which are jointed by means of reinforced rubber sleeves, which locate the ends and form a seal against ingress of laitance during concreting.

The multistrand anchorage is composed of two forged steel components between which the twelve strands of the tendon are gripped and spaced circumferentially by grooves in the male and female components. The grooves of the male cone are roughened to improve the grip on the strands.

The grip is obtained by jacking the inner cone into the outer with the stressed strands of the cable lying between them. A steel bearing plate is placed under the anchorage. The entire anchorage remains outside the concrete and is so arranged that the specially designed stressing jack can be used at any time to lift the anchorage off the bearing plate without upsetting the grip on the cable between the male and female cones. With a calibrated jack and pressure meter the force to do this can be ascertained to give a measure of the load in the cable. Means are available (by shims between the anchorage and the bearing plate) to adjust the cable load in event of relaxation.

Arrangement of Tendons

The prestressing tendons are arranged in two principal systems, one consisting of tendons following a helical trace on a barrel shape within the wall thickness and continuing to the outer surface of the end slabs and the other horizontally within the end slabs. In the helical system, the layers are arranged alternately clockwise and counterclockwise, with 160 cables in each of 22 layers on a 45° helix. In the slabs, the tendons are arranged horizontally in layers, the direction of the tendons in the center part of the layers alternating at right angles.

Structural Analysis—Ultimate Load

The vessel is designed to withstand an ultimate pressure of 1155 p.s.i.g. at ambient temperature, three times the maximum operating pressure.

The ultimate analysis is based on a consideration of the forces required to maintain equilibrium of the structure at failure. The mode of failure has been confirmed in model tests, but other modes of failure have also been examined. The action of the tendons on the concrete was broken up into its component parts, i.e., the force of the anchorages acting on a ring at the center of the helical system anchors, a reaction between the helical cables and the concrete of the cylinder wall and the forces from the anchorages of the horizontal cable system on the edges of the slabs. At failure, the wall was assumed to be cracked into vertical strips with horizontal cracks providing hinges at the first line of slab cable anchorages and at the mid height of the vessel. By equating moments about hinge points the number of helical cables required was derived.

Similarly, for the slabs, sufficient cables are provided to maintain equilibrium when the slab is divided into segments by radial cracks.

Elastic Analysis

A preliminary analysis was made in which the vessel was split into three structural elements, a thin cylindrical shell and two circular plates. All sections were considered as thin with regard to rotations and deformations but for direct stresses in the cylinder, thick cylinder theory was adopted. The rotations and displacements at points of connection of the three systems were equated. This method gave a pessimistic indication of the stresses at the junction of wall and slabs.

A more sophisticated analysis has been carried out with the aid of the computer. The results of both methods compare satisfactorily with observations from model tests.

Liner

The liner strains vary considerably over its surface, the greatest value which has been considered is one of 1710 microstrain (compressive) in the vertical direction near the bottom of the cylindrical wall. In operation, large parts of the liner will be beyond compressive yield strain.

The liner top and side wall is keyed and tied to the concrete by flat fins and hooked bars, while the bottom is keyed and tied by its attachment to a framework set into the concrete. At the stiffened junctions of the side wall with the top and bottom liners, large keys have been incorporated on to which the concrete bears in order to strain the liner.

The liner materials, ½ in. mild steel for the top and side wall and 7/16 in. Fortiweld for the bottom, were chosen for ductility and weldability; the use of Fortiweld, a high yield steel, permitted a 1 ft. pitch of bottom framework members.

Penetrations

Penetrations of the vessel fall into two categories: the first consisting of the eight large openings for boiler access and the gas circulators, these, being closed at their inner ends, are not subject to gas pressure and temperature along their lengths; and the second consisting of the numerous relatively small openings for steam and water feed pipes, charge and control rod tubes, instrumentation pipes etc., which are closed at their outer ends.

The closures for the circulator openings are the circulator casings themselves, while the closures for the rectangular boiler access slots are made by plating against a rigid grillage which is supported across the inner end of each penetration.

