

ACI 361R-86

Composite Concrete and Steel High-Pressure Vessels for General Industrial Use

Reported by ACI Committee 361



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State-of-the-Art Report**ACI 361R-86**

Composite Concrete and Steel High-Pressure Vessels for General Industrial Use

Reported by ACI Committee 361

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Robert C. Griffin

F. Edward Linck
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F. S. Ople
Da-Lih Wu

Consulting Members

Richard Gallagher

Ben C. Gerwick, Jr.

T. Y. Lin

This report covers the background, rationale and the use of non-nuclear prestressed concrete pressure vessels (PCPV), as currently practiced by the industry. It addresses, in separate chapters, the following topics concerning the PCPV: vessel classification, safety considerations, materials, design and analysis, fabrication and construction, acceptance testing and operation of the PCPV, in-service surveillance and cost considerations. The report also includes a substantial list of reference literature pertaining to the PCPV.

The report points out the need for a code of practice that is separate from the code for nuclear pressure vessels because it is unsuitable and will discourage the development and use of the PCPV in non-nuclear applications.

The industrial PCPV should have as its main objectives the achievement of leak-tightness and the structural integrity of the vessel throughout its service life. Within the limits of serviceability and structural safety, the vessel may be designed by alternative methods, particularly the partial prestressing method for concrete structures.

Keywords: acceptability; building codes; concrete construction; costs; ductility; inspection; linings; partial prestressing; post-tensioning; pressure vessels; prestressed concrete; reviews; safety; serviceability; strength; structural analysis; structural design; thermal insulation.

*Denis C. Pu became secretary of the committee in September 1984

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CHAPTER 1: INTRODUCTION1.1 GENERAL

Recent progress in the development of prestressed concrete pressure vessels for general industrial use, referred to as PCPVs has resulted in design methods, criteria and materials that will permit pressure vessels to be designed for higher internal temperatures and pressures than are normally encountered by nuclear PCPVs. With the publication of study reports on this subject by Oak Ridge National Laboratory for coal gasifiers (1), and by the University of Kentucky, T.Y. Lin International and others for coal conversion pressure vessels (2,3), an international effort was initiated by the Federation Internationale de la Precontrainte (FIP) in the middle of 1978, to report on the non-nuclear PCPVs. Similar effort was initiated in the United States by ACI. Since the study could lead to the formulation of a code on non-nuclear PCPVs under Section VIII of the ASME Boiler and Pressure Vessel Code, ASME took joint action with ACI to form a committee on "Composite Concrete and Steel High Pressure Vessels", in 1979. The first meeting of the steering committee, composed of T.E. Northup, W.G. Corley, and P.Y. Chow, representing ACI, P.M. Brister, R.J. Cepluch, W.E. Cooper, and M.R. Green, representing ASME, and S.F. Harrison of the National Board of Boiler and Pressure Vessel Inspectors, was held in New York. At this meeting the steering committee approved the mission of the joint committee, and appointed P.Y. Chow as its Chairman. The mission, as it stands today, reads:

"(1) Report and disseminate information on the technology and practicality of composite concrete and steel pressure vessels for general industrial services at pressure higher than 100 KPa (15 psi) at the top of vessel."

"(2) Establish rules in the form of a code for the design, construction, inspection, and testing of composite and steel pressure vessels for general industrial services. Interpret these rules when questions arise regarding their intent. Periodically update code provisions using standard, expedited and code case procedures for revision of code as necessary and applicable."

This report will fulfill the first part of this mission. A committee that subsequently stabilized at 11 members representing research organizations, consulting firms, industries and contractors was formed. It also enlisted the assistance of the three consultants who are authorities on various aspects of PCPV technology.

The Committee met several times in different parts of the country during the three years of development of this report, initially to collect data, and later to produce this report. Each chapter was assigned to a group of writers under a chairman, as follows:

	<u>Chapter</u>
1	INTRODUCTION
2	CLASSIFICATION

Chairman

P.Y. Chow
D.L. Wu



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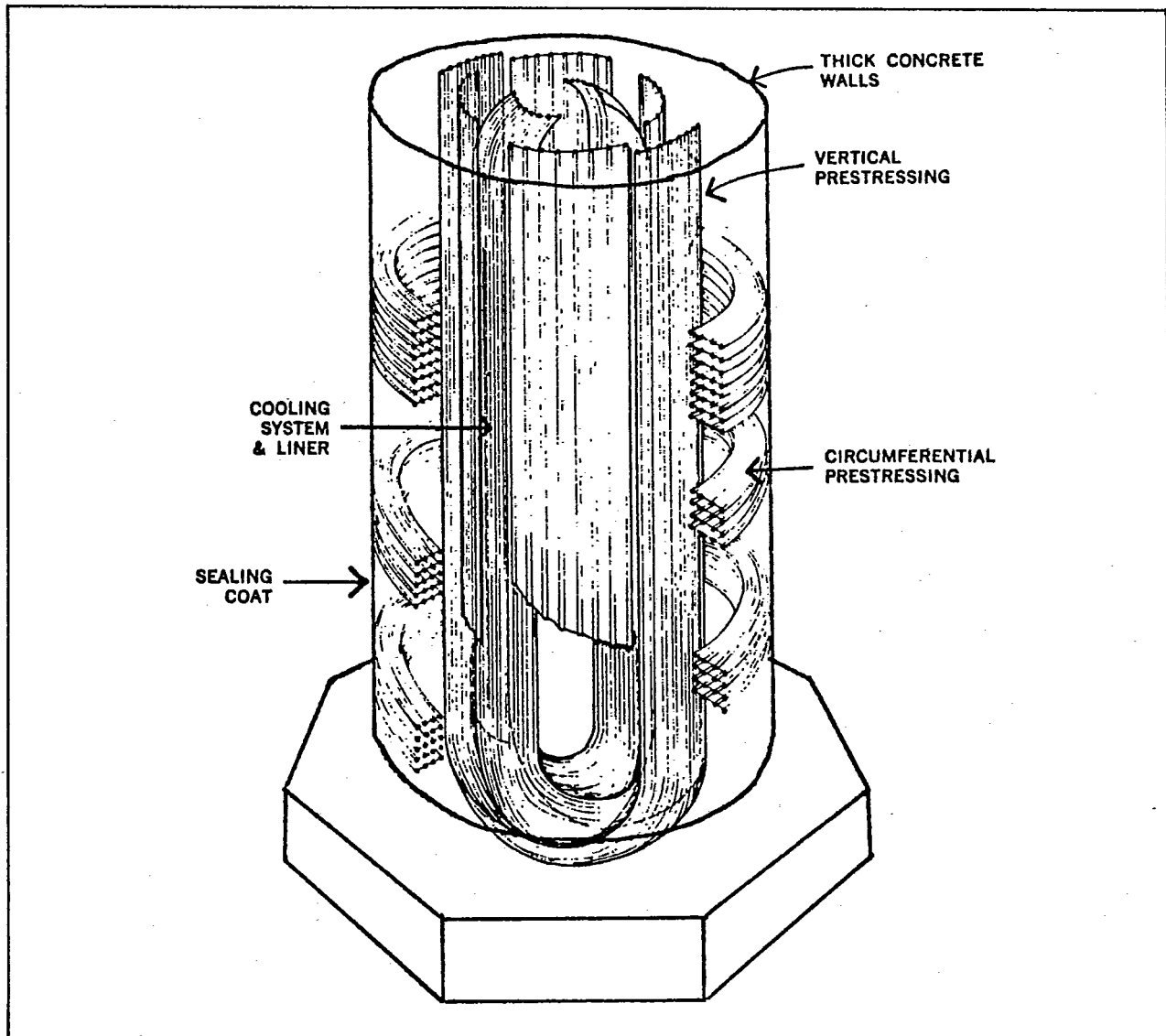


Fig 1.1 A Conceptual PCPV Design (4)

Fig. 1.1 is an illustration of a conceptual PCPV showing the following components.

