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Feasibility Study of Prestressed Concrete Pressure Vessels for Coal Gasifiers

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OAK RIDGE NATIONAL LABORATORY
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SUMMARY AND CONCLUSIONS

The use of prestressed concrete pressure vessels (PCPVs) as gasifier vessels in commercial coal conversion systems has been examined. Applications considered were those where large, thick-walled steel vessels will be required; these are exemplified by gasifier vessels for the Synthane and HYGAS processes. In these gasifier vessel and other applications in commercial systems, the large heavy-walled steel vessels must be field fabricated, and, in many cases, the limits of present steel fabrication and field erection capabilities will be approached or exceeded. In addition, operational safety can become a pivotal issue because of the combined temperatures, pressures, and hostile environments presented by the contained media.

Prestressed concrete pressure vessels offer advantages of direct suitability for field erection, ease of fabrication, nonrestrictive limitations on size, use of readily available and relatively inexpensive materials, and inherent structural safety. Catastrophic failure of a PCPV is virtually impossible because of built-in structural redundancies which assure that failure will occur in a progressive and detectable manner.

Welding and postweld heat treatment problems are greatly reduced for PCPVs as compared to steel vessels because the steel pressure retaining member is a thin-walled structure. This also gives a large reduction in the quantity of high-alloy steel used. Similarly, inspection and examination during fabrication as well as in-service inspection problems are lessened for prestressed concrete in comparison to steel vessels.

Conceptual designs for commercial-sized Synthane and HYGAS vessels were developed and used as vehicles for assessment. Considered were existing knowledge and experience in the design, construction, and operation of PCPVs and special requirements associated with coal conversion system applications that differ from those of past practice.

The essential components of a PCPV and a steel vessel for a commercial HYGAS gasifier (250 × 10^9 Btu/day capacity) are shown in the central sketch of Fig. S.1. Other sketches in the figure compare expected cost trends and safety. Materials for the two HYGAS vessels are listed in Table S.1 along with cost estimates for both labor and material for vessel erection.

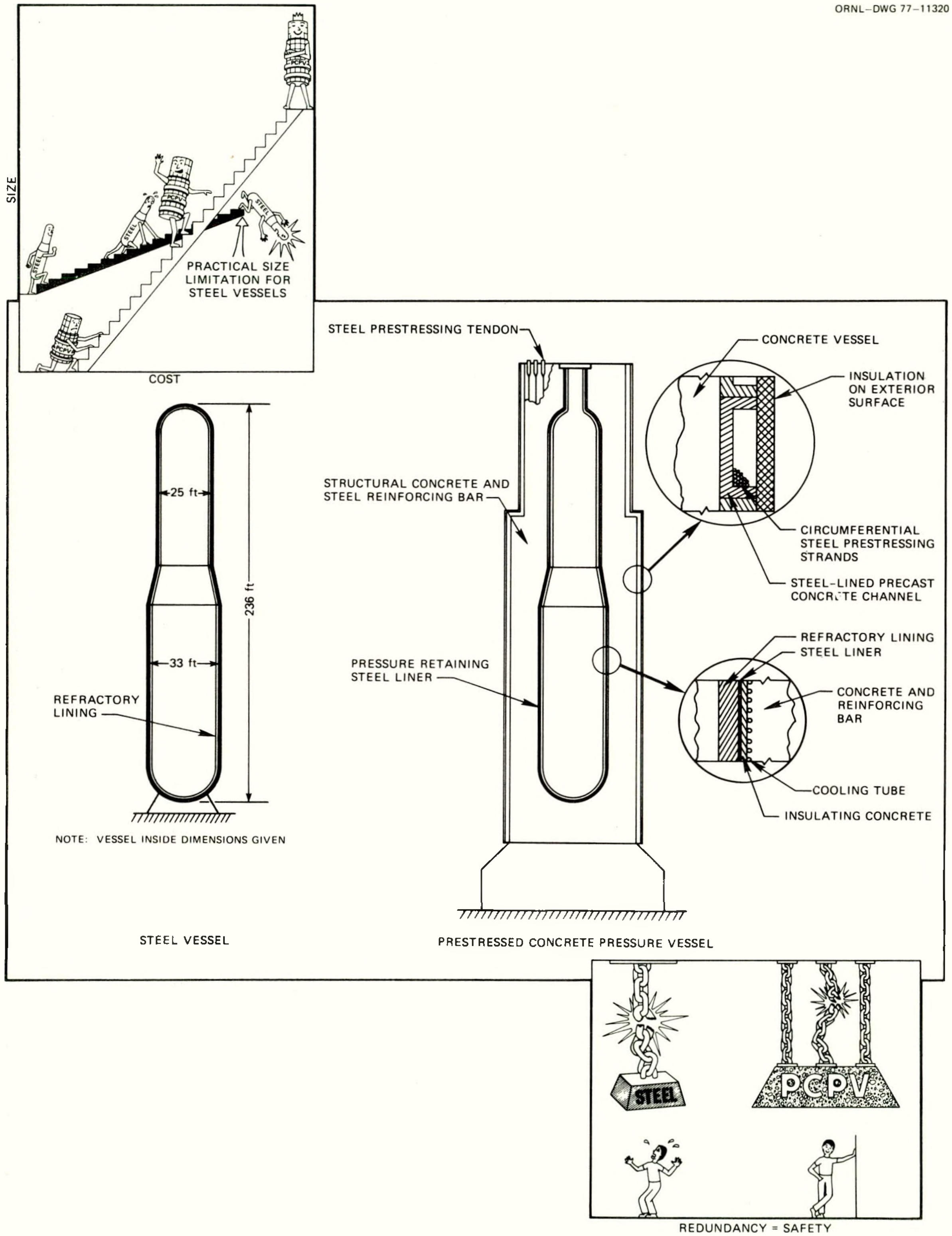

Fig. S.1. PCPV versus steel vessel (particular details for HYGAS gasifier).

Table S.1. Weights of materials and estimated costs for prestressed concrete and steel vessels for a HYGAS gasifier

Item	Weight (ton)	Estimated[a] cost ($ × 10^3)
Steel vessel		
Vessel	4,585	26,520
Flanges, cover plates, nozzles and overlay	191	4,380
Refractories and anchors	695	1,703
Support skirt	190	570
Totals	5,661	33,173
Prestressed concrete vessel		
Concrete	38,000	3,800
Reinforcing bars	1,698	4,750
Prestressing system		6,945
Wire winding machine (lease)		1,400
Steel liner and cladding	830	6,500
Forgings and overlay	20	470
Anchors, plates, flanges, closure plug, bearing rigs, toggle bolts	303	5,827
Refractories, external insulation and insulating concrete	1,257	2,608
Cooling system		926
Totals	44,808	33,226

[a]Includes labor and material for vessel erection.

The required steel is almost the same for both cases (5551 tons for the PCPV versus 5661 tons for the steel vessel); however, the steels for the PCPV are largely abundant low-cost carbon steels compared to the high-alloy material required for steel vessels. Total costs are essentially the same.

The major PCPV elements in Fig. S.1 are 1) the high-strength concrete and conventional steel reinforcing bars, 2) posttensioned prestressing steel, 3) a top head closure plug, 4) a vessel and penetration liner, 5) a thermal barrier system (insulating and cooling systems), and 6) an insulating system for the exterior surface. Design methods and rules for these elements have been codified on the basis of experience in design and practical application, and PCPV fabrication has been reduced to relatively common practice. Since PCPV advancements have been spearheaded by the nuclear industry, the existing structural design code (Section III, Division 2 of the ASME Code) was developed by drawing heavily on experience from nuclear applications.

Although the available rules and guidelines are directly applicable to most of the components of PCPVs for coal conversion systems, there are significant differences between these vessels and those for nuclear reactors. The major differences are in the details of the head regions and of the combined liner and thermal barrier system. Another factor is the presence of significant amounts of hydrogen in the cavity and throughout the concrete portion of a gasifier vessel.

The first difference is not highly significant because, in order to meet the requirements of the ASME Code, a model of the vessel must be tested to examine structural response and demonstrate acceptable behavior of untested designs. Testing is also required to help finalize the top-head closure design and to demonstrate its structural adequacy.

The proposed liner and thermal barrier system is notably different from the basic combination used in a nuclear reactor vessel. In the proposed design, the thermal barrier includes the refractories inside the liner and the coolant circuits, analogous to features of existing designs, but it also includes the insulating concrete outside the liner. Finally, the operating temperature of this liner is higher. Studies so far indicate that this liner and thermal barrier system should perform satisfactorily; however, a carefully executed experimental study must be carried out to demonstrate acceptable performance under projected service conditions. Satisfactory design and performance in this area are the keys to determining the feasibility of the concept and the acceptability for the intended use.

Environmental effects on structural materials in coal conversion systems are currently being studied. Differences in the studies required for PCPVs as compared to steel vessels may arise due to differences in the materials used. In either case, sufficient information on material behavior must be made available for rational, acceptable material selections and component design. For the PCPV, information is needed on hydrogen diffusivity to determine concentrations at locations removed from the vessel cavity and thus permit suitable choices of materials. Although available information does not suggest that there will be detrimental hydrogen effects on prestressing tendons, this aspect must be examined. Tensile testing of tendon materials in hydrogen-rich atmospheres is recommended. A mitigating factor here is the replaceability of the tendons, and, if necessary, periodic replacement could be included in the operating procedures.

The external insulation system proposed does not involve any novel features and will make use of commercially available materials. Therefore no insurmountable problems are expected to arise.

The major advantages of PCPVs over steel vessels for these examples are (1) greatly enhanced safety against catastrophic failure, (2) direct suitability for field fabrication, and (3) nonrestrictive limitations on size. As noted, financial considerations show roughly equivalent costs for the two types of vessels.

In summary, the studies described in this report lead to the tentative conclusion that the use of PCPVs for gasifier vessels is both technically and economically feasible. A follow-up program is outlined to provide technical support for this conclusion.

FEASIBILITY STUDY ON PRESTRESSED CONCRETE PRESSURE VESSELS FOR COAL GASIFIERS

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ABSTRACT

Prestressed concrete pressure vessels (PCPVs) have potential for use as gasifier vessels in commercial-sized coal conversion plants. This was established through a study of two conceptual designs. Problem areas are identified, and a test program is defined for concept verification and performance examination and demonstration. The gasifiers considered are for two-train plants based on the HYGAS and the Synthane processes. The plant output was assumed to be 500×10^9 Btu/day for the HYGAS process and 250×10^9 Btu/day for the Synthane process.

In preparing the designs, extensive use was made of existing developments for containment vessels. On the bases of the examinations made, it was concluded that the use of prestressed concrete gasifier vessels is both technically and economically feasible. A program of follow-up study is outlined to provide backup experimental data needed for support of this conclusion.

1. INTRODUCTION

A study of the feasibility of using prestressed concrete pressure vessels (PCPVs) for gasifier vessels in coal conversion systems was conducted under the sponsorship of ERDA, Division of Materials and Exploratory Research, Materials and Power Generation. The cognizant engineer was J. J. Forst, Components Branch. The specific objectives were to investigate the potential use of PCPVs for gasifier vessels in coal conversion systems, to identify major problems that may be encountered with construction, and to define and outline a test program, or programs, to demonstrate the acceptability of a PCPV for the intended purpose. Conceptual designs of pressure vessel and liner combinations for commercial-size plants were to be developed and studied for assessment and guidance. The major tasks under the study are summarized in Table 1.1.

Table 1.1. Feasibility study on prestressed concrete pressure vessels for coal gasifiers

Task	Description
1	Develop conceptual designs for commercial-size PCPVs. Two processes are to be selected.
2	Consider and evaluate various tendon arrangements, tendon strengths, preloads, and preloading techniques applicable to PCPVs subjected to the loading conditions of the above-mentioned processes.
3	Consider the effect of discontinuities (for example, vessel openings, vessel heads and their geometries, and vessel supports) on the load distributions and their magnitudes about these discontinuities and formulate, where possible, mathematical expressions of these loading conditions.
4	Evaluate refractories, leakproof liner materials for both cold and hot concepts, and alternate cooling schemes, and formulate expressions for temperature gradients, to the extent necessary for PCPV feasibility determinations, for the processes selected in Task 1.
5	From the above investigations, make a feasibility evaluation of using PCPVs for the processes of Task 1. In this evaluation, the contractor shall also identify problem areas and make corrective recommendations.
6	Define and outline test programs for feature and/or concept evaluation and performance verification. A test program(s) that will demonstrate the acceptability of a PCPV for the intended process is to be defined and outlined.
7	Prepare comparative cost analyses for steel and concrete vessels.

The impetus for consideration of PCPVs stems from at least two major factors. Steel gasifier vessels for commercial coal conversion plants are expected, in many cases, to be very large, heavy-walled structures that must be field fabricated. The requirements for such construction approach the limits of current steel production capability for plate thickness and related quality assurance, and field fabrication experience must be extended. In addition, there are important safety considerations associated with containment of the high-temperature, high-pressure process media, which present hostile environments for structural components.

Prestressed concrete pressure vessels offer a number of advantages which make them attractive for use in coal conversion plants where very large containment vessels are required. These advantages include field fabricability, nonrestrictive limitations on size, ease of fabrication, and use of readily available and relatively inexpensive materials. The vessels consist of relatively high-strength concrete which is reinforced by conventional reinforcing steel in conjunction with a posttensioning system consisting of vertical tendons and circumferential wire-strand windings. Conventional construction concepts are utilized for field fabrication of these structures, and the current technology required for design, analysis, and construction is advanced sufficiently to realistically consider concrete vessels for coal conversion process applications. PCPVs have been used for nearly two decades as containment structures, and, thus, relatively advanced concepts are available which permit the use of concrete pressure vessels for current nuclear reactors that operate at temperatures above 1033 K (1400°F) and pressures above 4.83 MPa (700 psi).

Catastrophic failure of a PCPV is virtually impossible because these vessels are designed so that failure will occur in a progressive and readily detectable manner. This does not suggest that such structures are impervious to failure or that steel vessels will fail catastrophically. However, low-alloy high-strength steel structures can fail catastrophically and, for extremely large vessels, with severe consequences.

Welding and postweld heat treatment (PWHT) problems in field fabrication are minimized for a PCPV as compared to a thick-walled steel vessel because the leaktight boundary in a PCPV is created by a thin steel liner. Although both welding and PWHT are generally important considerations, they can be particularly significant for the applications under discussion, since the Cr-Mo steels that are currently candidates for fabrication of the thick-walled steel pressure vessels are sensitive to PWHT temperature and time.

The process environments of coal conversion systems are harsh, and the behaviors of many structural steels in these environments are unknown. Most evidence to date suggests that alloys such as 2 1/4 Cr—1 Mo steel will be required to avoid problems with hydrogen attack. Further, a protective high-alloy cladding will be required on the inner wall. Since the bulk of the liner material in prospective PCPV designs will be loaded in compression under operating conditions, there is a possibility that corrosion will be minimized for these structures. In addition, enhanced economic feasibility would accrue in the PCPV case if only high-alloy structural materials are found acceptable for use in coal conversion system environments.

Inspection and examination present special problems in field erection. Again, these problems are lessened for the pressure boundary of a PCPV in comparison to a steel vessel. Similar advantages are realized in inservice inspection.

Background information for the feasibility study was obtained from published documents and discussions with personnel of a number of organizations, especially architect-engineering (AE) firms engaged in coal conversion system work. In particular, C. F. Braun and Co. supplied conceptual design information on commercial gasifier designs that was used directly in this study.

Gasifiers for the HYGAS and Synthane processes were selected for consideration. Two-train plants were assumed for the two processes; the plant output was 500×10^9 Btu/day for the HYGAS plant and 250×10^9 Btu/day for the Synthane plant. The design requirements for the vessels are given in Appendix A. These are based on information from the conceptual design studies by C. F. Braun and Co., with augmentations from other sources in the case of the Synthane gasifier vessel. The two C. F. Braun and Co. steel gasifier vessels are shown in Figs. 1.1 and 1.2; the design temperatures and pressures are also given. In keeping with the plant sizes, the HYGAS gasifier of Fig. 1.1 is designed for 250×10^9 Btu/day output, while the Synthane gasifier of Fig. 1.2 is designed for 125×10^9 Btu/day output. Both vessels are refractory-lined, and the inside dimensions in Fig. 1.1 are for the refractory. In the case of Fig. 1.2, the grid structure below the fluidized bed region is shown as an assembly of nested 60° conical members. However, this design was later changed to a single 45° cone. The process conditions used in the studies reported here are shown in Fig. 1.3 for the HYGAS gasifier and in Fig. 1.4 for the Synthane.

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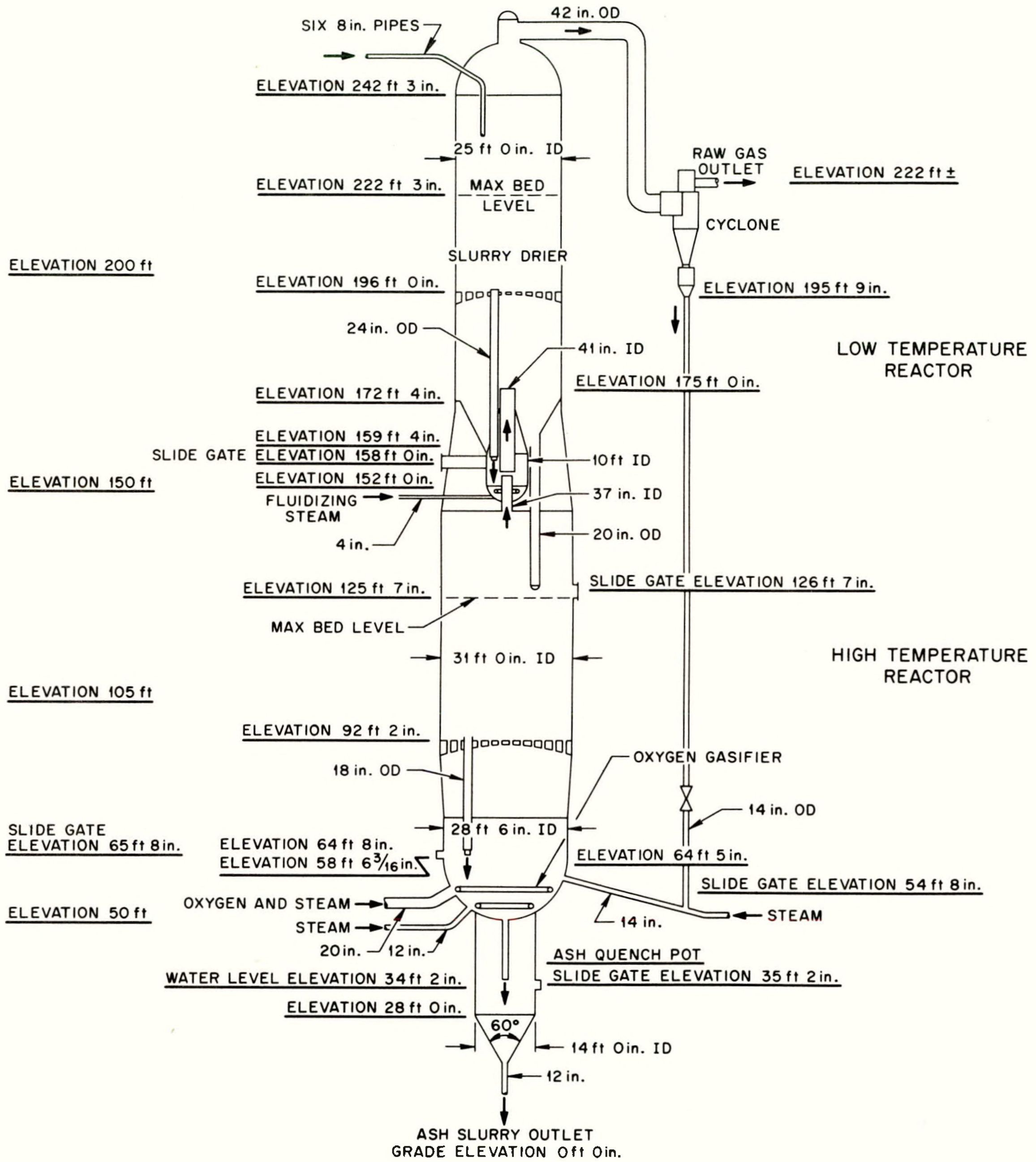

Fig. 1.1. C. F. Braun & Co. conceptual design of steel HYGAS gasifier vessel [design pressure: 8.96 MPa (1300 psig), design temperature: 589 K (600°F)].

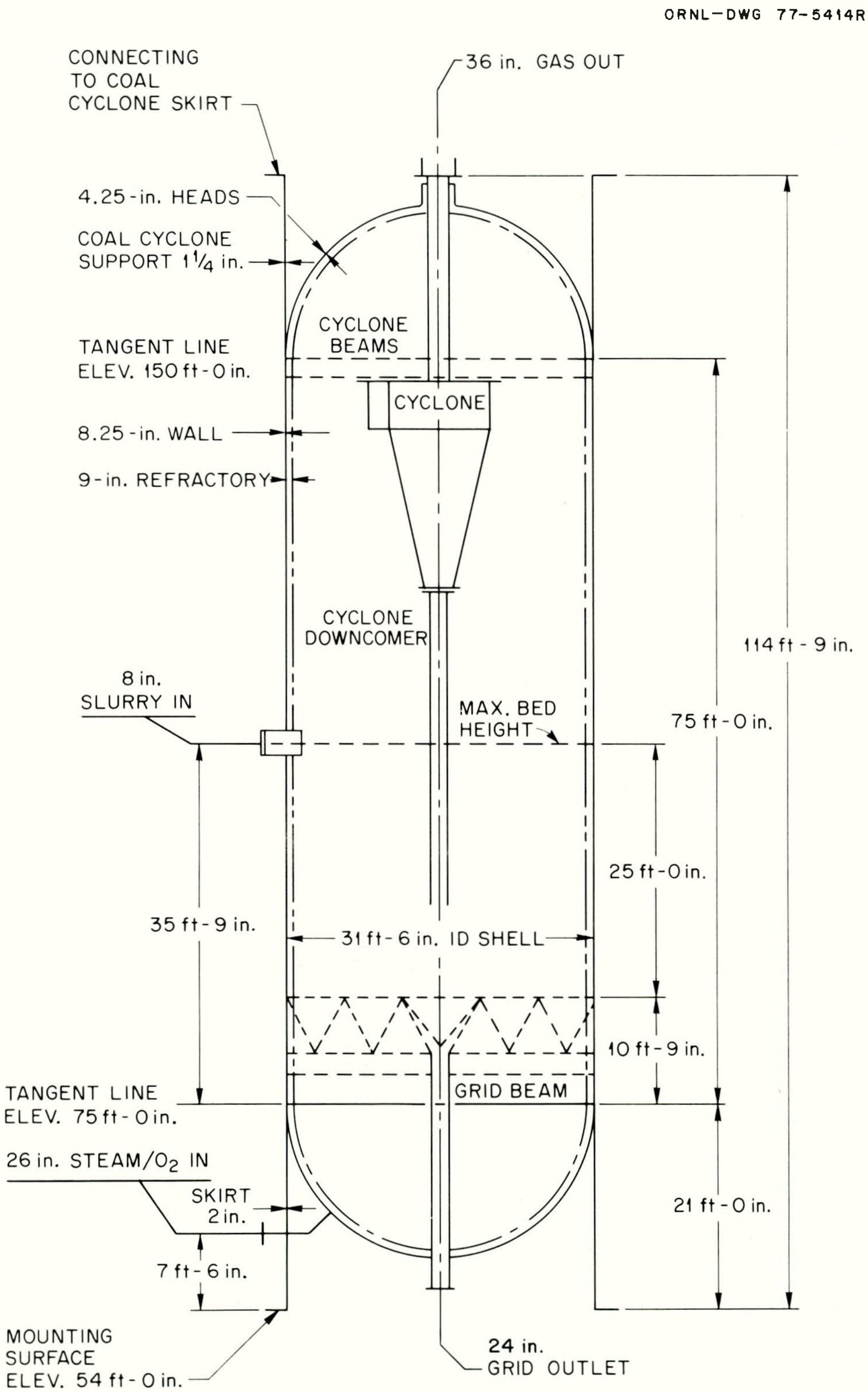

Fig. 1.2. C. F. Braun & Co. conceptual design of steel Synthane gasifier vessel [design pressure: 7.41 MPa (1075 psig), design temperature: 616 K (650°F)].

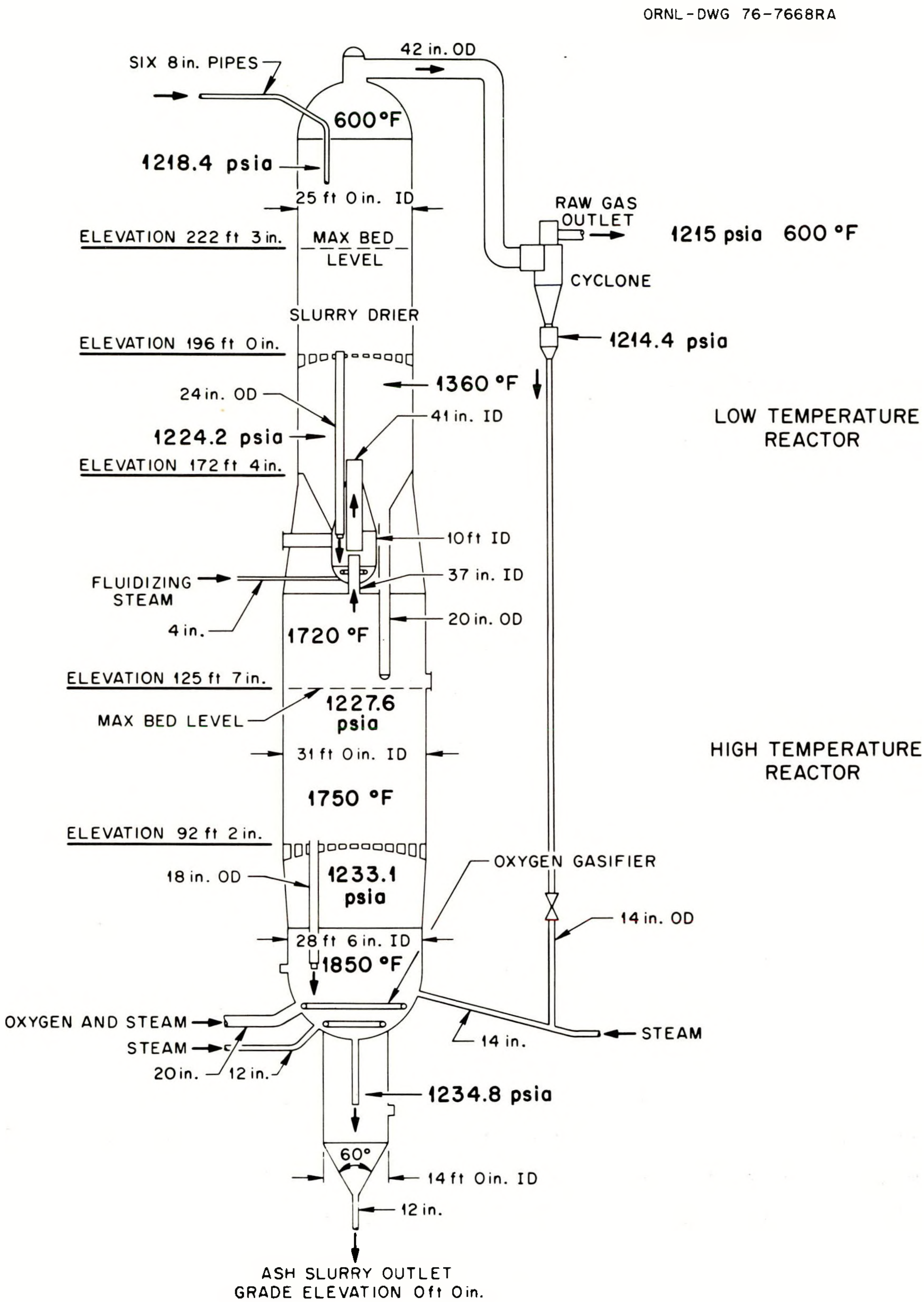

Fig. 1.3. Temperatures and pressures for HYGAS process.

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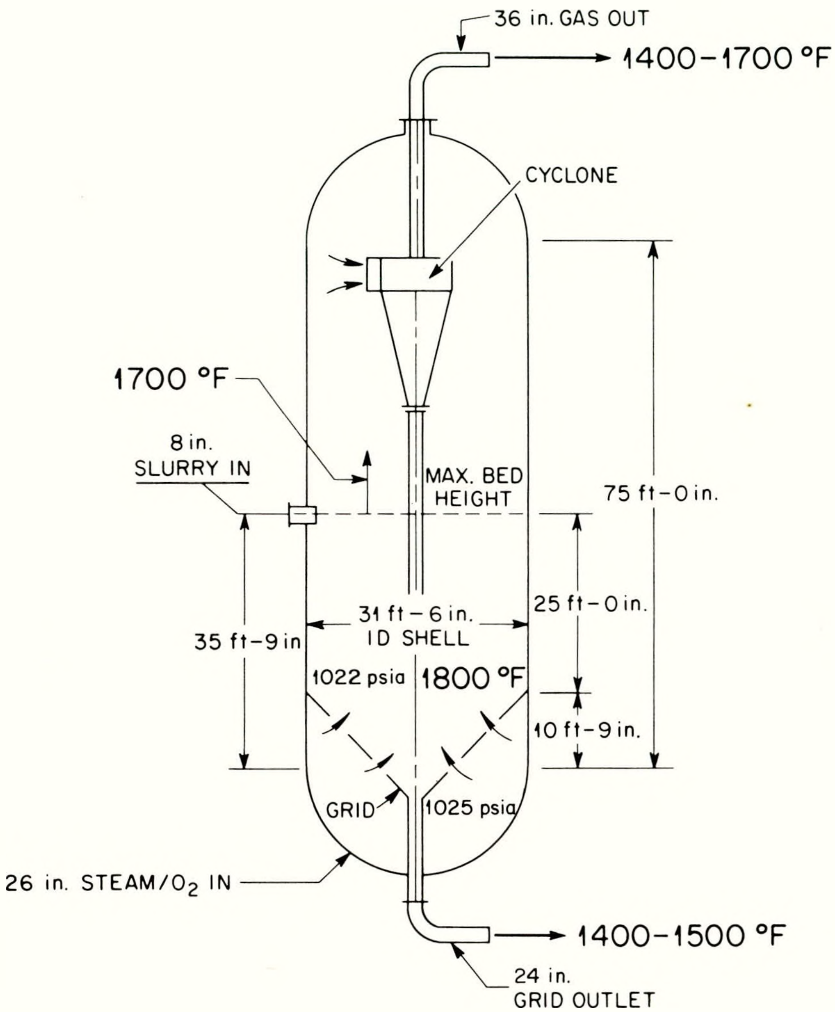

Fig. 1.4. Temperatures and pressures for Synthane process.

Not shown in the drawings are a number of the openings, or penetrations, in the two vessels. These openings, which include access and instrumentation penetrations, are very important to the designs. As described in Appendix A, the HYGAS vessel is projected to have about 50 connections 0.05 m (2 in.) in diameter for level, temperature, and pressure measurement and control, which will be located at all levels of the gasifier. Large openings envisioned include a 1.22-m-diam (4-ft) opening at the top, three 1.22-m-diam (4-ft) and two 0.91-m-diam (3-ft) openings at the side for general access, and four 0.91-m-diam (3-ft) openings for slide gate valve operator mechanisms. Penetration requirements for the Synthane vessel were assumed to correspond to those for the HYGAS vessel.

The conceptual design studies were limited to the pressure vessels; that is, the vessel internal structural members were not considered except as they would interact with the vessel. Connecting equipment was also omitted from consideration. Base supports for the vessels were included in the scope of the study, but foundation systems were not. The loadings addressed were those for normal operating and startup and shutdown conditions; seismic loadings were not considered.

In this report, background information on PCPVs is reviewed, conceptual designs developed for coal gasifiers are described, and, from the results presented, it is shown that PCPVs appear acceptable for the intended use. A program is outlined for experimental examination of key aspects related to feasibility and for concept development and design demonstration.

ACKNOWLEDGMENTS

A number of individuals, representing a range of expertise, participated in the studies conducted. The contributors and areas of contribution are as follows: C. B. Oland and J. P. Callahan, concrete pressure vessel design and analysis; D. W. Goodpasture and J. L. Lott, consultants, concrete vessel and prestressing system design; D. A. Canonico and R. K. Nanstad, structural material behavior and selection; K. W. Childs and W. K. Sartory, heat transfer analyses; A. E. Pasto and V. J. Tennery, refractories and insulating system for exterior of vessel; and M. L. Myers, cost estimates.

2. BACKGROUND INFORMATION ON PRESTRESSED CONCRETE PRESSURE VESSELS

J. P. Callahan*
D. W. Goodpasture†

Significant advances have been made in PCPV design and development during the past two decades, and a relatively sophisticated technology now exists. In particular, many advances have been made in the design of nuclear reactor containment vessels, with gas-cooled reactor vessel development being the most prominent. Much of this development can be of direct benefit in the design of coal gasifier vessels. Because of these factors, details of gas-cooled reactor PCPVs are reviewed in this chapter.

Gas-cooled nuclear power reactors, by the very nature of the coolant, call for very large pressure vessels in comparison with light-water types of reactors. As the size of pressure vessels increases, a point is reached where technological difficulties inherent in the construction of very large steel pressure vessels develop. Prestressed concrete pressure vessels have no similar technological size-related difficulties and offer the following advantages:

1. Vessel dimensions in combination with operating pressures remain virtually unrestricted, within ranges of interest.
2. Virtually any shape known to be advantageous from a structural and/or functional sense can be realized.
3. They exhibit unique and highly desirable performance features from the standpoint of operational safety.
4. They can be constructed using aggregates and cements available in the immediate region, and the steel elements used are relatively simple standard shapes which are easily transported to relatively inaccessible locations by conventional methods.

Thus, prestressed concrete pressure vessels offer potential advantages in performance, safety, and economy. This chapter will provide a

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*Engineering Technology Division.

†Consultant.

general description of the vessels and their functional parts and summarize the basic design considerations and supportive information.

General Description

The prestressed concrete pressure vessel is, in essence, a spaced steel structure, since its strength is derived from a multitude of linear steel elements composed of prestressing tendons and deformed reinforcing bars. The PCPV is designed to fail progressively only in small steps; consequently, a high degree of safety is realized.

The concept of a prestressed concrete pressure vessel originated in France over twenty years ago. The motivation for employing this type of vessel was the direct result of the size requirements for gas-cooled reactors and the existing limitations on fabricability of large relatively thick-walled steel vessels. Thus, the original design was a one-to-one substitution for a conventional steel vessel, an example of which is shown in Fig. 2.1. The relative size is indicated in the drawing by inclusion of a figure representing a man. As can be seen in Fig. 2.1, these vessels are generally massive, thick-walled, structures having flat heads.

The first two PCPVs, which were designed for French reactors, provided horizontally oriented (axis horizontal) rather than vertically oriented cylindrical cavities, such as that shown in Fig. 2.1 for the later French EDF-3 reactor. Other geometrical variations that have been employed include two vessels having spherical cavities, which were used for the British Wylfa Power Station and the more recent multicavity PCPV design shown in Fig. 2.2. These examples indicate the latitude that prestressed concrete structures offer the designer, in that there are virtually no restrictions of structural and system layout imposed by either shape or size limitations. The variety of sizes and basic shapes that have been employed for single-cavity geometries that are more applicable to coal gasifiers are shown in Fig. 2.3. (The operating pressures are given in psi.)

