DESIGN AND ANALYSIS OF MULTICAVITY PRESTRESSED CONCRETE REACTOR VESSELS*

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1. INTRODUCTION

During the past 25 years, we have witnessed a rather rapid evolution in the design and use of prestressed concrete reactor vessels (PCRVs). Initially the concrete vessel served as a one-to-one replacement for its steel counterpart. This was followed by the development of the integral design which led eventually to the more recent multicavity vessel concept. Although this evolution has seen problems in construction and operation, a state-of-the-art review which was recently conducted by the Oak Ridge National Laboratory indicated that the PCRV has proven to be a satisfactory and inherently safe type of vessel for containment of gas-cooled reactors from a purely functional standpoint. However, functionalism is not the only consideration in a demanding and highly competitive industry. The following sections will summarize what the authors have concluded to be important considerations in the design and analysis of multicavity PCRVs together with overall conclusions concerning the state of the art of these vessels.

2. DESIGN AND ANALYSIS

PCRVs have been designed and constructed in several countries. Consequently, when design and analysis procedures are reviewed, one must take cognizance that the accepted procedures may vary from country to country and frequently between different groups within the same country. The following discussion is based primarily on design and analysis procedures that have been formalized and published as codes, licensing documents and in technical publications. Thus, it may provide a less-than-universal viewpoint of PCRV design and analysis methods.

2.1 General Design Philosophy

Many loads and loading combinations must be considered in the design of a PCRV. For example, the U.S. Code [1] identifies six loading categories and lists combinations of loads in each category. The British specification [2] is less explicit about the various loading combinations and treats the categories as eight stages plus an additional ultimate load condition. Figure 1 compares the various pressure levels as defined by three different sources.

Two distinct sets of requirements must be considered by the designer. First, the PCRV must exhibit elastic response to pressures exceeding the normal operating pressure. The analysis for service loading conditions should take into account the time and temperature-dependent characteristics of concrete with due regard for the complexity of the geometry and the loading conditions. For prestress and dead loads both during construction and to the time of the vessel pressure test, the concrete may be assumed to be a linear elastic material. For all other service load conditions, the stress-strain relation for concrete should take into account age, temperature, and time under load. Net compression in the concrete should be maintained under service loading conditions but localized tensile cracking may exist when passive reinforcement is provided and if l .er integrity is not impaired.

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The second design requirement is that the PCRV must have an adequate factor of safety against failure even though the pressure levels may not be attainable from the practical standpoint. Limit design, with assumptions of failure mechanisms, is used to establish the ultimate capacity of the PCRV. The U.S. Code [1] requires only that the ultimate pressure be twice the maximum cavity pressure and does not specify the mode of failure except that it be gradual, observable and predictable. Generally, designers have proportioned PCRVs so that a ductile failure would occur in the barrel region prior to a potentially sudden failure in the head regions. The British Code [2] requires a slightly higher factor of 2.5 for failure pressure over design pressure.

With regard to many design aspects, the U.S. Code is vague while other aspects are specified in detail. For example, the code has detailed requirements for rebar splices and liner welds, while the sections covering concrete and prestressing steel lack detail; also, in several sections the analysis methods are required to predict behavior with "reasonable accuracy." It is expected that this vagueness will be eliminated as the code is used and experience is gained in the design and performance of PCRVs.

Both the U.S. and British Codes indicate that ungrouted prestressing tendons should be used; the latter code would allow grouted tendons but does not encourage their use. In contrast, the French adopted the use exclusively of grouted tendons because of corrosion problems encountered in the first two PCRVs having ungrouted tendons.

Analysis plays an important role in the design of PCRVs. The following section discusses the various types of analysis that are employed.

2.2 Elastic Methods of Analysis

Elastic methods for the analysis of PCRVs fall into three major categories. The first two are used for sizing of the vessel, whereas the third is used mainly to study the local effects of penetrations and other discontinuities. Approximate methods have been developed to aid the designer in the initial sizing of the vessel and employ rather crude approximations. Two-dimensional finite difference and finite element computer programs constitute the second major category of analysis methods. The finite element method appears to be preferable, expecially for structures having irregular geometries. Originally the constant strain triangle was the basic element employed but has since been superceded by higher order linear strain triangular and rectangular elements. A combination of planar-section and axisymmetric analyses was used in the analysis of the Fort St. Vrain PCRV [3]. Two-dimensional elastic analyses have also been used in conjunction with relationships derived from three-dimensional analyses to estimate the elastic behavior of multicavity PCRVs [4].

The third major category of elastic analysis includes three-dimensional finite element computer programs. There are numerous programs available with elements that vary from the constant strain tetrahedron to higher order elements. Analyses made using these programs are generally expensive and the input is complicated; therefore, three-dimensional analyses are generally performed on the final configurations rather than at an earlier stage of the design process and are used primarily to study the effects of penetrations and other regions having complex geometry.