- (a) Concrete walls, 3.3 to 9.8m (10 to 30 feet) thick.
- (b) Prestressing system.
- (c) Steel liners for the cavities, 13 $\pm$ mm (0.5 $\pm$ in) thick.
- (d) Refractory on inward side of the steel lining as required.
- (e) Cooling system outside the steel liner as required.
- (f) Sealing coat on outside face of vessel.

	<u>Chapter</u>	<u>Chairman</u>
3	SAFETY CONSIDERATIONS	R.D. Ciatto
4	MATERIALS	D.J. Naus
5	DESIGN AND ANALYSIS	F.S. Ople, Jr.
6	FABRICATION AND CONSTRUCTION	D.L. Wu
7	ACCEPTANCE TEST	A.M. Smolen
8	OPERATION AND IN-SERVICE SURVEILLANCE	A.M. Smolen
9	COST CONSIDERATIONS	D.L. Wu
10	REFERENCES	D.C. Pu

To the above, and particularly Secretaries S.J. Thoman and D.C. Pu, who have contributed so selflessly to this project, and Committee member R.D. Ciatto and his assistant K. Clausen who had the final draft retyped, the Committee owes its deep thanks.

1.2 THE POTENTIAL OF NON-NUCLEAR PCPVs

The advantages of a PCPV are well known and proven with nuclear PCPVs. These advantages, with the exception of radiation shielding, will be equally applicable in the case of the non-nuclear PCPVs. Relative to steel vessels, the PCPVs have better resistance against corrosion, thermal and mechanical shock loadings, fire and fatigue. They also have better failure characteristics because of their ductility and redundancies, and they can be constructed in virtually any size and shape. Through application of the technology developed for nuclear PCPVs, the industry may now consider possible more efficient processes requiring higher pressures without the constraint of vessel size.

Since the non-nuclear PCPVs must compete on the basis of cost, the report has included a chapter, Chapter 9, that deals with the economics of these vessels, and a reference, in Appendix B that gives cost comparisons between pressure vessels for use in coal conversions. Even though potential cost savings of PCPVs was found to vary widely, the information collected indicate potential economic advantages of large PCPVs, as compared to a number of smaller steel vessels of equivalent capacity. Indications of cost savings of large magnitude are sufficient to justify the serious consideration of PCPVs for general industrial applications in the United States.

1.2.1 General Description of a PCPV

As developed today, a PCPV is simply a composite concrete and steel structure generally in the form of a vertically standing cylinder (4). Depending on size requirement, the cylinder may have an outside diameter of 31m (100 ft) and more, and a height of 76m (250 ft). There can be single or multiple cavities within the cylinders which may be subjected to high internal pressures and process temperatures. To resist pressure, the cylinder is pre-compressed by circumferential and vertical prestressing tendons as shown in Figure 1.1. Confining the concrete this way also has the effect of considerably increasing its compressive strength. The cavities are made gas and liquid-tight by a thin impervious liner, which may also serve as framework for the cavities during construction. For PCPVs subjected to high process temperatures, it may be necessary to provide a thermal protection system to keep the material temperature within acceptable levels.

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1.3 THE CASE FOR A NEW CODE FOR GENERAL INDUSTRIAL PCPVs

The case for and against the development of a new code for the PCPV had been argued prior to the formation of this committee. The following were typical questions that were asked:

- Why is a new code necessary? Couldn't ASME Section III, or an extension of Section III also serve the non-nuclear PCPVs?
- Who will have jurisdiction over these vessels?
- Do data exist to justify a new code?
- How are requirements of nuclear PCPVs different from those of the PCPV for general industrial use?

Answers to these and other related questions have shown that a separate code for PCPVs was both necessary and timely. Justifications for the development of a new code and how such a code will enhance safety are summarized in the following sections.

1.3.1 Justification of a New Code

The construction of a pressure vessel using composite concrete and steel is not novel. Numerous such vessels have been constructed in Europe and in the United States for nuclear installations. The successful operation of these vessels demonstrates that composite concrete and steel construction, technology and practices are available now for general industrial use. Codes of construction for nuclear applications exist in the United States and in Europe. Two examples are:

- (a) BS 4975 (1973) Specification for Prestressed Concrete Pressure Vessels for Nuclear Reactors. British Standard Institution.
- (b) Code for Concrete Reactor Vessels and Containment (ACI 359-80) forms Section III, Division 2 of ASME Boiler and Pressure Vessel Code (1980).

A separate code for the non-nuclear PCPVs is necessary because of the different nature and purpose of these vessels. Section III of the ASME code was specially tailored for nuclear application, and if adopted for non-nuclear PCPVs could be detrimental to their development. A non-nuclear PCPV should be evaluated, designed and constructed according to the same criteria by which a conventional industrial pressure vessel or structure is measured, i.e., competency, safety, efficiency and economy, and not subjected to the unique, sometimes emotional considerations associated with nuclear structures.

1.3.2 Requirements of Non-Nuclear PCPVs

It will be the responsibility of the user or his designated designer to establish the requirements for pressure vessels, taking into consideration factors associated with normal operation, and other conditions such as start-up and shutdown. For non-nuclear steel pressure vessels, the requirements are generally in accordance with the rules specified in Section VIII of ASME code.

which in nearly all United States and provinces of Canada are regulated by local authorities. Nuclear pressure vessels are designed in accordance with Section III and controlled by the US Nuclear Regulatory Commission (USNRC).

In the case of non-nuclear PCPVs, sections of ASME code (5) are not directly applicable without modification. For example:

- (a) Section VIII does not cover the design and construction of pre-stressed concrete vessels.
- (b) Section III emphasizes the quality assurance programs and the associated quality control procedures strictly structured for nuclear service.
- (c) Other stringent procedures called for or referred to in Section III serve the same purpose as mentioned in the above. These requirements need not apply to non-nuclear PCPVs.
- (d) Design pressure and temperatures are of wider range than those encountered in nuclear vessels.

A code for general industrial PCPVs should consider the following:

- (a) The basic PCPV design objectives are to achieve leak-tightness and to ensure the structural integrity of the vessel throughout its service life for the conditions postulated for plant safety.
- (b) Within the limits of serviceability and structural safety, alternative design methods such as the partial prestressing may be adopted for the non-nuclear PCPV design.
- (c) On the basis of the given process environments, particularly in vessel class T3P1 or T3P2 (see Chapter 2 for classifications), the design and construction of liner and thermal protection systems deserve special attention.
- (d) Quality control and special protection measures be established in parallel with existing code requirements, but modified as appropriate for general industrial use, on the basis of the safety requirements of the plant.