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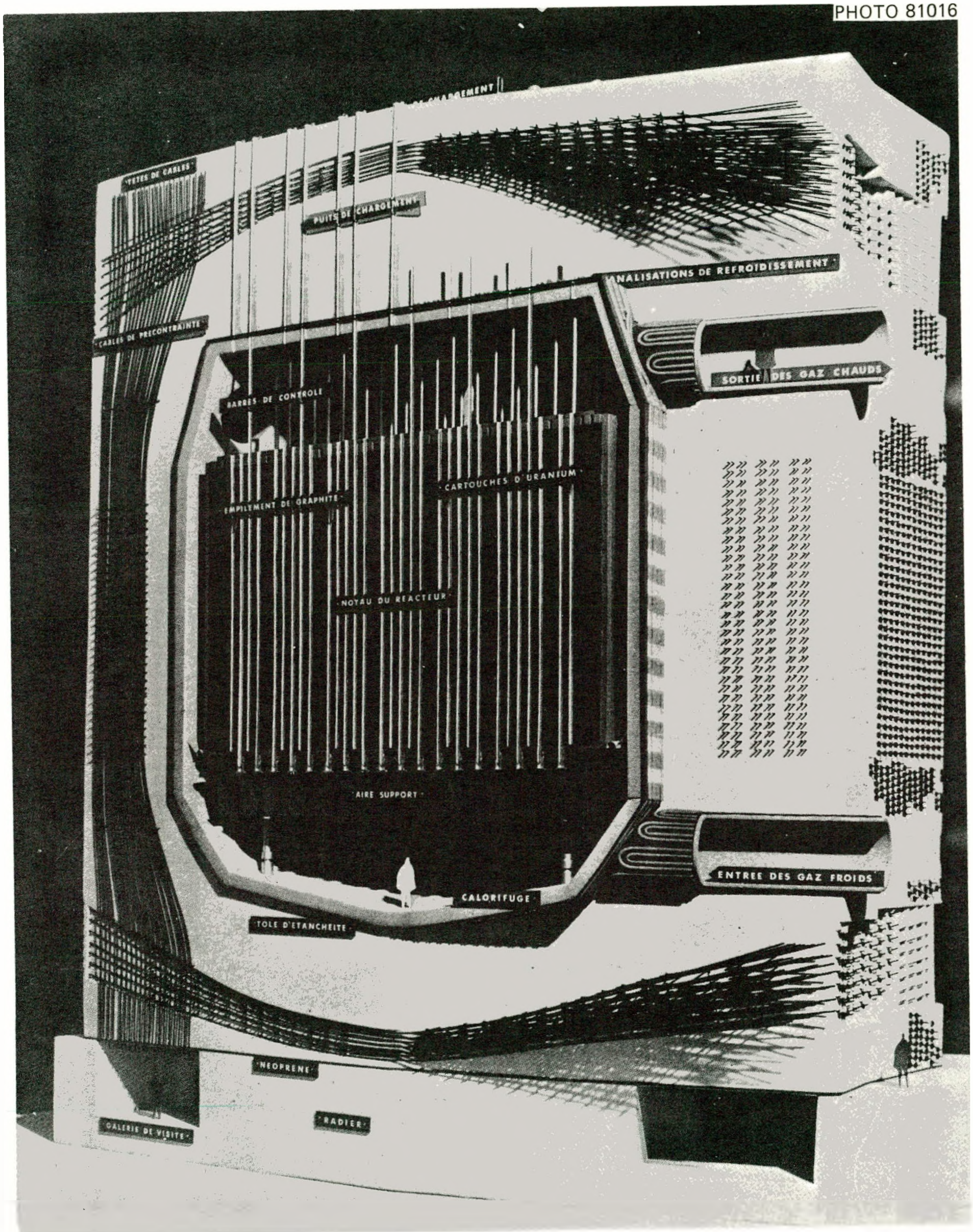

Fig. 2.1. Cross section of PCPV for the French EDF-3 gas-cooled reactor.

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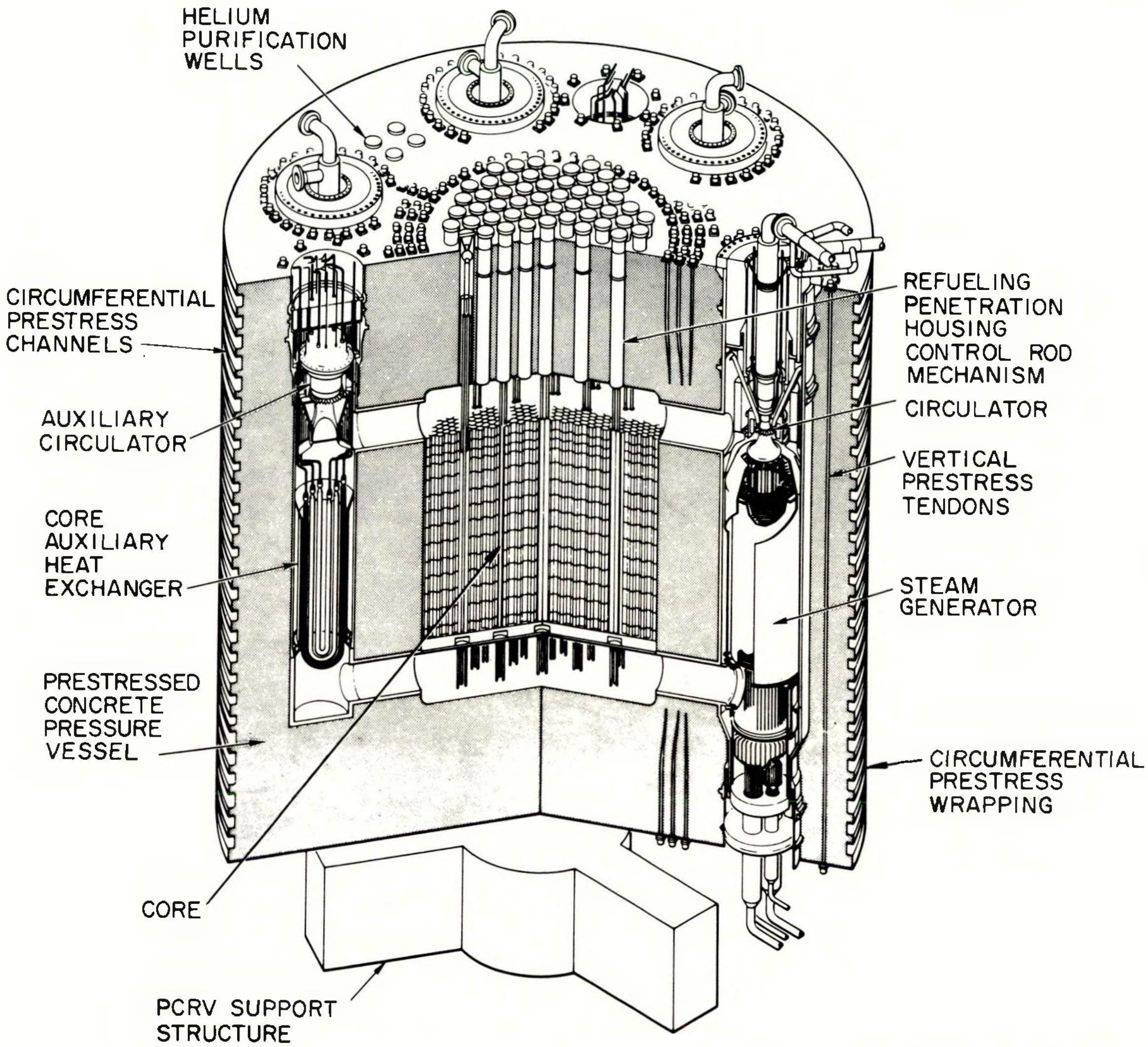

Fig. 2.2. HTGR with multicavity PCRV. Source: *Planning Guide for HTGR Safety and Safety-Related Research and Development*, ORNL-4968 (May 1974).

Liners

A continuous-welded steel liner is attached to the walls of the vessel cavity. This relatively flexible membrane serves to contain the process environment, while the concrete vessel supports the liner and provides resistance to the pressure loading. Figure 2.4 shows the cross

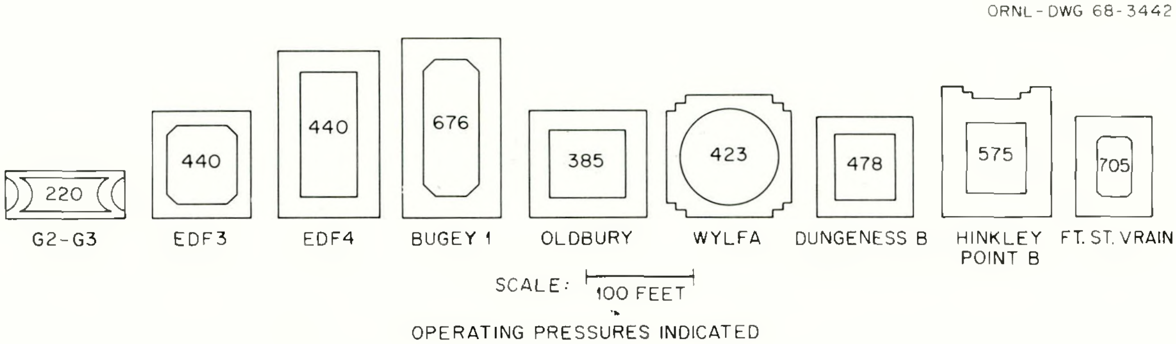

Fig. 2.3. Comparison of single cavity vessel shapes (100 ft = 30.48 m).

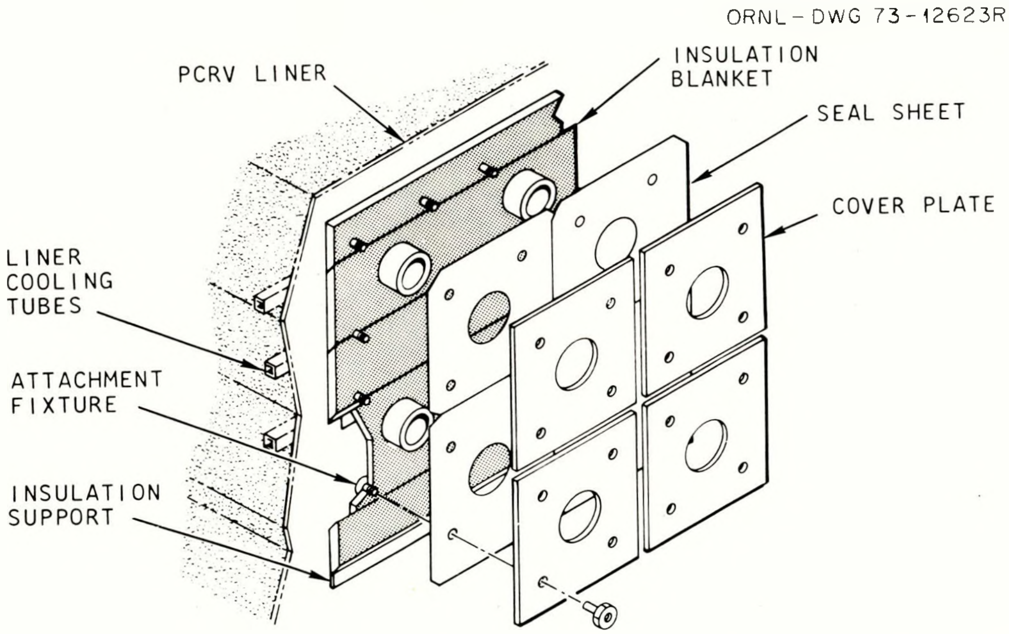

Fig. 2.4. PCRV liner and thermal barrier. Source: *Planning Guide for HTGR Safety and Safety-Related Research and Development*, ORNL-4968 (May 1974).

section of a typical liner and thermal protection system. This particular combination is designated as a cold-liner system, since it is designed to maintain a relatively low temperature of about 338 K (65°C) at the liner-concrete interface during normal operation. Water is circulated in cooling tubes, which may be either square or circular in cross section.

Several variations of the cold-liner design have been employed. Figure 2.4 shows a fibrous insulation blanket made of a ceramic material such as Kaowool, while many European vessels have employed a more expensive multi-plate metallic foil type of insulation. The cover plates and seal sheet are designed to prevent flow, or streaming, of gas through the insulation, but not to prevent gas from entering the insulation entirely. In certain regions of the vessel, particularly in the bottom, a block type of ceramic insulation may be used in layers with the blanket material to provide a more effective (but also more expensive) thermal barrier. A refractory type of insulation was used in some of the earliest French vessels; however, this practice was discontinued due to the dusting tendency of the material with a rapidly flowing gas. The insulated liner and cooling system is one of the most expensive elements of the PCRV, and every effort should be made to minimize its surface area to produce a cost-effective vessel. Liner thicknesses from about 2 to 4 cm (3/4 to 1 1/2 in.), which are based on requirements to contain the process environment and to bridge small voids in the concrete, provide a corrosion allowance and permit the liner to serve as the supported formwork for casting the concrete.

Penetrations

Collectively, the liner and penetrations form the gastight pressure boundary for the reactor primary coolant. The penetrations are, for the most part, backed by concrete. Also, cooling tubes are attached to the concrete side, and a thermal barrier is attached to the inner surface of some of the metallic components of the penetrations to prevent excessive heating. These openings in the PCPV are of special concern to the designer. First, penetrations are the source of stress concentration in the steel liner and in the concrete. Second, the penetration must be sealed to ensure a leaktight reactor vessel pressure boundary. Tan[1] describes the types of penetrations employed in single-cavity PCPVs. These penetrations go through the head regions and walls of the PCPV. Cylindrical single-cavity PCPVs are characterized by numerous small penetrations in the top head and fewer, but larger, penetrations in the bottom head. The number of penetrations through the cylindrical walls are held to a minimum, especially when wire or strand wound vessels are employed.

Penetrations in multicavity pressure vessels (Fig. 2.2) may be separated into two categories, namely, large and small penetrations, with the size description depending on whether or not the penetration is lined with insulation. Those penetrations which are lined with insulation are referred to hereinafter as large, and the remainder are small.

Penetrations in multicavity vessels are located in the top and bottom heads of the PCPV, as shown in Fig. 2.2. The penetrations may be grouped into three locations for multicavity PCPVs.[2] First, there are a large number of small penetrations in the top-head region which provide access for refueling, core instrumentation, and control rods. Second, there are large penetrations in the top head which are associated with the steam generator and auxiliary cooling loop cavities. Third, there are several penetrations through the bottom head below the steam generator cavities.

There are generally a few other small penetrations for pressure relief valves, instrumentation, etc., in addition to the penetrations already noted. Cylindrical shafts connect the main cavity to the steam generator and auxiliary cooling loop cavities. These shafts are 1.5 to 1.8 m (5 to 6 ft) in diameter and may be either horizontal or inclined.

All external penetrations must have a leaktight closure.[3] The penetration liners have a primary and secondary shear anchor.[2] Only the main cavity liner, the lower head portion of the auxiliary cavity liner, and the lower floor plate of the steam generator cavity liner are anchored to the concrete by welded studs, as for example in the proposed large multicavity PCPV for high-temperature gas-cooled reactors.[2]

Prestressing systems

A major change in the type of prestressing systems used for PCPVs has taken place in the past five years. Previously, circumferential tendons were housed in tubes 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, conventional 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 PCPV designs are of the wire- or strand-wound type. The vertical tendons (i.e., the tendons oriented parallel to the axis of the vessel) are still designed to be constructed of individual wires or strands housed in tubes and left ungrouted. An exception to this type of construction is the use of helical tendons in the British Oldbury, Hinkley Point B, and Hunterston B PCPVs.[1] All of these types of tendons are known as linear prestressing tendons to differentiate them from wire-winding tendons.

There are only a few prestressing systems which have been used in PCPVs. Table 2.1 lists the PCPVs 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 PCPV designs. Bangash[4] 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).

In the United States, there are five prestressing systems that have been approved by NRC,[5] and four of these have been used either in PCPVs

Table 2.1. Prestressing systems employed with recent PCPVs

Name	Prestressing system type[a] LPS	WW	System[b]	Diameter mm (in.)	Number per tendon
Fort St. Vrain	X	X	BBRV	6.4 (0.25) wires	169
Summit[c]	X		BBRV	6.4 (0.25) wires	169
		X	GA	15 (0.59) strand	
Hinkley Pt B	X		CCL	18 (0.71) strand	7
Hunterston B	X		CCL	18 (0.71) strand	7
Hartlepool	X			18 (0.71) strand	28
		X	TW	5 (0.192) wire	
Heysham A	X			18 (0.71) strand	28
		X	TW	5 (0.20) wire	
THTR Uentrop	X		BBRV	7 (0.28) wire	151
		X	BBRV		
HTR II	X		BBRV	7 (0.28) wire	163
		X	BBRV	9.5 (0.37) 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]The order for this reactor was recently cancelled.

or in containment vessels. These systems are listed below.

1. BBRV — 90, 169, 170, 186 wires of 6.4 mm (1/4 in.) diameter
   — 163 wires of 7 mm (0.28 in.) diameter
2. VSL — 55 strands
3. Stressteel S/H — 54 strands
4. Stressteel — 6 bars of 3.5 cm (1 3/8 in.) diameter
5. PCPV Strand-Wrap; General Atomic — 1.3 cm (1/2 in.) diameter

A more complete discussion of the systems is given in the following sections.

Strand and wire windings

As indicated earlier, strand or wire winding is used for the circumferential prestressing system for multicavity PCPVs. Some of the advantages were mentioned, but a more detailed list has been given by Burrow and Crowder in a paper[6] describing the design of PCPVs for the wire-winding system. The following list is taken from the Burrow–Crowder paper.

1. It is possible to provide very high intensities of prestress in a very compact arrangement.
2. There is no loss of efficiency in the tendon system arising from frictional losses.
3. The outside surface of the vessel can be kept free of the heavy anchorage ribs, or their equivalent, which are required to accommodate the tendon exits and anchorages when conventional tendons are used.
4. The walls of the concrete vessel are not congested by large concentrations of horizontal prestressing ducts, and it is therefore easier to construct the vessel and to maintain a consistently high quality in the placing and compaction of the concrete.
5. There is a considerable saving through the omission of anchorages and the reduction in the quantity of prestressing steel required to achieve a given prestress.
6. Since the winding bands provide a uniform radial force around the circumference of the vessel their effects can be represented simply and precisely in the analysis.

Linear prestressing

The various linear prestressing systems in present use for concrete reactor vessels and containments may be separated into three categories, namely, wire, strand and bar-type systems. The term *system* will be used herein to designate the type of tendon, the anchorage device, and the process of applying the prestress force. A short summary of 69 prestressing systems has been compiled by Tan,[1] and three of them were described and compared in detail. Of the three systems, only one — the BBRV system — has been used in the United States. Descriptions of these systems are given below.

The BBRV system utilizes a number of parallel wires to form a tendon. The anchorage of each wire consists of a cold-formed button head which bears on a plate at each end of the tendon. Theoretically, any number of wires may be grouped to form a tendon, but thus far 90, 163, 169, 170, and 186 wires per tendon have been used in the U.S. for PCPVs and containment vessels. The wire diameter is 6.4 mm (1/4 in.) in all cases except for the 163-wire tendon, which uses 7-mm-diam (0.28-in.) wire.

Strand systems utilize a number of strands to form a tendon. Seven-wire strand with a diameter of 12.7, 15.2, or 17.8 mm (0.50, 0.60, or 0.70 in.) has been used in most cases. The VSL and Stressteel S/H systems have been used in containment vessels in the U.S. Normally, all the strands in a tendon are stressed simultaneously; however, individual strands were stressed in the Hinkley Point B and the Hunterston B PCPVs in England.[7] This system was manufactured by CCP Systems Ltd. Two other systems have been considered for use in the U.S. but have not been reviewed or approved by the U.S. Nuclear Regulatory Commission.[5] These systems are the SEEE and Freyssinet, both of which were described in detail by Tan.[1]

The VSL system provides for a maximum of 55 strands per tendon with a guaranteed ultimate tensile strength (GUTS) of 10.1 MN (1,135 ton). The standard strand is 12.7 mm (1/2 in.) in diameter and meets the ASTM A416 specifications. Other types of strand, such as Dyform, can be furnished for the system. The anchorage consists of a two-piece split cone wedge type of anchor for each strand. The strand may be installed by the pull-through method, which allows the tendons to be built up after the concrete has been cast. A sheathing is positioned prior to concrete placement, and then, during the curing time, the strands are inserted into the sheathing. An alternative method of fabrication is to assemble the tendons in the sheathing prior to placement in the concrete forms. In either method the exact determination of the tendon length is unnecessary, since the stressing anchorages are fitted after the placement of concrete. The Stressteel S/H system uses 12.7-mm-diam (1/2 in.), 1.2-MN (135 ton) strands. The strands are anchored in groups of three by a three-piece conical wedge. The maximum total number of strands per tendon is 54, with a GUTS of 9.9 MN (1,112 ton). As in the VSL system, the tendon sheathing can be installed prior to concrete placement, and then the strands are inserted during the concrete-curing period. Since the wedges are attached in the field, exact precut tendon lengths are not required.

Bar systems utilize a number of high-tensile-strength bars grouped together to form a tendon. The only bar system that has been used for nuclear applications in the U.S. is the Stressteel system, which has a tendon composed of six 34.9-mm-diam (1.37 in.) bars. The ultimate capacity of this tendon is 6.35 MN (713 ton). The anchorage is composed of Howlett grip nuts, which are wedge-type anchors and can be used at any point along the length of the bar. The bars are made from an alloy steel conforming to ASTM specifications A322 and A29. There is no ASTM specification for the minimum mechanical and physical requirements for the bars after processing,[5] and therefore a specification was written by the Prestressed Concrete Institute.[8]

All of the linear prestressing systems discussed have provisions for retensioning the tendon or removal and replacement of the tendon if required. The tendon length does not have to be predetermined for any of the systems, except for the BBRV system where the wire tendons use the button head anchorage. Each of the systems has a provision for application of a corrosion protection coating during manufacture of the tendon. The wire and strand systems have the capability of being curved if required, whereas the bar system does not. The handling of tendons which are 30 m (100 ft) or so in length would be facilitated by the ability to store and ship them in a coiled configuration. Therefore, it would appear that the wire and strand systems have certain practical advantages over the bar systems for use in PCPVs.

PCPV Design Considerations

General design philosophy

The pressure vessel is loaded by the contained pressurized media and temperature-induced strains. The concrete is maintained in compression by the prestressing tendons for most loading conditions. The typical PCPV is furnished with penetrations, an impermeable liner, insulation, a cooling system, passive reinforcement, and a means for pressure relief.

The vessel should respond elastically to short-term loads, whereas longer term stresses and strains are affected by creep and shrinkage of the concrete, relaxation of tendons, and possibly fatigue. Beyond the elastic range, the response becomes more inelastic and nonlinear, but this would occur only under the most severe overpressure fault conditions. The structure would remain stable, but may experience permanent damage. When the vessel becomes unable to contain a higher internal pressure due to excessive leakage or more extreme structural failure, the ultimate load condition is reached.

Two different methods of design and analysis are needed. Service load conditions are of primary concern, but the various limit states must also be considered.

The analysis for service load conditions takes into account the time- and temperature-dependent characteristics of concrete and also considers the complexity of the geometry, the loading conditions, and the accuracy required. The analysis provides stresses in the concrete, the passive steel reinforcement, and the liner. For the prestress and dead loads at the end of construction (which may be the most severe loading condition of all) and for the initial test pressure, the concrete can be assumed to be 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 load conditions. Limited cracking may be acceptable provided that passive steel reinforcement is utilized and due regard is paid to stress redistribution and that the integrity and leaktightness of the liner are not impaired. Local stress concentrations should be assessed individually and very localized self-limiting stress concentrations may be ignored. The use of increased compressive strength of concrete under a multiaxial stress state is permissible in design, but this is an area of limited knowledge. Therefore, the loading condition should be short-term only, the minimum stress must be shown to be compressive beyond all reasonable doubt, and careful attention must be paid to the effects of increased strain on the stress distribution under subsequent reduced or reversed loading conditions. Maximum concrete strengths should be based on values obtained under sustained loading tests — not just short-term tests.

Five limit states can be identified.

1. The limit of instantaneous linear elastic response. This defines the upper end of the range in which the response remains essentially linear and reversible. Minor, localized cracking may occur.
2. The limit of instantaneous reversible overall response, which is similar to (1) but not linear.
3. The limit of permissible deformation (short or long term) is the largest deformation under which the internal system still functions. This limit usually applies to penetrations and other parts where close tolerances must be preserved.
4. The limit of liner defect stability corresponds to substantial leakage and subsequent crack pressurization.
5. The limit of the ultimate strength of the PCPV.

U.S. design philosophy

According to the Final Safety Analysis Report (FSAR) for the Fort St. Vrain power station,[9] the design and analysis of the PCPV (shown in Fig. 2.5) are aimed at satisfying two primary requirements, namely, (1) elastic response within certain allowable limits to operating, accident, and seismic loads and (2) a margin of safety against failure to account for design, construction, operating, and material deficiencies. The first design requirement is met by the use of working stress design concepts and the specification of certain allowable stresses.[9] The second design requirement is met by means of a limit design concept in two parts. The first limit condition is intended to give reasonable assurance of overall elastic behavior of the PCPV for certain overloads, whereas the second limit condition provides assurance against structural failure at a hypothetical pressure of 2.1 times the reference pressure.

Similarly, in Amendment 4 of the Preliminary Safety Analysis Report (PSAR) for the Delmarva Power and Light Company's Summit Power Station,[10] the design criteria includes serviceability and safety requirements. For serviceability, the PCPV should respond essentially elastically to short-term pressure changes up to the maximum cavity pressure (MCP). Also, leaktightness of the liner and closures is assured under normal and upset

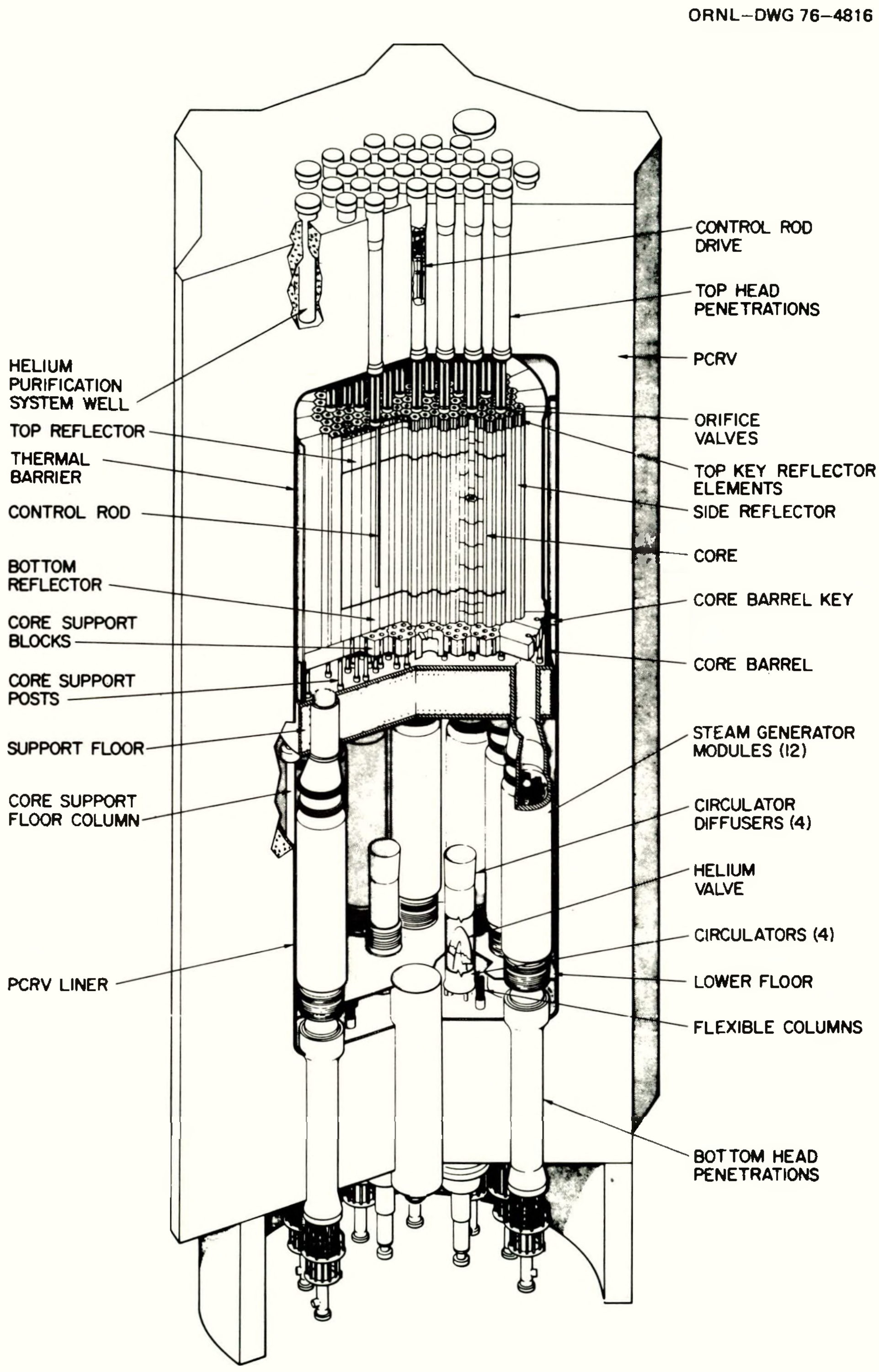

Fig. 2.5. Fort St. Vrain PCPV.

operating conditions throughout the design life of the PCPV. For safety, the structural integrity of the PCPV and its support must be assured during the design life, and it must have certain specified ultimate load capacities. Again, it is emphasized that the ultimate load design is based on a hypothetical overpressure condition. The PCPV structure is designed to resist an ultimate pressure of 2.0 MCP, and the top head is designed for 3.0 MCP, although the ASME Code requires only a minimum of 2.0 MCP for both regions.

The overall structural response of the PCPV is depicted by General Atomic as having three distinct regimes, as Fig. 2.6 indicates. Figure 2.7 is a more detailed representation for the Fort St. Vrain vessel in particular. The ordinate axis to the left illustrates the nomenclature utilized by General Atomic, whereas the ordinate axis at the right of the graph depicts the nomenclature used by Waters & Barrett.[12] This figure also indicates the effect of prestressing relaxation losses during the life of the vessel.

The specifications that govern the design of PCPVs for nuclear applications in the U.S. have recently been formalized. In April 1973, an

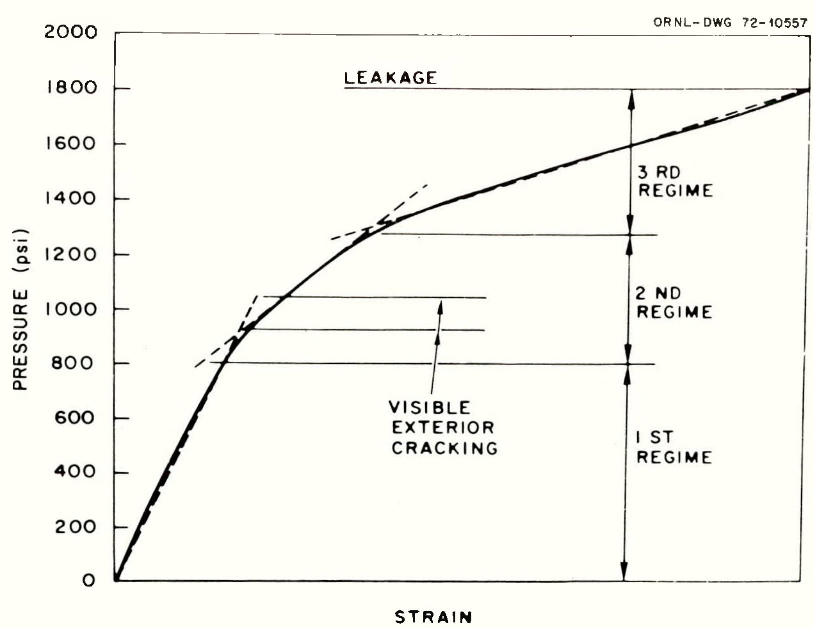

Fig. 2.6. PCRV structural response to increasing cavity pressure (1 MPa = 1450 psi).

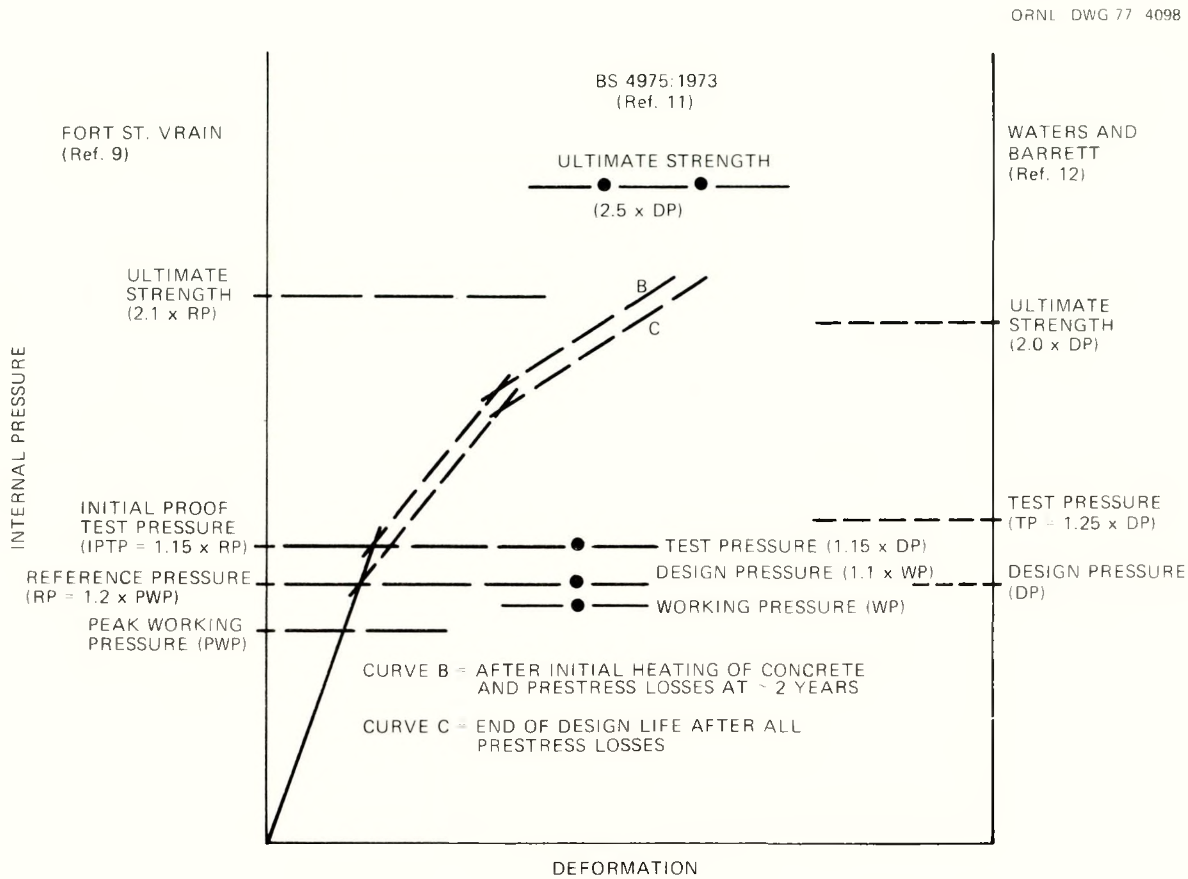

Fig. 2.7. Comparison of pressure loadings for PCPV.

initial version was issued for trial use and comment. Revisions were made, and a committee draft was reissued in May 1974. The final code version was published by the end of 1975[3] and was used as the source of information in the following paragraphs.

With regard to many aspects of the PCPV, the specification is very vague, while other aspects of the design are specified in great detail. Where the design of the PCPV is similar to more traditional structures, the code has many detailed requirements. The sections on splices for reinforcing steel (CB-3531, CB-4300) and on welding of the liner and attachments (CB-3840, CB-4500) are typical of the explicit requirements. However, in areas where the PCPV differs from the more traditional pressure vessel, the requirements are much less extensive. The sections on concrete (CB-3440, CB-3450, CB-4200) and prestressing steel (CB-3510, CB-3520, CB-4400) are good examples of the latter category. This lack of detail is understandable in the infancy of PCPVs, and it will certainly be corrected as experience in the design and behavior of PCPVs is achieved.

PCPV analysis methods

Elastic methods. Elastic methods for the design analysis of PCPVs fall into three major categories. The first two are utilized in the design process, whereas the third is used mainly to study the local effects of penetrations, etc.

1. Approximate methods

Approximate methods are important in the initial sizing of the vessel and consist of rather crude approximations of the vessel for the sake of simple analysis techniques. Bangash[4] has derived charts for the ultimate analysis of single-cavity, thick-walled capped cylinders. General Atomic[13] has developed equations to relate the results of axisymmetric analyses to the multicavity vessel presently being proposed. Sozen et al.[14] derived an empirical method for the design of the head region both with and without penetrations. The head will fail, with the failure surface taking the shape of a "cryptodome." The shape of the failure surface must be obtained by trial and error.

2. Two-dimensional computer programs

There are numerous computer programs utilizing the finite elements for solving plane strain and plane stress types of problems. The fundamental element originally used was the constant strain triangle, and the only difference between plane strain and stress formulations is the form of the elasticity matrix.[15] Later, higher order elements were developed, notably the triangular linear strain elements and rectangular elements developed by combining triangular elements in various ways.[15] Any of these programs (STRUDL, SAP, ELAS, NASTRAN, SAFE-2D, SAFE-PLANE, etc.) can be used for the analysis of PCPVs when only a planar section is to be investigated.