2.3 Inelastic Methods of Analysis

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There are numerous computer programs [5] available for performing inelastic analyses of structures, made of metallic materials rather than those made of a combination of metallic materials and concrete. The finite element program SAFE-CRACK [6], has provisions for viscoelastic, cracking and plastic analysis of plane or axisymmetric steel-concrete composite structures. Concrete is characterized in the program as an age- and time-dependent linear viscoelastic material. Concrete cracking is characterized mainly by tensile strain criterion which takes into account multiaxial stress-strain interactions. Once cracking occurs, an orthotropic stress-strain constitutive law is utilized. The creep properties included in this computer program were based on data from the British Wylfa PCRV concrete tests. Other codes such as ADINA and NØNSAP have recently come into use; however, there exists a need for the development of analysis methods and more specifically algorithms that can accurately represent the behavior of concrete-steel composite structures. The major obstacle at present is the lack of a unified theory of failure for concrete which can account for the various complex stress states.

2.4 Collapse Mechanisms

As indicated in Section 2.1, the PCRV must be designed for a certain factor of safety against failure. Model tests have been used to identify the various modes of failure of the cylindrical walls and end slabs. Tests of end slabs conducted in Australia [7,8] identified a total of five primary and secondary modes of failure. These tests indicated that a direct relationship exists between the level of circumferential prestress and the failure pressure. Model tests were also performed in the U.S. [9,10,11] to study the influence of several variables including: (a) the ratio of end slab thickness to interior diameter of the vessel, (b) the presence of penetrations in the end slab, and (c) the level of longitudinal and circumferential prestressing forces. Flexural and shear modes of failure were observed in the end slab. Shear failures caused by development of inclined cracks tended to be abrupt. Although measured deflections were sizable prior to failure, they were apparently not related to the failure mechanism. As a result of these tests, the cryptodome analysis method was developed to predict the ultimate strength of the end slab. Failure surfaces are assumed and an axisymmetric analysis is performed for each trial surface until a surface meeting specified strain criteria is identified. The vessel tests also showed that the presence of penetrations removing up to one-half of the circumference of the head at the radial location of the holes did not reduce the shear strength of the end slab significantly.

Perhaps the most extensive testing of head slabs has been conducted in England. Three possible modes of failure were identified for PCRV end slabs [12,13]. The first mode is a yield-line collapse, the second is the failure of the circumferential prestress, and the third is a shear failure. Lateral restraint was found to be important for efficient utilization of materials in the end slab; however, increases in the level of restraint have minimal effects on the shear strength of the slab.

Considerable understanding of the behavior of PCRV head slabs has resulted from these experimental investigations, and empirical analysis techniques such as the cryptodome method appear to be satisfactory for analyzing solid slabs and those with less complicated penetration configurations. However, a truly systematic method of analysis for head slabs remains to be developed.

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3. MODEL TESTING

The use of models of PCRVs is universally recognized as an essential part of the design process. The U.S. Code [1] specifies that models must be used whenever accurate analytical procedures for the ultimate strength have not been established or whenever models of a prototype of similar characteristics have not been tested. In addition. scale limitations are also specified depending on the purpose of the test. Table I summarizes the numerous model tests that have been performed. Emphasis in model testing has been directed toward relatively large models. These models are used to provide an overall confidence in the integrity and safety of the PCRV design since prestressing forces, pressure forces, and thermal gradients can be realistically simulated in larger models. Most of the tests listed in Table I were performed on single-cavity models.

3.1 Multicavity Vessel Model Tests

The first test of a multicavity model was for the English Hartlepool PCRV [14]. The 1:10-scale model was tested to determine the behavior under elastic loads, the mode of failure, and the ultimate load factor for the PCRV. The model behaved elastically up to a pressure of 1.5 times the design pressure and had an ultimate load factor greater than three. A 1:20-scale model of a multicavity PCRV has been tested in the U.S.A. [15], but this model is not typical of present design since slip planes were built into the vessel at the head-to-cylindrical wall junction. Failure was not achieved because of excessive liner leakage.

Two 1:20-scale models have been tested by Ohbayashi-Gumi, Ltd. [16] in Japan. The models were of the same overall dimensions. One model had six steam generator cavities around the central core cavity and a star support structure connected rigidly under the bottom slab; the second model did not have steam generator cavities nor support structure. The mode of failure was not established for either vessel; however, the possibility of a complex failure mode involving both the head and wall regions was mentioned.

Two 1:20-scale models of a multicavity PCRV were tested by the Kajima Institute of Construction Technology [17] also in Japan. The models were identical except that one had 19 penetrations in the top head whereas the other was unpierced. Both models were tested in a similar manner and the responses of the two models were essentially identical.

A 1:14-scale multicavity model was also tested in England [18]. The model contained a central cavity and eight smaller cavities equally spaced around the main cavity. Linear elastic behavior was observed up to the design working pressure (WP). Nonlinear, but elastic, behavior was noted up to 1.5 WP. First cracking was indicated at 1.75 WP at the top corner of the central cavity, followed by cracking at midheight of the wall and in the top slab at 2.1 WP. The maximum pressure was 2.9 WP with failure occurring in two bands of the circumferential prestressing near midheight of the vessel which resulted in the ejection of a block of concrete from the wall external to the small cavity at that level. This test indicates the need for careful evaluation of the equilibrium of various portions of the vessel; it is not sufficient to merely balance forces across a diameter.