1.3.3 How a Code Enhances Safety - Historical Review

The primary objective of the eventual Code for Composite Concrete and Steel High Pressure Vessels for General Industrial Use is to safeguard public safety. It is relevant to review historically the development of the ASME Boiler code (5), and how this code accomplished this goal for steel pressure vessels.

At the turn of last century, steam boilers constituted the majority of pressure vessels. Steamships already had been constructed and operated for many years, and by this time industrial and heating boilers were commonplace. The number of boiler accidents attests to widespread use of boilers. From 1898 to 1903, about 1600 boiler explosions were recorded which resulted in 1200 fatalities. In one instance, in Massachusetts, a single boiler explosion killed 58

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people and injured 117. The first state law regulating the construction and operation of pressure vessels was passed in Massachusetts in 1907 (6).

By 1915, a number of states had adopted differing laws. But boiler explosions continued to occur. It was then felt that a set of technically sound rules would offer uniform protection against boiler accidents throughout the United States, was required. In 1915, the first ASME Boiler Code was published. Even though steam pressures have increased dramatically over the years, the number of annual boiler accidents has since diminished drastically, as seen in Fig. 1.2, even though steam pressures have steadily increased.

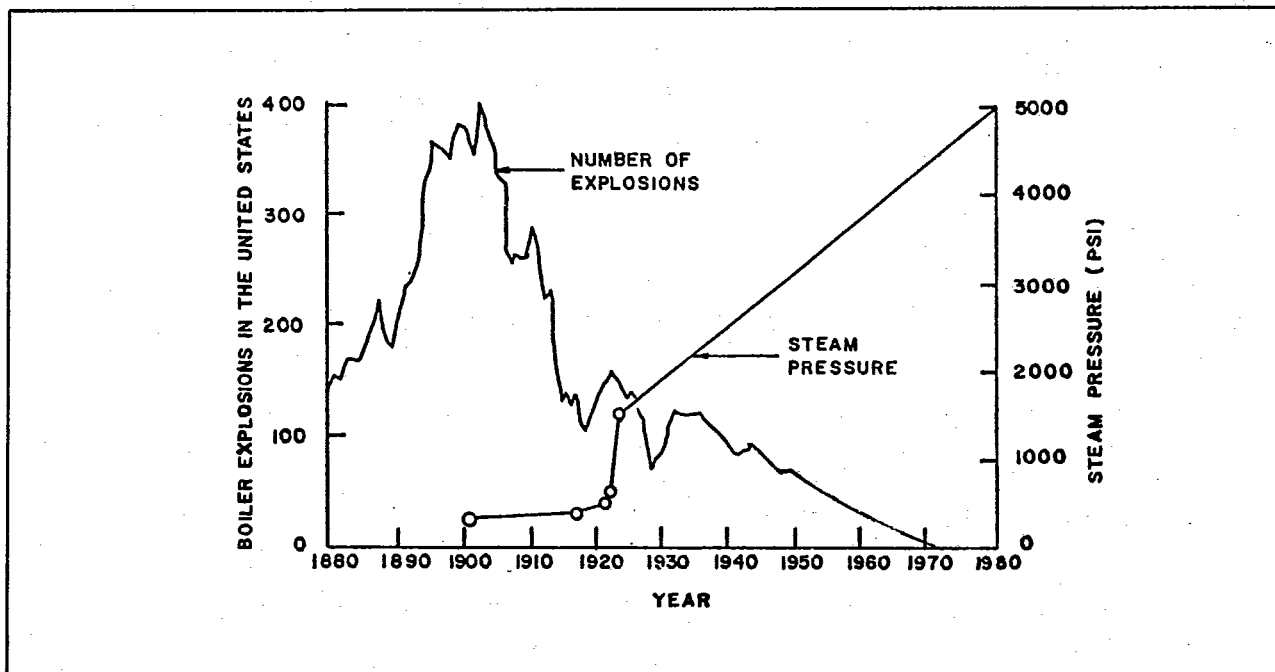


Fig. 1.2 Boiler Explosions During the Last 100 Years (6)

One or more sections of the ASME Boiler and Pressure Vessel Code have been accepted and enacted into law in 47 states in the USA, and in all the provinces of Canada. Section VIII, the pressure vessel portion of the code has been used almost exclusively on a voluntary basis within the United States even where no laws applied (7). Its widespread acceptance has been one of the major contributing factors in reducing pressure vessel failures.

1.4 SUMMARY OF THE COMMITTEE'S WORK

It is recognized that the non-nuclear PCPV is a newcomer to a field of application that has traditionally been the domain of steel, and as such, its development can derive little support from past experience and practice. The Committee's work was handicapped because it did not have the benefit of previous committees on nuclear PCPVs, of developing a code after several such vessels had been built. By publishing a state-of-the-art report on the subject, a building block is developed upon which the final edifice hopefully will one day stand.

Due to the scarce past of the non-nuclear PCPV, the data and information on the nuclear PCPVs has also been included where such data is pertinent. The report is divided into ten chapters, each dealing with a specific aspect of a PCPV. Under Appendix B is included cost comparisons between pressure vessels for use in coal conversion plants. Except for this first chapter, each is briefly described as follows.

1.4.1 Chapter 2 - Classification

In view of the multiplicity of purpose and function of non-nuclear PCPVs, it was necessary and convenient to have them classified in groups according to the range of operating conditions to which they are subject. The two major parameters, pressure and temperature, have been selected as the controlling criteria for classification purposes. A PCPV classification matrix of six categories is presented. Considerations within each class are given to the limitations of prestressing systems and thermal protection systems to be incorporated into the PCPV.

1.4.2 Chapter 3 - Safety Considerations

The inherent safety features of PCPVs are highlighted. Safety aspects of design safety factors, materials, overpressure protection, and fabrication and construction are discussed.

There are several safety features inherent in PCPVs. The foremost of these is redundancy of the structure. Failure of one or more prestressing tendons does not result in loss of integrity. The next significant safety feature is its ductility, i.e., failure is gradual, permitting cracking within the concrete and extensive deformations, allowing shutdown before total failure occurs.

The prestressing system installed during construction provides initial active pretension to the steel and precompression to the concrete and counteracts the operating pressure loads. Thus the primary load carrying materials are load tested before the process operations begin.

1.4.3 Chapter 4 - Materials

The five major material components in a PCPV include: (1) concrete, (2) post-tensioning system, (3) conventional mild steel reinforcement, (4) liner and cooling system, and (5) thermal insulation. Proper design of the vessel requires a knowledge of the component (material) properties. Concrete and speciality concretes (high strength, steel fiber, polymer and high temperature) are discussed with respect to mixing, placing, curing and typical properties which are attainable. Linear and circumferential post-tensioning systems are described with respect to their function, material requirements, and protection from hostile environments (corrosion and elevated temperature). The function, material requirements and typical properties of mild steel reinforcement are presented. Basic requirements for thermal insulation systems are presented as well as a discussion of the basic types of insulation which have been utilized.