Also included under the umbrella of two-dimensional programs are the axisymmetric analyses. The main difference between the axisymmetric analysis and the planar analysis is the consideration of four stress and strain components for each element instead of three.[15] The fourth value arises because a radial deformation causes a circumferential strain. Many programs, such as BERSAFE, ELAS, MARC, NASTRAN, SAP, and SAFE-2D, are available for axisymmetrical analysis.

3. Three-dimensional computer programs

There are several computer programs available for the analysis of general three-dimensional elastic solids. There are at least twelve programs,[16] in addition to SAFE-3D,[17] that are available. SAFE-3D was developed by General Atomic for the analysis of the Fort St. Vrain PCPV and is available from the Argonne Code Center. The basic element in three-dimensional analysis is the constant strain tetrahedron. Improved elements have been developed and General Atomic has upgraded SAFE-3D by including a higher order tetrahedron with 12 degrees of freedom at each node. The improved version, which is called SAFE-SOLIDS, can handle loading conditions including linear temperature fields, nodal forces and moments, and surface pressures.[18]

Inelastic methods. There are numerous codes available[16] for the inelastic analysis of structures. Tables 2.2 and 2.3, which were taken from Ref. 16, illustrate the capabilities of ten two-dimensional and six general-purpose programs, respectively. These programs were developed for use with material properties for metals rather than for concrete. A short description of each of these codes is given in Ref. 16 along with a listing of more detailed references for each code.

General Atomic has developed SAFE-CRACK for the nonlinear analyses of PCPVs. The program includes two-dimensional elements and has provisions for the viscoelastic, cracking, and plastic analysis of plane or axisymmetric composite structures. The program permits finite-element idealization of the concrete, bonded steel reinforcement, steel liner, and prestressing steel. Concrete is characterized as an age- and temperature-dependent linear viscoelastic material, whereas steel is assumed to be elastic—perfectly plastic. Concrete cracking is controlled mainly by the tensile strain criterion accounting for the multiaxial stress-strain interactions. The von Mises yield criterion for steel is used. After cracking, an orthotropic stress-strain constitutive law is utilized.

Table 2.2. Two-dimensional structural codes

		EPAD	EPIC-II	H326	OASIS	PLAST2	SAAS III	ASAAS	DYNS	HONDO	SAMSON	ISA
Static		X	X	X	X	X	X	X			X	X
Dynamic									X	X	X	
Thermal Loading			X	X	X		X	X				
Temperature-Dependent Materials			X	X	X		X	X				
Axisymmetric Solids	Axisymmetric Loading	X	X	X	X	X	X	X	X	X	X	X
	Asymmetric Loading	X						X				
Geometric Nonlinearities			X						X	X		
Large Strains										X		
Material Model	Metal Plasticity	X	X	X	X	X	X	X		X	X	
	Soils/Rocks					X			X	X	X	
	Crushable Foams									X		
	Rubber Elasticity									X		

Table 2.3. General-purpose codes

			ANSYS	ASKA III-1	MARC	NASTRAN	NEPSAP	NONSAP
Static			X	X	X	X	X	X
Dynamic			X	X	X	X		X
Elements	1-D		X	X	X	X	X	X
	2-D		X	X	X	X	X	X
	3-D		X	X	X		X	X
	Shells	Shells of Revolution	X		X			
		Arbitrary	X		X		X	
Thermal Loading			X	X	X		X	
Temperature-Dependent Material Properties			X	X			X	
Geometric Nonlinearities			X		X	X	X	X
Large Strains					X		X	X
Material Model	Metal Plasticity		X	X	X		X	
	Soils/Rocks				X			

Time-dependent loadings for SAFE-CRACK include pressure loads, concentrated nodal forces, prestressing forces, and thermal loads.

Collapse mechanisms. It was stated earlier that a factor of safety against failure has been established for PCPVs. Nominally the factors are 2.0 for the barrel portion of the vessel and 3.0 for the top-head portion. In order to determine the ultimate strength of the vessel, several analytical methods have been developed.

The ultimate load capacity of the Fort St. Vrain PCPV was calculated by using the finite-element program, SAFE-CREEP,[9] and the results were reported as agreeing fairly well with those obtained from other methods of failure analysis. The program takes into account cracking of the concrete, but creep was not included in the failure analysis. Only the upper half of the PCPV was considered in the analysis, although the penetrations in the bottom head were fewer, but larger than those located in the top head.

An extensive research project[14,19] was conducted at the University of Illinois to investigate the type of failure occurring in the head region of the PCPV. The mode of shear failure of the head was described as a "cryptodome." There are three possible failure mechanisms with the cryptodome: (1) The section of concrete gets smaller near the center of the slab until the increasing radial and shear stresses cause a shear failure at the tip of the inclined diagonal tension crack. (2) The inclined crack may propagate to the center of the slab, carving out a plug like a segment of a sphere. A complete cryptodome is formed and may be able to resist a further increase of internal pressure. The dome fails due to a combination of high normal and shear stresses. (3) The horizontal support, which is provided by the circumferential prestressing, may be lost due to failure of the wire; the slab deflection increases due to yielding of the longitudinal wire and rotation of the slab at the edge. This type of failure was classified as a flexural failure. As a result of these tests, a proposed method for determining the shape and strength of the cryptodome was developed and has been subsequently used in the design of PCPV heads.

Comparison of Actual Vessel Behavior With Calculated Values

The completion of several nuclear power plants allows a comparison to be made between the calculated behavior and the actual behavior of the PCPV. The PCPVs at Oldbury and Wylfa have been completed, and reports of in-service behavior have been published.[20,21] The Fort St. Vrain PCPV has also been completed, and pressure and leakage tests were completed on August 18, 1971.[22] These reports indicate that the general patterns of strain development recorded for operating vessels compare favorably with predicted values. In the case of the Fort St. Vrain pressure test, generally good agreement was seen between the measured and predicted strains, particularly where the strain levels were large. The predicted values were computed using a three-dimensional finite-element elastic analysis (SAFE-3D).[17] It was noted that the response of the PCPV was essentially linear up to 6.69 MPa (970 psig), and the strain levels were stable during an 8-hr period when the pressure was held at 6.69 MPa (970 psig).

Penetrations

The design of penetrations is probably one of the most complex and least understood aspects of PCPV design. Steel vessel penetrations are designed using the straightforward ASME Section III, Division 1 and Section VIII area replacement rules. The principal objective of the PCPV 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 not to compromise the integrity of the overall structure. The achievement of this objective is more complicated in a PCPV, since the larger penetrations, in particular, disturb the idealized layout of the prestressing and give rise to variations in the stress field. Since the thick-walled concrete vessel penetrations are usually pressurized, the uniform field of compressive stress imposed by the prestress is significantly reduced beyond the amount resulting from vessel pressurization. Consequently, in the concrete vessel, the excess stress must be compensated for by using steel pads or nozzles or by transferring load 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.[23] In addition, considerable conventional steel reinforcement is employed to control and distribute any potential concrete cracking in the region immediately adjacent to the penetration.

Small isolated penetrations may have little disturbing influence on the normal stress field of a PCPV, but clusters of small penetrations can have even more influence than a single large penetration. Large penetrations or clusters of small penetrations cannot be readily reduced to axisymmetric geometries. Moreover, it is difficult to take into account the resulting localized stress variations, even when sophisticated three-dimensional analysis methods are employed as a design tool. This is especially true for penetrations in the vessel head regions. As a result, empirical relationships are frequently used, and experimentation may be required to provide convincing proof of the adequacy and soundness of the design.

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. It should also be kept in mind that, in general, penetration closure plugs which must be regularly removed and replaced for operational reasons are more prone to failure.[24]

Two closure plug designs that are particularly relevant to the proposed gasifier vessels are shown in Figs. 2.8 and 2.9. They consist of a composite concrete and steel plug employing a multiple strut or toggle hold-down (Fig. 2.8) and a multiplate steel plug employing a bolted flange type of hold-down (Fig. 2.9).

The highly desirable and well publicized structural response of a PCPV to overpressurization in a gradual and highly predictable manner can be achieved only if the penetration closures also respond in a manner consistent with this philosophy or if they have been demonstrated to be significantly overdesigned to preclude premature failure. Consequently, the structural behavior of the various types of closures must be evaluated according to whether their behavior is in concert with that of the PCPV if the full safety potential of the PCPV is to be realized.

A plug employing a bolted steel flange type of closure can be expected to behave like a steel vessel, while a composite plug coupled with a multiple toggle hold-down, such as is proposed for the top removable plug in the gasifiers, provides a closure that is structurally in harmony with the prestressed concrete vessel. Consequently, from a reliability and safety standpoint, the latter system appears to be preferable. Also, if the toggles are properly designed, the plug could conceivably serve as a pressure release valve, and depending upon the sealing technique employed, the plug might be designed to actually reseal upon the release of excess pressure.

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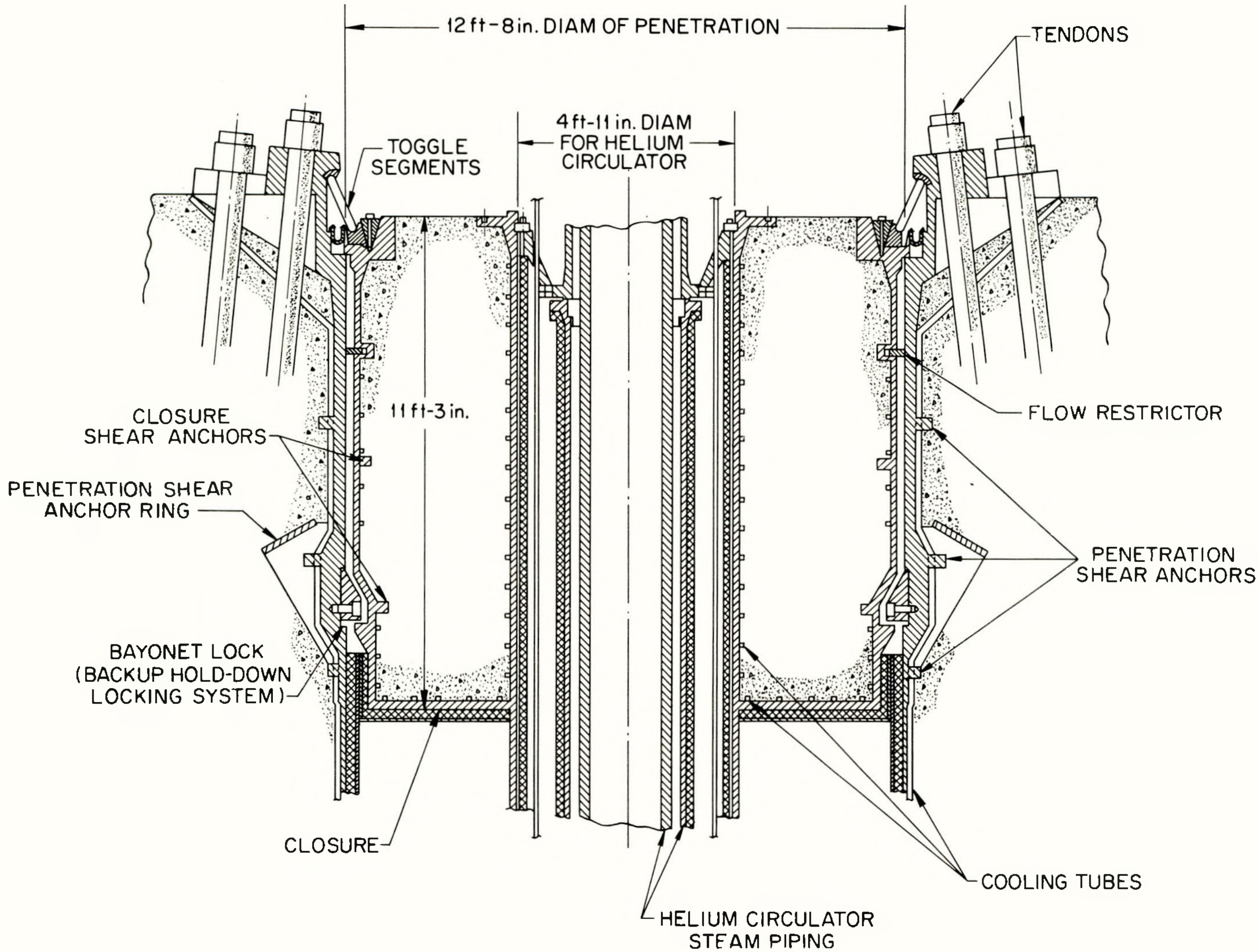

Fig. 2.8. Reinforced closure plug with toggle hold-down (1 ft = 0.305 m, 1 in. = 0.025 m).

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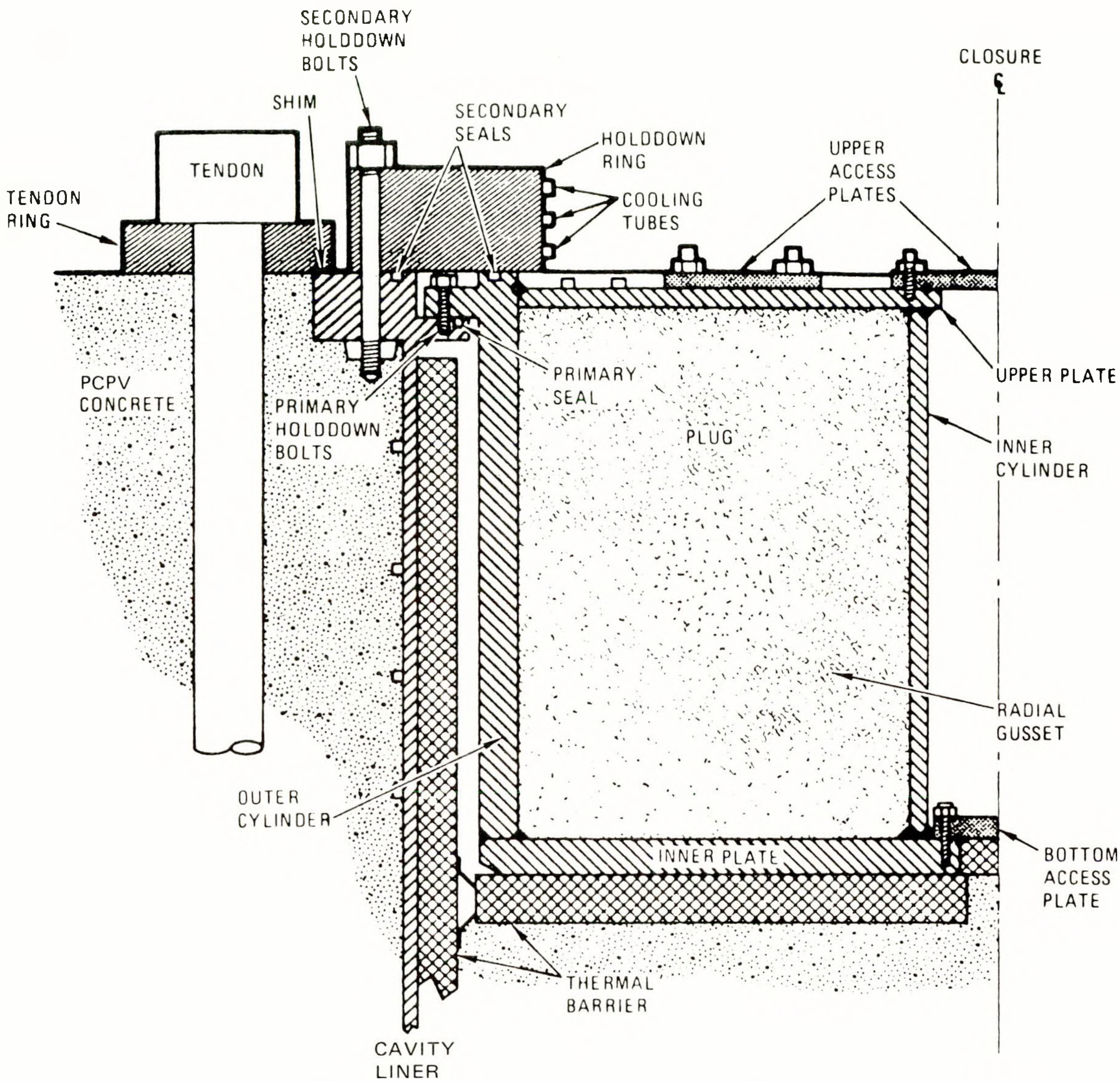

Fig. 2.9. Steel PCPV closure plug with bolted flange.

It should be pointed out that the size of the large closures and the possible seriousness of their failure means that the design must be subjected to critical review and should be backed by extensive verification. In situ pressure testing of the prototype plug is useful to check on design stresses providing the closure is suitably instrumented; however, it will not demonstrate the integrity of the unit.[24] Also, the stresses due to the combination of pressure and other design loadings must be considered. Thus, the usefulness of a pressure test on a component whose working stresses are due primarily to loads other than pressure may be quite limited. On the other hand, an overpressure test is usually easy to conduct, and if taken to a modest overpressure using adequate strain instrumentation, it does provide a demonstration of predicted vs measured behavior within the range of pressure employed.

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3. CONCEPTUAL DESIGNS OF PRESTRESSED CONCRETE PRESSURE VESSELS FOR SYNTHANE AND HYGAS GASIFIERS

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Background Description

It was noted in Chapter 2 that, in general practice, a prestressed concrete pressure vessel (PCPV) is constructed of relatively high-strength concrete and reinforced by a combination of conventional steel reinforcing bars and posttensioned prestressing steel. A steel liner creates the leaktight pressure boundary for the contained medium, or media, and transmits pressure-induced forces to the prestressed concrete structure.

Although there are no severe limitations on the geometry of PCPVs, significant geometrical complexities are not required in gasifier vessel applications for the Synthane and HYGAS systems. Circular cylindrical vessels are used, and the liner geometries for these single-cavity vessels are essentially the same as the geometries proposed by C. F. Braun and Co. for the Synthane and HYGAS commercial steel gasifier vessels (see Figs. 1.1 and 1.2).

The steel liner, in addition to serving as a leaktight pressure boundary, acts as internal formwork for concrete casting. For gasifier vessels, the liner is protected from the process temperature and the deleterious effects of the process media by the refractory lining systems. Cooling tubes near the inner surface of the structural concrete remove the heat that flows through the refractory and liner and maintain the temperature of the structural concrete within specified limits.

There are numerous penetrations through the PCPV heads and walls for process control, equipment removal, process piping, and inspection access. All of these penetrations are lined and sealed and complete the pressure boundary.

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In addition to acting in combination with the structural concrete to resist the internal process pressure, the prestressing steel gives the vessel adequate reserve strength to ensure that the structural concrete remains in compression during normal vessel operating conditions. The vertical prestressing steel used in the conceptual designs consists of individual tendon systems which extend from the top head of the vessel to the bottom head or to the base supports. The circumferential prestressing system consists of prestressing steel which is wrapped circumferentially around the vessels in discrete segments.

The structural materials selected for use in the conceptual designs of the two gasifiers are representative of the structural materials used to build prestressed concrete nuclear reactor vessels.

In preparing the conceptual designs, two alternatives were considered for the liner in each case — a hot-liner and a cold-liner concept. For the first alternative, the operating temperature of the liner is above the dew point of the process media to minimize corrosive attack from condensation, while, for the second, the operating temperature is about the same as the temperature at the inner surface of the structural concrete [∿339 K (150°F)]. The hot-liner concept was used as the reference design, since maintenance of the temperature of the liner above the dew point appears to be a most desirable feature. However, since all past operating experience with concrete vessels has involved the cold-liner system, it was selected as the backup design.

Synthane PCPV conceptual design

The conceptual design for a Synthane gasifier PCPV is illustrated in Figs. 3.1, 3.2, and 3.3. This is the reference design which features the hot-liner concept. The design pressure is 7.41 MPa (1075 psi); process temperatures were discussed in Chapter 1.

The inside diameter of the steel liner is 9.75 m (32 ft). A 0.30-m (12-in.) refractory lining protects the 0.03-m (1.25-in.) steel liner from the 1255 K (1800°F) process temperature. The PCPV rests on a base support which consists of four 52.5° concrete segments. The height of the vessel, excluding its supporting structural head, is 41.76 m (137 ft), and its outer diameter is 16.76 m (55 ft).

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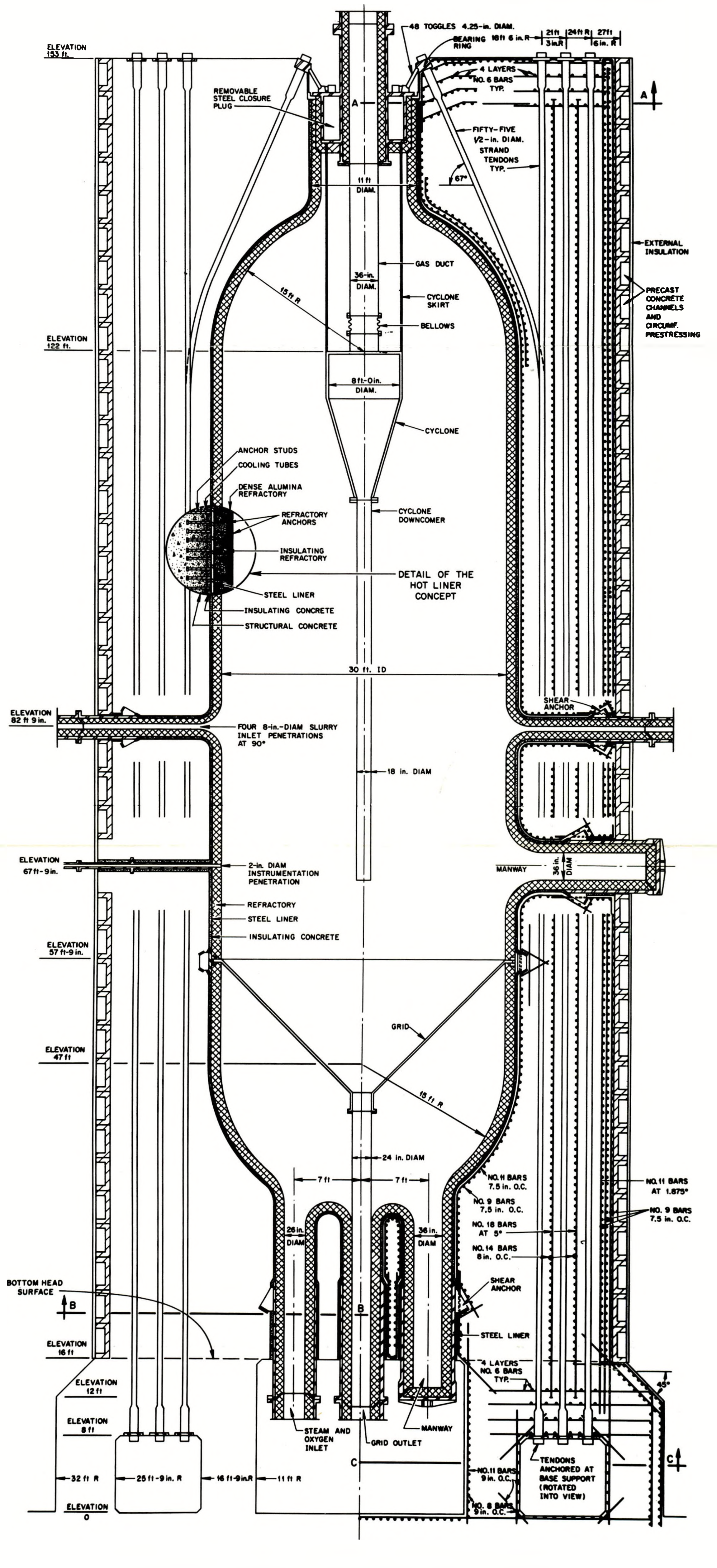

Fig. 3.1. Synthane gasifier PCPV cross section.

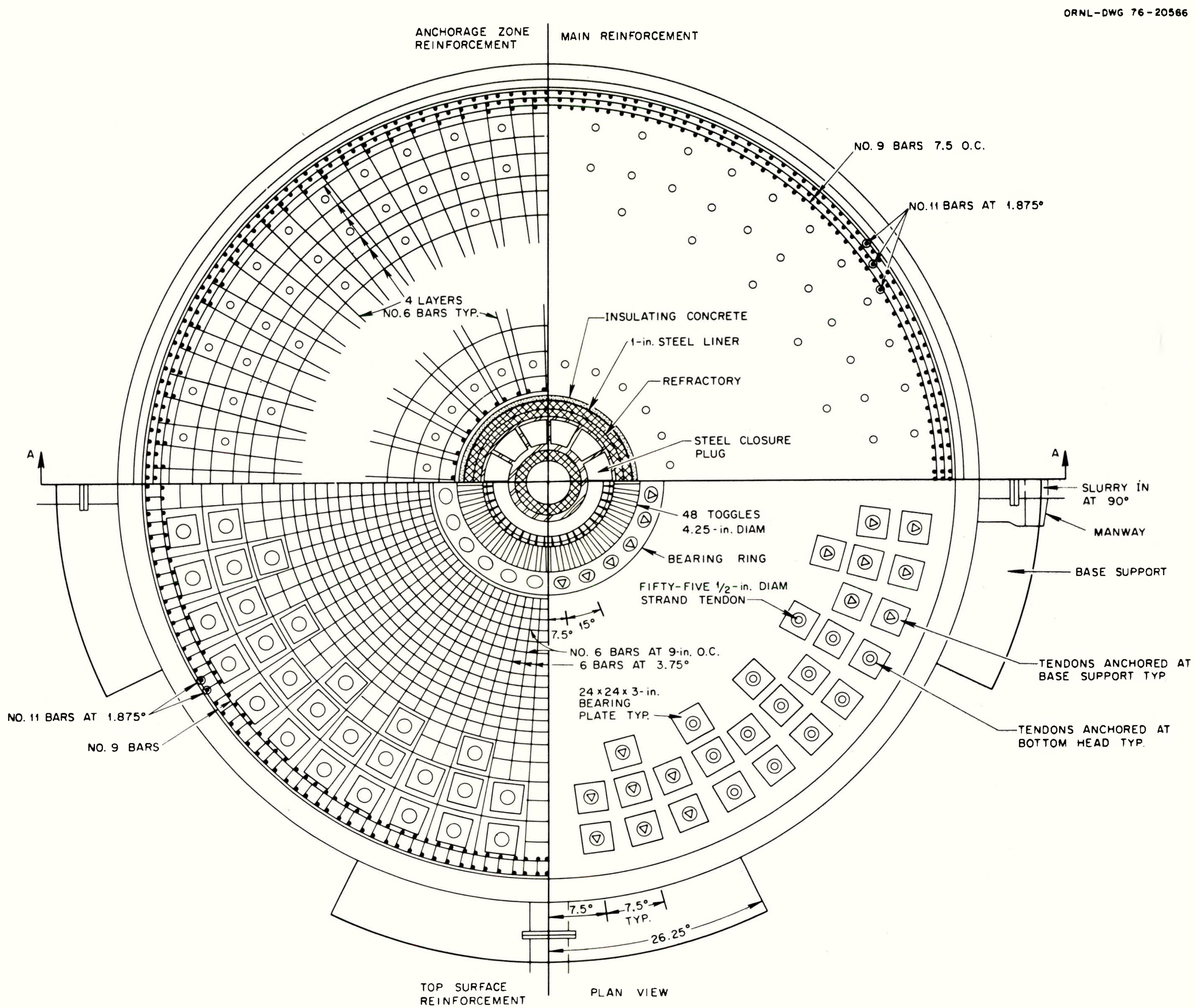

Fig. 3.2. Synthane gasifier PCPV, top view.

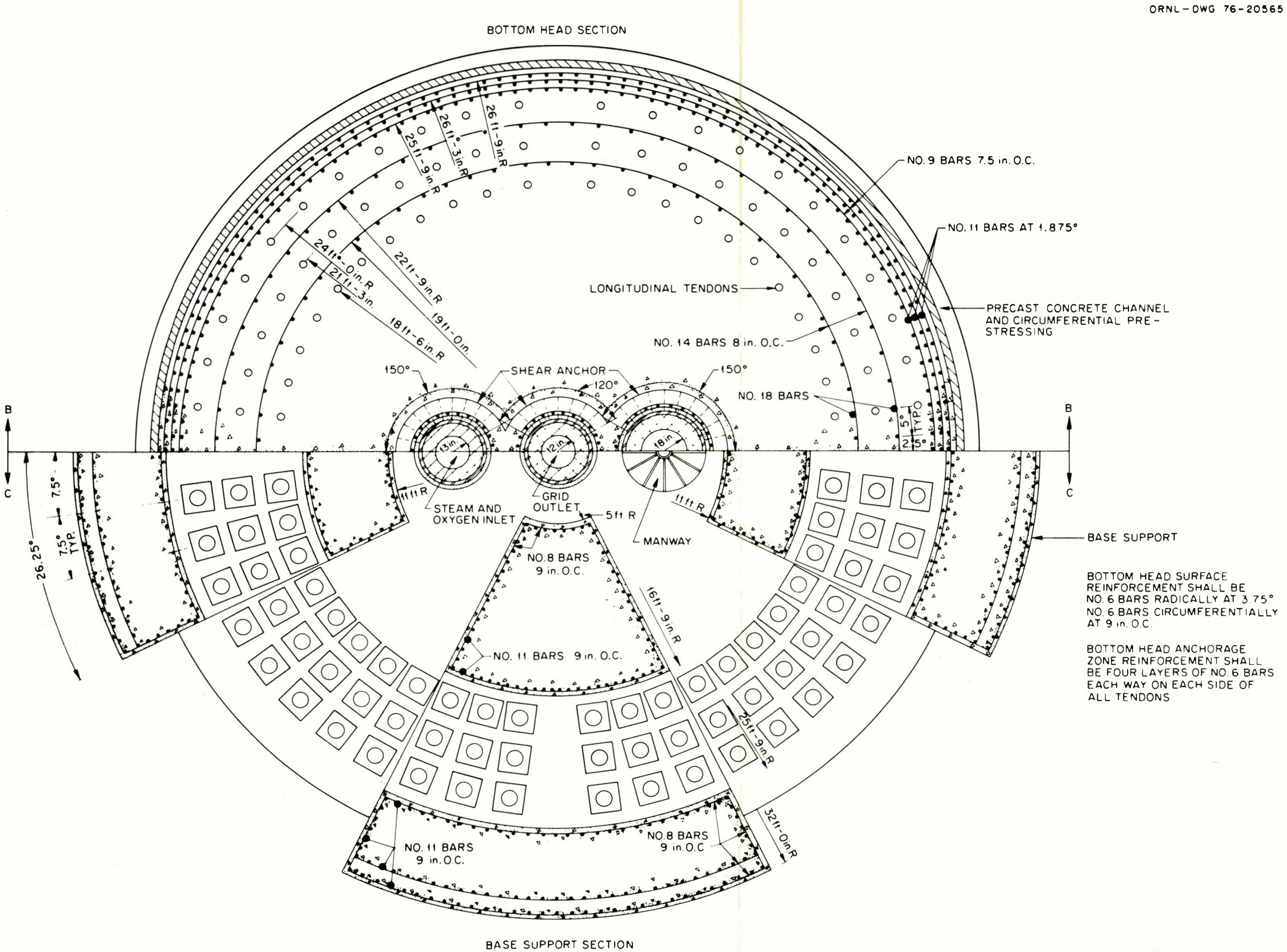

Fig. 3.3. Synthane gasifier PCPV, bottom view.

The lateral penetration design shown in Fig. 3.1 consists of a refractory-lined sleeve that extends through a circular radial opening in the concrete vessel. The sleeve is integrally attached to the liner and is actually an extension of this member. The pressure-tight seal for the larger penetration (manway) is provided by a cover plate, or blind flange, at the outside surface of the vessel. This design has a number of advantages, but other designs, such as the use of flanged openings directly in the liner, could be used if properly developed. This alternative design would help to minimize interior volume and eliminate collection pockets for process materials. The HYGAS vessel utilizes features of both designs.

Four 0.20-m-ID (8-in.) coal-slurry inlet penetrations are located at 90° intervals around the vessel at elevation 25.22 m (82.75 ft). These inlet penetrations are refractory lined. A typical 0.05-m-diam (2-in.) instrumentation penetration is shown at elevation 20.65 m (67.75 ft); additional instrumentation penetrations will be required at unspecified locations. The manway, which is also located at elevation 20.65 m (67.75 ft), provides access to the region of the vessel above the conical grid. A second manway through the bottom head of the concrete vessel permits access to the region below the grid. Both manways are refractory lined, with the inside lining diameters being 0.91 m (36 in.), and are sealed at the external surface of the concrete by removable steel cover plates. A 0.61-m-ID (24-in.) refractory-lined grid outlet penetration is provided through the bottom concrete head at the vessel centerline. A 0.66-m-ID (26-in.) refractory-lined steam and oxygen inlet penetration also extends through the bottom concrete head. All of these penetrations have steel liners, which derive their structural support from liner anchor studs and shear anchor assemblies that are embedded in the structural concrete.

The 2.74-m-ID (9-ft) penetration through the top concrete head is sealed by a removable steel closure plug, which also supports the cyclone and cyclone downcomer. The gas that enters the cyclone passes out of the gasifier through a 0.91-m-ID (36-in.) opening in the center of the steel plug. Forty-eight 0.11-m-diam (4.25-in.) toggles secure the steel plug during operation of the vessel. These toggles are designed for easy release to permit removal of the closure plug and attached cyclone, if required, for maintenance. The pressure loadings acting on the plug are transferred from the steel forging or bearing ring to toggles and finally to the adjacent 24 prestressing tendons. In addition to these 24 tendons, another 108 vertical prestressing tendons extend down from the top of the PCPV. Seventy-two tendons pass through the base supports, while 60 are anchored at the bottom vessel head. Four 15° segments contain no vertical tendons so that penetrations can be made through the vessel wall. It is also necessary, in the case of the horizontal manway, to curve the adjacent tendons slightly to allow for the opening and still provide the necessary prestress.

Each prestressing tendon consists of a cluster of fifty-five 1.27×10^{-2}-m-diam (0.5-in.) seven-wire strands. During construction, tendon ducts are positioned and cast into the concrete. After casting of the vessel has been completed, each tendon cluster is pulled through its duct and subsequently stressed to approximately 80% of its ultimate tensile strength. This tensioning is accomplished by using a 9.8-MN (1100-ton) capacity hydraulic jack [which weights 2500 kg (5000 lb)]. Each stressed tendon is anchored to a 0.61×0.61-m (24×24-in.) steel bearing plate, which distributes the prestress force to the supporting concrete. The concrete below each bearing plate has an embedded network of conventional nonprestressed reinforcing bars to control any possible cracking that might develop during tensioning or possible overpressure conditions.

The circumferential prestressing consists of posttensioned strand windings, which are confined and anchored in steel-lined precast concrete channels on the outside surface of the PCPV. These channels also serve as formwork during concrete casting operations and support the waterproofed external insulation. The vessel requires 1.1×10^{-3} m^2 (1.7 $in.^2$) of high-strength prestressing steel per 0.025 m (1 in.) of vessel height based on ultimate strength considerations. Each of the 37 channels contains 890 wraps of 0.95×10^{-2}-m-diam (0.375-in.) strand. The strand is tensioned initially to about seven-tenths of the ultimate tensile strength.

Bonded reinforcing steel is placed near the outside surface of the concrete walls in the circumferential and horizontal directions to provide crack control and added resistance to overpressurization.

A layer of insulating concrete is used between the steel liner and the structural concrete. Steel anchor studs, which are 0.38 m (15 in.) long and 0.02 m (0.75 in.) in diameter, are welded to the liner, extended through the insulating concrete, and are embedded in the structural concrete. These anchors are spaced on a 0.15-m (6-in.) square pitch. The refractory lining, which is placed on the inside of the steel liner, consists of a layer of insulating refractory and an inner layer of erosion-resistant dense alumina refractory, which is in direct contact with the process environment. Stainless steel anchors secure the refractory to the liner.

Finned tubes, through which cooling water is circulated to remove the excess heat, are located between the insulating concrete and structural concrete. The cooling tubes are arranged into two discrete circuits in which tubes extend halfway around the vessel. Every other tube is supplied from an independent coolant source, with each of the two sources being capable of providing adequate vessel cooling. Each circuit is equipped with devices to measure coolant flow rates and inlet and exit temperatures; these devices are monitored to detect vessel hot spots and possible cooling system malfunctions.

The structural materials associated with the Synthane PCPV and estimated weight for the various items are listed in Table 3.1.

Since the vessel is not contained in another structure or enclosure, the top of the PCPV must be protected from moisture and temperature extremes by an insulated and waterproofed roof system. It is anticipated that the roof will be a conventional-type structure which is supported by the PCPV and has no unique features; therefore, the details were not included in this study. The insulating material and an outer water-resistant protective coating to be installed on the outer lateral surfaces of the vessel are discussed in a later chapter.