Cooling System and Insulation

Both the vessel and smaller penetration liners are insulated from the hot gas and have completely duplicated cooling water pipes welded to their external surfaces. The cooling system and insulation were primarily designed to ensure that the temperature distribution in the concrete is acceptable, but they also determine the liner temperatures and hence the thermal component of the liner strains. The design conditions were that the bulk concrete temperature in the top and side walls should not exceed 55°C and the temperature difference across the walls should not exceed 30°C. The bulk concrete temperature in the floor is limited to 60°C. It was possible to achieve these conditions without exceeding a liner mean temperature of 65°C.

The primary cooling medium is demineralized deaerated water of boiler feed quality, dosed to give a high *pH* for corrosion inhibition. Tests have shown that for the water quality used, radiolysis has little effect on tube corrosion. The secondary cooling medium is river water, with a maximum temperature of 24°C; the heat being transferred from primary to secondary coolant in shell and tube type heat exchangers.

The insulation on the liner inside surface is made up of layers of thin stainless steel sheet with suitable spacers incorporated between each layer.

Research and Testing

As the vessel design evolved each step was consolidated by a series of tests mounted either to obtain realistic parameters or to prove and develop the components.

Cables and Ducts

With the adoption of the helical cable pattern it was decided in 1959 to construct a full scale test bed consisting of a 3 ft.-9 in. square helical section of the vessel wall containing five pairs of different types of cable duct. This test bed was used to determine the relative suitability of various types of cable, ducts and jacks and to establish the friction and anchorage losses developed and the effect of various lubricants.

Other full scale models of parts of the vessel structure were made to examine the feasibility of duct erection and concreting in areas of apparent congestion.

Anchorages

Various anchorage designs were tested in order to arrive at one which might be readily manufactured and yet be capable of withstanding at least 95% of the guaranteed minimum ultimate strength of the cable and this standard has been obtained with the first production anchorages.

Concrete

Research into the properties of concretes has concentrated on those using limestone aggregates obtained from quarries located near Oldbury. Mixes having adequate site workability and compressive strength have been tested to determine their properties of creep, moduli of elasticity, Poisson's ratio, shrinkage, thermal expansion, thermal conductance and their relative variation with moisture content, temperature and age.

Vessel Models

A concrete model vessel to ⅛th scale of an early design was built in 1959 at Hayes in Middlesex. This model preceded the settlement of detail of the Oldbury design but is a near simulation in general.

The prestressing cable arrangement and levels of prestress simulated as nearly as possible those employed in the full scale design using ½-inch diameter, 7 wire strand having a 36,000 lb. guaranteed minimum ultimate strength in 6 helical layers in the walls. It was necessary, from practical considerations, to use an out-of-scale steel liner thickness of ⅛ inch.

The model vessel was subjected to a protracted series of onerous tests for pressure, temperature and combination of the two. The pressure was hydraulically applied and temperature effects were simulated by heating the water. However, to investigate reactor fault conditions, pneumatic testing was employed and high temperatures induced by internal heaters.

The Hayes model vessel was designed for an ultimate pressure of 675 p.s.i.g. Cracking of the vessel concrete was first observed at a pressure of 470 p.s.i.g. This pressure was equivalent to a concrete tensile stress of about 700 p.s.i., a figure which previously had been obtained in tensile tests of concrete specimens.

At an average temperature in the concrete of 100°C there was no measurable increase in the forces in the cables. No damage was detected in the model structure as a result of application of heat, with peak temperatures of about 180°C and local recorded gradients of 18°C/inch. Extensive cycling of pressure at ambient temperature and with the water at 90°C indicated only small changes in the deflection characteristics in the cylinder wall.

A similar model vessel to ⅛th scale but constructed to simulate closely the Oldbury design was built at Leatherhead, Surrey, for the C.E.G.B. In this case, the ultimate pressure was 1155 p.s.i.g. Testing continues but the behavior pattern of the Hayes model is expected to be repeated.

To avoid the cost of constructing complete model pressure vessels, several small-scale end slabs, each about 2 ft. diameter were tested. The tests of these prestressed concrete discs have confirmed the methods of end slab failure and the influence of the varying boundary conditions. It is considered that the general pattern of cracking can be forecast, together with the corresponding pressures and the deflected forms, at any stage up to failure.