1.4.4 Chapter 5 - Design and Analysis

This chapter discusses the design of PCPVs with respect to present codes, design concepts, serviceability and strength limits, loads, and analytical tech-

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niques, design details, liner and thermal protection systems, penetration and closures, and model tests.

In general, PCPVs under similar operating conditions as the nuclear PCPV, may be designed in accordance with existing codes and standards. In higher pressure applications, new design solutions will be necessary. Analytical techniques, and alternate design methods resulting in a more economical design, are generally available. In most cases, the design can be justified through analytical solution instead of model tests, based upon the excellent correlation between model testing and analytical techniques gained in the nuclear industry.

1.4.5 Chapter 6 - Fabrication and Construction

Various aspects of fabrication and construction of PCPVs, specifically in regard to the construction and installation of prestressing, thermal protection systems, corrosion protection, anchorages, liner systems, penetrations and closures, as well as quality control measures are discussed.

Although the current technology on PCPV fabrication and construction is intended for nuclear applications, it is also generally applicable to non-nuclear PCPVs. The integrated concept of PCPVs deserves special attention. Its adoption will entail the simultaneous construction of several functional components within a single vessel, and requires careful planning and execution in coordinating and controlling the parallel construction streams. As for the quality control measures to be used for non-nuclear PCPVs, some degree of relaxation from the stringent nuclear requirements is necessary in order to have an efficient and economical system.

1.4.6 Chapter 7 - Acceptance Testing

This chapter deals with acceptance tests and examinations for non-nuclear PCPVs consistent with present practice, which begins with construction and continues through operation to demonstrate that structural design objectives have been met.

1.4.7 Chapter 8 - Operation and In-Service Surveillance

In-service surveillance programs established for nuclear PCPVs are considered with a view to their applicability to the non-nuclear PCPVs. The practices for monitoring, instrumentation and examination are discussed.

1.4.8 Chapter 9 - Cost Considerations

Cost considerations when comparing PCPVs with steel vessels include:

- (a) Cost of lead time required for manufacture or construction of vessel.
- (b) Cost of auxiliary systems (piping, controls, etc.) that can be saved by increasing the vessel's capacity, i.e., reduction in trains.
- (c) Saving in land usage by increasing vessel capacity.

(d) Cost of providing resistance to extreme environmental loadings: shock, fire, fatigue, and missile impact.

(e) Maintenance costs.

Cost comparisons should be made on the basis of total investments, that include the costs of engineering, planning, and model testing. Information collected has shown that the cost saving of a PCPV increases as design pressure increases, and decreases if the PCPV has a high process design temperature. PCPVs also have less size limitations compared to steel.

1.4.9 Chapter 10 - References

Reference literature is listed under this chapter according to the standard format of ACI.

1.4.10 Summary

In summary, the work of the Committee has disclosed that PCPV technology, mainly drawn from the development and experience of the nuclear PCPVs, is sufficiently advanced for the purposes of designing and constructing PCPVs for general industrial applications. These applications will probably impose higher pressures and temperatures than are normally encountered by nuclear PCPVs. This would be made feasible by a combination of two measures: (1) the relaxation of the current code-specified stringency for nuclear service that are not appropriate for non-nuclear PCPVs, and (2) the employment of less stringent design approaches such as the partial prestressing concept.

Technical input has been derived from members of ACI and ASME. The ACI Technical Activities Committee has approved the report.

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CHAPTER 2: CLASSIFICATION2.1 GENERAL

While steel pressure vessels have been in use for many years, PCPVs usage began with the advent of the nuclear industry only two decades ago. Partially because a PCPV is relatively unlimited in size, it tends to be a large unit often catering to high pressure and/or temperatures. A partial list of modern pressure vessels has been prepared to show the trend. It illustrates the many types of pressure vessels being built today and the materials being used. The list is included as Appendix A of this report.

In view of the wide range of PCPV types that are required to accommodate the multiplicity of purposes and function of general industries, it is convenient to treat PCPVs in groups according to temperature and pressure. There are other conditions such as those postulated for plant safety, but they are not as significant as temperature and pressure in affecting the design of PCPVs.

Known design range of typical non-nuclear pressure vessels in terms of temperature and pressure are summarized in Table 2.1.

Table 2.1 Service Conditions

Petrochemical		
Catalytic Reformers	425 ⁰ C to 540 ⁰ C (800 ⁰ F to 1000 ⁰ F)	6.90 MPa (1000 psi)
Hydrocrackers	425 ⁰ C to 480 ⁰ C (800 ⁰ F to 900 ⁰ F)	6.90 MPa to 27.60 MPa (1000 psi to 4000 psi)
Hydrodealkylation	595 ⁰ C to 760 ⁰ C (1100 ⁰ F to 1400 ⁰ F)	5.50 MPa to 8.30 MPa (800 psi to 1200 psi)
Hydrodesulfurizers	425 ⁰ C (800 ⁰ F)	0.10 MPa to 10.35 MPa (15 psi to 1500 psi)
Coal Conversion*		
Solvent Refined Coal	370 ⁰ C to 540 ⁰ C (700 ⁰ F to 1000 ⁰ F)	0.07 MPa to 68.95 MPa (10 psi to 10000 psi)
Pyrolysis	230 ⁰ C to 875 ⁰ C (450 ⁰ F to 1600 ⁰ F)	0.10 MPa to 37.90 MPa (15 psi to 5500 psi)
Gasification	260 ⁰ C to 1815 ⁰ C (500 ⁰ F to 3300 ⁰ F)	0.10 MPa to 31.00 MPa (15 psi to 4500 psi)
*Including laboratory models		



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2.2 VESSEL CLASSIFICATION FOR PCPVs

2.2.1 Rationale for Classification

An attempt has been made to determine the number and range of divisions between classes mainly in terms of pressure and temperature.

2.2.1.1 Pressure Ranges

While advances in both the construction techniques and materials would permit PCPVs to withstand pressures in excess of 27.50 MPa (4,000 psi), it has been pointed out (8) that the majority of the existing and proposed non-nuclear PCPVs fall below the pressure range of 13.80 MPa (2,000 psi) level. From another point of view, 13.80 MPa (2,000 psi) may represent the limit for embedded prestressing tendons, and surface-wound prestressing method may be the only prestressing alternative when the pressure exceeds this limit. From these considerations, 13.80 MPa (2,000 psi) appears to be an appropriate dividing line for the purpose of classification.

2.2.1.2 Temperature Ranges

Considering the service conditions (Table 2.1) of petrochemical and coal-conversion industries, it is observed that most pressure vessels do not operate above a temperature of 1095°C (2,000°F). In the chemical industry, a few large vessels do operate at 600°C to 1200°C (1110°F to 2190°F). These are normally cold wall steel vessels lined with refractory, so that the shell temperature is maintained below 200°C (400°F). A few fairly small vessels operate up to 900°C (1650°F) but with quite low internal pressures. The significant range of temperature therefore appears to be between 65°C (150°F) and 1095°C (2000°F). For reasons of economy, and in consideration of creep, and scaling behavior, it is unlikely that operating temperatures for steel shells will exceed 540°C (1000°F) even with special steels.