Synthane PCPV backup design featuring a cold-liner concept

The overall characteristics of the PCPV backup design, which features a cold-liner concept, are similar to those shown in the reference design (Figs. 3.1, 3.2, and 3.3). The steel liner in this case is designed to operate at temperatures that are below the dew point of the process. The deformation behavior of the liner is elastic, except possibly in local regions such as around penetrations.

Table 3.1. Estimated weight of structural materials for Synthane PCPV

Item description	Estimated weight [kg × 10^3 (ton)]
Concrete	18,228 (20,051)
Refractory	548 (603)
Circumferential prestressing	
Prestressing steel	731 (822)
Precast concrete channel steel liners	70 (73)
Anchorage assemblies	13 (14)
Vertical prestressing	
Bearing plates	55 (60)
Conduits	66 (73)
Prestressing steel	237 (261)
Anchorage assemblies	23 (25)
Liner, shear anchors, anchor studs, cover plates	381 (420)
Steel closure, toggles, bearing ring, anchorage, cyclone	82 (91)
Reinforcing steel	807 (888)

The insulating concrete layer is not used between the liner and the structural concrete, and the cooling tubes are welded directly to the outside surface of the liner. Since the liner is exposed to approximately the same temperatures during operation as the structural concrete and since differences between liner and ambient temperatures remain small, the liner stresses are minimized. In addition, any forces exerted on the structural concrete by the liner due to the thermal loading (differential thermal expansion) would be much less than those exerted by the insulating concrete-liner combination for the hot-liner concept. Consequently, reductions can be made in the outside diameter of the concrete vessel, in the number of vertical prestressing tendons, and in the amount of bonded reinforcement when a cold-liner system is specified.

The outside diameter of the PCPV is reduced to 15.85 m (52 ft) for this design, but the height remains the same; that is, the top concrete head surface is 41.76 m (137 ft) above the bottom concrete head surface.

Since the sizes and locations of the process piping and access penetrations are specified for the Synthane process, the overall PCPV layout for a cold-liner system would be the same as for the reference design.

The circumferential prestressing system remains unchanged, but the number of vertical prestressing tendons is reduced from a total of 132 to 108. The vertical tendons have the same dimensions and general layout as the tendons described earlier. In this case, 72 tendons anchor the PCPV to the four base-support segments, and the remaining 36 are anchored at the bottom concrete head surface.

The steel liner in this instance is 0.025-m (1-in.) thick; during construction, it also serves as internal formwork for concrete casting operations. The steel anchor studs have the same dimensions as those for the hot liner and are attached in the same way. However, they are spaced on a 0.18-m (7-in.) square pitch for the cold liner. The refractory and refractory anchors are the same as for the hot-liner system.

The cooling tubes that are welded to the liner are spaced on 0.18-m (7-in.) centers. As for the hot liner, they are arranged to form two alternative and independent cooling systems. Overall, fewer circuits are required for the cold-liner system.

HYGAS PCPV conceptual design

The conceptual design for the HYGAS PCPV features the hot-liner concept and was sized for a design pressure of 8.96 MPa (1300 psi). A backup design using the cold-liner concept was also developed for this process, and it is discussed in the next section. This section will deal exclusively with the conceptual design based on the preferred hot-liner concept.

The PCPV conceptual design for the HYGAS process is shown in Figs. 3.4, 3.5, and 3.6. The inside diameter of the steel liner in the upper-vessel region (the cooler region) is 7.82 mm (25 ft 8 in.), while in the lower-vessel region it is 10.06 m (33 ft). The refractory in the upper-vessel region is 0.10-m (4-in.) thick and is generally 0.30-m (12-in.) thick in the hotter lower-vessel regions. A 0.03-m (1.25-in.) steel liner, the shape of which resembles the C. F. Braun steel vessel configuration, provides the pressure boundary. The PCPV rests on four 60° concrete support segments. The overall vessel height is 71.78 m (235 ft 6 in.). The two

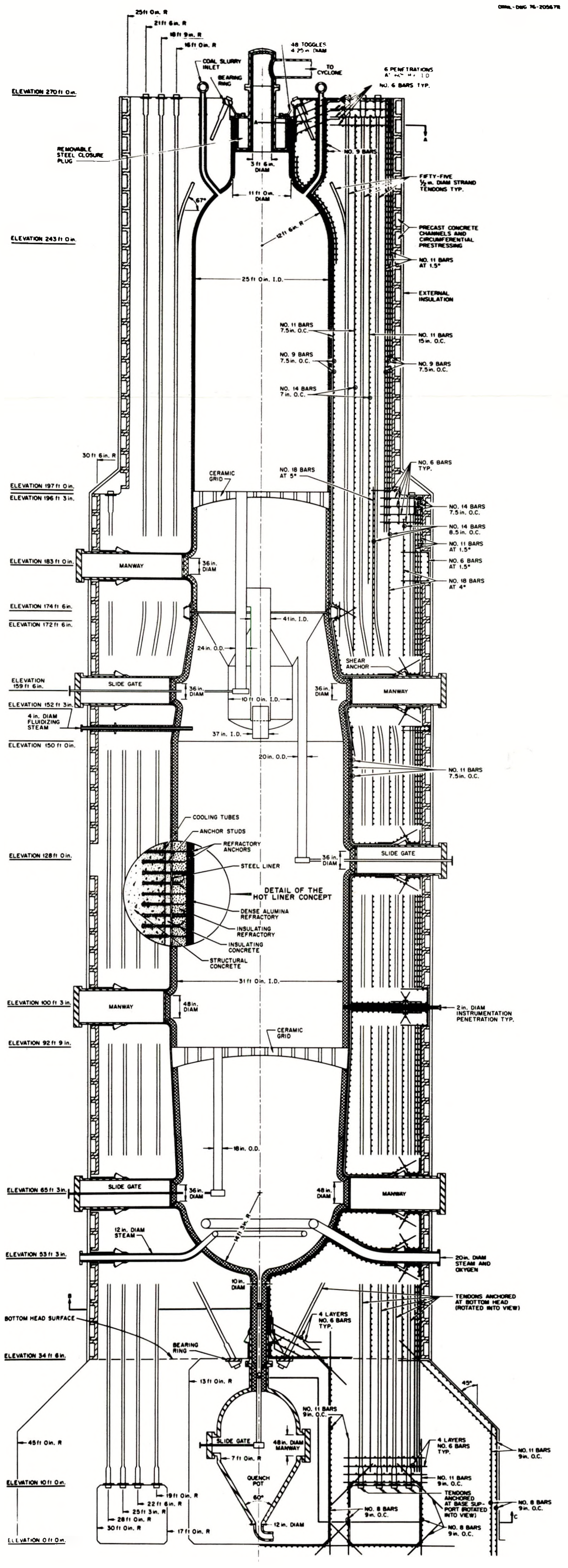

Fig. 3.4. HYGAS gasifier PCPV cross section.

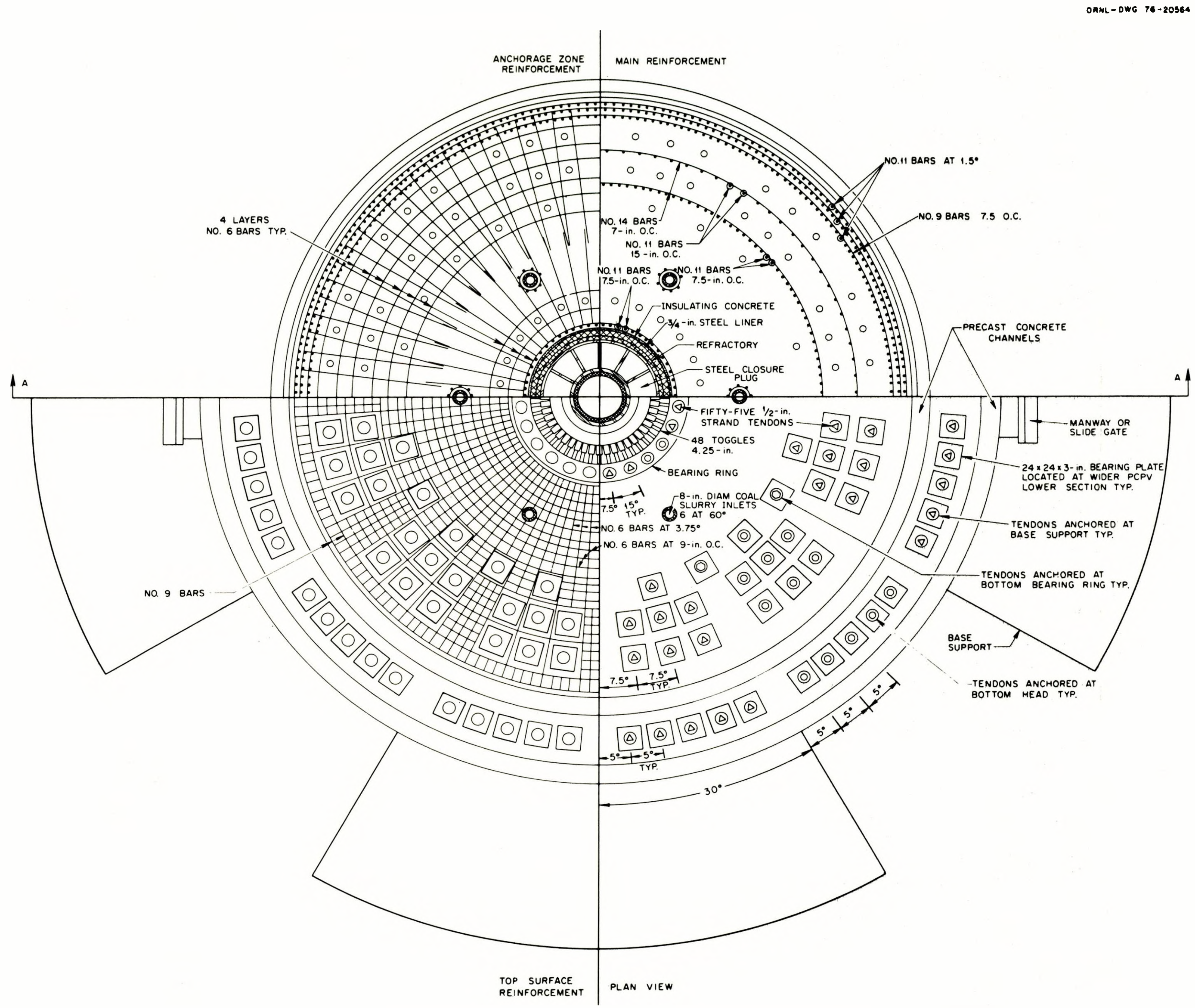

Fig. 3.5. HYGAS gasifier PCPV, top view.

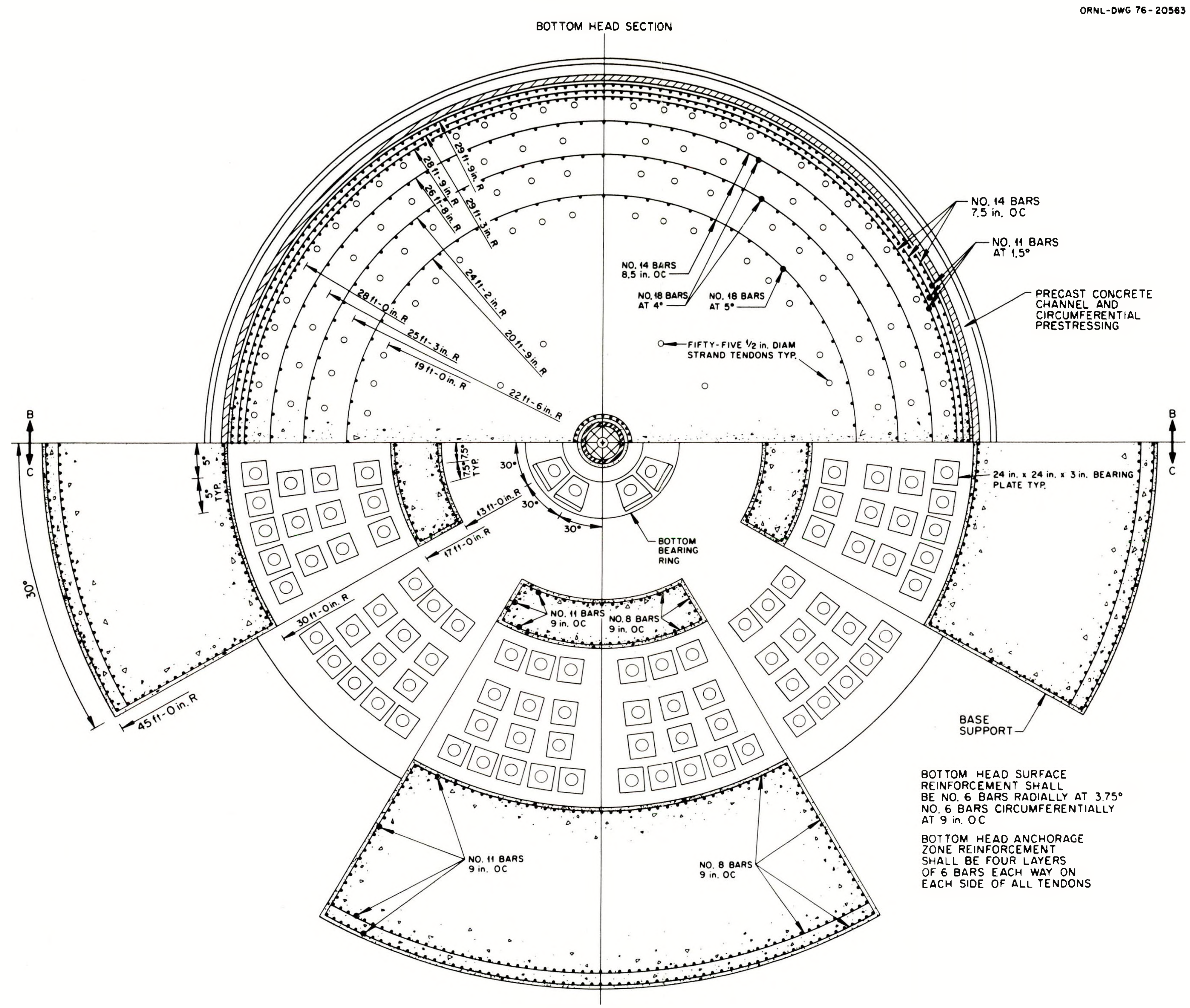

Fig. 3.6. HYGAS gasifier PCPV, bottom view.

cross sections with different inside diameters have different outside diameters. The top section, which extends 22.48 m (73 ft 9 in.) down from the top of the vessel, has an outside diameter of 15.4 m (50 ft), and the bottom section has an outside diameter of 18.6 m (61 ft).

Six 0.20-m-ID (8-in.) coal inlet penetrations pass through the top head. These penetrations are located at 60° intervals and pass between the inclined vertical prestressing tendons. A 0.10-m-ID (4-in.) fluidizing steam inlet penetration is located at elevation 46.71 m (152 ft 3 in.). As in the case of the Synthane PCPV, only one typical 0.05-m-diam (2-in.) instrumentation penetration is shown at elevation 30.56 m (100 ft 3 in.).

Three piping penetrations are located at elevation 16.23 m (53 ft 3 in.). The two penetrations shown in Fig. 3.4 are a 0.30-m-ID (12-in.) steam inlet and a 0.51-m-ID (20-in.) steam and oxygen inlet. The third penetration is a 0.36-m-ID (14-in.) steam inlet which links the cyclone dipleg to the gasifier. A 0.25-m-ID (10-in.) refractory-lined penetration is located at the vessel centerline in the bottom concrete head to allow char to pass from the gasifier to the attached quench pot.

The manway and slide gate penetrations specified by C. F. Braun have been included in the PCPV conceptual design. However, the elevations of these penetrations have been adjusted slightly to accommodate an efficient layout of the circumferential prestressing system. In contrast to the Synthane process PCPV, each penetration is insulated from the process temperatures by removable refractory-lined steel plates located at the intersection of the penetration liner and the cavity liner. The penetrations are sealed at the external surface of the vessel by removable steel cover plates. All the penetrations are of the same basic design described previously for the Synthane vessel.

The large-diameter penetration through the top head is sealed by the same type of removable steel closure plug described previously. The clear inside diameter of this access opening is 3.15 m (10 ft 4 in.). Process gases flow out of the vessel through a 1.07-m (3.5-ft) refractory-lined opening at the centerline of the steel closure plug. Forty-eight 0.11-m-diam (4.25-in.) toggles secure the removable steel closure plug and are easily released to permit removal of the plug during shutdown for repair. The transfer of loading from the plug to the prestressing tendons is the same as for the Synthane vessel.

In addition to the 24 vertical prestressing tendons which secure the removable steel closure plug, another 92 vertical prestressing tendons extend down from the top concrete head surface of the PCPV. Sixty prestressing tendons are anchored at the top of the large-diameter section and extend down through the concrete walls. One hundred twelve of the tendons are anchored at the base supports, 56 are anchored at the bottom concrete head surface, and 8 are anchored at the bearing ring near the center of the bottom concrete head surface. Four 10° segments contain no vertical tendons so that penetrations can be made through the vessel walls. However, in the case of the horizontal manway and slide gate penetrations, adjacent tendons must be curved slightly to clear the passages.

The vertical prestressing tendons and details of construction and tensioning are the same as for the Synthane vessel.

The circumferential prestressing consists of posttensioned strand windings located in steel-lined precast concrete channels on the outside surface of the PCPV as in the Synthane vessel application. From ultimate strength considerations, 1.06×10^{-3} m^2 (1.65 $in.^2$) of high-strength prestressing steel per 0.025 m (1 in.) of vessel height is required for the smaller upper part of the PCPV. The larger-diameter lower section requires 1.35×10^{-3} m^2 (2.1 $in.^2$) of high-strength prestressing steel per 0.025 m (1 in.) of vessel height. Approximately 810 strands are wrapped into each of the 21 precast concrete channels in the upper region of the vessel, and approximately 1360 strands are wrapped into each of the 36 precast concrete channels in the lower region of the vessel.

For this vessel as well as for the Synthane vessel, bonded reinforcing steel is placed in the concrete walls near the outside surface of the vessel in the circumferential and horizontal directions to provide concrete crack control and added resistance to overpressurization forces. The basic features of the hot-liner concept and vessel cooling system are the same as described previously for the Synthane PCPV. A waterproof roof system and insulation on the outer lateral surface of the vessel are also employed in this design. The insulation and outer protective coating will be discussed in a later chapter.

A list of structural materials associated with the HYGAS PCPV and weight estimates for the various items is given in Table 3.2.

Table 3.2. Estimated weight of structural materials for HYGAS PCPV

Item description	Estimated weight [kg × 10^3 (ton)]
Concrete	34,864 (38,350)
Refractory	1259 (1385)
Circumferential prestressing	
Prestressing steel	1575 (1732)
Precast concrete channel steel liners	81 (89)
Anchorage assemblies	20 (22)
Vertical prestressing	
Bearing plates	71 (78)
Conduits	148 (163)
Prestressing steel	530 (583)
Anchorage assemblies	30 (33)
Liner, shear anchors, anchor studs, cover plates	982 (1082)
Steel closure, toggles, bearing ring, anchorages	64 (71)
Reinforcing steel	1543 (1698)

HYGAS PCPV backup design featuring a cold-liner concept

The cold-liner concept for the HYGAS PCPV is as described in connection with the Synthane vessel, and corresponding savings in amounts of structural concrete, prestressing steel, bonded reinforcement, and liner cooling circuits are realized. The inside diameters of the steel liner, which is 2.54 × 10^{-2}-m (1-in.) thick in this case, are unchanged from the hot-liner dimensions, but the refractory thickness is increased to 0.15 m (6 in.) in the upper region of the vessel. The thickness remains 0.30 m (12 in.) in the lower region of the vessel. The outside diameter of the concrete in the upper vessel region is reduced to 14.33 m (47 ft), and the diameter in the lower vessel region is reduced to 17.98 (59 ft). From ultimate strength considerations, 1.08 × 10^{-3} m^2 (1.67 in.^{2}) of high-strength prestressing steel per 0.025 m (1 in.) of vessel height is required for the smaller-diameter upper part of the PCPV. The requirement for the larger-diameter lower section is unchanged.

The vertical prestressing consists of 160 prestressing tendons instead of 176 used in the hot-liner case. In addition to the 24 tendons which secure the removable closure at the top of the vessel, an additional 80 tendons are anchored at the top concrete head surface, and the remaining 56 are anchored at the top of the larger-diameter vessel section. These tendons extend down through the vessel walls to the bottom of the vessel, where 8 of the tendons are anchored to the bearing ring near the center of the bottom concrete head surface, 48 are anchored at the bottom concrete head surface, and 104 are anchored in the four base-support segments.

Prestressing and Base-Support Design

The design considerations for the vertical and horizontal prestressing systems, the bonded reinforcement, and the base-support section are discussed below.

Vertical prestressing system

The prestressing tendons were selected to provide the greatest prestressing effect from the least number of tendons. They are the largest commercially available tendons for which jacking equipment has been developed.

Each strand is equipped with a tapered wedge anchor. The prestress force is transmitted from the strands to the steel-bearing plates which rest on the structural concrete. When the load is transferred from the jack, the strands shorten slightly as the wedges are seated. The prestress loss associated with wedge seating is a function of the strand length. For strands which are 41.76 m (137 ft) long, as in the Synthane PCPV, this loss amounts to about 21 MPa (3 ksi); and for strands which are 80.77 m (265 ft) long, as in the HYGAS PCPV, this loss amounts to about 10 MPa (1.5 ksi). These losses can be offset by slightly overtensioning the strands during jacking.

For the curved tendons illustrated in the PCPV vertical cross sections, the prestressing steel rests against the metal conduit, and friction is produced during tensioning. The frictional losses for curved tendons were calculated from the following equation:[1]

$$P_x = P_s e^{-(\mu\alpha + k\ell)} , \tag{3.1}$$

where

P_x = force at a distance x from the jacking end,

P_s = force at the jacking end,

e = base of the Napierian logarithm,

μ = coefficient of friction,

α = total angle change (in radians) between the tangents to the tendon at the end and at a distance x, assuming single curvature,

k = wobble coefficient,

ℓ = length of tendon from jacking end.

For this study, the coefficient of friction is 0.15 and the wobble coefficient is 2.7×10^{-4}.

The frictional loss for the tendons in the HYGAS PCPV which extend from the bearing ring to the base support was determined to be a force reduction of 17%. If the tendons are jacked from one end and then the other, this loss is reduced to below 10%. Overjacking also tends to reduce these frictional losses.

In regions of the vessel where the tendons are curved, the tendons produce forces normal to the tendon which are resisted by the structural concrete. If the radius of curvature of the tendons is constant, the resulting force per unit of tendon length can be calculated from the following expression:[2]

$$q = \frac{P_x}{r} , \tag{3.2}$$

where

q = force per unit of tendon length,

P_x = tendon force at the point of curvature,

r = radius of curvature of tendon.

The most severe curvature occurs in the top heads of each vessel where the tendons curve toward the bearing ring. For the HYGAS PCPV, r is equal to 9.14 m (30 ft). During prestressing, the force per unit of tendon length equals 0.88 MN/m (5 kips/in.). When the effects of 24 tendons are included, the curved tendons produce an average pressure loading on the concrete normal to the tendons equal to about 0.69 MPa (100 psi), which is considerably less than the tensile strength of the concrete.

The curved tendons at the change in section of the HYGAS PCPV produce average concrete stresses equal to 2.14 MPa (310 psi). These stresses are not excessive and do not significantly affect structural behavior.

To reduce the losses associated with relaxation of prestressing steel, a low-relaxation type of steel was selected for use in the conceptual designs. Relaxation losses increase with time and are affected by the temperature. The stress reductions associated with relaxation may approach 10% of the initial stresses at the end of life of a PCPV and must be considered in an actual design.

Additional losses in prestress that occur with time result from concrete creep and shrinkage. These losses must also be considered when designing a PCPV. The magnitudes can be estimated for a specific set of vessel requirements and a particular concrete mix.

The tendon loads for nongrouted tendons can be monitored by providing load cells which are placed on selected tendons. By monitoring tendon forces, one can detect any variations in the vertical prestress. Nongrouted tendons can also be retensioned or removed and replaced if excessive losses occur or if either tendon corrosion or hydrogen attack occurs. Since the prestressing tendons in the conceptual designs are not grouted, a corrosion inhibitor is required in the ducts to protect the prestressing steel from possible corrosive environments. Although the gasifiers produce hydrogen, the prestressing steel is not expected to be affected by the hydrogen that passes through the steel liner. Prestressing steels in PCPVs are not significantly affected by cyclic stresses, since the anticipated stress variations are small.

Circumferential prestressing system

The circumferential strand winding system was selected for the conceptual designs to provide efficient circumferential prestressing and to reduce the congestion inside the PCPV walls.

The 9.5×10^{-3}-m-diam (0.375-in.) seven-wire strand is tensioned into precast concrete steel-lined channels by a machine which travels around the outside of the PCPV. The winding machine consists of four main components. The drive unit propels the machine around the PCPV at a speed of 0.4 to 0.68 m/sec (4 to 6 mph). The strand is tensioned by a drag or breaking-type of device which controls the applied stress and speed as the strand is applied into the precast concrete channels. The machine is also equipped with a device to control the elevation of the strand as it is played out and a load cell to monitor the tensioning force. An operator rides in the cab, where he monitors the machine speed and strand force continuously.

The strand is continuously applied to the vessel until the desired level of prestressing is reached. The strand is anchored to the steel channel liners by tapered wedges. Prestressing losses associated with wedge seating are assumed to be insignificant, since the strands are extremely long. Frictional losses are also insignificant, since the strands are wrapped onto the walls at the design tension. Circumferential prestress losses must also be considered in the selection of the tensioning load. The adjustment is somewhat greater for the windings, since concrete creep is larger in the circumferential direction than in the vertical direction.

In regions of the PCPVs where penetrations extend through the concrete walls, the circumferential prestressing system is discontinuous. In the conceptual designs, the heights of these disruptions are only about one-half the wall thickness and pose no serious structural behavior problems during construction and under operating loadings. Stress variations in the circumferential prestressing strands during construction and under operating conditions should be very small, and fatigue problems are considered to be unlikely.

Since the outside surface of the PCPV is exposed to the atmosphere, waterproof external insulation is required to protect the prestressing steel from low temperatures and corrosion. A corrosion inhibitor is to be applied to the strands to resist possible corrosive environments.

The use of circumferential strand windings provides the designer with a degree of freedom to position the circumferential prestressing at locations where additional prestress is required. For this study, it was possible to distribute the required prestressing steel evenly between the precast concrete channels.

Bonded reinforcing steel

Bonded reinforcing steel is required in a PCPV for crack control and to ensure ductile vessel behavior during overpressurization. Reinforcement ensures that concrete cracks are relatively small and evenly distributed. If a PCPV were to have nongrouted tendons and no bonded reinforcement, a single crack could develop and produce excessive local liner strains leading to possible puncture of the liner. Cracks in the concrete are caused by shrinkage, thermal gradients, and mechanical loadings which produce concrete tensile stresses. These cracks may develop either before or after the vessel is prestressed. Reinforcement is provided just beneath concrete surfaces to restrict crack widths to 3.8×10^{-4} m (0.015 in.), since cracks of this width are acceptable for concretes which are not subjected to long-term weathering and which provide adequate corrosion protection of the reinforcing steel. Reinforcing steel is also required in the anchorage regions of all prestressing tendons in order to prevent bursting or spalling. Subsection CB-3520 of Section III, Division 2 of the ASME Code[3] specifies the design requirements for anchorage zones.

Subsection CB-3534 of the ASME Code requires that reinforcement be provided across principal sections through the PCPV in which the average stress is tensile. For the types of PCPVs considered, an average tensile stress develops across a principal section at an internal pressure above the design pressure. In order to satisfy the Code requirements, sufficient reinforcement is required across the section to resist a tensile stress of at least $7.5\sqrt{f_{cua}}$ in the concrete (f_{cua} is the design concrete compressive strength). For the concrete strength used in this study, the reinforcement requirements expressed as percentage of the horizontal and vertical sections of the vessels are as follows:

ASTM A615	Percentage of steel area to concrete area
Grade 40	1.512
Grade 60	1.008
Grade 75	0.806

Large-diameter ASTM A615 grade 75 reinforcement was selected in order to reduce the labor costs associated with installation of this reinforcement and to reduce the number of individual bars. Although the ASME Code does not permit the use of grade 75 reinforcement, changes in the Code are being considered. The use of a lower-strength reinforcement would mean only that a greater amount is required. Hence, the grade of reinforcement selected is not expected to affect the structural behavior of the PCPVs during overpressurization.

The thermal gradient through the concrete walls produces tensile stresses at the outside concrete surfaces of the vessels. Reinforcement is provided in these regions to control widths of potential thermally induced concrete cracks. Reinforcement is also provided near the surfaces of the cavity and penetration liners to prevent the formation of a single large crack during overpressurization which could possibly cause failure of the liner. The remaining reinforcement is distributed in the walls near the prestressing tendons.

Fatigue of the bonded reinforcing steel is not expected to be a problem, since the stresses are designed to remain within the elastic limit both during construction and under operating conditions and anticipated stress variations are small.

Base-support sections

The base-support sections for each PCPV consist of four individual segments. The vessels rest on these segments, which transmit the dead load to the foundation. The segmented base supports permit access to the piping at the center of the bottom PCPV heads, and openings through the supports permit access to the tendons which anchor the PCPV to the supports.

The base-support segments can be enlarged if seismic loadings are a problem. The attachment of the base supports to the foundation system could be accomplished by conventional reinforcement or, if seismic loadings are significant, the prestressing tendons could be extended into the foundation structure.

Access Penetrations Through the Heads

The conceptual designs for both the Synthane and the HYGAS vessels require a large-diameter opening, or penetration, in the top head. The closure for the penetration must, in turn, have a central opening to accommodate a gas outlet duct. The primary penetration closure is a removable multiplate steel structure, which is supported by a steel support ring when the vessel is not pressurized. It is held in place by a system of short columns or toggles when the vessel is pressurized. These toggles transfer the forces directly to the nearest row of vessel tendons.

The closure design for the Synthane vessel is illustrated in Figs. 3.7, 3.8, and 3.9. Figures 3.7 and 3.8 show the hold-down system, the support ring, the insulation details in the vicinity of the closure, the cyclone support skirt, and the gas outlet duct. Also shown is the torus-shaped sealing ring between the edge of the upper plate and the support ring rib; the seal ring is welded in place to prevent gas leakage. The cross-sectional view in Fig. 3.9 shows the inner and outer rings and the radial shear plates used for strength and stiffness. Refractory layers insulate the liner, plug, and piping from the high temperatures and yet permit removal of the closure plug. The plug is to be fabricated using ordinary steel plate rolling and welding procedures. This basic type of access penetration closure is also used for the HYGAS vessel.

Structural Design Bases and Material Selections

The conceptual designs for the two gasifier applications were developed to provide a structure which is leaktight under vessel operating conditions and which will safely resist an overpressurization condition for an internal pressure of up to twice the design value. The design

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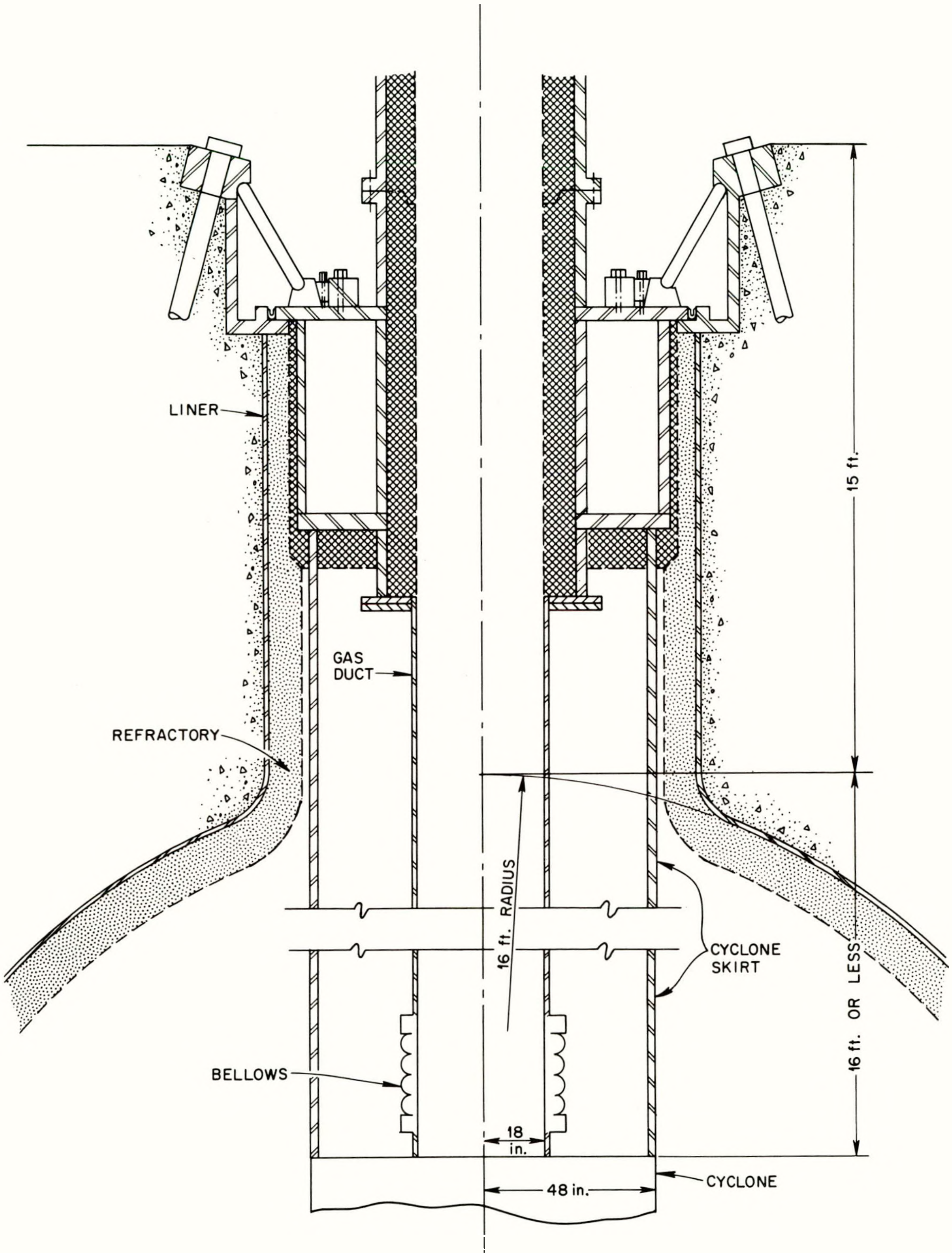

Fig. 3.7. Removable steel closure plug for Synthane PCPV.

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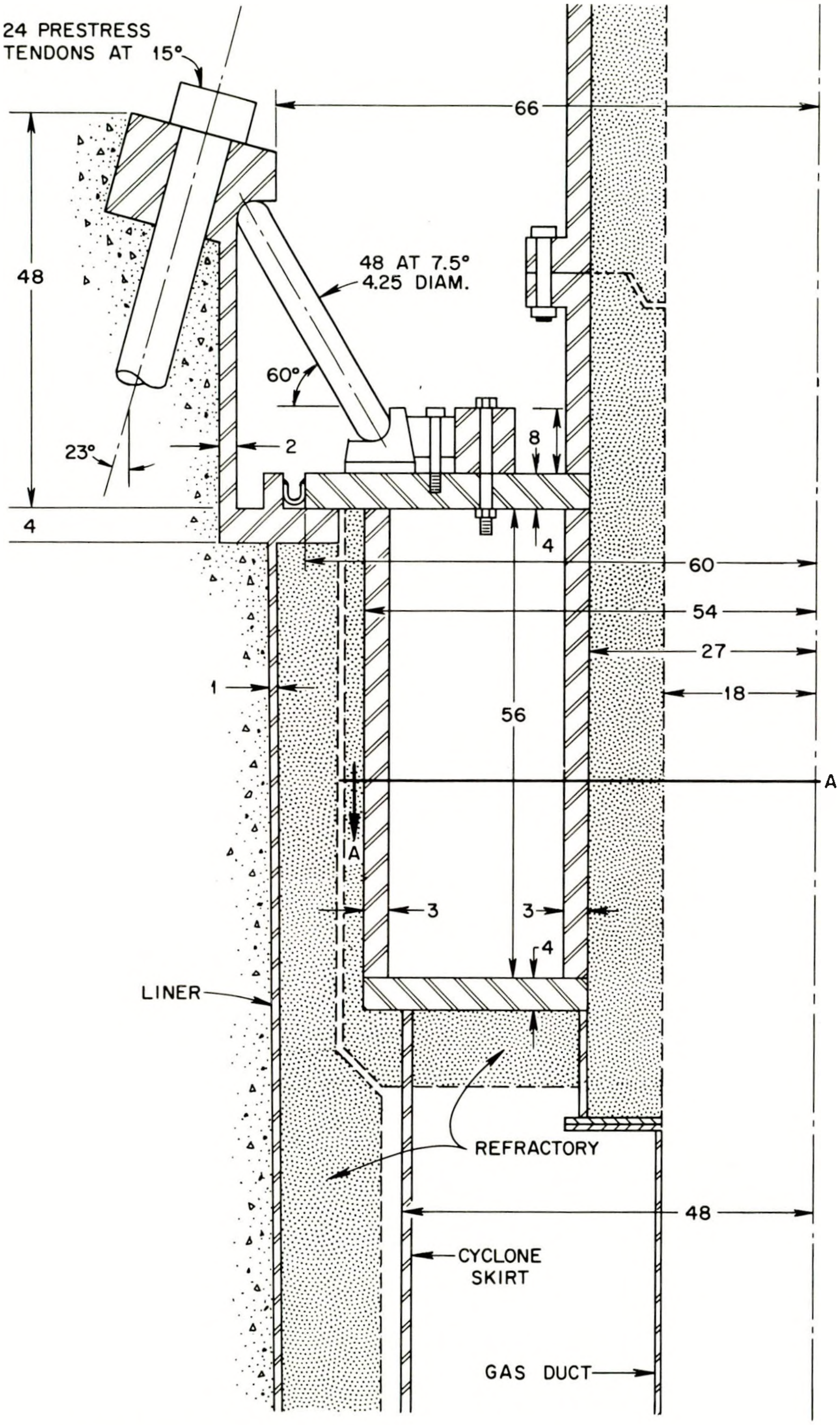

DIMENSIONS ARE IN INCHES

Fig. 3.8. Detail of removable steel closure plug for Synthane PCPV.