In summary, there have been eight multicavity PCRV models tested to date and only the two English models were of sufficient size to satisfy the requirements of the U.S. Code [1].

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In summary, there have been eight multicavity PCRV models tested to date and only the two English models were of sufficient size to satisfy the requirements of the U.S. Code [1]. Three facets of the model tests discussed above are of significance. (1) The cylindrical wall portion of the models have a nominal strength of three times the design pressure rather than the generally accepted factor of two. (2) Failure has not occurred in the head of any multicavity model. (3) A special liner is required to transmit high pressures to the model if the mode of failure is to be determined experimentally. It is hard to conceive that the liner of a prototype vessel would be capable of developing comparable pressures.

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3.2 Tests on PCRV Heads

Single-cavity PCRVs were designed with the cylindrical walls weaker than the heads; consequently, the models failed in the barrel sections. Therefore, very little information was obtained relative to the mode of failure in the head region. Several series of tests have been conducted on the PCRV heads in order to establish the behavior and mode of failure. Table I reveals the organizations that have conducted tests on the head slab alone using various boundary conditions.

The number of tests performed on models containing the head and barrel section is small in comparison to the number of tests on end slabs alone. Many of the English tests were for specific prototype vessel design verification. For example, two 1:13-scale models were tested for the Fort St. Vrain PCRV. One interesting conclusion of these tests was that about 2/3 of the ultimate shear force was resisted by aggregate interlock in the tension zone of the slab and the remainder was resisted by shear compression [19]. The barrel sections of these models were relatively short with the maximum barrel length being approximately equal to the thickness of the end slab [13]. As far as the authors could determine head failure tests have not been conducted on typical multicavity vessel head configurations except for one series of U.S. tests [11]. In these tests, the head region above the central core cavity was simulated using single-cavity models. It is recognized that significant differences exist between the behavior of head slab models and the behavior of more complete PCRV models [13]. Consequently, the effects of the slab boundary conditions on behavior and mode of failure must be carefully evaluated. A full understanding of the head failure mechanisms has yet to be achieved.

3.3 Thermal Tests

The presence of a temperature gradient in the PCRV presents problems in design, particularly with respect to whether analyses can accurately predict the resulting stresses. The conditions of mass concrete in the actual vessel cannot be readily duplicated in small-scale models and this fact is recognized in the U.S. Code [1] where the minimum scale for models to investigate long-term temperature response is 1:4. The minimum thickness of models to investigate short-term temperature response is 0.6 m.

Recently tests of a model of the penetration region of the Oldbury PCRV were conducted after excessive heating was recorded during the vessel commissioning [20]. The model was 3.66 m in diameter and 1.52 m thick. The test results indicated that localized cracking probably did occur in the vessel due to the hot spots, but the embedded anchors apparently remained effective, and therefore the liner was considered acceptable even with the cracked concrete.

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Two 1:5-scale models of the Bugey PCRV were constructed in France. One of these models was subjected to thermal tests and buckling of the liner occurred [21]. In general the tests confirmed the earlier computer analyses and only slight modifications in the design were required near some of the penetrations.

A 1:6-scale representation of the barrel section of a single-cavity PCRV was tested in the U.S. [22]. The major objective of the test was to evaluate the present capability to predict temperature and time-dependent stress-strain behavior of a relatively simple prestressed concrete vessel. The model was subjected to loadings simulating the anticipated loading history of an operating PCRV. A hot-spot test was also conducted. Good agreement was generally seen between experimental and calculated values with the greatest variation occurring during the hot-spot test. No buckling or detectable distortion of the liner occurred as a result of the hot-spot heating; however, a number of axial prestressing tendons experienced failure due to corrosion. After considerable study, it was concluded that the corrosion was caused by the existence of contaminants that would not normally be present in a PCRV.

4. VERIFICATION OF ACTUAL VESSEL PERFORMANCE

Proof testing and in-service performance of PCRVs in nuclear power plants provide data used to evaluate original design calculations. Reports of the performance of the British Oldbury and Wylfa PCRVs have been published.

The Oldbury PCRV required two years to cast and nine months to prestress. The vessel was proof tested in May 1966 and startup began in October 1967. An analysis of the vessel was performed for the period from the completion of the prestressing operation, July 1965, to March 1970. Selected results presented in Ref. [23] indicated that the axisymmetric analysis, including the rate of creep method, predicted the general behavior of the structure reasonably well.

Construction of the Wylfa PCRVs began in 1964, and the prestressing cables in both vessels were tensioned in 1968. In 1971 a program was begun to provide data on the long-term properties of concrete. The results from selected strain gages were reported in Ref. [24]. The general patterns of strain development compared favorably with predicted values and results from gages at four meridians of the vessel indicated symmetry of behavior.