Since temperature ranges are closely related to the thermal protection required for PCPVs, the following temperature classification based on this protection requirement is proposed:

- (a) From -18°C (0°F) to 100°C (212°F) no special provision for a thermal protection system is required.
- (b) From 100°C (212°F) to 315°C (600°F) a light thermal protection system must be provided to protect the PCPV.
- (c) Above 315°C (600°F) a heavy thermal protection system is required.

2.2.2 Classification Matrix

Based on the above discussion, PCPVs have been grouped into six categories as shown in the matrix provided in Table 2.2. For the purpose of illustrating into which group most non-nuclear pressure vessels would currently be assigned, the distribution of service conditions (pressure and temperature) for the existing and proposed coal-conversion processes have been plotted in Figure 2.3.

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Essentially, all current vessels proposed for coal conversion would be classified as either T3P1 or T3P2.

Table 2.2 Vessel Classification

Temperature/Pressure	0.10 MPa to 13.80 MPa (0.015 to 2 ksi)	Above 13.80 MPa (2 ksi)
-18 to 100°C (0 to 212°F)	T1P1	T1P2
100 to 315°C (212 to 600°F)	T2P1	T2P2
Above 315°C (600°F)	T3P1	T3P2

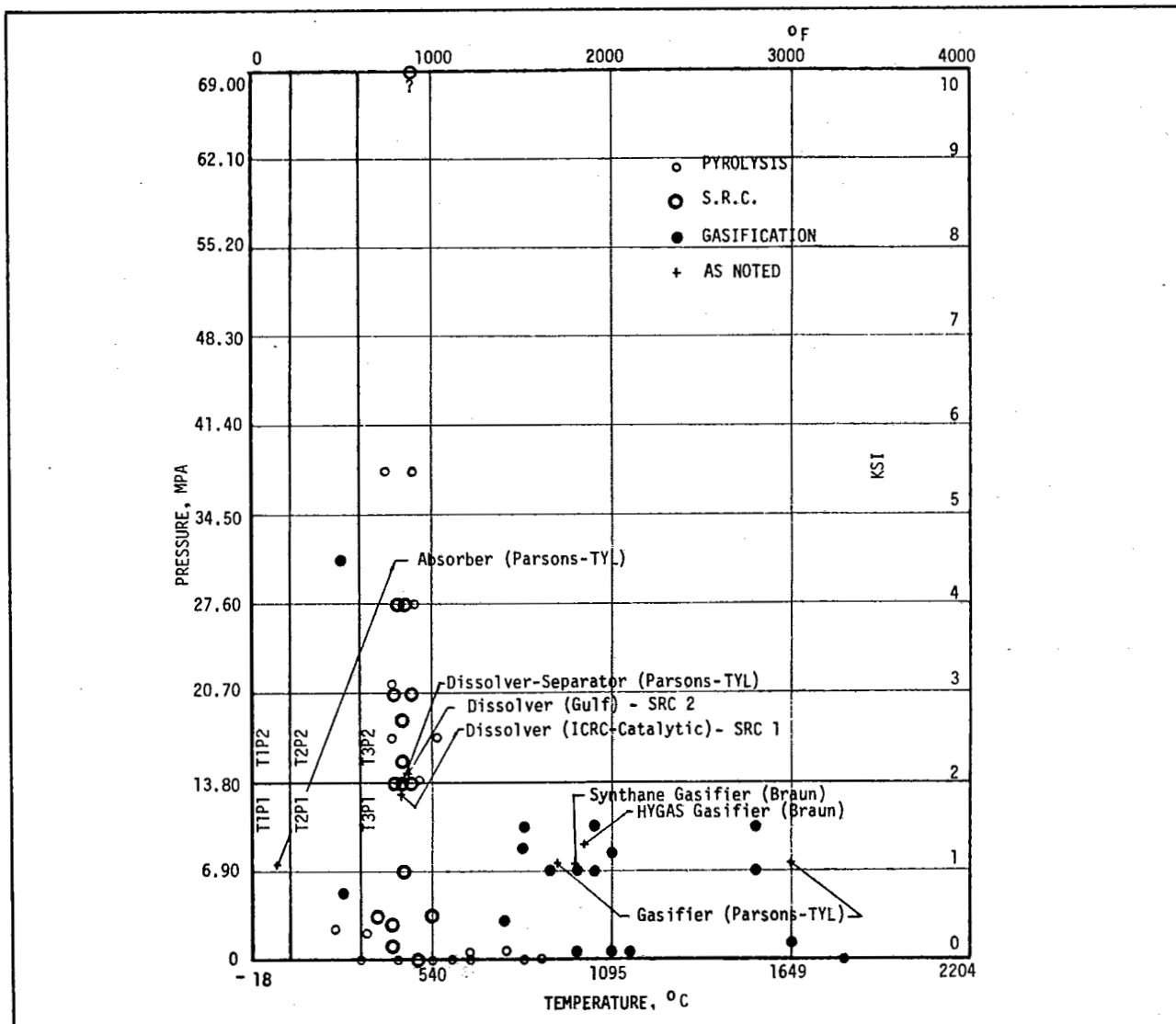


Fig. 2.1 Distribution of Service Conditions (Pressure and Temperature) for Coal Conversion Processes (1)

CHAPTER 3: SAFETY CONSIDERATIONS3.1 GENERAL

Safety requirements for a PCPV must be considered first at the stage of conceptual design. They continue through the life of the vessel, and end when the vessel has been discarded in a safe manner. The user, designer, materials supplier, constructor, inspector and operator must give due attention to safety. The primary objective of the eventual Code for Composite Concrete and Steel High Pressure Vessels for General Industrial Use will be to ensure public safety through the enforcement of rules to which these parties must conform.

There are several safety features inherent in prestressed concrete pressure vessels. The foremost of these is redundancy of the structure. Failure of one or more prestressing tendons does not result in loss of integrity. In fact, designs of PCPVs account for continued operation of a vessel when a single tendon (or more) fails or is removed for inspection and/or replacement. The next significant safety feature is the inherent ductility of prestressed concrete. Because of the inherent ductility, failure is gradual, permitting cracking and extensive deformations to take place before total failure occurs. If the cavity pressure is reduced after a large deformation, by leakage or by means of a relief device, the tendons will often recover and close the concrete cracks. This feature of PCPVs is often a distinct safety advantage over metal vessels since a local, through-thickness crack in a steel vessel may propagate and result in loss of the complete pressure boundary.

Because of the composite nature of a PCPV, several materials are relied upon for its strength whereas an equivalent metal vessel relies upon only one material. The PCPV liner provides pressure retaining integrity in two distinct ways. As a composite part of the shell, its membrane resistance adds to the ultimate vessel strength. Also, it seals the inner surface of the vessel and thus prevents vessel fluid from penetrating concrete and pressurizing cracks. A PCPV liner is subjected to corrosion just as a metal vessel is, but stress-corrosion cracking can result in loss of the pressure boundary in a metal vessel. In a PCPV a corrosion failure will only allow leakage and will not lead to complete failure until the main structural elements (tendons) have failed, provided that pressurized cracks are taken into account in the design.