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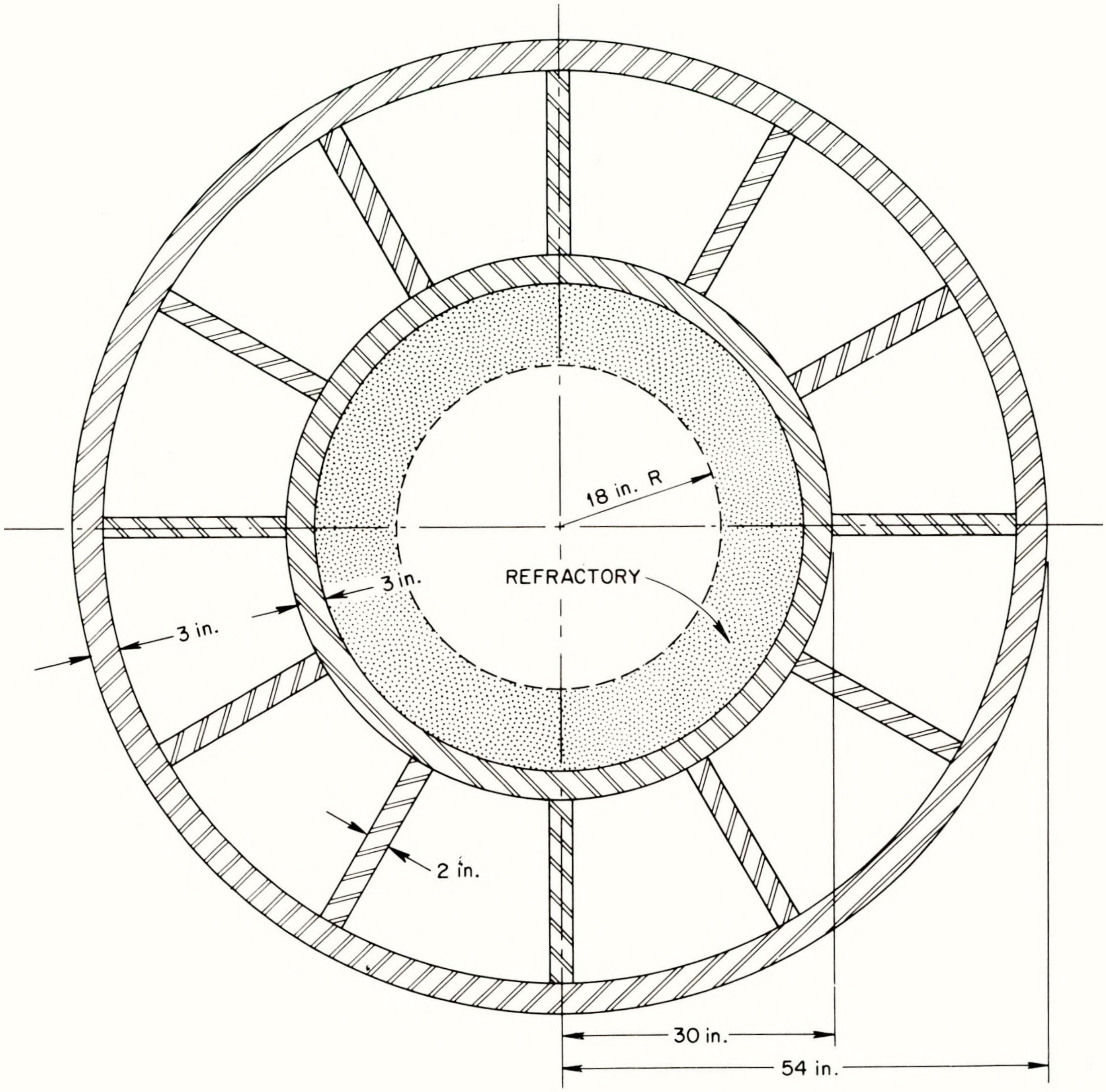

SECTION "A-A"

Fig. 3.9. Cross section of removable steel closure plug for Synthane PCPV.

pressure for the Synthane vessel was 7.41 MPa (1075 psi), while the design pressure for the HYGAS vessel was 8.96 MPa (1300 psi).

The temperature limits established for this study for normal operating and off-design conditions are listed in Table 3.3. The off-design conditions correspond to failure of one of the two independent cooling systems. The allowable radial temperature difference through the structural concrete was taken as 22 K (40°F), with a maximum limit being 39 K (70°F). Ambient temperature extremes were taken to be 239 and 308 K (—30 and 95°F).

The materials selections were made on the basis of strength considerations, operating environments, economic considerations, fabricability, etc. Those to be used for the various components are as described below. Omitted from these discussions are insulating material for the vessel outer surfaces and refractories to be placed inside the liner, both of which are discussed in Chapter 5.

Table 3.3. Temperature limits for normal and off-design conditions

Location	Temperature limit	
	Normal [K (°F)]	Off-design [K (°F)]
Bulk concrete	339 (150)	366 (200)
At prestressing tendons	339 (150)	366 (200)
Concrete at cooling tubes	339 (150)	366 (200)
Concrete between cooling tubes	366 (200)	405 (270)
Cold-liner concept at liner—structural concrete interface	339 (150)	366 (200)
Hot-liner concept at liner-refractory interface	561 (550)	589 (600)

PCPV materials

Structural concrete. Structural concretes for use in design and construction of a PCPV should have engineering properties which include (1) a reasonably high and uniform density, (2) reasonably high compressive and tensile strengths, (3) low heat of hydration, (4) high specific heat, (5) high thermal conductivity, (6) low thermal expansion, (7) low creep and shrinkage, (8) low elastic deformation characteristics, and (9) good workability. For the design of a particular PCPV, these properties are established from trial mixes of candidate materials proposed for use in the actual PCPV construction. For this study, the engineering properties of the structural concrete used in developing the conceptual designs are typical of concretes used to construct prestressed concrete vessels for nuclear reactors. The properties selected for this study are as follows:

Design concrete compressive strength (f_{cua}): 44.82 MPa (6500 psi)
Modulus of elasticity (E_c): 34.5 GPa (5×10^6 psi)
Poisson's ratio (μ): 0.25
Coefficient of thermal expansion (α_c): 9.5×10^{-6}/K (5.3×10^{-6}/°F)
Thermal conductivity (k_c): 2.16 W/m·K (1.25 Btu/hr·ft^2·°F/ft)
Creep shrinkage: For design purposes, the creep and shrinkage strains were assumed to be three times the elastic strains.

Insulating concrete. Insulating concretes for use between the structural concrete and the steel liner in the hot-liner design should have engineering properties which include (1) low shrinkage, (2) low coefficient of thermal expansion, (3) low compressibility, (4) low elastic modulus, (5) low thermal conductivity, (6) good mechanical resistance, and (7) good workability. These properties should remain virtually unaffected by the maximum working temperature.

Candidate insulating concretes include those made with artificial aggregates such as expanded clay as well as those made with natural aggregates such as limestone, porphyry, and diorite. Testing to evaluate the engineering properties of these candidate concretes is required before a final selection can be made.

The engineering properties selected for use in the development of the hot-liner system are as follows:

Design insulating concrete compressive strength (f_{cua}): 24.1 MPa (3500 psi)

Modulus of elasticity (E_c): 10.34 GPa (1.5×10^6) psi

Poisson's ratio (μ): 0.25

Coefficient of thermal expansion (α_c): 7.2×10^{-6}/K (4.0×10^{-6}/°F)

Thermal conductivity (k_c): 0.73 W/m·K (0.42 Btu/hr·ft^2·°F/ft)

Bonded reinforcing steel. The bonded reinforcing steel used in the conceptual designs is to conform to the requirements of ASTM A615. Grade 60 reinforcing steel is to be used for anchor zone reinforcement and for all exposed concrete surface reinforcement. Grade 75 reinforcing steel is to be used for the main circumferential and vertical reinforcement.

Vertical prestressing system. The prestressing steel for the vertical tendons is to conform to the requirements of ASTM A416 for seven-wire stress relieved strand. Each prestressing tendon has the following specified properties:

Guaranteed ultimate tensile strength of prestress steel (f_{su}): 1.86 GPa (2.7×10^5 psi)

Minimum elongation at failure: 3.5%

Steel area per tendon: 5.4×10^{-3} m^2 (8.42 in.^{2})

Modulus of elasticity: 186 GPa (2.7×10^7 psi)

Ultimate load of prestress tendon: 9.6 MN (2160 kips)

Guaranteed yield strength at 1% elongation (f_{sy}): 0.9 f_{su}

The tendon ducts are carbon steel tubing which conforms to ASTM A513 grade 1010. The 0.61 × 0.61 × 0.076 m (24 × 24 × 3 in.) tendon-bearing plates were to be made from ASTM A36 steel.

Each strand is to be secured at the ends by a strand wedge-grip anchorage system. These anchors are to develop at least 95% of the minimum guaranteed ultimate load of the strand.

Circumferential prestressing system. The prestressing steel for the circumferential system is to conform to the requirements of ASTM A416 for seven-wire stress-relieved strand. The strand has the following material properties.

Guaranteed ultimate tensile strength of prestressing steel (f_{su}): 186 GPa (2.7×10^5 psi)

Minimum elongation at failure: 3.5%

Steel area per strand: 5.5×10^{-5} m^2 (0.085 in.^{2})

Modulus of elasticity: 186 GPa (2.7×10^7 psi)

Ultimate load of strand: 0.1 MN (22.9 kips)

Guaranteed yield strength at 1% elongation (f_{sy}): 0.9 f_{su}

The steel liners for the precast concrete circumferential channels (see Fig. 3.10) are to be 3.1×10^{-3} m (0.125 in.) thick and must conform to the requirements of ASTM A36. Each steel liner is 0.76 m (30 in.) high and 0.30 m (12 in.) deep (inside dimensions).

Steel liner material for the hot-liner concept

The liner material selected for the hot-liner concept conforms to the requirements of SA 387 grade 22. This material is to be heat treated to produce a minimum yield strength of 421 MPa (61 ksi). The thickness of the liner plate is to be 2.5×10^{-2} m (1 in.), which permits a 6.4×10^{-3}-m (0.25-in.) corrosion allowance on the outer side. The inside surface is to be covered by a 6.4×10^{-3}-m (0.25-in.) thickness of type 304 stainless steel roll-bonded cladding for protection against process corrosives. The total liner thickness is therefore 0.03 m (1.25 in.).

Forgings to be used around openings in the vessel are to conform to the requirements of SA 335 grade F22 steel. Protection from the process environment is to be provided by type 308 stainless steel weld overlay.

Steel liner material for the cold-liner concept

The liner material selected for the cold-liner concept conforms to the requirements of SA 537 class 1 and is tempered to a yield strength of 379 MPa (55 ksi). The plate thickness is 0.02 m (0.75 in.), and a 6.4×10^{-3}-m-thick (0.25-in.) roll-bonded (or explosive-bonded) cladding of type 304 stainless steel is to cover the inside surface of the liner for protection against process corrosives. The total thickness of the liner is therefore 0.025 m (1 in.).

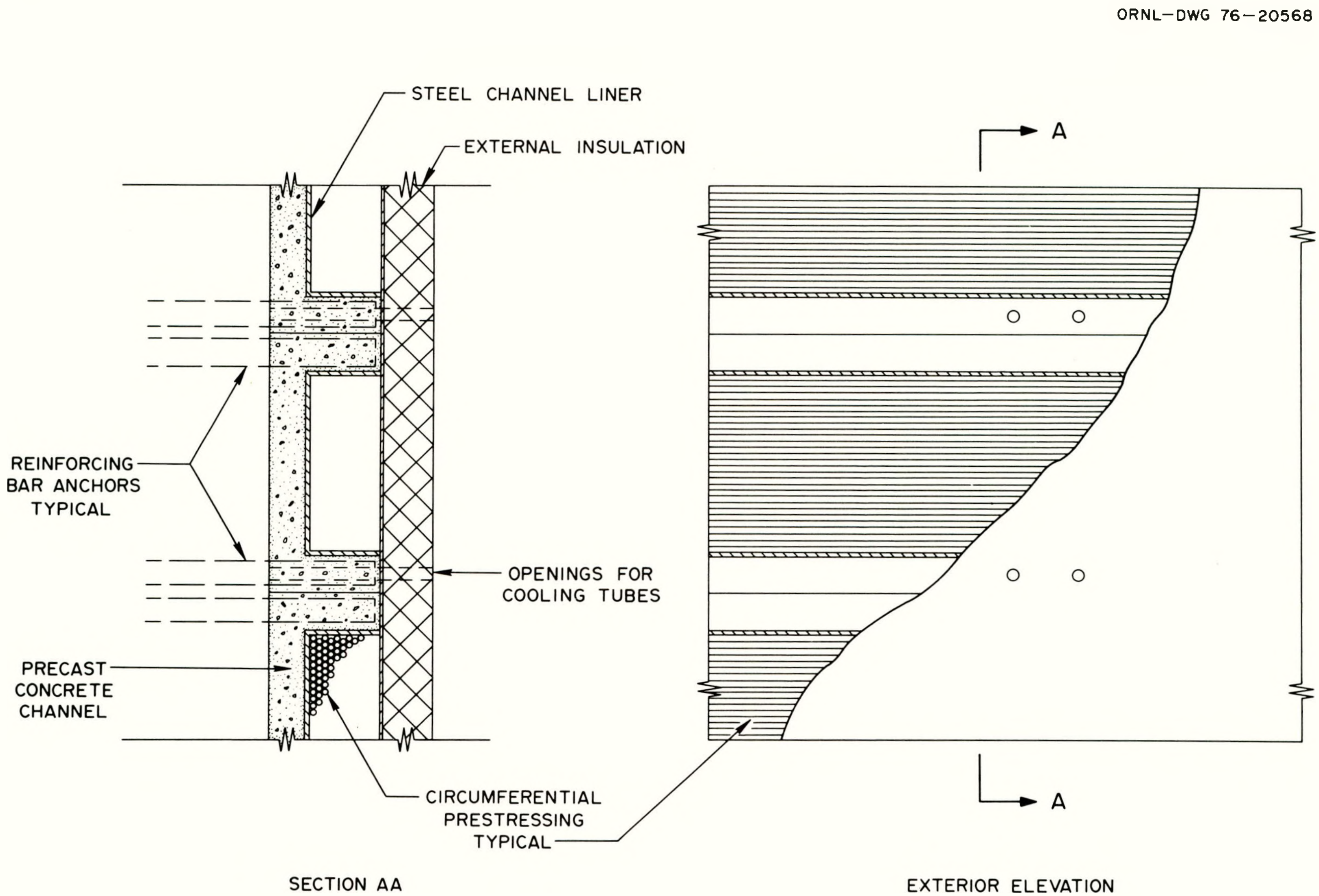

Fig. 3.10. Circumferential precast concrete channel layout.

Forgings for reinforcement around openings are to conform to the requirements of SA 508 class 1 steel. Protection from the process environment is to be provided by weld overlay of type 308 stainless steel.

Shear anchor assemblies

Shear anchor assemblies will be used in the penetrations to transfer load from the liner to the structural concrete. These assemblies, which are embedded in the concrete adjacent to the large-diameter penetrations, consist of individual 0.03-m (1.25-in.) steel plates welded to the penetration liner. These, in turn, are attached to a 0.064-m (2.5-in.) conical bearing plate which provides for load transfer to the concrete.

Materials for the shear anchor assemblies conform to the following requirements:

Hot-liner concept	SA 387 grade 22
Cold-liner concept	SA 537 class 1

Anchor studs

The anchor studs are attached to the liner and extend into, and bond with, the structural concrete. They are to be made from steel which conforms to the requirements of ASTM A108 grade 1015, regardless of which liner concept is to be used.

Bearing ring forgings

The bearing rings located at the top of each vessel are to be made from forgings conforming to the requirements of SA 508 class 1 steel.

Removable steel closure plug

The removable steel closure plug at the top of each vessel is to be fabricated from relatively thick plate sections. The inside and the outside cylindrical members are to be 0.076 m (3 in.) thick, and the top and bottom plates are to be 0.10 m (4 in.) thick. The twelve radial shear plates, which are to be welded to the bottom and cylindrical portions, will be 0.05 m (2 in.) thick. The surfaces exposed to the process environment will be clad with weld overlay. Materials for the plug components for both cold- and hot-liner concepts are as follows:

Plates and cylinders	SA 387 grade 22 steel
Cladding	Type 308 stainless steel

Cooling tubes

The cooling tubes for the hot-liner concept are to have an outside diameter of 0.025 m (1 in.) and an inside diameter of 0.02 (0.75 in.). They will be finned tubes, with two diametrically opposed fins 0.02 m (0.75 in.) long and 0.0032 m (0.125 in.) thick. The tubes will be spaced on 0.15-m (6-in.) centers and extend halfway around the vessel liner. Figure 3.11 depicts the cooling system layout. Material for the finned cooling tubes is to conform to the requirements of ASTM A587 for low-carbon steel.

The cooling tubes for the cold-liner concept are to be made of the same material used for the tubes in the hot-liner concept. The low-carbon content of this steel should make it suitable for welding and compatible with the A537 class 1 liner. Tubes with square-shaped cross sections are to be produced from round steel tubes. These square tubes are to be welded to the liner on 0.18-m (7-in.) centers, and each tube is to extend halfway around the vessel liner. Again, Fig. 3.11 depicts the cooling system layout.

Structural design codes

Although there is no standard design code for concrete pressure vessels for non-nuclear applications, appropriate requirements of Subsection CB of the *Code for Concrete Reactor Vessels and Containments*, Section III, Division 2 of the ASME Boiler and Pressure Vessel Code[3] were used to develop the conceptual designs. The primary objective was to ensure that vessel response to the design internal pressure is essentially elastic and that response to overpressurization is gradual and predictable.

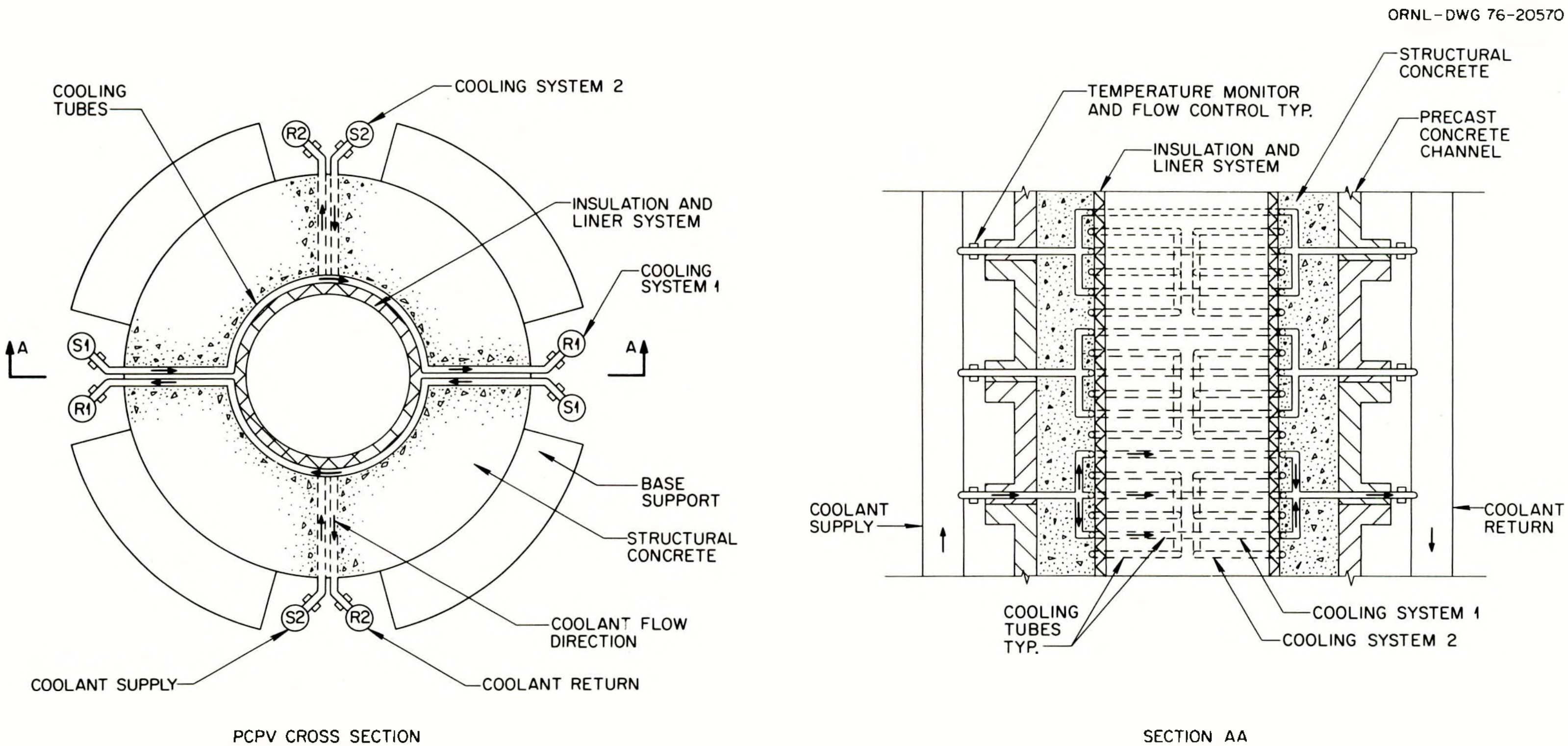

Fig. 3.11. Typical cooling system layout.

Structural evaluations

The vessel loadings that were considered during the development of the conceptual designs for gasifier PCPVs are those associated with construction, operation, and overpressurization. Since a PCPV is to respond essentially elastically under the construction loadings and normal operating conditions, elastic responses are to be expected for the following loads and load combinations.

1. Construction loadings
   a. Prestress
   b. Prestress and test pressure
2. Operating loadings
   a. Prestress and temperature
   b. Prestress, design pressure, and temperature

Stresses produced in the concrete during elastic vessel response are not to exceed the limits specified in Section III, Division 2 of the ASME Boiler and Pressure Vessel Code. The elastic stress limits applicable to this study are listed in Table 3.4. Although the ASME Code permits higher compressive stress limits when triaxial compressive stresses occur, higher limits were not considered in this study.

Criteria for concrete temperature limits are also given in Section III, Division 2 of the ASME Code to ensure that satisfactory long-term concrete properties are maintained. These criteria were used in developing the bases for the conceptual designs described in this report. The resulting temperature limits are given in Table 3.3 along with other limits adopted in this study.

The two types of overpressurization loadings which were considered in the design are a hypothetical vessel pressure of twice the design pressure and a pressurized horizontal or vertical crack occurring while the vessel is subjected to the design pressure. Since the PCPV will respond inelastically to these overpressurization loadings, the vessels are designed to have a minimum factor of safety of 2.1 in order to ensure adequate structural resistance to these loading conditions.

Table 3.4. Stress limits for concrete[a]

Loading	Average stress		Point stress	
	Primary stress	Primary stress + secondary stress	Primary stress	Primary stress + secondary stress
Construction	$f_{cc} = 0.4\ f_{cua}$ $f_{ct} = 0$	$f_{cc} = 0.53\ f_{cua}$ $f_{ct} = 3.0 \sqrt{f_{cua}}$	$f_{cc} = 0.5\ f_{cua}$ $f_{ct} = 6 \sqrt{f_{cua}}$	$f_{cc} = 0.67\ f_{cua}$ $f_{ct} = 7.5 \sqrt{f_{cua}}$
Operating	$f_{cc} = 0.3\ f_{cu}$ $f_{ct} = 0$	$f_{cc} = 0.4\ f_{cua}$ $f_{ct} = 3 \sqrt{f_{cua}}$	$f_{cc} = 0.45\ f_{cua}$ $f_{ct} = 6 \sqrt{f_{cua}}$	$f_{cc} = 0.6\ f_{cua}$ $f_{ct} = 7.5 \sqrt{f_{cua}}$

[a]Nomenclature:

f_{cc} = concrete compressive stress limit

f_{cua} = design concrete compressive strength: 44.8 MPa (6500 psi)

f_{ct} = concrete tensile stress limit

In determining the minimum factor of safety, the ultimate load capacities associated with various possible modes of structural failure were determined. The following criteria were used to evalute the ultimate load capacities of the cylindrical sections of a PCPV.

1. The tendon force is set equal to the ultimate load of the prestressing tendon, and the axial load resultant is the summation of the individual forces.

2. The force in the circumferential prestressing steel strand is set equal to the ultimate load of the strand, giving the circumferential resultant for the vessel.

3. The stress in the bonded reinforcing steel is set equal to the yield stress. This gives both axial and circumferential resisting forces to be added to items 1 and 2 above.

The ultimate load capacity of the head regions of a vessel is attained when the principal tensile stress in the concrete equals $4 \sqrt{f_{cua}}$, where f_{cua} is the design compressive strength of the concrete.

Structural analysis methods

The analytical techniques and methods employed in the development of the PCPV conceptual designs are based on the linear elastic stress-strain properties of concrete and steel. These properties are directly applicable for both the construction and operating loading conditions. The linear elastic method of analysis is permitted under Subsection CB 3310 of the ASME Code, provided that the geometric characteristics of the thick section of the PCPV are represented and that the concrete tensile stresses do not exceed the f_{ct} values of Table 3.4. Concrete cracking and creep effects were considered in the designs only as described in the previous section.

The initial vessel size was determined by assuming various concrete wall thicknesses and then evaluating the elastic structural response using the classical expressions for stresses and displacements in an uncracked thick-walled cylinder and assuming the plane strain case with no longitudinal constraint of strain. Homogeneous concrete structures were assumed in these computations. These preliminary analyses were performed using the following equations:[4]

$$\sigma_{ta} = \frac{2pb^2}{a^2 - b^2} - q\,\frac{(a^2 + b^2)}{a^2 - b^2} + \frac{\Delta T \alpha_c E_c}{2(1 - \mu)\,\ell n\,\frac{a}{b}}\left(1 - \frac{2b^2}{a^2 - b^2}\,\ell n\,\frac{a}{b}\right); \quad (3.3)$$

$$\sigma_{tb} = \frac{p(a^2 + b^2)}{a^2 - b^2} - \frac{2qa^2}{a^2 - b^2} + \frac{\Delta T \alpha_c E_c}{2(1 - \mu)\,\ell n\,\frac{a}{b}}\left(1 - \frac{2a^2}{a^2 - b^2}\,\ell n\,\frac{a}{b}\right); \quad (3.4)$$

$$\sigma_{va} = \frac{pb^2}{a^2 - b^2} - \frac{F}{(a^2 - b^2)\pi} + \frac{\Delta T \alpha_c E_c}{2(1 - \mu)\,\ell n\,\frac{a}{b}}\left(1 - \frac{2b^2}{a^2 - b^2}\,\ell n\,\frac{a}{b}\right); \quad (3.5)$$

$$\sigma_{vb} = \frac{pb^2}{a^2 - b^2} - \frac{F}{(a^2 - b^2)\pi} + \frac{\Delta T \alpha_c E_c}{2(1 - \mu)\,\ell n\,\frac{a}{b}}\left(1 - \frac{2a^2}{a^2 - b^2}\,\ell n\,\frac{a}{b}\right); \quad (3.6)$$

where

σ_{ta} = tangential stress at outside concrete surface,*

σ_{tb} = tangential stress at inside concrete surface,

σ_{va} = vertical stress at outside concrete surface,

σ_{vb} = vertical stress at inside concrete surface,

a = outside radius of vessel,

b = inside radius of vessel,

p = internal pressure,

q = external pressure (produced by circumferential prestress),

F = total effective vertical prestress force,

α_c = coefficient of thermal expansion of concrete,

E_c = modulus of elasticity of concrete,

μ = Poisson's ratio for concrete,

ΔT = temperature difference between the inside and the outside surfaces of the vessel.

Results for each assumed wall thickness were obtained for combinations of internal pressure, external prestress, and steady-state logarithmic thermal gradient. Tangential stresses were evaluated at the inner surface of the structural concrete at the cooling tube interface and at the juncture of the outer surface of the structural concrete and the circumferential prestressing. Axial stresses were evaluated by assuming that the axial prestress and the internal pressure produced an average stress across a concrete section. The calculated tangential thermal or secondary stresses produce identical stresses in the axial direction.

The computed stresses from the construction and operating loadings were compared to the stress limits listed in Table 3.4 until an acceptable combination of wall thickness, vertical prestress force, circumferential prestress, and thermal gradient was identified. After the wall thickness had been determined, the vessel heads, prestressing, bonded reinforcement, liner system, penetrations, and base supports were added to complete the conceptual design layout.

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*Positive values of stress are tensile.

The preliminary conceptual design was then analyzed using the finite-element computer program ISA to verify the accuracy of this strength-of-materials type of analysis for computing stresses in the cylindrical regions of the PCPVs as well as to calculate stresses in the head regions. This type of elastic analysis procedure was used to design both HYGAS and Synthane PCPV configurations. The computer program ISA is described in Appendix B and listed in Table 2.2.

The models used in the axisymmetric finite-element analyses consisted of a 1-radian sector of the PCPV, excluding the base supports. The concrete liner and prestressing forces were represented in the analyses, but the effects of the bonded reinforcing steel were neglected.*

The calculated finite-element stresses were compared with the concrete stress limits listed in Table 3.4 to determine the final acceptability of the PCPV configurations and structural response to construction and operating loadings.

The stresses calculated using the finite-element analysis were compared with those calculated using the thick-walled cylinder analyses, and the following conclusions were reached concerning the cylindrical wall sections of the PCPVs.

1. The classical expressions for stresses and displacements for a thick-walled cylinder provide reasonable predictions of concrete stresses compared to predicted stresses from an axisymmetric finite-element analysis.

2. The effect of radial displacements and the associated increase in circumferential prestress were negligible due to the construction and operating loadings.

3. Vertical stresses in the concrete were essentially uniform due to prestress and internal pressure loadings.

4. The influence of head stiffness on bending of the cylindrical concrete walls was insignificant at approximately 1.5 times the wall thickness from the head and cylinder intersection under design prestress and pressure loadings.

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*For the PCPVs being considered, the ratio of bonded reinforcing steel area to concrete area is 0.8%. Neglecting the effects of the reinforcing steel in the analyses yields concrete stresses that are 4.7% above their computed values. Thus, this assumption produces a conservative design.

5. Use of the classical expressions for calculating stresses and displacements of a thick-walled cylinder is a reasonable approach for initial PCPV design purposes.

6. Since the top and the bottom heads of the PCPVs are irregularly shaped, the expressions for thick-walled cylinders do not apply to the head regions.

The ultimate load capacities of the cylindrical sections of the vessel were evaluated using the static-equilibrium method. In this method, the total forces associated with the ultimate load capacity of the prestressing steel and the yield strength of the bonded reinforcing steel were divided by the appropriate internal cavity area to yield the ultimate internal pressure.

The ultimate load capacities of the PCPV heads were conservatively estimated using semiempirical expressions[5] developed at the University of Illinois. These shear failure expressions are based on experimental data from structural model tests.

The static-equilibrium method was also used to verify that the PCPVs could adequately resist pressurized horizontal and vertical cracks through the cylindrical walls.

For vessels that differ from the PCPVs that have already been designed and built, the ASME Boiler and Pressure Vessel Code requires a structural model test to demonstrate vessel behavior in the range approaching failure. Since both gasifier vessels are in this category, a structural model test program is defined to comply with the Code requirements. This program is discussed in Chapter 6.

Elastic load response

The basic loadings of the PCPV are prestress, design pressure, and thermal loads. The concrete stress limits listed in Table 3.4 are not exceeded during construction and operation. The largest stresses in the prestressing tendons occur during initial tensioning operations and thereafter remain essentially constant during normal vessel operation. The stresses in the concrete are below the assumed tensile strength of this material, and the bonded reinforcing steel does not yield.

When a hot-liner concept is employed, the liner and insulating concrete are restrained from expanding as they are heated. The effect on the concrete vessel was assumed to be that of an increased internal pressure; however, similar effects associated with the refractory lining were not considered. The bulk compressive strain of the liner can exceed the yield strain when the liner is at operating temperature, and the tensile yield strain can be approached when the liner is cooled. The insulating concrete behind the steel liner is initially compressed due to prestressing operations, and the compressive load increases as the concrete heats up. Upon cooling down, the insulating concrete could tend to crack in tension. Demonstrative testing is required to verify the behavior of the hot-liner components and to demonstrate the feasibility of the hot-liner concept.

In the cold-liner concept, the steel liner is compressed initially during the prestressing operations. Upon pressurization, the compressive stresses are reduced until the liner stresses may be only slightly compressive. Since the liner remains at approximately the same temperature as the structural concrete, thermal stresses due to restrained thermal expansion are minimized and elastic behavior is generally obtained. Experience with vessels having cold liners is extensive, and the requirements of Section III, Division 2 of the ASME Code are applicable to this concept.

Ultimate load response

As the internal pressure of a PCPV is increased above the normal operating value, the concrete approaches a state of net tension; pressures associated with this condition are approximately 1.5 times the design value. The prestressing steel, bonded reinforcing steel, and liner act in combination to resist the increase in pressure. As the concrete tensile stress increases, the bonded reinforcement provides for uniform concrete crack distribution, thus preventing excessive deformation at any location and also preventing excessive strain accumulation in the steel liner.

The resisting capacities of the steel components were calculated in terms of internal pressure loading for both vessel designs. The results are listed in Table 3.5, where it may be seen that the internal pressures corresponding to the resisting capacities of the steel components are greater than twice the design pressures for all cylindrical sections. The two PCPV designs, therefore, satisfy the minimum-factor-of-safety design requirement of Section III, Division 2 of the ASME Code.

The vessels were also designed to resist loading conditions associated with postulated accidental pressurized cracks. The two possible crack cases considered were a vertical radial crack through the vessel wall and a horizontal crack which separates the vessel into two parts.

Table 3.5. *Internal pressure-resisting capacity of PCPV steels*

	Prestressing steel at ultimate strength plus bonded reinforcement at yielded strength [MPa (psi)]	Ratio of ultimate internal pressure to design pressure
	Synthane PCPV	
Vertical direction[a]	22.68 (3289)	3.06
Horizontal direction[b]	18.61 (2700)	2.51
	HYGAS PCPV (Top section)	
Vertical direction[a]	34.90 (5062)	3.89
Horizontal direction[b]	23.90 (3466)	2.67
	HYGAS PCPV (Bottom section)	
Vertical direction[a]	31.01 (4495)	3.46
Horizontal direction[b]	23.21 (3367)	2.59

[a]Internal pressure equals the ultimate tendon load times the number of tendons through the vessel cross section plus the yield stress of the bonded reinforcing steel times the area of steel through the vessel cross section divided by the cross-sectional area of the internal cavity.

[b]Internal pressure equals the ultimate load of circumferential prestress strands times the number of strands per unit of vessel height plus the yield stress of the loaded reinforcing steel times the area of steel per unit of vessel height divided by the inside diameter of the vessel.