The first unit of Fort St. Vrain was subjected to a combined pressure and leak test program from July 29 to August 14, 1971 [25]. The vessel was pressurized to 1.32 times the operating pressure after preheating the liner to the design operating temperature. The temperature gradient was maintained for one month to ensure thermal equilibrium. The response of the PCRV was essentially linear, and the measured deflections at midheight of the vessel exceeded the calculated values slightly. A comparison was also made between measured prestress forces and an analysis obtained by using a two-dimensional axisymmetric viscoelastic finite element computer program. The measured prestress forces were consistently larger than the design value but agreed reasonably well with the axisymmetric analysis which took concrete creep into consideration.

The results of pressure tests on full-size PCRVs indicate that calculations made using relatively unrefined elastic analyses have agreed reasonably well with data obtained for the normal operating and slight overpressure conditions of the vessel. This conclusion, however, is valid only for the gross structural behavior of the PCRV during a short-term test conducted early in the life of the vessel. Only continued observation of the PCRV in service liner occurred as a result of the hot-spot heating; however, a number of axial prestressing tendons experienced failure due to corrosion. After considerable study, it was concluded that the corrosion was caused by the existence of contaminants that would not normally be present in a PCRV.

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5. LINERS

The entire internal concrete surface of a PCRV which is exposed to primary coolant is covered and sealed by a relatively thin continuous steel liner. Nelson-type studs are welded to the liner and embedded in concrete; and an insulation blanket is placed against the inside face of the liner and held in place by a metal cover plate to form a thermal barrier. Cooling tubes are welded to the outside surface of the liner, and water is continuously circulated through the tubes to control the temperature of the concrete. The combined liner, thermal barrier, and liner cooling system accounts for a substantially large part of the total vessel cost.

Tests [26,27] on liner plate segments, where they are subjected to both biaxial tension and biaxial compression loadings, are reported in the FSAR for Fort St. Vrain [19]. The purpose of these tests was to demonstrate the capability of the liner plate to sustain stresses and deformation well beyond those predicted to occur under postulated PCRV accident conditions. Other tests have been performed to describe the post-yield load-vs-strain relationship of a panel with rib-type anchors [28,29].

Tests have been performed to determine the load-vs-deflection relationship under shear loading of rib-type anchors [30], stud anchors [31,32], and cooling tubes [33,34]. The tests on stud anchors, though extensive, were performed on studs welded to wide-flange beams, a condition which does not accurately represent the loading condition of a PCRV liner anchor. No data are readily available which describe the shear load-vs-deflection behavior of stud anchors and cooling tubes acting in series, which is the actual PCRV liner situation.

Lee and Gurbuz [27] list and briefly describe seven methods of analysis of liner anchorage systems, and an explanation and extension of one of these methods in common use for containment liners is given in Ref. [35]. All but one of these methods are one-dimensional, and all attempt to predict the final deformed state of a liner anchorage system in which the liner is subjected to compressive stress.

The U.S. Code [1] gives requirements for PCRV and containment liner design and fabrication. The design criteria have one major objective: to assure that the liner in a PCRV or containment functions as a leak-tight membrane throughout the range of loading for which the vessel is designed. To accomplish this end, values for maximum anchor forces under mechanical loads and maximum liner and anchor strains under displacement limited loads are specified. Although the design procedures and supporting test data appear adequate from the design standpoint the capability to detect, locate and repair a leak in the liner appears to need further development.

The allowable strains in the liner are predicted on the basis of a ductile material; other Code requirements for the liner material assure that such ductility exists. Allowable displacements and forces in the liner anchors are based on either yield or ultimate dis- [illegible] Thus, reference must be made to test results on liner covered and sealed by a relatively thin continuous steel liner. Nelson-type studs are welded to the liner and embedded in concrete; and an insulation blanket is placed against the inside face of the liner and held in place by a metal cover plate to form a thermal barrier. Cooling tubes are welded to the outside surface of the liner, and water is continuously circulated through the tubes to control the temperature of the concrete. The combined liner, thermal barrier, and liner cooling system accounts for a substantially large part of the total vessel cost.

Tests [26,27] on liner plate segments, where they are subjected to both biaxial tension and biaxial compression loadings, are reported in the FSAR for Fort St. Vrain [19]. The purpose of these tests was to demonstrate the capability of the liner plate to sustain stresses and deformation well beyond those predicted to occur under postulated PCRV accident conditions. Other tests have been performed to describe the post-yield load-vs-strain relationship of a panel with rib-type anchors [28,29].

Tests have been performed to determine the load-vs-deflection relationship under shear loading of rib-type anchors [30], stud anchors [31,32], and cooling tubes [33,34]. The tests on stud anchors, though extensive, were performed on studs welded to wide-flange beams, a condition which does not accurately represent the loading condition of a PCRV liner anchor. No data are readily available which describe the shear load-vs-deflection behavior of stud anchors and cooling tubes acting in series, which is the actual PCRV liner situation.