In a PCPV, internal hoop forces are easily overcome by prestressing. Placing high pressure equipment within the primary containment, which has been constructed to high safety standards, increases the safety of the facility. Multi-cavity vessels are sometimes constructed in which auxiliary vessels are included in the prestressed primary containment. This feature is utilized in the High Temperature Gas-Cooled Reactor (HTGR) program in which steam generators and other components surrounding the nuclear reactor core are included within the boundary of the PCPV. The concept of an integrated gasifier for coal conversion will include this feature. In this case, PCPV tendons are placed in a low temperature area. This reduces the effects associated with relaxation.

3.2 EFFECTS OF MATERIAL SELECTION ON SAFETY

To prevent brittle failures of steel vessels, special consideration is given to the material properties of both the base and weld metals of the vessel.

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materials of construction. In particular, properties such as fracture toughness, yield stress and strain, and ultimate stress and strain are evaluated for the environment in which the vessel will be subjected during its service life. In general, materials are desirable which exhibit high fracture toughness and a high ratio of ultimate strain to yield strain (high ductility). These properties are preferred because high fracture toughness is indicative of a material which restricts the propagation of cracks and high ductility is indicative of a material which is capable of absorbing significant amounts of energy prior to failure. These characteristics would generally lead to highly visible distortions of the vessel which would warn personnel of an impending failure.

In the design of PCPVs, the safety considerations and the requirement of ductility are still the same, i.e., failures are progressive and accompanied by large deformations. Prestressing tendons have much larger strain capacity than concrete and would permit the PCPV to deform and crack long before they reach ultimate strength. The ultimate strain capacity of the prestressing tendons is therefore of great safety concern, and they should be selected to ensure that the ductility requirement of the PCPV is met.

There are five structural materials of interest in the design of a PCPV. These are the concrete, the prestressed reinforcing steel, the non-prestressed reinforcing steel, the liner plate material and steel portions of penetrations and closures. The mechanical properties of these materials are discussed in Chapter 4 of this report.

3.3 SAFETY ASPECTS OF DESIGN

The safety of a PCPV in terms of ultimate capacity should compare to a vessel designed in accordance with Section III, Division 2 of the ASME Boiler and Pressure Vessel Code (5).

The design criterion for PCPVs accounts for the structural redundancy and ductile failure modes associated with the concrete vessels, the analysis, the degree of quality control, and inspection. Ductile failure modes are implied in ASME Code, Section III, Division 2, which requires that

"...as its ultimate structural capacity is approached, vessel response will be gradual, observable, and predictable and in a manner such that the minimum ultimate load capacity is clearly developed."

The code further requires that the lowest mode of failure which conforms to this characteristic shall be at a lower pressure than any nonconforming mode such as a shear failure. This requirement is intended to ensure that corrective action can be taken before a failure occurs and precludes a sudden failure that could occur in a steel vessel. The opening of exterior cracks is one warning mechanism. This is illustrated in the pressure-strain plot of Fig. 3.1 which shows a substantial strength margin and ductility after visible cracking occurs. Of course, liner leakage will cause cracks to become pressurized, thereby reducing the vessel's ultimate strength. This phenomenon is taken into account in PCPV design.

Chapter 5 gives an in-depth discussion of design and analysis including design details which enhance safety, as well as the load factors used for design.

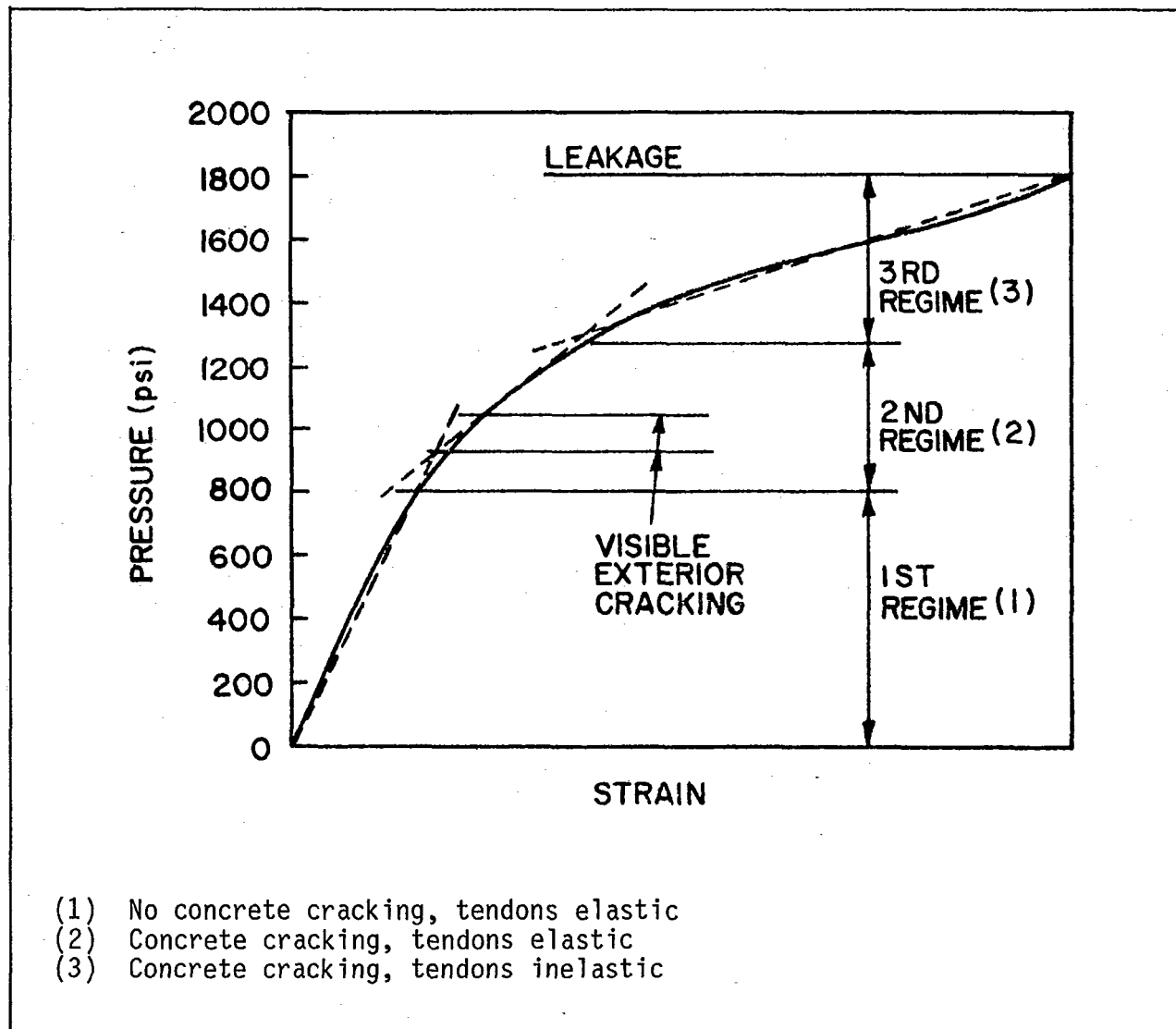


Fig. 3.1 Predicted Strain Behavior of a PCPV (9)

3.4 FABRICATION AND CONSTRUCTION

In the construction of PCPVs, one must realize the limits of codes of practice or standards as applied to concrete structures such as these very large pressure vessels, which are usually unique and do not offer the benefits of replication. Standards lay down requirements for construction of the various parts of the vessel, to ensure that it is fit for its purpose, safe, reliable and not unnecessarily costly. The PCPV safety, as it is affected by a number of large vulnerable components such as penetrations and their closures, etc., should be considered during construction. The critical areas for the PCPV construction are discussed in this section.