These pressurized cracks were assumed to occur while the vessel is operating at the design pressure. The pressure distributions on the crack surfaces were assumed to vary linearly from the design pressure at the inside or liner surface to zero at the external concrete surface. On this basis, the crack loadings plus the design pressure loadings were computed, and the induced loadings plus the design pressure loadings were compared to the corresponding resisting capacities of the steel components (see first column of Table 3.5). These comparisons are listed in Table 3.6 and indicate adequate reserve strength to ensure ductile structural response to the addition of pressurized crack loadings.

Table 3.6. Resisting capacity of PCPV steels to pressurized crack forces

	Synthane	HYGAS	
		Top	Bottom
Vertical radial crack[a]	0.44	0.38	0.41
Horizontal crack[a]	0.75	0.84	0.81

[a]Ratio of force produced by the combination of a pressurized vertical radial crack or pressurized horizontal crack plus design internal pressure force to the resisting capacity of prestressing steel at ultimate strength plus bonded reinforcement at yielded stress.

Simple mathematical expressions have not been developed for evaluating the ultimate strength of the PCPV heads employed in these conceptual designs. However, semiempirical methods for evaluating PCPV head strength, which are based on model tests of cylindrical vessels having flat heads, are available. Thus, for conceptual design purposes, the curved haunches, penetrations, and prestressing tendons through the concrete heads were disregarded.

From these evaluations, the following conclusions were drawn concerning the conceptual design configurations.

1. When flat heads are assumed, the internal pressure at failure is at least twice the design operating pressure.

2. The curved tendons in the top head regions provide a prestressing effect perpendicular to the direction in which the diagonal tension crack occurs and also provide additional load-resisting capacity.

3. The small-diameter penetrations through the bottom heads of the vessels reduce the strength of these heads slightly.

4. The magnitude of circumferential prestressing in the head regions influences the shear and the flexural strength of the heads.

5. The magnitude of vertical prestressing influences the flexural strength of the concrete heads.

Long-term PCPV response

The initial compressive stresses that are produced during prestressing operations are gradually but only slightly reduced during the entire life of a PCPV. Factors contributing to this loss include concrete creep and shrinkage, prestressing steel relaxation, and losses resulting from elastic deformation during subsequent prestressing operations. Section III, Division 2 of the ASME Code requires that prestress losses be considered in design; however, predicting long-term vessel behavior requires a broad understanding of time-dependent concrete characteristics, temperature and stress distributions, and prestressing steel relaxation. Although the effects of long-term vessel response were not included in the development of the conceptual design configurations, these effects should not influence the feasibility evaluation.

Seismic PCPV response

Stresses produced by earthquakes were not calculated in this feasibility study, since no specific site locations are considered. The PCPVs are attached to the base-support sections by prestressing tendons and since the cross-sectional areas and the moments of inertia of the cylindrical vessels are extremely large, the base-support segments can be proportioned to provide adequate base shear and overturning resistance. The magnitude of the overturning moments will also dictate the designs for attaching the base-support segments to the foundation system. The base-support systems shown in Figs. 3.3 and 3.6 provide design flexibility to accommodate specific foundation and seismic requirements.

Overall PCPV response

The overall response of the HYGAS and Synthane conceptual design configurations to construction and operating loadings is essentially elastic, with the stresses in the concrete, prestressing steel, and reinforcing steel remaining below allowable limits. During hypothetical overpressurization, the designs provide adequate resistance to pressure-induced forces corresponding to an internal pressure of at least twice the design value. The responses of the vessels to pressurized cracks are also satisfactory. However, a structural model test of each vessel configuration is required by the ASME Code to demonstrate adequate ductile overpressure resistance, to identify the mode of failure, and to determine the corresponding ultimate internal pressure. Procedures required for experimental demonstration and verification of the load-resisting capacities of the two gasifier vessels are discussed in the follow-up program definition section of this report.

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4. BACKGROUND ON LINER PERFORMANCE REQUIREMENTS AND MATERIALS SELECTION AND BEHAVIOR

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Performance criteria to be met by the PCPV liners are described in this chapter along with results from examinations of stresses and stress histories that will be imposed. Finally, the bases for materials selection are addressed.

Performance Criteria

PCPV liners, penetrations, and closures, which create the leaktight pressure boundary for the contained process, are expected to perform satisfactorily for the design lifetime of the vessel. The steel penetration and vessel liners are backed by concrete and are not designed as structural elements. On the other hand, penetration liners and closures which are not backed by concrete are designed as pressure vessels to resist all pressure-induced loadings.

The liners, which also serve as the internal formwork for the concrete during vessel construction, are to be fabricated from steel plates and welded together at the construction site. Anchor studs, which are welded to the liner, are embedded in the concrete to ensure that liner strain patterns conform to the adjacent concrete strain patterns. Large deformations and liner buckling are to be prevented, since they are detrimental to liner integrity and adversely affect refractory and cooling tube performance. These studs also resist loads applied to the liner by internal equipment, structural discontinuities, and external pressure resulting from possible cooling system leakage. Shear anchor assemblies, consisting of radial steel plates and a conical-shaped bearing ring, are welded to penetration liners near the outside concrete surfaces to transfer loads imposed on the closures to the structural concrete.

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Stainless steel cladding is used on the pressurized sides of liners, penetrations, and closures to prevent deterioration of the steel through exposure to the corrosive process environment. Stainless steel refractory anchors are welded to the cladding and support the refractory linings.

The liner material selected for use in the hot-liner concept must be resistant to the hydrogen contained in the process, to corrosion by free water in the concrete, and to fatigue. This material must also be sufficiently ductile to accommodate yielding without serious consequences.

Liner Stresses

The liner used with a hot-liner application is installed at a temperature of about 294 K (70°F) and operates at a temperature of about 561 K (550°F). A portion of the thermal expansion associated with this 267 K (480°F) temperature change is constrained and creates thermal stresses which can be large compared with the yield stress.

When the liner is installed at a temperature of 294 K (70°F) and the PCPV is prestressed, compressive stresses equal to about 117 MPa (17 ksi) are imposed on the liner in the circumferential direction. Since pressurization of the vessel is assumed to create a liner tension of 117 MPa (17 ksi) in the circumferential direction, the prestress- and pressure-induced stresses will balance. The maximum liner compressive strain occurs when the vessel is prestressed, the liner temperature is 561 K (550°F), and there is no internal pressure. If the radial displacement (including thermal expansion of the inner concrete region) of the PCPV is neglected and the liner remains elastic, the maximum compressive strain induced in the liner is given by

$$\sigma/E_s + \Delta T\alpha_s \ , \qquad (4.1)$$

where

σ = stress due to prestressing [117 MPa (17×10^3 psi)],
E_s = modulus of elasticity of the liner [207 GPa (30×10^6 psi)],
ΔT = increase in temperature from ambient [267 K (480°F)], and
α_s = coefficient of thermal expansion of the liner.

The compressive yield stress required to avoid plastic deformation in a carbon steel would be above 758 MPa (110 ksi). Since steels suitable for liner materials do not have yield strengths this high, yielding will occur in compression.

The maximum tensile liner strain occurs when the liner is cooled and the vessel is pressurized. Assuming the liner has yielded in compression, the tensile strain associated with these conditions will be

$$\sigma/E_s + \Delta T\alpha_s - \varepsilon_y \ . \tag{4.2}$$

here ε_y is the yield strain of the liner and perfectly plastic behavior is assumed.

If the liner material is perfectly elastic-plastic and yields in compression, the yield strain which will permit elastic response for the operating conditions just discussed is $(\sigma/E_s + \Delta T\alpha_s)/2$. If the liner material is carbon steel with $\alpha_s = 11.7 \times 10^{-6}$/K ($6.5 \times 10^{-6}$/°F), the yield strength must be at least 379 MPa (55 ksi). If the liner material is stainless steel with $\alpha_s = 16.2 \times 10^{-6}$/K ($9.5 \times 10^{-6}$/°F), the yield strength must be at least 503 MPa (73 ksi).

Since the liner will experience inelastic strains, fatigue must be considered. The proposed design life of a PCPV gasifier is assumed to be 40 years, with two shutdown and startup cycles expected per year. The effects of these eighty loading cycles were included in the material selection criteria for a hot-liner steel.

The steel liner in the cold-liner concept, in the main, remains elastic during normal vessel operation. Exceptions may be found in discontinuity regions, such as the vicinities of openings or penetrations. Section III, Division 2 of the ASME Code contains specific requirements for cold-liner designs, including maximum allowable liner stress and strain limits.

In summary, factors which influenced the selection of a material for hot-liner use are as follows:

Thickness	0.02 m (0.75 in.) minimum
Design temperature	589 K (600°F) maximum
Yield strength required for elastic behavior	503 MPa (73 ksi) minimum (stainless steel) 379 MPa (55 ksi) minimum (carbon steel)
Corrosion aspects	
Inside surface	Process environment
Outside surface	Evaporation and condensation of free water in concrete
Thermal fatigue	80 startup and shutdown cycles
Hydrogen partial pressure	1.79 MPa (260 psi)

Liner Material Selection

A low-alloy steel, 2 1/4 Cr—1 Mo steel, was selected for the hot-liner application. The choice of carbon steel is unattractive because of the hydrogen atmosphere—operating temperature combination. Stainless steels are also unattractive because of cost and unavailability of stainless steels that have yield strengths of 503 MPa (73 ksi) to minimize inelastic strains and are stable for the service life. The experience-based Nelson diagram[1] (see Fig. 4.1) was used as an aid in making the selection. At 589 K (600°F), the minimum alloy content required for the liner is 0.5% Mo. As mentioned, the Nelson curves are based on experience with various alloy steels, and the limits of hydrogen attack are estimates.

For the material selected, the inner surface of the liner must be protected from the process environment. This requires that the steel be clad or weld overlaid. The alloying elements of 2 1/4 Cr—1 Mo steel will ensure that hydrogen attack is not an embrittlement mechanism; this steel should provide protection against methanation up to about 672 K (750°F). (Methanation, the combination of the C in steel and H_2 in the atmosphere to form CH_4 gas, which concentrates as bubbles at the grain boundaries, is the elevated-temperature hydrogen attack mechanism.)

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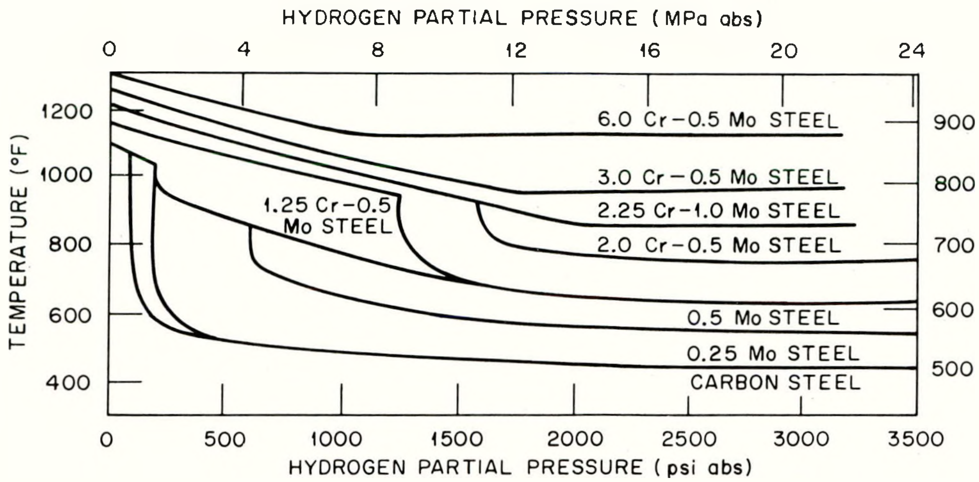

Fig. 4.1. Operating limits for steels in hydrogen service — the Nelson curves.

The 421-MPa (61-ksi) yield strength requirement associated with this steel poses a problem. There are two ASME specifications that cover 2 1/4 Cr—1 Mo steel plate; these are SA 387 grade 22 and SA 542. The minimum yield strength requirement for SA 387, grade 22, class 2 is 310 MPa (45 ksi). The minimum requirement for SA 542 is 586 MPa (85 ksi). The section size required for this application, 0.02 m (0.75 in.), is thin enough that the 421 MPa (61 ksi) requirement can be met with a normalizing (air cooled after austenitizing) and tempering heat treatment. (The SA 542 specification is for quenched and tempered plate.) The material selected* is SA 387 grade 22, which must be heat treated to a minimum yield strength of 421 MPa (61 ksi). This can be done by austenitizing the plates at 1200 K (1700°F) for about 1 to 2 hr followed by air cooling. The steel would then be tempered at temperatures between 950 K (1250°F) and 977 K (1300°F) for about 1 hr.

To protect the low-alloy plates from the process corrosion, an 18-8 stainless steel layer is applied to the inner surfaces. Since there are data[2] which show that the corrosion rates for materials with less than

*This may necessitate obtaining an ASME Code Case to allow the use of SA 387 grade 22 at higher stress levels.

17-18% Cr increase rapidly, 18% was chosen. Roll cladding was selected over the less expensive weld overlay method to avoid warping of the plate. By roll cladding the plates and then heat treating the composite, the desired properties in the 2 1/4 Cr—1 Mo steel can be obtained. The cladding operation can be done in accordance with SA 264, *Specification for Stainless Chromium-Nickel Steel Clad Plate Sheet and Strip*.

Protection against the vaporization and condensation of free water in the insulating concrete will be provided by the alloying elements, particularly Cr, in the steel. A corrosion allowance of 6.4×10^{-3} m (0.25 in.) is to be added to the plate to ensure that the minimum required thickness of the base material of the liner is maintained.

In the case of the cold liner [liner operating temperature of about 339 K (150°F)], hydrogen attack and the formation of methane need not be considered. Therefore, carbon steel, which conforms to the requirements of SA 537 class 1 steels, was selected for this application. A 6.4×10^{-3} m (0.25 in.) type 304 stainless steel cladding which is roll bonded, or explosively clad, will provide protection from the process environment. No corrosion allowance is required on the outer surface of the liner, since the concrete free water does not vaporize on this surface.

The selection of forgings, which are required to complete the pressure boundary, was assumed to be governed by the same criteria as the
since the concrete free water does not vaporize on this surface.

The selection of forgings, which are required to complete the pressure boundary, was assumed to be governed by the same criteria as the
liner materials. Forging materials were therefore selected to be entirely compatible with the liner materials.

Anchor Studs and Shear Anchor Assemblies

The steel anchor studs which are welded to the steel liner provide both resistance to liner buckling and support for loadings which are perpendicular to the liner. They also resist forces parallel to the liner, which are created when a force imbalance occurs on opposite sides of an anchorage due to such factors as temperature differences, liner material thickness variations, liner-to-concrete bond variations, and liner curvature acting singly or in combination.

A 0.03-m-diam (0.25-in.) head is used on the end of each stud to provide a mechanical bond with the concrete to ensure that the full tensile strength of the anchor stud can be developed. In order to ensure adequate liner buckling resistance up to liner strains of at least twice the liner yield strain, the anchors must be located at a spacing less than or equal to ten times the liner thickness. This requirement is met, since the anchor stud spacing for the hot-liner concept is 0.15 m (6 in.) and the spacing for the cold-liner concept is 0.18 m (7 in.). However, these spacings may require modification in regions of the vessels where there are discontinuities or where liner force imbalances from sources like those listed above are likely to occur.

Section III, Division 2 of the ASME Code requires that an analysis be made to predict the behavior of the liner and liner anchorage system. The behaviors of hot-liner systems have been addressed only through analytical feasibility assessments, and demonstration testing has not been performed. In order to meet the intent of the ASME Code, a feasibility demonstration is required. The associated developmental work is discussed in the follow-up program definition section.

Shear anchors are provided in the PCPVs to efficiently transfer pressure-induced loadings to the structural concrete vessel. The shear and bearing stress limits given by the Code for concrete were used to develop the anchor assembly design. Bonded reinforcing steel is to be located near the shear anchor to provide confinement for the concrete. In the hot-liner concept, additional cooling of the supporting concrete near the shear anchor assemblies is required to maintain concrete temperatures within allowable limits. Since these anchorages are not in contact with the process environment, cladding is not required.

The anchor studs in either the hot-liner or cold-liner concepts will operate at temperatures below 533 K (150°F). Furthermore, the service environment in which these studs will operate is nearly identical to that of a nuclear reactor vessel. Thus, material permitted in paragraph CB 2621.1 of Section III, Division 2 of the ASME Code is taken as being applicable to the coal conversion system under study. The Code permits the use of ASTM A108, *Cold Finished Carbon Steel Bars and Shafting,* for the designs being discussed. The preferred grade in that specification is 1015, which will match the carbon content of the SA 387 grade 22 liner steel. Furthermore, the low carbon should minimize welding problems.

Removable Steel Closure Plug

The design temperature for the removable steel closure plugs is 589 K (600°F) maximum. Since the temperature of the gas to flow through the Synthane vessel plug is approximately 1200 K (1700°F), a refractory lining is to be provided on the plug for both insulating purposes and erosion resistance. The operating temperature at the plug in the HYGAS process is 589 K (600°F), and therefore this member generally does not require an insulating refractory lining, but a refractory lining is to be provided to protect the closure plug from erosion. The removable steel closure plug for the Synthane vessel is illustrated in Figs. 3.7, 3.8, and 3.9. The steel closure plug for the HYGAS vessel is of similar design.

Since the closure plug material operates at hot-liner temperatures, SA 387 grade 22 steel was selected. A type 308 stainless steel cladding is to be applied to the faces of the plug which are exposed to the corrosive environment. This plug can be classified as a steel pressure vessel and therefore is to be designed according to Section VIII of the ASME Code.[3]

Penetration Liners and Closures

The sections of penetration liners which are backed by concrete are designed as PCPV liners, and the sections which are not backed by concrete are designed as steel pressure vessels. Section III, Division 2 of the ASME Code provides design procedures for the transition regions of penetrations.

The Code does not specify design procedures for the design of penetration liner—cavity liner intersections. The three-dimensional analytical procedures that are required to verify the design configurations in these regions were not used in this study for the conceptual designs.

Two different penetration configurations were investigated. In the Synthane PCPV, the refractory extends the full length of the manway penetrations. In the HYGAS PCPV, the refractory is terminated near the cavity liner to reduce the degree of discontinuity of the inside vessel surface. Process requirements will dictate which design is more acceptable; however, from the standpoint of liner temperature protection and accessibility, the design features in the Synthane PCPV are more acceptable.

In any case, penetrations create disruptions in the vessel cooling system and require cooling system modifications. Additional cooling circuits can be added to maintain the required temperature profiles.

References

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5. REFRACTORY LINING AND COOLING SYSTEM

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A refractory lining and a cooling system are required in a PCPV design to protect the liner, concrete, and prestressing materials from the process temperatures. As previously stated, two design concepts were considered in this study. The hot-liner concept featured in the reference design configurations maintains the liner temperature above the dew point temperature of the process 505 K (450°F). The cold-liner concept discussed in this report maintains the liner temperature at about 339 K (150°F).

Design Criteria

The hot-liner and cold-liner designs illustrated in Figs. 5.1 and 5.2 were developed according to the criteria defined in this section.

Temperature limits

In order to ensure adequate vessel cooling, the cooling system is laid out according to Fig. 3.11 in discrete cooling circuits, with every other cooling tube supplied from the same coolant source. Each design concept was developed so that the temperature limits identified in Table 3.3 are not exceeded during normal vessel operating conditions, in which all of the cooling tubes are in operation, and during the off-design condition in which every other cooling tube is in operation. The structural design requirements limit the temperature drop through the structural concrete walls to 22 K (40°F) during normal operating conditions and to 39 K (70°F) during off-design operating conditions.

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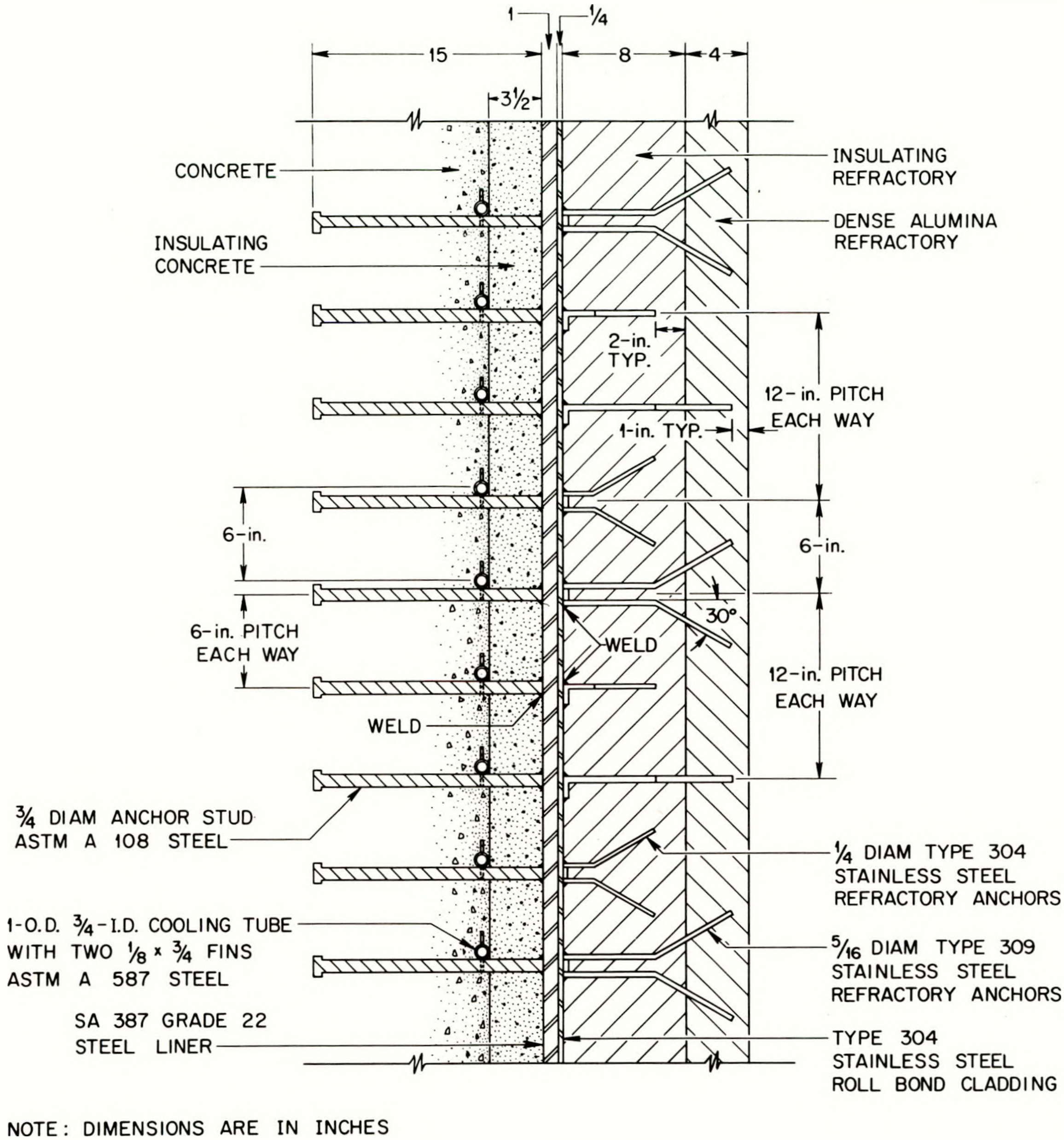

Fig. 5.1. Hot-liner concept.

Refractory thickness limitations

The vessel design configurations and requirements established by C. F. Braun and Co. specified inside diameters of the inner surface of the refractory lining. In establishing the inside diameters of the steel liner surfaces, the following refractory thicknesses were assumed at an early

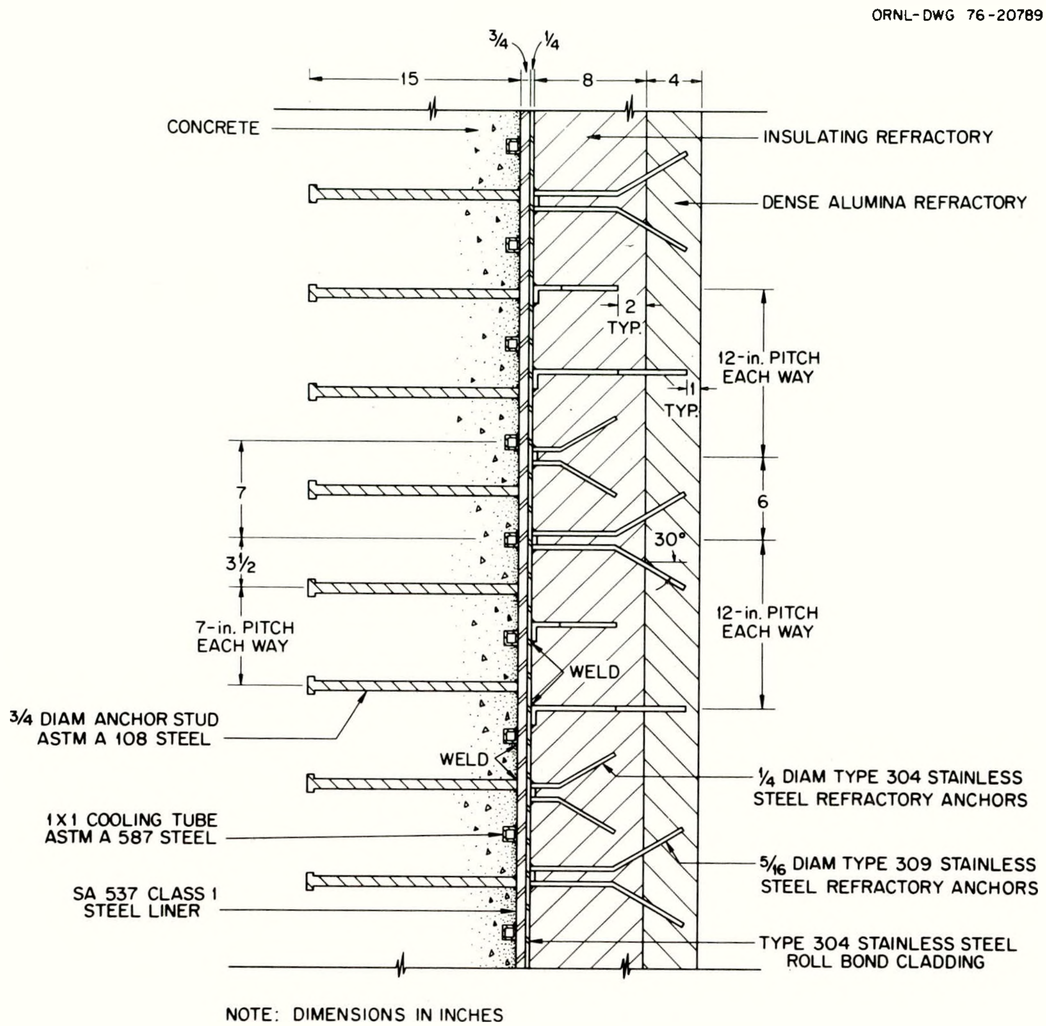

Fig. 5.2. Cold-liner concept.

stage in this study so that the development of the conceptual PCPV designs could proceed concurrently with the development of the liner concepts.

Vessel region	Refractory thickness	
	Hot liner	Cold liner
HYGAS upper section	0.10 m (4 in.)	0.20 m (8 in.)
HYGAS lower section	0.30 m (12 in.)*	0.30 m (12 in.)*
Synthane	0.30 m (12 in.)	0.30 m (12 in.)

*This thickness was treated as a variable in the heat transfer analyses and is discussed further in the succeeding sections.

The thickness of refractory generally included a 0.10-m (4-in.) thickness of dense alumina refractory to protect the steel liner from the erosive process materials.

Component Description

The components which are considered part of the refractory lining and cooling system include the dense alumina refractory, insulating refractory, insulating concrete, and cooling tubes. Items included in the development of the liner concepts were refractory anchors, anchor studs, and the steel liner.

Refractory linings

The refractory liner system must serve at least two major functions: (1) abrasion-erosion protection of the metal liner pressure boundary from high-velocity coal, char, and ash particles, and (2) thermal insulation to provide desired temperatures at the inner surface of the metal liner. These two properties are usually not found in the same material, since good abrasion resistance typically requires a high density, with its accompanying higher mechanical integrity, and the thermal conductivity of a solid typically increases as a direct function of the density. It is common practice in such cases to utilize two or three component linings, with a high-density erosion-resistant material covering a less abrasion-resistant refractory having lower thermal conductivity.

Two types of refractory wall construction are available, those consisting of bricks and the so-called monolithic type. The latter type of refractory installation is poured, rammed, or gunned into place and is favored for this installation, since it is much easier and cheaper to install and repair in a vessel of the size considered here.

The presence of H_2 and H_2O in the process atmosphere imposes a limitation on the materials which can be used. The SiO_2 content must be kept very low, since these gases will preferentially remove SiO_2 from refractories[1,2] under these conditions. This type of attack produces a structure which is very weak and susceptible to erosion. A further limitation is that the Fe_2O_3 content of the refractory must be low. This is due to the so-called "carbon disintegration" effect, whereby Fe catalyzes the reduction of CO from the atmosphere to C within the refractory, causing local concentrations of carbon in the pores with resultant refractory spalling.[1] The major constituent of the refractory for gasifier application might be Al_2O_3, since alumina-based castable or gunnable refractories have shown excellent performance[3,4] in ammonia reforming plants where the atmospheric chemical constituents are similar to those in a gasifier atmosphere. Due to these considerations, the refractory system of choice is the following: (1) a dense high-alumina castable with low Fe_2O_3 and SiO_2 contents covering (2) an insulating castable refractory of lower density. The insulating castable should also be of high-alumina content with low iron and silica, since the dense castable must be assumed to contain cracks which allow the active gas species to contact the insulating material.

A survey of 59 refractory manufacturers in the U.S. disclosed 25 companies which produce materials of the type described. At least 47 brands of the dense abrasion-resistant refractory and 14 of the insulating high-alumina castable refractory were identified, and information on their chemical and physical properties was collected. Based on currently available data, most of these materials appear suitable for the intended application. The thermal conductivity values for the dense materials were found to vary from 1 to 2.7 W/m K (7 to 19 Btu/hr ft^2 °F/in.) at 1089 K (1500°F). For the insulating castables at the same temperature, the range was from 0.5 (3.5) to about 0.9 (6.5). All reported conductivity vs temperature data, $\lambda(T)$, were measured in air atmosphere at 0.10 MPa (1 atm).

Both the Synthane and HYGAS processes involve a high-pressure [~6.89 MPa (~1000 psi)], high-temperature [~1255 K (~1800°F)] atmosphere, a significant proportion of which is the very highly conductive gas, H_2. Previous investigations[5,6] of the effect of highly conductive gas atmospheres on the thermal conductivity of refractory castables have shown that the simple Ribaud equation will properly describe the contribution of the conductive gas. This equation is

$$\lambda_R = \lambda_S\,(1 - P^{2/3}) + \lambda_G\,P^{1/3}\ , \qquad (5.1)$$

where

λ = thermal conductivity,

λ_R = thermal conductivity of refractory in gas atmosphere,

λ_S = thermal conductivity of pure dense refractory,

λ_G = thermal conductivity of gas in pores of refractory,

P = volume fraction porosity.

Since the manufacturer's data is essentially $\lambda_{R,air}$, the equation could be written

$$\lambda_{R,air} = \lambda_S (1 - P^{2/3}) + \lambda_{air} P^{1/3} \quad (5.2)$$

and used to solve for λ_S, knowing P (Ref. 7) and λ_{air} (Ref. 8). Then, again using P and the λ_S obtained along with literature data for λ_G (Ref. 8), one gets λ_R from Eq. (5.1). Or combining Eqs. (5.1) and (5.2),

$$\lambda_R = \lambda_{R,air} + P^{1/3} [\lambda_G - \lambda_{air}] \; . \quad (5.3)$$

This process was followed in adjusting the λ(T) data available from the refractory manufacturers so that they were relevant to gasification processes, making the following assumptions: (1) the process gas is 100% H_2 and (2) the entire pore volume of the refractory is filled with H_2. These assumptions are made to force the conductivity data to describe the worst possible case, that is, a gas of the highest possible conductivity completely replacing the gas in the pores. They are also necessary for simplifying calculations, since estimating λ(T) for the possible gas mixtures present in a gasifier is extremely difficult, and we have no data on how this atmosphere would be distributed in the pores of the refractory during gasifier operation.

The material selected for the dense innermost wall was Harbison-Walker Castolast G. This is a representative material for this application, since its λ(T) behavior resembles that of the majority of the candidate materials and its composition (see Table 5.1) is typical of those

Table 5.1. Thermal conductivity of refractories

T [K (°F)]	Thermal conductivity, W/m K (Btu/hr ft^2 °F/in.)					
	Dense castable[a]			Backup insulation[b]		
	in air	in H_2[c]	in H_2[d]	in air	in H_2[e]	in H_2[f]
366 (200)						
422 (300)						
473 (392)	1.92 (13.35)	2.05 (14.24)	2.08 (14.42)	0.95 (6.60)	1.13 (7.85)	1.15 (7.95)
573 (572)	1.87 (12.95)	2.02 (13.99)	2.05 (14.20)	0.88 (6.10)	1.09 (7.55)	1.11 (7.67)
752 (673)	1.80 (12.50)	1.97 (13.68)	2.00 (13.91)	0.82 (5.70)	1.06 (7.35)	1.08 (7.49)
773 (932)	1.74 (12.05)	1.92 (13.33)	1.96 (13.59)	0.79 (5.45)	1.04 (7.24)	1.07 (7.39)
873 (1112)	1.68 (11.65)	1.88 (13.06)	1.93 (13.36)	0.76 (5.30)	1.05 (7.28)	1.07 (7.45)
973 (1292)	1.63 (11.30)	1.85 (12.82)	1.89 (13.13)	0.74 (5.15)	1.05 (7.28)	1.08 (7.46)
1073 (1472)	1.58 (10.95)	1.81 (12.57)	1.86 (12.90)	0.74 (5.15)	1.07 (7.42)	1.10 (7.61)
1173 (1652)	1.55 (10.75)	1.80 (12.48)	1.85 (12.83)	0.74 (5.10)	1.08 (7.51)	1.11 (7.72)
1273 (1832)	1.53 (10.60)	1.78 (12.38)	1.84 (12.75)	0.73 (5.05)	1.09 (7.55)	1.12 (7.76)

[a]Castolast G, Harbison-Walker Refractories, 93.7% Al_2O_3, <0.5% Fe_2O_3, SiO_2.

[b]Harbison-Walker Lightweight Castable 33, Harbison-Walker, 92.6% Al_2O_3, <0.5% Fe_2O_3, SiO_2.

[c]Assumed porosity is 20% when the pores are completely filled with H_2.

[d]Assumed porosity is 35% when the pores are completely filled with H_2.

[e]Assumed porosity is 55% when the pores are completely filled with H_2.

[f]Assumed porosity is 70% when the pores are completely filled with H_2.

currently considered to have adequate performance. Furthermore, Castolast G was previously selected for the Synthane prototype plant in Bruceton, PA.

The conductivity data for Castolast G are listed in Table 5.1, and the curves are shown in Fig. 5.3. Since the porosities of this material after firing usually amount to 20 to 35 vol.%, the thermal conductivity data presented are for these two values of *P*. Also given are the manufacturer's data (air data).

The backup insulation chosen as a representative material was Harbison-Walker Lightweight Castable 33. The reasons for this selection are as described above. The data was similarly adjusted, but the much higher final porosities (55 through 70%) for this material cause larger changes in thermal conductivity when H_2 is present, as shown in Table 5.1 and Fig. 5.4.

Refractory anchor

An important component of the liner system is the anchor network, which mechanically holds the refractory in place and transfers part of the support load to the shell. Numerous types of anchors exist, the most

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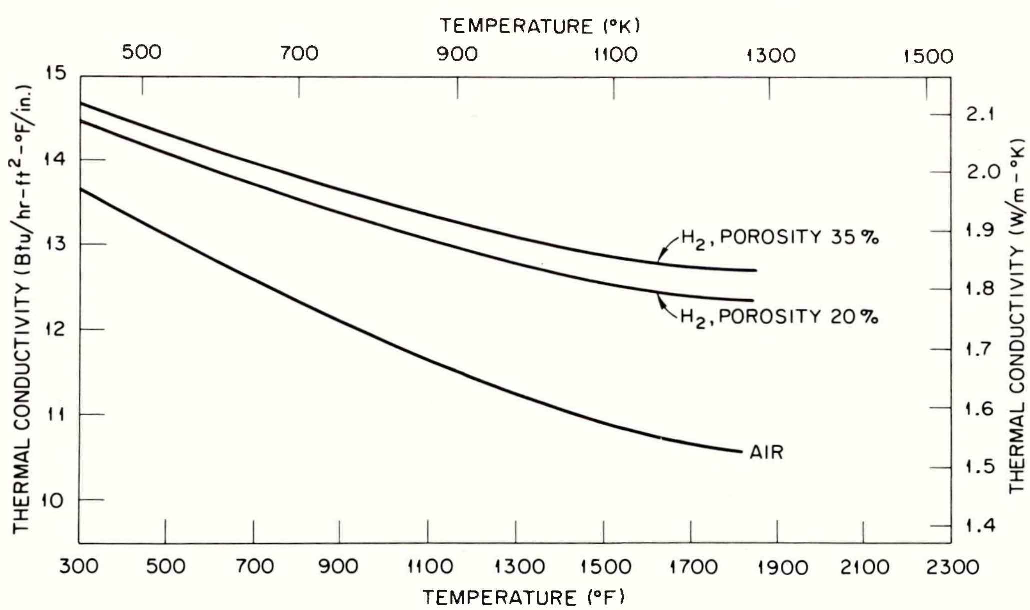

Fig. 5.3. Thermal conductivity of Harbison-Walker Castolast G refractory.