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1

6. PENETRATIONS

The design of penetrations is probably one of the most complex and least understood aspects of PCRV design. Steel vessel penetrations are designed, for example, using the straightforward ASME Section III, Division 1, and Section VIII area replacement rules. The principal objective of the PCRV penetration design is consistent in purpose with the requirements for steel vessels; namely, the strength of the penetration must be at least as good as that of the unpenetrated vessel so as to not compromise the integrity of the overall structure. The achievement of this objective is more complicated in a PCRV since the larger penetrations in particular disturb the idealized layout of the prestressing and give rise to variations in the stress field. Consequently, in the concrete vessel the excess stress must be compensated for by the use of steel pads or nozzles, or by transfer to the concrete and in turn to the prestressing using shear anchors. The direct use of steel reinforcement is more appropriate for small penetrations and the anchorage solution is more common with large penetrations [36]. Considerable conventional steel reinforcement is also employed to control and distribute any potential concrete cracking in the region immediately adjacent to the penetration.

In addition to the penetration, an equally important aspect is the closure or plug. Closures are generally designed to be removable; however, the ease with which this can be accomplished can vary considerably and will depend to a great extent upon the type of hold-down system and seal employed, and whether or not the system has been perfected.

The design philosophy of closures has undergone a distinct evolution as has design of the overall PCRV. Since PCRVs were originally intended to function without secondary containment, the closures were designed with double seals, and primary and secondary hold-downs. A flow restrictor was also included to limit maximum area of gas leakage to a predetermined value in the event of failure of the primary seals. Since secondary containments have been integrated into the HTGR system, however, only the double seal has been eliminated from the closure design requirement. Recent studies undertaken to reduce PCRV capital costs have motivated a reexamination of the need for secondary hold-down and flow restrictors since comparable LWR systems have no such similar requirements.

Possible serious consequences to the secondary containment structure must be evaluated in the event that a plug could be forceably ejected from the PCRV. A decision must be made as to whether secondary hold-down and/or flow restrictors can be either eliminated or further strengthened to resist a postulated severe impact loading resulting from sudden failure of the primary hold-down. One must therefore decide whether it is necessary to adopt the philosophy that large closure units be designed so as to make failure a virtual impossibility, or for failure during extreme overpressurization to be predictable and gradual.

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7. PRESTRESSING SYSTEMS

A major change in the type of prestressing systems used for PCRVs has taken place in the past five years. Previously, circumferential tendons were housed in ducts embedded in the concrete wall. Also, there were vertical tendons and cross-head tendons that were constructed in the same manner. With the development of the circumferential wire-winding technique, several important improvements were realized. First, the placement of the circumferential tendons on the outer surface of the vessel removed much of the congestion in the vessel wall and allowed this space to be utilized more effectively, with the inclusion, for example, of steam generators in cylindrical cavities around the central cavity. Second, the circumferential prestress in the head region eliminated the need for the cross-head tendons. This was important, since the penetration region of the top head was highly congested by the presence of penetrations, vertical tendons, cross-head tendons, and the conventional reinforcement required immediately adjacent to penetrations. However, the circumferential wire-winding technique makes the use of penetrations through the vessel wall more difficult; consequently, large-diameter access penetrations must be provided in the top and bottom heads. Another limitation of the wire-winding technique is that specialized equipment is required to install, prestress, and monitor the prestressing. However, the advantages of the wire-winding system seem to far outweigh the disadvantages, and newer PCRV designs are of the wire- or strand-wound type. Vertical tendons are still designed to be constructed of individual wires or strands housed in tubes. An exception to this type of construction is the use of helical tendons in the British Oldbury, Hinkley Point B, and Hunterston B PCRVs [26].

There are only a few prestressing systems which have been used in PCRVs. Table II lists the PCRVs which have been designed in the past few years. Tendon sizes have become larger, with ultimate tendon loads of 8.9 MN (1000 tons) not uncommon in present multicavity PCRV designs. Bangash [37] lists nine different linear prestressing systems, and all but two have an ultimate load capacity equal to or greater than 7.1 MN (800 tons).

8. CONCLUSIONS

PCRVs have a demonstrated capability of satisfactory performance for extended operating periods. Since their strength is derived from literally a multitude of independent members, PCRVs have the potential for unparalleled inherent safety. It is somewhat inconsistent that during a period of almost overwhelming public concern for reactor safety, PCRVs have not come into more widespread use for all types of reactors.

The one area of potential vulnerability of the PCRV appears to be the liner. Together with the thermal barrier and liner cooling system it is extremely expensive and any possible break or puncture in the liner would be very difficult to locate and repair. Thus, inspectability and repairability of the liner should be given further consideration.