3.4.1 Construction Details

The safety of the PCPV is dependent on not just the design but the construction, construction details, and operation as well. The question of the integrity

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of concrete vessel penetrations has been a key factor in consideration of safety. The problems include both the effect of the large penetrations on the structural properties of the envelope and the integrity of the penetration closure units themselves. To ensure the structural integrity, the construction of these units should conform to the construction details provided in the construction drawings and be in accordance with procedures defined in construction specifications. In addition, pressure testing should be conducted to provide assurance regarding the soundness of construction.

In most PCPVs the liner or membrane does not play a significant role in the overall strength of the structure. It is the indirect effects of liner on the design and construction of the PCPV which should be carefully examined. Where a liner is used as formwork for concrete placement, it is important that its shape and construction features should not inhibit the placement of good quality concrete. On the other hand, its functions include the location and support of the insulation and cooling system and the transfer of loads from internal structures and penetrations to the concrete structure. In light of these, the importance of the liner construction is obvious and it should be constructed in accordance with the detail provided in the design drawings and the construction specifications.

3.4.2 Material Traceability

Uncertainties associated with PCPV materials are inevitable and different structural elements or components of a PCPV have different degrees of uncertainties associated with them. The safety factor provided for the PCPV is dependent upon the control of materials being used. The material chosen in the construction should conform to the requirements of the material specification. The material manufacturers are responsible for the quality as identified in their test report.

3.5 OVERPRESSURE PROTECTION

All pressure vessel codes, including Sections III (Divisions 1 and 2) and VIII (Divisions 1 and 2) of the ASME BPVC, have requirements for overpressure protection that may be adapted in the proposed code for non-nuclear PCPVs. Although the existing codes do not cover pressure vessel operation, which is the cause of possible overpressure, protection against overpressure is so fundamental to safety that requirements for overpressure protection devices are included in the present codes and should form a part of the future code for non-nuclear PCPVs.

Overpressure protection is accomplished by a number of different devices. Single or multiple spring-loaded non-reclosing relief valves can be used in those cases where closing and regaining the pressure boundary after overpressurization is not required. Sometimes, rupture discs are used in series with relief valves. Power actuated pressure relief valves, which require an external energy source, are allowed by the codes when certain redundancies are included in the system (a minimum of two such valves are required by Section III, Division 2). Also, pilot operated valves may be used. These do not require an external energy source because the pilot control system is actuated directly by the contained pressure of the vessel.

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Whatever the relief device may be, it is designed to actuate at the "set" pressure which, for general industrial applications, is not higher than design pressure. The relieving devices have adequate capacity such that when valves are fully open they will prevent the vessel pressure from rising more than 1.1 times design pressure.

In Sweden, the design of PCPVs for boiling water reactors includes a venting system in the concrete adjacent to the liner. The purpose of this system is to limit pressure in the concrete to "acceptable levels" (10) in the event of a gas leakage through the liner. This system also provides a means to monitor and ensure the continued integrity of the liner pressure barrier.

Overpressure protection is considered to be so important that code symbol stamping and certification of overpressure protection devices is required for vessels designed in accordance with the ASME BPVC. For nuclear PCPVs, a certified overpressure protection report is also required. It is considered prudent to require similar provisions as a part of the Designer's Construction Report because of the importance and complexity of the typical PCPV for general industrial use. This is an exception to current practice for pressure vessel systems of customary construction.



CHAPTER 4: MATERIALS

PCPVs are designed to serve as the primary pressure containment structures. The safety of these vessels depends, firstly, on a correct assessment of the loadings, including overloads, likely to be applied to the vessel, together with the probability of these occurring and, secondly, on the proper design of the vessel to accept these loadings. Proper design of the vessel thus requires a knowledge of the component (material) properties.

4.1 CONCRETE AND SPECIALTY CONCRETES4.1.1 Materials, Mix Proportioning, Production, Placement, Consolidation, and Curing

Recommended procedures for material selection, mix proportioning, production, placement, consolidation, and curing of structural concrete are well established (Section 6.2.2). Procedures and test intervals used to test materials for conformance with requirements are contained in the construction specification. (Table CB-5200-1 (5) presents requirements, test methods, and frequency of testing for materials used in fabrication of PCPVs for nuclear applications.)

4.1.2 Properties

Table 4.1 lists preferred concrete properties for PCPVs (11). Specified concrete properties to be determined, the age and temperature at testing, and any special environmental and loading considerations are defined in the construction specification. Properties to be considered include strength (compressive, tensile, shear, concrete-rebar bond), modulus of elasticity, Poisson's ratio, thermal (thermal expansion, conductivity, diffusivity, specific heat), and shrinkage and creep. Reference (12) presents a review of available concrete property data and the effects of loading and environmental factors on concrete properties. Property data obtained from such a report can be utilized for preliminary PCPV designs, however, the property data which are used for the final design are generally obtained from specimens fabricated using the same materials used for fabrication of the PCPV.

4.1.3 Specialty Concretes4.1.3.1 High-Strength Concrete

High-strength concrete is a relative term and as such, for purposes of definition, it will be considered to be concrete with compressive strengths in excess of 41.4 MPa (6000 psi). Although concretes having compressive strengths in excess of 172.4 MPa (25000 psi) are attainable using special fabrication procedures, the current practical and economic limit of ready-mixed concrete appears to be on the order of 80 MPa (12000 psi).

Table 4.1 Preferred Concrete Properties for PCPVs (11)

Preferred Property	Reasons
High compressive strength at normal and elevated temperature	To reduce vessel thickness and increase allowable stresses. Other strength properties are to some extent related to compressive strength.
Good mix workability	To ensure good consolidation in placing, particularly in areas where high concentrations of reinforcement and prestress ducting exist
Low elastic and creep deformation under load	To minimize movements and redistribution of stresses under varying load and temperature cycles. To reduce prestress losses.
Low drying shrinkage	To minimize movements and temperature stresses
Low thermal expansion	To minimize movements and temperature stresses
Resistance to thermal shock	To prevent damage to structure in areas subject to rapid heat application; i.e., adjacent to steam openings
High thermal conductivity	To minimize the cooling system required to keep the vessel concrete at a permissible temperature.

Optimization of mix characteristics is required to achieve high-strength concrete. These include, but are not limited to:

- (1) characteristics of the cementitious materials;
- (2) characteristics of the aggregate;
- (3) proportions of the paste;
- (4) paste-aggregate interaction;
- (5) mixing, consolidation, and curing; and
- (6) testing procedures.