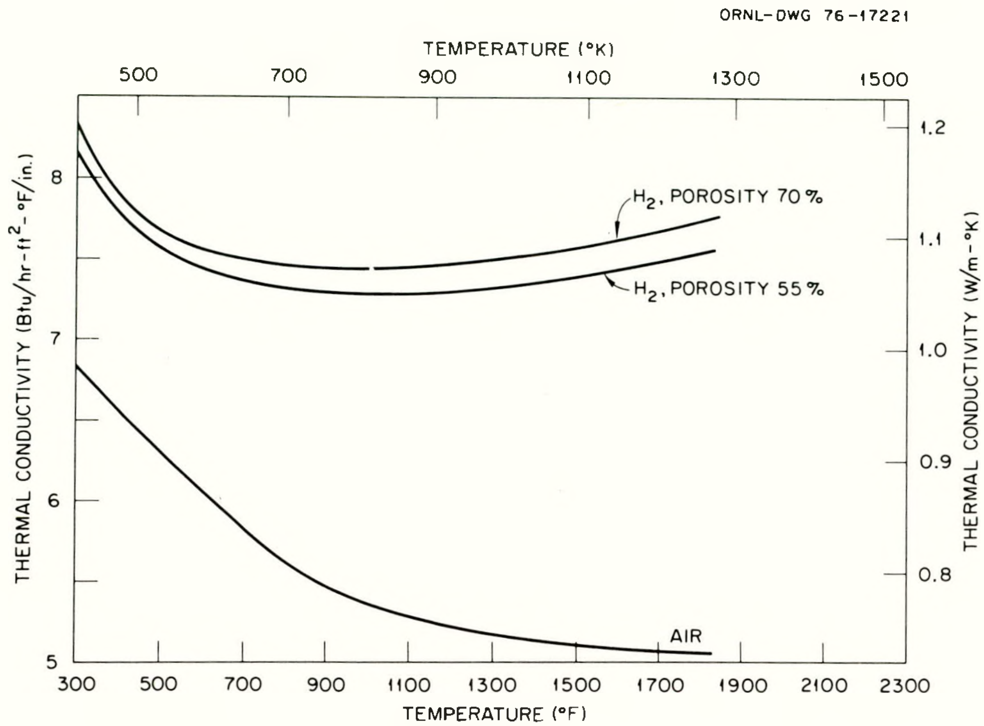

Fig. 5.4. Thermal conductivity of Harbison-Walker Castable 33 refractory.

common being "V"- or "Y"-shaped metal pieces which are welded to the shell prior to emplacement of the ceramic lining. For temperatures below 1366 K (2000°F) but above 922 K (1200°F), stainless steel is typically used. Since stainless steel has a higher thermal expansion coefficient than the ceramic refractory, the refractory may tend to be pushed away from the metal shell during heatup. Because it is desirable to prevent the flow of hot gas into the region between the refractory backup and the metal, a double anchoring system consisting of two separate networks of steel anchors is recommended. One would extend from the liner to three-fourths of the distance through the backup castable insulating refractory and consist of 6.4×10^{-3}-m-diam (0.25-in.) type 304 stainless steel rod bent into a "Y" configuration, as shown in Fig. 5.5. These anchors would be spaced on 0.30-m (12-in.) centers. The second anchor system would extend from the shell through the backup refractory and three-fourths of the thickness of the dense castable refractory front wall. These would be

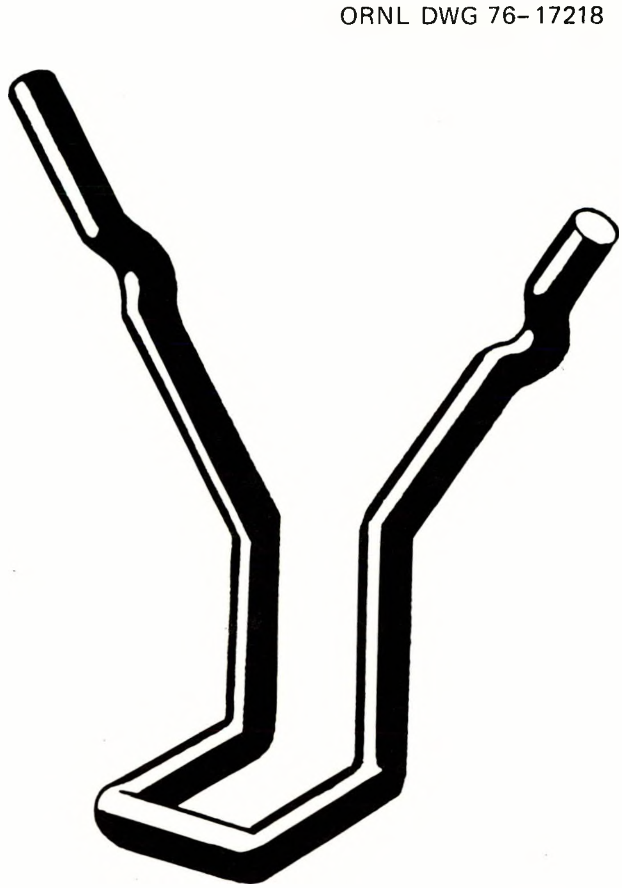

Fig. 5.5. Refractory anchor, showing "Y" configuration.

"Y"-shaped, 7.8×10^{-3}-m-diam (0.31-in.), type 309 stainless steel anchors spaced on 0.30-m (12-in.) centers and located in a staggered pattern halfway between the shorter anchors described previously. The planes of the "Y" shapes, as shown in Fig. 5.5, should be rotated 90° with respect to each other at adjacent locations. Thermal conductivity data for types 304 and 309 stainless steel are presented in Fig. 5.6 and Table 5.2.

The $\lambda(T)$ data given, when combined with the proper process heat release rate, inner and outer wall temperatures, and geometrical parameters, should be sufficient to calculate the thickness of the various required refractories. Mechanical performance must also be considered, and, if the refractory thicknesses are too great from this standpoint, other materials with lower thermal conductivities must be examined.

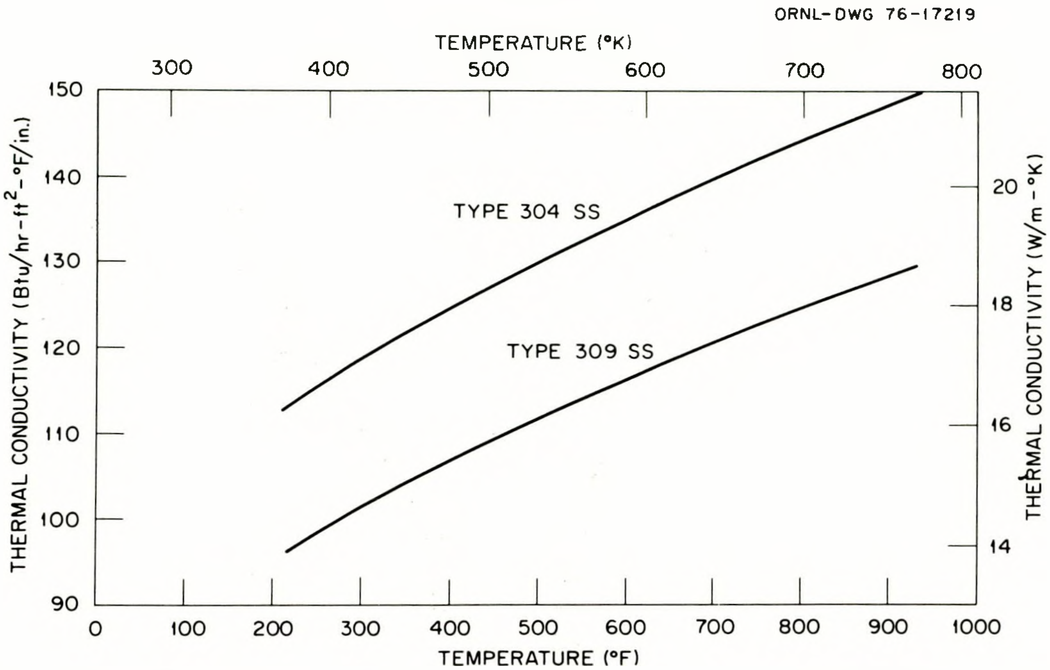

Fig. 5.6. Thermal conductivity of stainless steel refractory anchors.

Table 5.2. Thermal conductivity of stainless steel refractory anchors

T [K (°F)]	λ [W/m K (Btu/hr ft^2 °F/in.)]	
	Type 304	Type 309
373 (212)	16.3 (112.8)	13.8 (96.0)
473 (392)	17.8 (123.6)	
573 (572)	19.0 (132.0)	
673 (752)	20.4 (141.6)	
773 (932)	21.6 (150.0)	18.7 (129.6)

Insulating concrete

The insulating concrete layer in the hot-liner concept serves to protect the structural concrete from hot steel liner temperatures and to transmit temperature- and pressure-induced loadings from the liner to the structural concrete. Desirable insulating concrete properties include low thermal conductivity, low coefficient of thermal expansion, low elastic modulus and low compressibility. Materials which are very good insulators generally are undesirable, since they are too compressible and do not satisfactorily transmit pressure-induced liner forces to the structural concrete. Materials which are stronger and less compressible are generally poor insulators and therefore larger thicknesses are required. The material selected for the insulating concrete must be a compromise between these two extremes; the properties of this material were given in Chapter 3. Candidate materials include artificial aggregate concretes of expanded clay as well as natural aggregate concrete of limestone, porphyry, and diorite.[9] Refractory concretes may also have suitable properties; however, additional investigations and testing are required to evaluate the engineering properties of the candidate materials before a final selection can be made.

The insulating concrete layer must be placed before the cooling tubes and structural concrete are installed. The constructibility of a PCPV with a hot-liner must be demonstrated to ensure that the materials behind the liner which cannot be repaired or replaced can be properly installed before the structural concrete is cast.

Cooling tubes

Cooling tubes permit vessel temperature control and provide a means for vessel hot-spot monitoring. The shape and spacing of the tubes are different for the hot- and cold-liner concept, but the overall cooling circuit layout for each system is similar. The cooling tubes and coolant systems were described in Chapters 3 and 4.

In the cold-liner concept, adequate vessel cooling is obtained by welding 0.025 × 0.025 m (1 × 1 in.) square tubes having a wall thickness of 0.0032 m (0.125 in.) to the steel liner on a pitch of 0.18 m (7 in.). In the hot-liner concept, 0.025-m-OD (1-in.), 0.02-m-ID (0.75-in.) tubes are required. These tubes have fins attached to opposite sides; the fins are 0.02 m (0.75 in.) high and 0.0032 m (0.125 in.) wide and are continuously welded to the tubes. The tubes are installed by attaching the fins to the liner anchor studs at the outside surface of the insulating concrete layer and are thus located on a pitch of 0.15 m (6 in.). They are to be made from ASTM A587 steel in all cases.

Each tube is to extend halfway around the vessel liner and every other tube is to be supplied from the same coolant water source. Figure 3.11 depicts the cooling system layout. Three tubes are connected by one line to the coolant water supply and return headers. The single line which extends from the vertical header, through a precast opening in the concrete channel, and into the structural concrete is equipped with a temperature monitor and a flow-control device. These systems are located between the vertical header and the PCPV to permit measurement of coolant temperature rise and regulation of coolant flow.

The cooling tube system must also accommodate cooling requirements around penetrations and in the hemispherical head regions. These additional lines should employ the same type of redundant cooling circuits as used in the liner cooling system.

Thermal Analysis

The hot-liner and cold-liner designs were verified by thermal analysis investigations. The thermal analyses were performed using a computer program entitled *HEATING 5 — An IBM 360 Heat Conduction Program.*[10] Details of the program are discussed in Appendix C. The analytical models of the hot- and cold-liner designs were based on an axisymmetric section of the PCPV cylinder. The height of the model extended from a plane at the centerline of an operating cooling tube to the midplane between operating cooling tubes. Each model represented the hottest regions of the vessels, where the inside surface of the two-layered refractory system was at a temperature of 1255 K (1800°F).* The variables examined were the thickness of the insulating refractory, cooling tube spacing, cooling water inlet and exit temperatures, coolant flow rate, external insulation thickness, and (in the case of the hot-liner concept) the thickness of

*The temperature in the hottest region of the Synthane gasifier will be a little less than this value and a little more in the HYGAS gasifier.

the insulating concrete layer. In order to restrict the size of the problem, the following variables were held fixed:

Dense alumina refractory thickness	0.10 m (4 in.)
Steel liner thickness	0.02 m (0.75 in.)
Structural concrete thickness	3.05 m (120 in.)

The effects of the anchor studs, refractory anchors, and reinforcing bars were not included in the analysis, and all materials were assumed to be homogeneous. The refractory system was assumed to consist of an inner layer of dense alumina refractory (Castolast G) and an insulating refractory (Lightweight Castable 33). In the analyses, the thickness of the insulating refractory was allowed to vary to suit other requirements, as mentioned above. The temperature-dependent properties that were used for the Castolast G and the Lightweight Castable 33 are listed in Table 5.1 and illustrated in Figs. 5.3 and 5.4. In order to develop the most conservative design configurations, the highest conductivities (maximum porosity filled with H_2) were always used. The boundary conditions for the inner and outer surfaces were specified as isothermal. The inner surface was specified as 1255 K (1800°F), and the temperature of the outer surface of the structural concrete was not permitted to fall below 300 K (80°F). The tubes were represented in the model by a rectangular cutout with a forced convection boundary condition applied to the surface.

The temperature limits listed in Table 3.3 were used.

Thermal analysis of the hot-liner concept

Parameter study. Utilizing the computer model just outlined, a parameter study was carried out by running a series of cases in which the various thicknesses of interest, tube size, tube spacing, coolant temperature, and forced convection heat transfer coefficient were each varied over a range of values. As a result of this parameter study, several conclusions were reached.

1. As would be expected, the main effect of decreasing the tube spacing is a decrease in the temperatures midway between tubes, with the greatest change at the interface of the insulating concrete and the structural concrete.

2. For a given tube spacing, the heat transfer is primarily determined by the thicknesses of the refractories and insulating concrete. For a given bulk coolant temperature, large changes in the coolant mass flow rate had only minimal effects on the temperature around the cooling tubes and almost no effect at points removed from the cooling tubes. However, the coolant mass flow rate is important in that it directly determines the coolant temperature rise through the circuit. Varying the tube size also had a minimal effect on temperatures very near the tube and almost no effect farther away from the tubes. Even changes in the coolant temperature produced only localized temperature changes around the tube of approximately the same amount as the change in coolant temperature. At any appreciable distance away from the cooling tube, the temperature changes decreased rapidly.

3. The temperature of the outer surface of the structural concrete was varied to see what effect it would have on the temperature distribution. Since this is not truly an outer boundary in the actual pressure vessel, care was taken in applying a boundary condition to it in the computer model. A temperature of 300 K (80°F) was selected based on a consideration of the stress caused by a thermal gradient in the structural concrete. The outer insulation thickness was chosen to maintain a temperature of 300 K (80°F) at this surface when the ambient temperature is at its lowest anticipated value [239 K (—30°F)]. Obviously, when the ambient temperature is higher, the structural concrete temperature will also be higher. A series of test cases was run to determine the heat flow through the structural concrete for higher ambient temperatures. These test cases indicated that varying the outer boundary temperature over its entire possible range did not significantly affect the temperatures in the vicinity of the cooling tubes or inward from the cooling tubes, which is the area of interest. This result should be expected, since the heat flow through the structural concrete would be quite small compared to the heat flow from the inner surface of the pressure vessel to the cooling tubes. Therefore, the assumed outer boundary temperature of 300 K (80°F) appears to be a reasonable value.

4. Since it has been determined that the temperature distribution is largely dependent upon the thicknesses of the various materials and since the temperature restraints are at a minimum at one point and at a

maximum at others, it is very important to know how variations in the material thicknesses affect the temperature at various locations in the pressure vessel. To simplify the task of determining the various thicknesses, the erosion-resistant refractory was assigned a thickness of 0.10 m (4 in.) early in the problem analysis. Also, since the outer insulation thickness is determined separately using a heat balance calculation, the only thicknesses left to be determined by the computer program are the insulating refractory thickness and the insulating concrete thickness. The thicknesses of these two layers are interrelated since by increasing the thickness of the insulating refractory, the liner temperature and temperature along the insulating concrete—structural concrete interface are both decreased, and when the thickness of the insulating concrete is increased, the liner temperature is increased, but the temperature at the insulating concrete—structural concrete interface is decreased.

Results. The final design configuration was established on the basis of the parameter study results given in Table 5.3. The temperature distributions resulting from the normal and faulted condition cases for the final design configuration are presented in Table 5.4. In the cases run, the temperature restraint that was the most difficult to meet was the structural concrete temperature at the midplane between cooling tubes. In the final configuration selected, this restraint was compromised slightly in order to avoid decreasing the tube spacing below 0.15 m (6 in.).

Additional problems studied. A series of analyses was performed to determine the influence of various factors on the thermal response of the PCPV. In all of the analyses described below, the material thicknesses remain unchanged from those determined for the original problem.

1. Air gap around tubes. Since there is a possibility of the concrete shrinking away from the cooling tubes as it dries, an extreme case was considered where a 0.0016-m (1/16-in.) continuous gap would develop around each cooling tube. The heat transfer mechanisms across this gap were assumed to be radiation and conduction through air. The conclusion of this study was that the resistance to heat flow across the gap was so great that even if the tube spacing were decreased to the point where the tubes touched each other, sufficient heat could not be removed by the cooling tubes to attain the desired temperatures.

Table 5.3. Hot-liner design

Erosion-resistant refractory thickness, m (in.)	0.10 (4)
Insulating refractory thickness, m (in.)	0.30 (12)[a]
Insulating concrete thickness, m (in.)	0.09 (3 1/2)
Outer insulation thickness, m (in.)	0.25 (10)
Tube spacing, m (in.)	0.15 (6)
Tube size, m (in.)	0.025 (1 OD) 0.02 (3/4 ID)
Coolant mean velocity, m/sec (ft/sec)	0.70 (2.3)
Coolant inlet temperature, K (°F)	314 (105)
Coolant outlet temperature, K (°F)	319 (115)

[a]This thickness will be discussed further in the section, *Design Evaluation, Hot-Liner Concept,* which follows.

Table 5.4. Hot-liner concept temperature

	Normal[a]	Faulted[b]
Inner surface temperature, K (°F)	1255 (1800)	1255 (1800)
Liner temperature at tube centerline, K (°F)	577 (580)	608 (635)
Liner temperature midway between operating tubes, K (°F)	577 (580)	609 (637)
Structural concrete temperature at tube centerline, K (°F)	325 (126)	327 (130)
Structural concrete temperature midway between operating tubes, K (°F)	355 (180)	413 (284)

[a]Effective tube spacing: 0.15 m (6 in.).

[b]Effective tube spacing: 0.30 m (12 in.).

2. Finned tubes. Since the primary constraint had been the temperature of the structural concrete at a point midway between the cooling tubes, it was thought that improving the heat transfer between this point and the cooling tube might improve the results and possibly allow the tube spacing to be increased. In an effort to improve the heat transfer path, several cases were considered in which 0.02-m-long (3/4-in.) by 0.003-m-wide (1/8 in.) fins were attached to the top and the bottom of the cooling tube. The addition of the fins resulted in a decrease in the maximum structural concrete temperature as anticipated. For the normal operating condition [0.15-m (6-in.) spacing], the maximum structural concrete temperature was reduced from approximately 355 K to 352 K (180°F to 175°F).

In the faulted condition case, the decrease was from approximately 413 K to 407 K (284°F to 273°F).

3. Finned tubes with air gap. Another configuration studied was one with finned tubes in which it was assumed that the concrete had lost contact with the tube due to shrinkage, leaving a 0.0016-m (1/16-in.) gap around the tube, but was still in contact with the fins. Once again the heat transfer mechanism across the gap was assumed to be conduction through air and radiation. Since the maximum structural concrete temperature in the faulted case [0.30-m (12-in.) tube spacing] had been the controlling condition previously, a series of analyses was performed to determine the effect of various fin lengths on this temperature. For a fin length of 0.02 m (3/4 in.), the structural concrete temperature varied from approximately 369 K (205°F) at the plane of the tube to 422 K (300°F) at the midplane between cooling tubes. For a fin length of 0.025 m (1 in.), these temperatures decreased slightly, varying from 368 K (203°F) to 419 K (294°F), respectively. For a fin length of 0.032 m (1 1/4 in.), they dropped further to 366 K (200°F) and 415 K (288°F), respectively. It can be concluded from this study that adding 0.02-m (3/4-in.) fins to a tube having an air gap around it produces a significant improvement in heat transfer over that for a plain tube, but increasing the length of the fins gives only a minor benefit.

4. Effect of refractory anchors and concrete anchor studs. To determine the effects of the refractory anchors and concrete anchor studs on liner temperature variations, a separate analytical model, including the refractory anchors and anchor studs, was investigated. This axisymmetric model was a 0.15-m-diam (6-in.) cylinder with the longitudinal axis extending radially through the PCPV. Two models were considered. One model contained only the concrete anchor stud and provided a lower bound on the liner temperature. A second model contained the concrete anchor stud and a long stainless steel refractory anchor and provided a lower bound for the hottest liner temperature in an attachment area. The results of the local liner temperature analyses are listed in Table 5.5.

Difficulties in modeling the cooling tube produced conservative estimates of heat flow from the anchor studs to the cooling tubes; that is, the heat transferred is on the high side. For this reason, the results of Table 5.5 provide a lower bound on temperature variations of the liner. Actual liner temperatures would be expected to be below the computed temperature of 577 K (580°F) and above the dew point temperature of 505 K (450°F), which satisfies the hot-liner concept temperature limit criteria.

Table 5.5. Local liner temperature variations

Analytical model	Liner temperature at anchor stud
Concrete anchor stud only	476 K (398°F)
Concrete anchor stud and long refractory anchor	514 K (466°F)

Thermal analysis of the cold-liner concept

An axisymmetric thermal analysis was also performed for the cold-liner concept. In the cold-liner, the steel cooling tubes are 0.025 × 0.025 m (1 × 1 in.) square and are continuously welded to the steel liner with a 0.00047-m (0.1875-in.) fillet weld on each side of the tube. During the investigation the tube spacing, coolant temperature, and insulating refractory thickness were varied. An air gap of 0.0013 m (0.05 in.) was assumed between the liner and the cooling tube, and air gaps of 0.0016 m (0.0625 in.) were assumed between the cooling tubes and the structural concrete.

Results. The final design configuration developed on the basis of the thermal analyses is given in Table 5.6. The temperature distributions resulting from normal and faulted cases for the final design configurations are listed in Table 5.7.

Design Evaluation

The final design configurations for the hot-liner concept (Fig. 5.1) and the cold-liner concept (Fig. 5.2) satisfy the design requirements in

Table 5.6. Cold-liner design

Erosion-resistant refractory thickness, m (in.)	0.10 (4)
Insulating refractory thickness, m (in.)	0.30 (12)[a]
Outer insulation thickness, m (in.)	0.41 (16)
Tube spacing, m (in.)	0.18 (7)
Tube size, outside dimension, m (in.)	0.025 × 0.025 (1 × 1)
Tube size, inside dimension, m (in.)	0.02 × 0.02 (0.75 × 0.75)
Coolant mean velocity, m/sec (ft/sec)	0.52 (1.7)
Coolant inlet temperature, K (°F)	306 (92)
Coolant outlet temperature, K (°F)	317 (112)

[a]This thickness will be discussed further in the second section which follows.

Table 5.7. Cold-liner concept temperature distributions

	Normal[a]	Faulted[b]
Inner surface temperature, K (°F)	1255 (1800)	1255 (1800)
Concrete temperature at tubes, K (°F)	333 (140)	347 (165)
Concrete temperature between tubes, K (°F)	341 (154)	380 (224)
Concrete temperature at outside surface, K (°F)	314 (106)	337 (148)

[a]Effective tube spacing: 0.18 m (7 in.).

[b]Effective tube spacing: 0.36 m (14 in.).

that the temperature of the liner in the hot-liner concept is above the dew point temperature of the process, and the temperature of the liner in the cold-liner concept is as specified. An evaluation of the thermal behavior of the two liner concepts is discussed below.

Hot-liner concept

The final design configuration for the hot-liner concept provides adequate vessel cooling to ensure that the steel liner and structural concrete temperature limits are not exceeded during normal operating conditions as well as during faulted operating conditions in which every other cooling tube is not operational. The coolant inlet and exit temperatures and mean coolant velocity are realistic values, which can be monitored to identify cooling circuit malfunctions and vessel hot spots.

The 0.30-m (12-in.) insulating refractory layer thickness was determined from the most conservative thermal conductivity values and therefore provides an upper bound on the maximum required thickness of the insulating refractory. However, the total refractory thickness is 0.40 m (16 in.) instead of 0.30 m (12 in.) as postulated. To overcome this discrepancy, a material with lower thermal conductivity could be used; a thinner material layer would be expected to exhibit better mechanical behavior during operation. On the other hand, the 0.40-m (16-in.) thickness calculated could be used, in which case the sizes of the PCPVs must be increased slightly to accommodate the specified inside diameters of the process chambers.

The 0.09-m (3.5-in.) layer of insulating concrete should provide adequate thermal protection for the structural concrete and is a thickness which could be applied either by casting or gunning. The external insulation, which provides thermal protection for the circumferential prestressing steel and maintains the thermal gradient through the concrete wall in order to keep concrete stresses within acceptable limits, is to be 0.25 m (10 in.) thick. No problems are expected in this case.

The finned cooling tubes are capable of removing the excess heat that passes through the liner system and, at the same time, controlling the liner temperature. However, installation must be correct to ensure a good bond between the tubes and the structural concrete.

Before a final design configuration can be adopted, demonstrative testing of a section of a PCPV with a hot-liner concept should be performed to verify that the design will provide adequate vessel cooling and a means for monitoring vessel hot spots. Details of the necessary testing are discussed in the developmental program definition.

Cold-liner concept

The final design configuration for the cold-liner concept satisfies all specified structural concrete and steel liner temperature limits during both normal and faulted operating conditions. The coolant inlet and exit temperatures and mean coolant velocity are realistic values which can be monitored to identify cooling circuit malfunctions and vessel hot spots.

The computed total refractory thickness for the cold-liner concept is also 0.40 m (16 in.) The same comments concerning this thickness that were made previously in the hot-liner case apply here as well. The external insulation thickness in this case is to be 0.40 m (16 in.).

The square cooling tubes that were selected for the design provide adequate vessel cooling. However, the final design procedure of the cold-liner concept should include the consideration of round cooling tubes which are welded to the steel liner, since they would be more economical.

Overall evaluation

The hot-liner and cold-liner concepts have been examined using thermal conductivity values which were modified to reflect the atmosphere in a coal conversion process. Since the design requirements for the hottest regions of the PCPVs are the most stringent, these were considered in detail. Design configurations for cooler regions of the vessel would be addressed using similar procedures. Sophisticated thermal analysis techniques are required for carrying out these design procedures.

External Insulation

The external insulation thicknesses that are required to limit the temperature drop across the structural concrete walls were based on a thermal conductivity value of 0.065 W/m K (0.0375 Btu/hr ft^2 °F/ft); ambient temperatures assumed ranged from 239 to 308 K (—30 to +95°F). The insulating layer also protects the prestressing tendons from exposure to moisture and atmospheric corrosives.

Foamglas, which is a cellular or foam glass insulation manufactured by the Pittsburgh Corning Corp., was selected for the external insulating material. Although Foamglas has essentially zero moisture permeability, a waterproof coating is to be applied to the outside surface to seal the entire system. The insulation is to be installed in blocks and held in place by stainless steel strapping, or other suitable means.

Candidate materials for the finish coating include PITTCOTE 300, 400, 800, or 807AL (products of Plastics Coatings, Inc., and obtainable through Pittsburgh Corning Corp.) or perhaps JAXSAN 600 (also a product of Plastics

Coatings, Inc.) PITTCOTE 807AL would be the best choice if the color of the vessel is considered important. PITTCOTE 807AL is an aluminum pigmented asphaltic material and would give the vessel an aluminum appearance. The other coatings are black.

An alternate choice for the coating material for use in sealing the insulation against moisture intrusion would be one of the VAPALON coatings marketed by Exxon Chemical Co. of Houston, TX. These are butyl rubber-based coatings which are about one-tenth as permeable as the asphaltic coatings. These coatings adhere well to the foam glass insulation, and up to three coats can be applied according to the vendor's recommendations. The recommended material sequence for the application of this coating type for three coatings is (moving outward from the insulation) VAPALON Gray FR, Black FR, Gray FR.

Comparative Heat Loss Investigation for the HYGAS Vessel

Heat which flows through the pressure boundary of a vessel into the cooling water and/or surrounding atmosphere is lost from the gasification process. A rough estimate was made to obtain an indication of the amount of process heat that would flow through the liner of the HYGAS PCPV. For comparison, heat loss estimates were also made for an equivalent steel HYGAS vessel without external insulation.

In making these estimates, it was assumed that effects influencing the heat loss by less than ±20% could be ignored. It should be noted, in this connection, that the basic experimental data from which correlations for heat transfer from a solid surface to a fluid are derived typically scatter by about ±20% from the correlations. Since these correlations are important in the present estimates of heat loss, the computations for a steel vessel can be accurate only to within ±20%, even when refined calculations are made. Since significant extrapolations of the available correlations are required in the cases addressed here, the margin of error is probably about ±50%.

Because the heat loss computations were only approximations, detailed thermal designs were not made for all parts of the vessels, and computer studies were not carried out. However, use was made of the previously described computer studies for the high-temperature portion of the concrete vessel. Diameters of the steel liner and of the steel vessel were not exact, since the precise diameters depend on the thicknesses of refractory required.

The amount of heat that is lost from the steel vessel illustrated in Fig. 1.1 was considered. The design temperature for this vessel is 589 K (600°F), and the inner surface of the metal was assumed to be at this temperature. Computed heat losses for three different ambient conditions are listed in Table 5.8.

Table 5.8. Heat loss from steel HYGAS vessel

Condition	Heat loss [MW (Btu/hr)]
Still air at 308 K (95°F)	10.5 (36×10^6)
Still air at 239 K (—30°F)	12.6 (43×10^6)
13.4 m/s (30 mph) steady wind at 239 K (—30°F)	21.7 (74×10^6)

The heat loss calculations for the PCPV were performed for the reference design configuration illustrated in Figs. 3.4, 3.5, and 3.6. Since the thermal analysis results for the hot liner indicated that ambient conditions do not significantly affect the amount of heat lost from the vessel, only one calculation was performed, assuming still air at a temperature of 239 K (—30°F). The amount of heat removed by the cooling system and transferred to the atmosphere surrounding the PCPV is 3.2 MW (11×10^6 Btu/hr). From these results, the amount of heat lost from a PCPV could range from 15 to 30% of that from a bare steel vessel. Accounting for possible errors in steel vessel loss estimates, the maximum percentage could be about 60%.

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6. PROGRAM FOR FEATURE EXAMINATION AND CONCEPT DEMONSTRATION

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Much of the existing PCPV technology is based on 20 to 30 years of development and operating experience on concrete pressure vessels for nuclear power reactors. The ASME Code,[1] Section III, Division 2 provides the basis for designing prestressed concrete reactor pressure vessels and has been used to provide guidelines for designing the gasifier vessels. This Code has specific requirements for the development of vessels having geometries and operating conditions that differ significantly from existing types. In addition, all unique features, such as the proposed hot-liner system and the multiplate steel top-head penetration closure, will require demonstration of satisfactory performance potential and verification of design procedures.

The following tasks will provide the necessary information for design verification and concept demonstration for the proposed gasifier vessels.

1. PCPV structural behavior model tests.
2. Penetration closure development.
3. Liner, tendon, refractory, and insulating materials investigations.
4. Hot-liner system demonstration.

The proposed design verification program is based on past experience of the nuclear industry, on relevant code requirements, and on information developed to date under the present conceptual design effort. Information and procedures developed under parallel prestressed concrete reactor vessel development programs[2,3] will be integrated into the proposed program for development of coal conversion system gasifiers. Each of the four proposed tasks, which will provide the data for feature examination and concept demonstration, are discussed briefly in the following section.

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They will simultaneously provide data required by the ASME Code to support the design of the gasifier vessel selected for utilization in a coal gasification plant.

Because significant design information and guidance will be developed through the studies under the four task areas, the results are to be assembled for general use. This compendium is discussed in the second section of this chapter.

TASK DESCRIPTIONS

The tasks listed above are described in this section. These descriptions include the objective, scope, background information and status, work identifications, and the test plan for each. Generally, information pertinent to design development and demonstration is to be obtained; feasibility depends primarily on liner and thermal barrier system performance.

Task 1 — PCPV Structural Behavior Model Test

Objective

The objective of Task 1 is to demonstrate the structural adequacy of the vessel based on the proposed conceptual design and to demonstrate that the vessel will respond to overpressure in a gradual and predictable manner as required by the Code.

Scope

The proposed prestressed concrete gasifiers incorporate the following fairly unique features requiring verification by testing:

1. the top access penetration tendon and closure arrangement,
2. hemispherically shaped haunch regions,
3. interrupted sections of circumferential prestressing and pressurized penetrations through the concrete wall, and
4. transitions in internal cavity diameter and related change in external concrete diameter of the HYGAS PCPV.

Model tests must be conducted to

1. demonstrate that the structures behave elastically under design operating pressure,
2. determine the pressure which causes the first tensile stresses and the first concrete cracks and identify the locations of these areas in the two vessels,
3. determine the behavior of the regions near the top closures, the bottom heads, the penetrations through the concrete wall, the haunches, and the areas of the HYGAS PCPV where the cavity changes cross section,
4. determine the overall factor of safety for the vessels due to overpressure and identify the failure mode.

Background and status

Prestressed concrete pressure vessel designs are produced using sophisticated methods of analysis. Computer program forms of finite-element analysis methods which can consider three-dimensional, elastic, short-term deformation and axisymmetric creep and cracking behavior are available. Three-dimensional analysis methods capable of considering long-term time-dependent behavior of relatively complex geometries are in the developmental stage. Structural model testing is recognized by the Code as being a necessary part of the PCPV design process.

Considerable work has been done in Europe and the U.S. on the strength correlation between small-scale models and full-sized PCPVs. Evidence obtained to date indicates that tests using properly designed small-scale models can be relied upon to predict failure modes of a prototype vessel for short-term loadings. Table 6.1 compares some of the more significant characteristics of the Synthane and HYGAS PCPVs with nuclear single-cavity PCPVs and with a Scandinavian model of a boiling-water reactor vessel.

The model tests and associated analytical studies will not only verify the structural integrity of the proposed PCPVs and the analysis procedures, but will also contribute to the design methods development. Any subsequent design refinements could therefore be implemented using the analysis methods without additional model testing. The models also

Table 6.1. Comparison of single-cavity prestressed concrete vessel characteristics[3-7]

	Hinkley Point B (AGR)[a]	Bugey I (HTGR)[a]	Fort St. Vrain (HTGR)	Scandinavian model (model of BWR)[a]	Synthane (coal conversion)	HYGAS (coal conversion)
PCPV shape	Vertical cylinder, flat ends	Vertical cylinder, flat ends	Vertical cylinder, flat ends	Vertical cylinder, flat ends with a removable access penetration	Vertical cylinder, flat ends with a removable access penetration	Vertical cylinder, flat ends with a removable access penetration
Design pressure, MPa (psi)	4.03 (585)	4.48 (650)	4.86 (704)	8.48 (1230)	7.41 (1075)	8.96 (1300)
Design ultimate pressure, MPa (psi)	10.60 (1540)	11.87 (1720)	12.11 (1760)	21.2 (3075)	14.82 (2150)	17.93 (2600)
Interior cavity diameter, m (ft)	18.90 (62)	17.08 (56)	9.45 (31)	2.07 (6.8)	9.75 (32)	7.92 (26) 10.06 (33)
Exterior diameter, m (ft)	28.95 (95)	28.00 (92)	14.94 (49)	4.27 (14)	16.46 (54)	15.24 (50) 18.59 (61)
Height, m (ft)	35.65 (117)	53.15 (174)	32.30 (106)	6.40 (21)	41.76 (137)	71.93 (236)
Prestressing						
Circumferential	Helical linear tendons	240° wrapped tendons	180° wrapped tendons	180° wrapped tendons	Wire wrapped	Wire wrapped
Vertical	Helical linear tendons	Linear tendons	Linear tendons	Linear tendons	Linear tendons	Linear tendons

[a] AGR = Advanced gas-cooled reactor.
HTGR = High-temperature gas-cooled reactor.
BWR = Boiling-water reactor.

help to identify any unacceptable vessel features at an early stage in the developmental program, as well as potential problems relating to assembly of structural components, liner, thermal barrier, and vessel cooling system.