The most serious problem concerning the further development and use of PCRVs appears to be economic rather than technical. Since present designs have evolved from vessels not having secondary containments, there is a need to reexamine many features and optimize the design from a cost standpoint. Thus, new innovations and refinements are needed to (1) develop vessel configurations having a minimum of liner surface area and concrete volume without sacrifice of performance or constructability, (2) optimize penetration and closure systhe circumferential prestress in the head region eliminated the need for the cross-head tendons. This was important, since the penetration region of the top head was highly congested by the presence of penetrations, vertical tendons, cross-head tendons, and the conventional reinforcement required immediately adjacent to penetrations. However, the circumferential wire-winding technique makes the use of penetrations through the vessel wall more difficult; consequently, large-diameter access penetrations must be provided in the top and bottom heads. Another limitation of the wire-winding technique is that specialized equipment is required to install, prestress, and monitor the prestressing. However, the advantages of the wire-winding system seem to far outweigh the disadvantages, and newer PCRV designs are of the wire- or strand-wound type. Vertical tendons are still designed to be constructed of individual wires or strands housed in tubes. An exception to this type of construction is the use of helical tendons in the British Oldbury, Hinkley Point B, and Hunterston B PCRVs [26].

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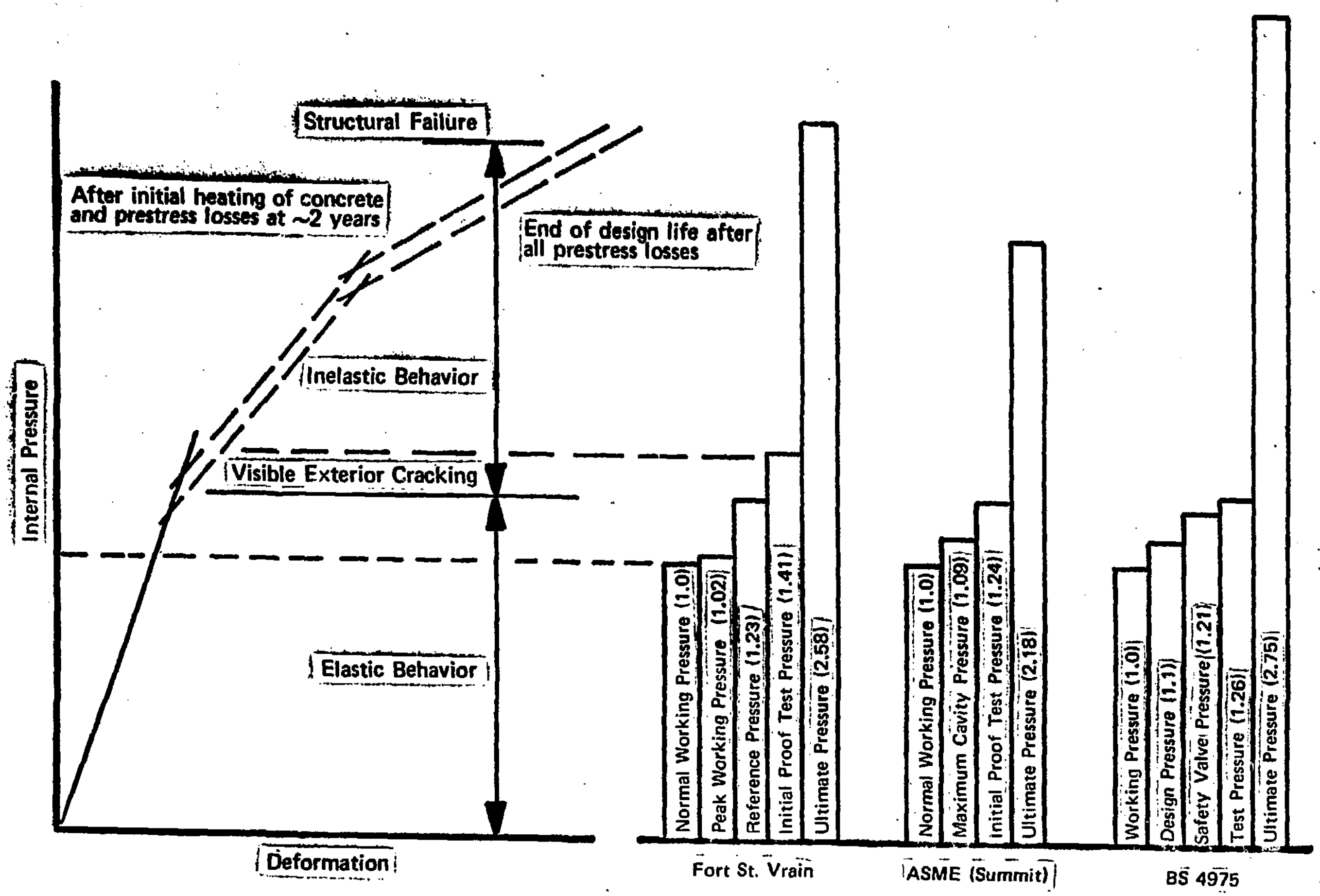

Fig. 1. Comparison of Pressure Levels for PCRVs (Normal Working Pressure = 1.0).