CONSTRUCTION

Vessel

The part of the vessel base slab which extends radially outwards beyond the mass concrete foundation contains, on the underside, the bottom anchorages for the helical stressing cables. There are 22 circumferential rows of anchorages; each row facing in the opposite direction at right angles to the adjacent row and at slightly different angles in plan and elevation. The accuracy called for in placing and fixing these anchorages was achieved by forming radial precast concrete beams which each contained two radial rows of 11 anchorages. The beams were temporarily supported at their outer ends on timber props, which were removed when the vessel walls reached mid-height. As prestressing cannot start until the vessel structure is complete, high tensile reinforcement was built into the lower part of the walls to make the vessel self-supporting.

The base slabs were poured in 5 lifts, each lift being broken into pours with a maximum size of 290 cubic yards. The stressing ducts which were fixed in position either on precast concrete stools, or temporarily held by scaffolding, were cut into lengths corresponding to the size of each pour and bent to shape on site with a hydraulically operated pipe bending machine. The walls were then concreted in lifts 6 ft. high, each broken into four parts of about 230 cubic yards. Work proceeded in a spiral sequence climbing between the base and top slabs of the vessel.

Shortly in advance of the concreting, the roof plating was completed and the penetration liners for the side walls and top slab were welded in.

Threading and Stressing

The strand for the stressing cables is delivered to site on drums in 5000-ft. lengths. The cables are made up by drawing off twelve drums simultaneously onto a table where the strands are bundled and the cable cut to length. The cables are transported into the works on a reel and pulled into the ducts by winch-operated ropes.

The stressing sequence is arranged so that disparity between zones does not exceed 10 percent. Jacks for stressing are carried on gantries or bogies with hydraulic lifting arms where required. Stressing is from both ends to a force of 210 tons (i.e. 77% guaranteed ultimate tensile strength). This loading is maintained for two minutes when the male cone is driven in by a secondary hydraulic jack and the pressure in the main cylinder released. The anchorage is then retracted as a unit until a force of 191 tons (i.e. 70% guaranteed ultimate tensile strength) is in the cable and shims of suitable thickness are inserted between the anchorage and the bearing plate to maintain this extension in the cable. This last operation can be repeated at any time to test the load in a cable and readjust if necessary by variation in the shims.

A system of sonic strain gauges, thermocouples and moisture cells are built into the concrete of the vessel and resistance and mechanical strain gauges fixed to the surface of the liner. These are read at intervals, at the same time as vessel surface deflections are measured, to compare the actual performance of the vessel and liner with calculated predictions and results from model testing.

Pressure Testing

Following the completion of prestressing, the vessel will be subjected to a pneumatic pressure proof test; this pressure is expected to be raised in successive stages from zero to 130, 260, 385 and 443 p.s.i.g. which is 1.15 times the design pressure of 385 p.s.i.g. At each of these stages the vessel and liner strain measurements will again be compared with those obtained by calculation and from the model testing.

Progress

At the time of reading this paper, No. 1 Pressure Vessel concrete work will be complete, threading and stressing of cables will be proceeding, the enclosing building will be completed up to pile cap level and preparations will be in hand for the erection of the Charge Hall. The construction of Pressure Vessel No. 2 will be following No. 1 closely, with half the top slab completed.

CONCLUSION

The adoption of prestressed concrete pressure vessels enclosing the complete reactor, coolant gas circuits and boilers is a major advance in the design of nuclear power stations.

The principal advantages are

1. A high standard of safety arising from the containment of the coolant gas circuit in a single vessel capable of withstanding the pressure under the maximum credible fault conditions.

2. The vessel may be designed so that ultimate failure is progressive and gives ample warning.

3. The massive nature of the

structure gives assurance against accidental damage from large external forces such as earthquakes.

4. The thick concrete vessel required structurally gives a standard of radiation shielding several orders of magnitude in excess of international requirements.

5. Large vessels for high pressures outside the range of practical steel designs are possible.

6. The integral design with a concrete vessel gives a significant reduction in the overall station costs, as compared with designs using steel or concrete pressure vessels with external gas ducts and boiler shells.

7. The facilities for testing, retensioning or replacing the stressing cables ensure that the life of the vessel may be extended without limit.

8. Prestressed concrete vessels may be economically constructed with semi-skilled labor and using local concreting materials in any part of the world.

9. There is no forseeable gas-cooled reactor design advance in either pressure or size which cannot be contained within a prestressed concrete pressure vessel. The Oldbury pressure vessel described in the paper has proved that the design and construction of prestressed concrete vessels can be carried out successfully in practice.

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