Work identification and test plan

Any model that represents the conceptual PCPV design of the Synthane or HYGAS gasifier vessel must include significant geometrical configurations and structural features which influence structural behavior. The size of the model must be determined both from the standpoint of accurate representation of the prototype vessel and the overall cost. Thus, the final selection is to be based on the specific code requirements and the use of as small a model as will accurately reflect prototype behavior. Design considerations include prestressing arrangement, reinforcing steel layout, penetration closure simulation, and modeling of materials properties. Modeling of the liner system is not required.

Providing an accurate representation of circumferential prestressing is a particularly difficult problem owing to limited availability of systems and techniques for accurately tensioning and winding of the models. However, it is anticipated that this can be accomplished with some refinement of existing equipment. Accurate modeling of the precast concrete channels and associated bands of circumferential prestressing is unnecessary.

Since the proposed vessels include vertical prestressing which is curved in the top head regions, the vertical prestressing system selected for the model and the actual size of the model must permit representation of this curvature. The vertical prestressing curvature represented in the HYGAS PCPV at the change in vessel section region must also be modeled. All model prestressing must have mechanical properties similar to the properties identified for the prestressing of the prototype vessels. The models are to be prestressed to concrete stress levels associated with vessel end-of-life conditions.

The PCPV model is to be pressurized in a series of discrete steps and the instrumentation read and recorded after the model has stabilized at each new step. Crack initiation and propagation is to be followed and cracking mapped on exposed surfaces. After attaining the design pressures, the test is to be repeated for at least three complete cycles.

The model is to be pressurized again in specified increments to twice the design pressure to verify overpressure response. Readings are to be taken after each pressure increment and any cracks identified. Then the model is to be depressurized and carefully inspected.

Finally, the models are to be pressurized incrementally to the ultimate pressure. During the pressure increments, readings are to be taken, any cracks noted, and the pressure associated with steel yielding identified. It is anticipated that the models will fail by excessive leakage through the cracked liner. These overpressure tests will identify the modes of failure of the models and determine the factors of safety of each design.

Upon completion of each model test, the data are to be analyzed and comparisons made between the response predicted using analytical methods and the actual vessel response. A complete report of the model tests, which includes an evaluation of the design, is to be prepared.

Task 2 — Penetration Closure Development

Objective

The objective of Task 2 is to verify the structural response and ultimate load capacity of the removable multiplate steel closure located at the top of the PCPV coal gasifier and to demonstrate the adequacy of the hold-down system.

Scope

A relatively large-scale model of the steel closure plug and the hold-down system is to be tested under pressure loadings, using a vessel which simulates the appropriate portions of a PCPV. In addition, full-scale mockups are to be used to demonstrate the insertability of the toggles and the adequacy of the closure seal.

Background and status

The steel closure plug and the toggle-type hold-down system that comprise the removable penetration closure represent relatively recent innovations. The steel plug is an adaptation of a design developed by General Atomic Co. (GA) in conjunction with the gas turbine HTGR development, and the hold-down system is based on a design developed by A. B. Atomenergi under the Scandinavian PCRV development program for light-water reactor applications. A closure model[7] employing the same basic type of hold-down has been tested to a maximum pressure of 3100 psi. These tests demonstrated that the toggle system performed satisfactorily to the maximum test pressure, which was 2.5 times the design value. A similar type of hold-down system has also been proposed by GA for the 300 MW(e) gas-cooled fast reactor (GCFR) prestressed concrete reactor vessel. The development plan[2] for the GCFR specifies that a test of the hold-down system be performed to demonstrate structural capacity and reliability under all proposed loading conditions. In addition, tests are to be designed to verify the mechanical behavior and pressure retention capability of the system and to demonstrate and perfect toggle installation and removal.

As stated previously, the proposed steel closure plugs are similar in design to the one proposed for the gas turbine HTGR (GT-HTGR) vessel. A preliminary stress analysis has been performed to demonstrate the feasibility of the HTGR closure, which is larger in diameter than the proposed gasifier vessel closures, while the design pressure of the HTGR vessel [7.03 (1020 psi)] is somewhat lower than for the gasifier vessels.[8] In spite of these dissimilarities, this study has provided an understanding of the relative influences of bottom plate thickness, outer cylinder wall thickness, and number of radial gusset plates employed on the closure stresses and deflections. An increase in total closure height was found to have very little effect on the stresses. The GT-HTGR closure design has yet to be verified by testing.

Work identification and test plan

The purpose of the model test of the steel closure and hold-down system is to verify the design and demonstrate acceptable structural behavior under both design pressure and overpressure conditions. The measured stresses and displacements are to be compared with respective analytical predictions.

The instrumented closure model is to be secured to the test fixture by the proposed toggle arrangement and tested hydraulically. Since the modeled hold-down system will most likely not include exact replicas of the full-sized toggles and since the assembly and disassembly of such a system has not been demonstrated, a full-size partial mockup is to be fabricated. The test plan is to consist of the following:

1. The steel closure is to be analyzed, and redesign and re-evaluation is to be performed until an acceptable arrangement is attained.
2. The closure model is to be designed and analyzed and a test procedure specified.
3. The model is to be fabricated.
4. The model is to be instrumented and placed in the test fixture.
5. The model is to be pressurized to the design pressure in successive load increments, with instrumentation readings taken after each increment. Three complete cycles of loading are to be performed.
6. The model is to be pressurized to twice the design pressure, after which the pressure is to be released. Instrumentation readings are to be taken after each load increment.
7. The model is to be pressurized to failure or until the capacity of the test fixture is reached.
8. The full-size toggle mockup is to be designed, fabricated, and assembled.
9. The results of the model test are to be compared with those predicted by computation.
10. The insertability of the toggles is to be demonstrated and details reported.

Completion of the penetration closure development will be accomplished when the experience gained from the closure model test has been formulated into recommendations and design procedures.

Task 3 — Liner, Tendon, Refractory, and Insulating Materials Investigations

Objectives

One purpose of Task 3 is to investigate and evaluate the effects of coal conversion process environments on the prestressing tendons and the steel liner materials selected. Secondly, structural material behavior data are to be collected and developed as required to meet design evaluation needs. A third objective is to collect and develop information for use in refractory material selection and to examine factors associated with insulating material to be used on the vessel exterior.

Scope

The capability of candidate prestressing tendon and liner materials to withstand effects of coal conversion system environments is to be examined and the means established for minimizing adverse effects. Hydrogen diffusivity values are to be established; fracture toughness data on forging materials are to be obtained; anchor-to-liner joint corrosion resistance and mechanical behavior are to be studied; and extensions of the Nelson diagram are to be considered. A refractory material test matrix is to be defined for use in connection with model testing.

Background and status

Work proposed under this task will provide results that are applicable for coal conversion systems in general as well as specific information for PCPVs. The latter will be derived from investigations of prestressing tendon material behavior, liner support anchor attachment regions, and, possibly, external insulation.

The steel liner used in a PCPV is a relatively thin member which confines the process media and transmits pressure loadings to the prestressed concrete structure. Since the liner must function satisfactorily throughout the lifetime of the vessel, the ability to resist environmental attack is essential to satisfactory performance. Liberal use is to be made of information being developed on the effects of coal conversion process environments on structural materials.

Anchor studs and refractory anchors are to be welded to the liner in both the hot- and the cold-liner designs. Failure of an anchor stud at the attachment point could allow the liner to buckle or to absorb a disproportionate amount of strain in a local region. Failure at the attachment point of a refractory anchor could result in exposure of the liner material to the corrosive process media. Thus, the anchor-to-liner joints should be examined for corrosion resistance and mechanical behavior under projected service conditions.

The large forgings in areas not backed by concrete will be subjected to tensile loadings. Section III, Division 2 of the ASME Code requires consideration of Division 1 fracture toughness requirements. However, toughness values are not given for the materials selected for PCPV application, and a testing program is needed to obtain this information.

Specific information regarding hydrogen effects on properties of materials is minimal, and augmentation is needed. Hydrogen diffusivity data should be collected and developed to allow hydrogen concentration estimates to be made throughout a PCPV. These estimates are essential to the selection of materials with needed hydrogen resistance for use at locations remote from the reaction chamber.

Although the liner materials were chosen for their resistance to hydrogen attack, acquisition of additional information on hydrogen effects is recommended. The Nelson diagram (applicable to the hot-liner design) does not consider microstructural differences, nor weldments, nor the applied stress level. Compressive as well as tensile loadings are to be studied.

Since the prestressing systems are very important to the structural integrity of a vessel, special attention is required to ensure that the adverse effects of corrosive environments and hydrogen are avoided. In a preliminary examination of possible detrimental effects of hydrogen on prestressing tendons, it was assumed that the hydrogen in the coal conversion process environment diffuses through the liner and concrete, causing the prestressed tendons to operate in a hydrogen-enriched environment at a pressure of 1 atm. Open literature information could not be found which specifically relates to the question of the effects on the tensile properties of cold-worked 1080 steel (0.8% carbon) stressed to 70% of the minimum ultimate tensile strength (UTS) [minimum UTS required by ASTM specification A416 is 1724 MPa (250,000 psi)]. Therefore, it appears that the most direct method for obtaining an answer is to conduct a limited number of tests in H_2 environments that bracket the limits possible in a PCPV application.

There are three basic types of hydrogen embrittlement:[9] (1) internal reversible embrittlement, (2) reaction embrittlement, and (3) environmental embrittlement. It can be concluded from the processing and operational environment of the prestressed tendons that only environmental embrittlement needs to be considered. The method of producing the prestressed tendon wires, a modification of the patent process (the 0.8% carbon steel is austenitized and then transformed by immersing the steel in a lead bath at a temperature that corresponds to the pearlite "nose" in a time-temperature-transformation diagram), will eliminate internal hydrogen. The operational temperature of the concrete in the PCPV [∿21—66°C (70—150°F)] will avoid the possibility of a hydrogen-carbon reaction; hence, reaction embrittlement will not occur.

The factors that affect embrittlement due to a hydrogen environment are:[10,11]

(1) Temperature — embrittlement is most severe near room temperature (the operational temperature of the concrete in the PCPV).

(2) Gas purity — contamination of a pure H_2 environment with relatively small amounts of oxygen (200—400 ppm) will eliminate H_2-induced crack growth.

(3) Strain rate — embrittlement is more severe at low strain rates.

(4) Strength level — high strength (quenched and tempered) structural steels are particularly susceptible to embrittlement, whereas severely cold-worked medium carbon steels are more resistant.

(5) Gas pressure — the embrittlement is more pronounced at higher hydrogen pressures.

In reviewing these factors, it was concluded that the hydrogen that may diffuse from the process environment in a PCPV will not have a detrimental effect on the performance of the prestressing tendons. The presence of oxygen in the free system will minimize the hydrogen embrittlement. Furthermore, the cold-worked steel and the low gas pressure (1 atm) will also minimize the effect of hydrogen.

It must be emphasized that this conclusion is based on general information from the literature. Since definitive tests can be conducted easily on tendon steels in environments that simulate those anticipated in a PCPV, it is strongly urged that such tests be conducted.

Prestressing tendon corrosion problems were experienced in early European PCPVs. The mechanisms of prestressing steel corrosion are understood, and adequate protective measures appear to have been developed. Protection from corrosion is achieved by controlling the relative humidity of the air surrounding the tendons and by applying corrosion-inhibiting compounds; another method is to grout the tendons. These methods of corrosion protection may also be satisfactory for prestressing steels used in coal gasification PCPVs, provided that the corrosive agents are satisfactorily identified and the effectiveness of the various protection methods are adequately demonstrated.

Material selections for the erosion-resistant refractory to be used inside the liner and the backup insulating refractory are to be guided by results obtained under other programs. Two ERDA Fossil Energy programs currently underway and expected to provide important input are:

1. "Improvement of the Mechanical Reliability of Monolithic Refractory Lining for Coal Gasification Process Vessels," at Babcock and Wilcox Company, and
2. "Study of Heat Transfer Through Refractory Lined Gasifier Vessel Walls," at Battelle Columbus Laboratories.

In addition, updated information from selected refractory vendors on currently available materials, the properties of these materials, and state-of-the-art installation and curing practices will be employed.

A small test matrix is to be developed for inclusion in Task 4 studies. The anticipated variables are the specific refractory combination, the curing cycle, and the anchor design and placement. Only a limited effort is anticipated to be needed in each case.

Work identification and test plan

Liner materials. Studies are to be made of environmental influences on liner materials, making maximum use of information being developed under other programs. Tests are to be performed to provide information on the following:

1. Anchor-to-liner attachment joint corrosion and mechanical behavior.
2. Fracture toughness of forging materials.
3. Hydrogen diffusivity and effects of hydrogen as a function of material microstructure and applied stress level.
4. Corrosion, as needed to augment information in existence or being developed.

Tendon materials. In reviewing the types of hydrogen embrittlement possible for tendon materials, it was concluded that environmental embrittlement is the one requiring consideration. Since directly applicable information does not exist, tests are to be conducted in H_2 environments that bracket the limits possible in a PCPV application.

The corrosive environments for gasifier vessels are to be characterized and relevant corrosion phenomena studied. Testing is to be performed to examine corrosion sensitivity and to identify protective measures. The work will consist of the following:

1. Define corrosive environments and identify testing procedures required to ensure satisfactory prestressing steel behavior.
2. Select suitable tendon corrosion inhibitors and evaluate their effectiveness under simulated operating conditions.

Insulating materials. The insulation system design is to be examined to confirm various elements. These examinations include the following:

1. Confirmation that the foam glass insulation can be satisfactorily interfaced with the concrete vessel and that the attachment of the required support members is feasible for a reasonable configuration.

2. Demonstration that the required strapping can be installed to hold the insulation in place.
3. Confirmation that the external coating material will prevent moisture intrusion under anticipated environmental conditions.

Task 4 — Structural Performance of Liner and Thermal Barrier System

Objectives

Because of the unique combination of thermal and pressure requirements of coal conversion gasifiers in comparison to those of previous PCPV applications, data are required to demonstrate satisfactory performance of liner and thermal barrier systems. Specifically, thermal and mechanical behavior information is to be obtained for a prototypic model of a hot-liner design. Structural responses of the refractory system and the insulating concrete are to be studied along with liner attachment design performance. Information applicable to thermal fatigue evaluations is also to be developed. Prior to the experimental study of the liner and thermal barrier systems, testing is to be performed to examine liner attachment requirements.

The prototypic model is to consist of a representative anchored liner segment together with the prescribed layers of refractory and insulating concrete, structural concrete, and coolant tubes. This model is to be subjected to the mechanical and thermal loading conditions of an operating gasifier. The effectiveness of cooling tubes between insulating and structural concrete as well as the capability for thermal barrier system failure detection is to be investigated. The representative cross section is to be subjected to cyclic heating and cooling to gain an understanding of performance under cyclic as well as under steady-state conditions.

Scope

Experimental studies are to be performed to identify acceptable liner attachment configurations and to codify requirements. Subsequently, a full-section mock-up of liner and thermal barrier systems and a portion of the adjacent structural concrete are to be subjected to simulated gasifier operating conditions to measure the response of the proposed liner and liner anchorage system, to demonstrate satisfactory performance of candidate refractories and insulating concretes, and to verify design assumptions and analytical procedures used to calculate the thermal response of the vessel.

Background and status

The need for insulating the liner and cooling the structural concrete was addressed in other sections of this report. Hot-liner and cold-liner systems have been proposed; however, only the latter has been employed in PCPVs for nuclear systems.

The hot-liner concept was probably proposed originally in France a number of years ago.[12] Tests were conducted using a circular plane hot-liner section. A 10-mm (0.40-in.) thick stainless steel liner was anchored by welded studs directly to structural grade concrete without insulating concrete being used between the liner and the structural concrete. The test consisted of repeatedly cycling the temperature from ambient to 300°C (572°F). The following results were reported.[8]

1. The liner buckled when the anchor studs were spaced at 15 times the liner thickness.
2. The liner did not buckle when the anchor studs were spaced at 7.5 to 10 times the liner thickness.
3. After over 700 thermal cycles, no liner fatigue damage was evident.

Since that time, various aspects of the hot-liner concept have been studied and other tests have been performed, again using a stainless steel liner. The results indicate that a hot-liner system is feasible, but additional work must be performed to verify that the system can perform satisfactorily under an actual design situation.

The anchor studs in the hot-liner design described in this report would extend through an insulating concrete layer and into the structural concrete. Hence, the behavior is expected to differ, for anticipated cyclic lateral and shearing loads, from that of models previously tested.

Insulating concrete is used to provide thermal protection for the structural concrete and to transmit internal pressure loadings. An insulating concrete for this particular application is to be identified.

The actual measured efficiencies of the insulating materials will directly affect the spacing and shape requirements for the structural concrete cooling tubes as well as the overall thermal efficiency of the gasifier. Thus, it may be necessary to investigate more than one overall configuration before an entirely satisfactory liner — thermal barrier system can be identified.

Work identification and test plan

Liner attachment design and response to imposed loadings is to be examined. Information is to be obtained on buckling characteristics and on response to fatigue loadings as a function of anchor size (mainly length) and spacing. A layer of insulating concrete is to be used between the liner material and the structural concrete.

A segment of a liner is to be used, and the liner temperature is to be repeatedly cycled over a temperature range corresponding to that expected in actual service. The liner is to be instrumented to record strains in critical locations, and visual post-test examinations will be made of each element of the assembly.

There appear to be a number of potentially satisfactory refractory materials for coal conversion processes. A limited preliminary evaluation is to be made to select materials having satisfactory erosion and spalling resistance and insulating characteristics. Consideration is also to be given to acceptable methods of installation, curing, and repair before refractories are selected for the full-scale mockup.

The overall task will consist of the following:

1. Specification of refractory and insulating concrete.
2. Design of the hot-liner system, employing experimentally backed selections for anchor studs and stud spacing, typical cooling tubes and tube spacing, and simulated prestressing (biaxial stresses).
3. Design of the system for applying thermal and pressure loadings to the liner segment.

4. Construction of assembly together with instrumentation required to measure selected temperatures and liner buckling and yielding.
5. Subjection of the mock-up to prescribed temperature and pressure cycles representing normal operation and startup and shutdown conditions while monitoring mechanical and thermal response of the various components.
6. Postmortem examination of cross sections to identify any problems with refractory, insulating concrete, steel liner and anchor studs, structural concrete, and cooling system.
7. Depending on whether the design proves to be satisfactory, it may be necessary to repeat steps 1 through 6 for a revised design configuration.

At the conclusion of the proposed test series, consideration is to be given to the need for additional test information on the design of the liner system in the vicinity of a discontinuity such as a penetration.

COMPENDIUM OF GUIDELINES, RULES, AND PROCEDURES

The studies described in this report together with those to be conducted under the task areas described in the last section will provide background information for direct use in the design of PCPVs for coal processing applications. Therefore, this information is to be assembled into a compendium of guidelines, rules, and procedures. The activity is outlined below using the format used in the task area descriptions.

Objective

The purpose is to assemble the design recommendations and procedures which were developed in the conceptual design development and the four developmental task areas into a compendium of guidelines, rules, and procedures for the design of PCPVs for coal conversion process gasifiers.

Scope

As coal conversion processes are developed to the stage where they can be used in commercial-size plants, the functional requirements and process constraints for gasifier vessels will no doubt change. Design rules and procedures are to be developed to provide the guidelines that will govern any modification of the proposed conceptual designs as well as to provide the basis for development of PCPVs for other candidate coal conversion processes. These methods can be used to develop and demonstrate the capabilities and limitations of several design configurations in order to provide the basis of the economic evaluations required to arrive at a vessel which will be functionally acceptable as well as cost effective.

Design guidelines, rules, and procedures will be provided for the following vessel features and concepts.

1. Prestressed concrete pressure vessel, including penetration layout, prestressing arrangements and configurations, and concrete head and wall thicknesses.
2. Removable access penetration closure, including hold-down systems.
3. Hot- and cold-liner systems, including steel liner refractory and insulating concrete, liner anchorage, and cooling tubes.

Background and status

Prestressed concrete reactor vessels are designed according to the requirements of Section III, Division 2 of the ASME Boiler and Pressure Vessel Code.[1] Similar codes to design PCPVs for other applications have not been developed. The previously described developmental tasks can serve as the basic information sources required to develop a code for coal conversion system PCPVs.

Work identification and test plan

The reports which document procedures and findings of the developmental tasks are to provide substantiation of the design methods. The following design considerations are to be prepared:

PCPV structural design. The Task 1 structural behavior test is to identify the mode of vessel failure and vessel response to gross overpressure. Using this information, methods are to be established to provide guidance for the selection of vessel wall thicknesses, concrete head thicknesses, penetration layouts, prestressing arrangements, and conventional reinforcing steel layout details to ensure ductile vessel response to overpressure loading conditions with an acceptable safety factor.

Penetration closure design. A comparison of the predicted closure plug response to the actual closure plug response from the developmental test will indicate the reliability of the design procedure. This comparison is then to be used as guidance for the design of full-sized steel closures. The experience gained from the full-scale toggle insertability demonstration is to be used to dictate design details of the closure plug, toggles, and bearing ring.

Liner, tendon, refractory, and insulating material selection. The examination of prestressing steel behavior in the corrosive environments and the demonstrated effectiveness of corrosion inhibitors is to be used to prepare design detail recommendations which can accommodate the required protective measures. The effect of hydrogen on prestressing steel may also require that certain design precautions be taken.

The liner materials investigations are to provide recommendations of specific design considerations, including which materials are most suitable and which fabrication procedures are acceptable. Guidance is to be provided on anchor-to-liner attachment joints, and pertinent data are to be obtained on refractories, refractory anchors, and insulating materials and moisture resistant coatings for the vessel exterior.

Liner and thermal barrier design. The hot-liner concept demonstration is to provide guidance for the design of the refractory linings, insulating concrete, and cooling tube arrangements. Recommendations are to be made on anchor stud spacing to prevent liner buckling, to maintain liner and concrete strain compatibility, and to avoid thermal fatigue failure through proper design. An understanding of the capabilities and limitations of each liner concept will permit an assessment of the design methods for predicting the overall behavior of the thermal barrier and liner systems.

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7. COMPARATIVE COST ANALYSIS OF HYGAS VESSELS

M. L. Myers*

A comparative cost analysis of steel and prestressed concrete gasifier vessels was made for the HYGAS coal conversion process. Specifically, the C. F. Braun and Co. conceptual design for the steel vessel, which is illustrated in Fig. 1.1, and the PCPV conceptual design, illustrated in Figs. 3.4, 3.5, and 3.6 were the bases for comparison.

The costs considered are for on-site fabrication and construction of the two types of vessels. As in the case of the conceptual design study, the internal components, the external equipment, the ash quench pot, the piping, and the below-grade foundation systems for each vessel were not considered. Additional items for each vessel which were not included in the analysis are site and construction management, design engineering, related indirect costs, and site construction facilities. No contingencies were assigned to either type of vessel, and no specific site location was considered.

The cost estimates are based on 1976 prices for the various items in the vessel structures and include field erection craft labor costs. The items considered in the cost estimates for each vessel and the related cost for each item are included in the following section.

Cost Estimates for Steel and Prestressed Concrete Gasifier Vessels

The steel gasifier vessel shown in Fig. 1.1 was sized according to the rules for Section VIII, Division 2 of the ASME Code[1] and on the basis of the design requirements for this vessel, which are discussed in Chapter 1 and listed in Appendix A. Since the design temperature is 589 K (600°F) and hydrogen effects are to be minimized, the material selected for use in the design was SA 387 grade 22 steel. The allowable stress for this material at the design temperature is 159 MPa (23 ksi). Hence, the computed thickness requirements are as follows. The upper vessel cylinder and top head are both 0.23 m (9 in.) thick, and the bottom vessel components are 0.29 m (11.5 in.) thick.

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*Engineering Technology Division.

The design shown in Figs. 3.4, 3.5, and 3.6 and the material list given in Table 3.2 were the bases for the PCPV estimate. The items considered in the cost analysis and the related cost figures are listed in Table 7.1 for the steel vessel and in Table 7.2 for the prestressed concrete vessel.

Table 7.1. Steel HYGAS gasifier vessel cost estimate (site fabrication, 1976)

Item	Weight (ton)	Estimated cost ($ × 10^3)
Vessel	4,585	26,520
Flanges, cover plates, nozzles, and overlay	191	4,380
Refractories and anchors	695	1,703
Support skirt	190	570
Total estimated site fabrication cost (1976)		33,173

Table 7.2. PCPV HYGAS gasifier vessel cost estimate (site fabrication, 1976)

Item	Weight (ton)	Estimated cost ($ × 10^3)
Concrete	38,000	3,800
Rebars	1,698	4,750
Prestressing system	2,700	6,945
Wire winding machine (lease)		1,400
Steel liner and cladding	830	6,500
Forgings and overlay	20	470
Anchors, plates, flanges, closure, bearing rings, toggle bolts	303	5,827
Castable refractories, external insulation and insulating concrete	1,257	2,608
Cooling system		926
Total estimated site fabrication cost (1976)		33,226

Based on these estimates for site fabrication and construction of the two types of HYGAS gasifier vessels, the costs for the two vessels are not significantly different. Additional cost studies which include cost items omitted, such as site construction facilities, foundation systems, erection of vessels on foundation systems, etc., are required in order to make selection on the basis of economics.

Reference

1. ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, *Rules for Construction of Pressure Vessels*, 1974.

8. CLOSURE

W. L. Greenstreet*

Background information on PCPV designs and design details, as well as operating experiences with these vessels, has been reviewed. Conceptual designs for two gasifier vessels were developed and examinations made to identify areas requiring critical investigation and areas for test evaluation and demonstration. A four-task program was outlined to provide (1) experimental data on structural response and guidance for design modification, (2) information on materials behavior, (3) requirements for avoidance of undesirable environmental effects, and (4) information on combined liner and thermal barrier system design and on behavior under service conditions. The feasibility of PCPV use in gasifier applications depends heavily on the latter, that is, on the combined liner and thermal barrier system design and performance. Although material behaviors and the control of detrimental environmental effects are important to successful vessel performance, such concerns are not limited to PCPVs and therefore generally do not have a direct bearing on the feasibility determination addressed in this study. The possibility of adverse effects of hydrogen on steel prestressing tendons should be explored, although no problems are suggested by available evidence. There is an advantage here since possible detrimental effects can be mitigated by periodic tendon replacement.

Except for the liner and thermal barrier system, existing design methods, rules, and fabrication practices apply for the major elements in gasifier vessels: (1) high-strength structural concrete, (2) conventional steel reinforcing bars, (3) posttensioned prestressing steel, and (4) top closure plug. The design methods and rules are given in Section III, Division 2, of the ASME Boiler and Pressure Vessel Code. For vessels, other than gasifier vessels, to be used in coal conversion systems, the rules and methods for liners and thermal barrier systems may partially apply. In the studies described in this report, the hot-liner concept is used for compatibility with the process; the cold-liner concept was developed for reference because of its close relationship to previous practice. In the hot-liner reference design, the combined liner and thermal

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barrier system is markedly different from the basic combination used in nuclear reactor vessels and addressed by Section III of the ASME Code. A carefully executed, in-depth experimental study must be conducted to verify and augment the information developed and to demonstrate acceptable performance under projected service conditions. The testing will also provide data for developing design methods and rules for general use.

Environmental effects on structural materials used in coal conversion systems are currently being studied. Although much of the information needed for material selection and vessel design is forthcoming, it is expected that limited augmentation will be required to meet PCPV needs. Among items to be addressed are additional information on hydrogen diffusivities, broader bases for guidance in material selection, and effects of hydrogen on tendon behavior, as noted above.

Because heat is to be removed from PCPVs by cooling circuits, a comparison was made of this removed heat and that lost from a bare steel vessel. The HYGAS system was used as a reference, and the amount of heat removed from a PCPV was shown to be significantly less than that lost from a steel vessel for the same application.

A comparison of material and labor costs for prestressed concrete and steel HYGAS gasifier vessels showed them to be virtually the same. The amount of steel used in the prestressed concrete version is almost as great as for the steel vessel; however, the steel for the latter is a relatively high-alloy material, while less expensive lower alloy steel is generally used for the former. Major factors supporting the use of PCPVs are their suitability for field fabrication and their inherently high resistance to failure because of the built-in structural redundancies. The former removes size restrictions, while the latter is extremely important from the safety standpoint.

In general, this study has shown that PCPVs are potentially both technically and economically feasible for gasifier applications. Since the requirements for gasifier vessels are probably the most stringent, it is expected that other uses in coal converion systems could be more readily accommodated.

APPENDIX A. DESIGN INFORMATION FOR HYGAS AND SYNTHANE CASIFIER VESSELS

The following design information for a HYGAS gasifier vessel was obtained from C. F. Braun and Co. It was transmitted by letter* to Preload Technology Inc. as a part of a request for an estimate of costs to construct such vessels of prestressed concrete. The information sheet transmitted is quoted below:

1. The sketch† *depicts the process requirement of the HYGAS gasifier for a single-train unit to produce 250 billion Btu per day of pipeline-quality gas.*

2. All dimensions shown are net inside dimensions. For example 31' 0" ID means inside diameter of refractory lining when refractory is used for inside lining. At the slurry drier, however, the 25'0" ID means inside diameter of metal since refractory lining will not be used for the operating temperature of 600°F.

3. The following conditions should be considered in the design of the gasifier.

- *a. Operating temperature as shown in the sketch, highest is 1850°F at the oxy-gasifier section.*
- *b. Design pressure is 1300 psig.*
- *c. Fluidized beds of char and coal solids with pressure differentials as indicated.*
- *d. Gas components of* H_2, H_2S, CO, CO_2, *and* H_2O.
- *e. Corrosive and erosive effect of gas, solid, and condensate.*

4. Only major process connections are shown in the sketch. Instrument connections, access manholes, and other connections required for operation and maintenance are not shown.

5. For the purpose of preliminary design consideration, we may assume 50 connections of 2-in. size will be required for level, temperature,

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*Letter from R. Detman, C. F. Braun and Co., to J. J. Closner, Preload Technology Inc., dated April 4, 1974.

†Information given in this sketch is included in Figs. 1.1 and 1.3 of this report.

and pressure measurement and control. These connections will be scattered at all levels of the gasifier.

6. We envision a large access opening of about 4 ft diameter will be provided at the top of the gasifier. Manholes at the side of the gasifier should be provided as follows.

ID	*Elevation*
3'-0"	*180'-0"*
3'-0"	*150'-0"*
4'-0"	*100'-0"*
4'-0"	*70'-0"*
4'-0"	*35'-0"*

7. A 3'-0" ID opening should be provided for each of the slide gate operator mechanisms at Elevations 158'-0", 126'-7", 65'-8", and 35'-2".

8. The cyclone at the raw gas outlet (Elevation 200') will be located external to the gasifier but adjacent to it.

9. The effect of hydrogen on concrete and reinforcing steel should be considered. At the high temperature reactor section, the gas contains approximately 21 mol % hydrogen, partial pressure about 260 psig.

10. We anticipate that metal internals subjected to the process operating conditions of high temperature will be made of Incoloy 800 or equivalent.

11. Refractory will be generally high strength castable of suitable thickness to maintain the containment shell at the proper temperature. It will contain vapor stops at intervals to prevent bypassing gas around the fluid beds. If metal walls are below the dew point of corrosive condensables (about 450°F), they must be of corrosion-resistant alloys.

The design requirements listed below for a Synthane gasifier vessel were developed using information provided by C. F. Braun and Co. as well as information from other sources.

1. The inside diameter of the refractory lining is 9.14 m (30 ft).
2. The following conditions are considered in the design.
    a. Maximum operating temperature of 1255 K (1800°F).
    b. Design pressure of 7.41 MPa (1075 psi).
    c. Gas components of H_2, H_2S, CO, CO_2, and H_2O.
    d. Corrosive and erosive effects of gas, solid, and condensate.

3. The following process connections are included in the design.

   a. Four 0.2-m-diam (8-in.) slurry inlets.

   b. One 0.61-m-diam (24-in.) grid outlet.

   c. One 0.66-m-diam (26-in.) steam and oxygen inlet.

   d. One 0.91-m--diam (36-in.) gas outlet.

   e. One typical 0.05-m-diam (2-in.) instrumentation penetration.

4. Two 0.91-m-diam (36-in.) manway access openings are considered; one is positioned above the grid, and one is positioned below the grid.

5. The conical grid is fabricated from metal and attached to the vessel for structural support.

6. An access opening is considered at the top of the vessel for removal of the cyclone and cyclone downcomer.

7. The hydrogen partial pressure used in the design is 1.72 MPa (250 psi).

8. The refractory lining is required to provide adequate vessel insulation and erosion protection. The dew point of corrosive condensables is considered to be 505 K (450°F).

APPENDIX B. DESCRIPTION OF FINITE-ELEMENT COMPUTER CODE ISA

The computer program used in this feasibility study for calculating elastic behaviors of concrete vessels is called ISA. The details are as follows:

Brief Program Description

ISA is a finite-element program for elastic analysis of two-dimensional structures. It was developed at the University of Illinois to analyze models of prestressed concrete reactor vessels. The program did not have to be changed and was readily adapted to analyze conceptual designs of PCPVs for gasifier vessels in the Synthane and HYGAS processes.

General Information

ISA is applicable to axisymmetric and to plane stress or plane strain analyses. The input and output data are typed in and printed out using a teletype linked to a time-sharing computer.

Element Library

Four-node isoparametric elements are available. The elements may have three or four sides so that any type of geometry or mesh layout can be accommodated.

Material Behavior

The program can accommodate vessels with five different material properties. Isotropic or orthotropic material properties for the different sets of elements can be input.

Thermal Analysis Capability

The program cannot compute thermal stresses.

Boundary Conditions for Structural Analysis

Nodal loads and pressures can be applied to the vessel.

Kinematics

The program is limited to small displacements and small strain theory only.

Mesh and Coordinate Generation

The program can generate nodal coordinates for a regularly numbered nodal pattern. Automatic mesh generation for four-sided elements which are regularly distributed can also be performed.

User's Manual

The user's manual reference is *ISA, Interactive Stress Analysis, A Program for Plane Stress, Plane Strain and Axisymmetric Analysis of Structural Continua,* H. O. Abdulrahman, University of Illinois, Structural Research Series No. 428, 1976.

APPENDIX C. COMPUTER PROGRAM FOR HEAT TRANSFER CALCULATIONS

Program Description

The computer program used for thermal analyses in this feasibility study was HEATING 5, which is the latest version of *The HEATING Program*. (HEATING is an acronym for Heat Engineering and Transfer in Nine Geometries.) HEATING 5 is designed to solve steady-state and/or transient heat conduction problems in one-, two-, or three-dimensional Cartesian or cylindrical coordinates. The thermal conductivity, density, and specific heat may have both spatial and temperature dependencies. Phase changes of materials may also be included. Heat generation rates may be dependent on position and time, and boundary temperatures may be time dependent. The boundary conditions, which may relate to transfer from surface to boundary or from surface to surface, may be fixed temperatures or any combination of prescribed heat flux, forced convection, natural convection, and radiation. The boundary condition parameters may be time and/or temperature dependent. The mesh spacing can be variable along each axis. The code is designed to allow a maximum of 100 regions, 50 materials, and 50 boundary conditions. The maximum number of lattice points can be easily adjusted to the problem and the computer storage requirements.

The point successive overrelaxation iterative method and a modification of the "Aitken δ^2 extrapolation process" are used to solve the finite-difference equations which approximate the partial differential equations for a steady-state problem.

The transient problem may be solved using any one of several finite-difference schemes. These include an implicit technique which can range from Crank Nicholson to the Classical Implicit Procedures, an explicit method which is stable for a time step of any size, and the Classical Explicit Procedure which involves the first forward time difference. The solution of the system of equations arising from the implicit technique is accomplished by point successive overrelaxation iteration and includes a procedure to estimate the optimum acceleration parameter. Transient problems involving materials with change-of-phase capabilities cannot be solved using the implicit technique with this version of HEATING 5.

User's Manual

The user's manual reference is *HEATING 5 — An IBM 360 Heat Conduction Program*, W. D. Turner, D. C. Elrod, and I. I. Siman-Tov, ORNL-CSD-TM-15, March 1977.

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