Table I. PCRV Scale Models

Organization	Test item	Scale	Project	Number of models	Test for[a]
1. French AEC	Head, PCRV	Not known	G-2, G-3	2	A, B, C
	Cylindrical PCRV	1/10	G-2, G-3	3	A, B, C
	Cylindrical Vessels	0.76 m ID[b] 2.29 m high[b]	Safety Studies	25	C, D
	Cylindrical Vessel	Unavailable	G-2, G-3	2	A, B, C
2. Societe d'Etudes et d'Equipments d'Entreprises (SEEE), France	Cylindrical PCRV	1/6	EDF-3	3	A, B, C, D
	Cylindrical PCRV	1/10	EDF-3	1	T
	Cylindrical PCRV	1/5	EDF-4	2	A, B, C, T
	"Hot Liner" Vessel	Not known	General	1	A, B, C, T
3. Electricite de France (EDF) France	Cylindrical PCRV	1/5	Bugey I	2	A, B, C, T
	2 Layer Cylinder	1/3	General	1	
4. Central Electric Research Laboratory, England	Cylindrical PCRV	1/8	Oldbury	1	A, B, C, T
	Cylindrical PCRV	1/8	Pre-Oldbury	1	B, C
5. Sir Robert McAlpine & Sons England	Cylindrical PCRV	1/7	Oldbury	1	A, B, C, T, D
	Cylindrical PCRV	1/10	Hinkley Pt B & Hunterston B	1	A, B, C
	Multicavity PCRV	1/14	HTR	1	A, B, C
6. Taylor Woodrow Constr. Ltd., (TWC), England	Spherical PCRV	1/12, 1/40	Wylfa	2	A, B, C
	Cylindrical PCRV	Not known	Wylfa	3	A, B, C
	Cylindrical PCRV	1/10	Hunterston B	1	A, B
	Heads, PCRV	1/24	Several	12	A, B, C
	Multicavity PCRV	1/10	Hartlepool	1	A, B, C
	Head, PCRV	1/13	Ft. St. Vrain	2	A, B, C, D
	Multicavity, PCRV	1/30	GT-HTGR	2	A, B, C
7. Kier Ltd., England	Spherical PCRV	1/12	Wylfa	1	A, B, C, T
8. Atomic Power Constr., England	Cylindrical PCRV	1/10	Dungeness B	1	A, B, C
	Cylindrical PCRV	1/26	Dungeness B	1	B, C
	Heads, PCRV	1/72	Dungeness B	1	B, C
	Heads, PCRV	1/24	Dungeness B	3	B, C
	Heads, PCRV	1/26	Dungeness B	2	B, C
9. Building Research Station, England	Cylindrical PCRV	1/10	Hinkley Pt B	1	T
	Cylindrical PCRV	1/20	Hinkley Pt B	4	T
10. Foulness, England	Cylindrical PCRV	1/20	Study by UKAEA Safety Group	10 models to date (30 total 40% pneumatic	C, D
11. General Atomic	Cylindrical PCRV	1/4	General	1	A, B, C
	Cylindrical PCRV	1/4	Ft. St. Vrain	1	A, B, C, D, T
	Multicavity PCRV	1/20	HTGR	1	A, B, C
12. Oak Ridge National Laboratory	Cylindrical PCRV	≤1/5	General	4	A, B, C
	Wall, PCRV	1/6	General	1	A, T
13. University of Illinois	Cylindrical Vessels		General	35	C, D
14. University of Sydney, Australia	Head, PCRV	1/20	General	21	C, D
15. Siemens, Germany	Cylindrical PCRV (Prefabricated Blocks)	1/3		1	A, B, C
16. Krupp, Germany	Cylindrical PCRV	1/20	Gas-Cooled Reactor	1	A, B, C
	Head, PCRV	1/20		1	A, B, C
17. ENEL/ISMES, Italy	Cylindrical PCRV	1/20	HTGR	2	A, B
	Head, PCRV	1/20	HTGR		C
18. Ohbayashi-Gumi, Japan	Cylindrical PCRV	1/20	HTGR	1	A, B, C
	Multicavity PCRV			1	A, B, C
19. Cement and Concrete Inst. Trondheim, Norway	Cylindrical PCRV	1/3.6	Scandinavian PCRV (LWR)	4	A, B, C
20. A. B. Atomenergi, Studsvik, Sweden	Cylindrical PCRV	1/2.5	Scandinavian PCRV (LWR)	1	A, B, T
21. [illegible]	Cylindrical PCRV	[illegible]	Hinkley Pt B	[illegible]	[illegible]