Production of high-strength concrete mixes generally involves the use of high cement factors [385 kg/m^3 ($> 650 \text{ lb/yd}^3$)], fly ash, silica fumes and other

pozzolans, and low water-cement ratios (0.3 to 0.4). Conventional and extended range water reducers can be utilized to reduce water requirements for a particular mix, but their compatibility with the particular cement utilized in the mix needs to be elevated. References (13) and (14) can be consulted to obtain information on mix proportions for high-strength concretes.

High-strength concretes generally have higher moduli of elasticity and reduced ductility* relative to normal concretes. Thermal properties are within the common range of conventional strength concretes. Creep and shrinkage data may be obtained from References (15) through (19). Reference (20) makes some general observations relative to high-strength concretes: 1) since creep is proportional to water-cement ratios, and high-strength concretes have lower water-cement ratios, they should have less creep; and (2) high aggregate contents reduce creep at working stress levels.

4.1.3.2 Steel Fibrous Concrete

Steel fiber reinforced concrete consists of concrete to which small cross-section steel fibers are added (0.5 to 2.0 percent, by volume) during the mix process. Addition of the fibers enhances concrete's material properties by increasing the first crack flexural strength, direct tensile strength, shear strength (diagonal tension), impact and spalling resistance, fatigue strength, thermal conductivity and ductility. Fiber addition to refractory concretes also increases its thermal shock and spall resistance. Typical properties of fibrous concrete can be obtained from Reference (21). Although addition of fibers to the mix increases the material cost, enhanced material properties may potentially produce PCPVs which are cost effective. Also, when random distribution of fibers is achieved, the concrete can be analyzed on a uniform basis with systems like the finite element method.

Details on fibrous concrete mix proportions can be obtained from Reference (22). Fibrous concrete can be provided using batch plant or ready-mixed concrete trucks. Techniques for batching, transporting, and placing fibrous concrete are similar to those used for conventional concretes. Reference (21) can be consulted for details on techniques which have been used in the field.

4.1.3.3 Polymers in Concrete

Due to their high cost relative to conventional concrete, polymer in concrete materials are generally utilized for special applications where their superior strength, durability, etc., properties can be effectively utilized. Another potential problem with these materials is that many of the polymers may be unstable at high temperature. However, there are many potential applications where polymer in concrete materials may be utilized to take advantage of their unique characteristics.

Polymers in concrete combine hydraulic cement with polymer technologies to form new and improved construction systems having compressive and tensile

*Ductility limitation is overcome in construction through the use of steel reinforcement.

strengths which may reach values exceeding 205 and 11 MPa (30 and 1.6 ksi), respectively. There are basically three types of systems: 1) polymer impregnated concrete (PIC) (hydrated portland cement impregnated with a monomer which is polymerized in-situ), 2) polymer portland cement concrete (PPCC) (premixed material in which either a monomer or polymer is added to fresh concrete in a liquid, powdery or dispersed phase, and subsequently allowed to cure, and if needed, polymerized in place), and 3) polymer concrete (PC) (composite material formed by polymerizing a monomer and aggregate mixture, with the monomer acting as a binder).

PIC exhibits reduced creep, improved resistance to aggressive environments, and similar thermal expansion values to conventional concrete. PPCC exhibits improved tensile and flexure strengths, increased ductility, improved durability and superior adhesion. PC exhibits shrinkage during hardening, thermal expansion coefficients which are high relative to portland cement concretes, high chemical resistance, creep behavior which can be significantly affected by the temperature and humidity of the environment, and the shape of the stress-strain curve can be varied to suit a particular application through selection of the polymer binder.

References (23) and (24) can be consulted for more details on polymer in concrete materials, fabrication techniques, and properties.

4.1.3.4 High Temperature Resistant Concrete

Refractory concrete, defined as concrete suitable for use at high temperatures and containing hydraulic cement as the binding agent, generally utilized calcium aluminate cement as the binder. However, selected aggregates which have been checked for stability at the temperature level of interest can be used with portland cement in some applications up to an approximate temperature of 1090°C (2000°F). Refractory mixes using sodium silicate and certain phosphates as a principal cementing agent have also been used.

Many common aggregates are unsuitable for high temperature service because they contain quartz which exhibits a large volume change at approximately 575°C (1065°F). Diabase traprock, olivine, emery, and expanded aluminosilicates can be used to temperatures of 1000°C to 1350°C (1830°F to 2460°F). Refractory aggregates such as crushed firebrick (30 to 45 percent Al_2O_3) are suitable to temperatures of 1600°C (2910°F). For temperatures up to 1800°C (3270°F) aggregates such as fused or sintered alumina can be used.

The effect of water content on the physical properties is critical. Excess water can severely degrade the strength and other properties of the refractory concrete.

Properties of refractory concretes are both time and temperature dependent. Casting, pumping and shotcreting techniques are used for installing refractory concretes. References (25) and (26) can be consulted to obtain additional information on refractory concretes.

4.2 STEEL REINFORCEMENT

Bonded reinforcement (deformed bars) are provided in PCPVs to: 1) resist the extent of cracking and width of cracks at operating temperatures; 2) resist

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tensile stresses and computed compressive stresses for elastic design, and 3) provide structural reinforcement where required by limit condition design procedures.

Nonprestressed steel reinforcement used in the fabrication of PCPVs conforms to the requirements of ANSI/ASTM 615 (27). Placement of reinforcement is generally done according to tolerances contained in a construction specification. When splicing of reinforcing bars is required, available techniques include:

- 1) lap (size number 11 and smaller),
- 2) sleeves with metal fillers,
- 3) arc welded joints,
- 4) swaging,
- 5) taper threaded, and
- 6) threaded deformed reinforcing bars.

Additional information on details of reinforcement (placement, bending, joints, etc.) can be obtained from references such as (5) and (28).

Properties of reinforcing steel used in design are generally a function of yield stress. Elevated temperatures decrease the material's ultimate strength, yield strength, and modulus of elasticity. Reference (29) provides information on effects of temperature on reinforcing steel properties.

4.3 PRESTRESSING MATERIALS

A post-tensioned prestressing system consists of prestressing tendons in combination with methods of stressing and anchoring the tendons to hardened concrete. To attain satisfactory performance, prestressing systems are designed to: 1) have consistently high strength and strain at failure, 2) be serviceable throughout the PCPV design life, 3) be reliable and follow safe prestressing procedures, and 4) have the ability to retension and replace (ungrouted tendons).

Three major categories of prestressing systems exist, depending on the type of tendon utilized: 1) wire (ANSI/ASTM A 421) (30), 2) strand (ANSI/ASTM A 416) (31), and 3) bar (ANSI/ASTM A 322) (32). Wound or circumferential prestressing could be a fourth category; but this system generally utilizes either a strand or wire system. Anchorage of the systems is accomplished by wedges, button heading or nuts. Prestressing systems are available having load capacities in excess of 13.6 MN (3000 kips). A listing of the various linear systems which are available can be obtained from References (9) and (33) through (36). Information on circumferential prestressing systems is contained in References (37) through (39).

Since the tendons are one of the primary strength producing members in the PCPV, it is important that they be protected from environmental factors, notably corrosion and elevated temperature. A construction procedure is required to specify the manner in which prestressing materials are to be received, identi-