	Cylindrical Vessel	Unavailable	G-2, G-3		
2. Societe d'Etudes et d'Equipments d'Entreprises (SEEE), France	Cylindrical PCRV Cylindrical PCRV Cylindrical PCRV "Hot Liner" Vessel	1/6 1/10 1/5 Not known	EDF-3 EDF-3 EDF-4 General	3 1 2 1	A, B, C, D T A, B, C, T A, B, C, T
3. Electricite de France (EDF) France	Cylindrical PCRV 2 Layer Cylinder	1/5 1/3	Bugey I General	2 1	A, B, C, T
4. Central Electric Research Laboratory, England	Cylindrical PCRV Cylindrical PCRV	1/8 1/8	Oldbury Pre-Oldbury	1 1	A, B, C, T B, C
5. Sir Robert McAlpine & Sons England	Cylindrical PCRV Cylindrical PCRV Multicavity PCRV	1/7 1/10 1/14	Oldbury Hinkley Pt B & Hunterston B HTR	1 1 1	A, B, C, T, D A, B, C A, B, C
6. Taylor Woodrow Constr. Ltd., (TWC), England	Spherical PCRV Cylindrical PCRV Cylindrical PCRV Heads, PCRV Multicavity PCRV Head, PCRV Multicavity, PCRV	1/12, 1/40 Not known 1/10 1/24 1/10 1/13 1/30	Wylfa Wylfa Hunterston B Several Hartlepool Ft. St. Vrain GT-HTGR	2 3 1 12 1 2 2	A, B, C A, B, C A, B A, B, C A, B, C A, B, C, D A, B, C
7. Kier Ltd., England	Spherical PCRV	1/12	Wylfa	1	A, B, C, T
8. Atomic Power Constr., England	Cylindrical PCRV Cylindrical PCRV Heads, PCRV Heads, PCRV Heads, PCRV	1/10 1/26 1/72 1/24 1/26	Dungeness B Dungeness B Dungeness B Dungeness B Dungeness B	1 1 1 3 2	A, B, C B, C B, C B, C B, C
9. Building Research Station, England	Cylindrical PCRV Cylindrical PCRV	1/10 1/20	Hinkley Pt B Hinkley Pt B	1 4	T T
10. Foulness, England	Cylindrical PCRV	1/20	Study by UKAEA Safety Group	10 models to date (30 total 40% pneumatic	C, D
11. General Atomic	Cylindrical PCRV Cylindrical PCRV Multicavity PCRV	1/4 1/4 1/20	General Ft. St. Vrain HTGR	1 1 1	A, B, C A, B, C, D, T A, B, C
12. Oak Ridge National Laboratory	Cylindrical PCRV Wall, PCRV	≤1/5 1/6	General General	4 1	A, B, C A, T
13. University of Illinois	Cylindrical Vessels		General	35	C, D
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15. Siemens, Germany	Cylindrical PCRV (Prefabricated Blocks)	1/3		1	A, B, C
16. Krupp, Germany	Cylindrical PCRV Head, PCRV	1/20 1/20	Gas-Cooled Reactor	1 1	A, B, C A, B, C
17. ENEL/ISMES, Italy	Cylindrical PCRV Head, PCRV	1/20 1/20	HTGR HTGR	2	A, B C
18. Ohbayashi-Gumi, Japan	Cylindrical PCRV Multicavity PCRV	1/20	HTGR	1 1	A, B, C A, B, C
19. Cement and Concrete Inst. Trondheim, Norway	Cylindrical PCRV	1/3.6	Scandinavian PCRV (LWR)	4	A, B, C
20. A. B. Atomenergi, Studsvik, Sweden	Cylindrical PCRV	1/2.5	Scandinavian PCRV (LWR)	1	A, B, T
21. Electric Power Development Co., Ltd. & Shimizu Construction Co., Ltd.	Cylindrical PCRV	1/10	Hinkley Pt. B	1	A, B, C
22. Nuclear Power Development Lab. & Kashmi Kenetsu, K.K.	Cylindrical PCRV	1/20		3	A, B, T
23. PCPV Research & Development Group, Kajima Corporation	Cylindrical PCRV Multicavity PCRV	 1/20	ORNL Model GA 1100 MW(e)	3 2	A, B, C, T A, B, C
24. Takenaka Technical Research Laboratory	Head, PCRV	1/20	General	14	A, B, C

[a]A. Elastic response, B. Design overpressure, C. Failure, D. Abnormal conditions, T. Long-term creep and temperature.

[b]2.5 ft ID by 7.5 ft inside height.

Table II. Prestressing Systems Employed With Recent PCRVs

Name	Prestressing system type[a] LPS	Prestressing system type[a] WW	System[b]	Diameter[c]	Number per tendon
Fort St. Vrain	X	X	BBRV	6.4-mm wires	169
Summit[d]	X		BBRV	6.4-mm wires	169
		X	GA	15-mm strand	
Hinkley Pt B	X		CCL	18-mm strand	7
Hunterston B	X		CCL	18-mm strand	7
Hartlepool	X			18-mm strand	28
		X	TW	5-mm wire	
Heysham A	X			18-mm strand	28
		X	TW	5-mm wire	
THTR Uentrop	X		BBRV	7-mm wire	151
		X	BBRV		
HTR II	X		BBRV	7-mm wire	163
		X	BBRV	9.5-mm strand	

[a]LPS = Linear Prestress System; WW = Wire Winding.

[b]BBRV = Ryerson BBRV Posttensioning, Joseph T. Ryerson and Son.
GA = General Atomic Co.
CCL = Prescon/CCL Strand System, Prescon Corp.
TW = Taylor Woodrow Construction, Ltd.

[c]1 in. = 25.4 mm.

[d]The order for this reactor was recently cancelled.

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